Published in Mercian Geologist (2011), 17/4, pp.274-279

Cool Britannia – from Milankovich wobbles to Ice Ages

Jonathan R. Lee

British Geological Survey, Keyworth, Nottingham, NG12 5GG.

Introduction

The snow and intense cold of December 2010 – the coldest month since meteorological records began, is a timely reminder that despite living in a warm ('interglacial') period – the Holocene, climate in recent Earth History has been markedly colder for periods lasting many thousands of years. These 'cold stages' form part of the Quaternary geological period which spans the past 2.6 million years (Ma). It marks the transition from the sometimes 'greenhouse' climates of the Cretaceous and earlier Cenozoic, through to 'Ice Age' earth. We often hear that the Quaternary is synonymous with the 'Ice Age'. In reality, this is somewhat misleading. Whilst there were numerous extended 'cold periods' or 'glacials' which did result in 'Ice Ages' during the Quaternary, equally, there were many 'warm periods' or 'interglacials' where the climate in Britain was at least as warm if not warmer than today. Quaternary 'climate change' has had a profound and lasting impact on our landscape. In particular, the form of much of the landscape is a legacy of our 'Ice Age' history. Understanding our 'Ice Age' history is important in understanding not just our landscape heritage and its conservation and sustainable use, but also in appreciating just how sensitive our land-mass is to the long-term forces of 'climate change'. Within this paper, we explore the long-term history of 'Ice Ages' in Britain and Ireland, focussing on why they occurred, and when and how big they were.

Cenozoic Ice Ages – a global perspective

Global climate has deteriorated progressively throughout the later part of the Cenozoic Era, with the first 'Ice Age' or 'glaciation' of Antarctica occurring as long ago as 34 Ma. In the Northern Hemisphere, the appearance of such large-scale glaciation occurred much later. Evidence from core samples collected from beneath the sea bed in the Nordic Seas indicate the first presence of glaciers on Greenland during the Miocene period about 12.7 Ma ago. The key evidence was thin layers of marine sediment called 'Ice Rafted Detritus' or 'IRD' for short. IRD records the deposition of debris dropped from melting icebergs that have broken-off or calved from a floating, often marine based, ice margins. In simple terms, IRD provides scientists with clues as to the extent of glaciers where land-based evidence such as moraines and tills (boulder clay), may have been long-since removed. Geologists can also use a range of geochemical techniques to examine the composition of the IRD to determine which rocks have been eroded and incorporated into the glacier, and indeed, where the iceberg and its host glacier came from – a form of glacier forensic fingerprinting (**Figure 1**).

Despite evidence for glaciation in Greenland dating back into the Miocene, it wasn't until the Late Pliocene and Early Pleistocene – some 9 million years later, that widespread glaciation occurred within North America, Greenland, Britain, Scandinavia and the Barents Sea region. Rather than being abrupt, the onset of glaciation was actually a gradual long-term transition that accompanied an increase in global ice volume that spanned a period of about 1.2 million years between 3.6-2.4 Ma.

IRD records from the North Atlantic demonstrate the established presence of large ice sheets on Greenland and around the Barents Sea region from about 3.3 Ma. Closer to home, ice sheets in Britain, Ireland and Scandinavia first became active at around 2.7-2.6 Ma. However, between their initial formation and the present day, their extent and the overall scale of glaciation has waxed and waned depending on the prevailing climate and the ability of the ice sheets to grow and maintain their size. Generally though, it has been recognised within the Northern Hemisphere that the scale and frequency of glaciation during the Quaternary 'cold stages' has increased progressively.

Now of course, we live in an 'interglacial' – a period where the amount of water locked into the world's ice sheets and glaciers naturally declines, and water previously locked-up as ice within ice sheets returns to the oceans and sea-levels rise. Since the peak of the last glaciation some 24,000 years ago, the progressive melting of glacier ice in high and mid-latitude areas has resulted in a global sea-level rise of about 130m. This has resulted in the drowning of large parts of the European continental shelf and the inundation of marine conditions into the North Sea and Irish Sea – both basins were largely devoid of sea-water during the 'Ice Ages', when sea-levels were much lower and more water was locked-up within the worlds ice sheets. The vast majority of the great Northern Hemisphere Pleistocene ice sheets have now largely melted and disappeared. This includes the Laurentide Ice Sheet, which once covered over a half of North America, and the British-Irish Ice Sheet which has been absent from our landscape for about the past 11,500 years. The majestic fjords of western Norway that were once cut by immense rivers of ice are now devoid of glaciers. Ice still clings to some of the high plateaus of western and northern Norway such as Jostedalsbreen, although many of the small alpine glaciers are now in a state of rapid retreat. The largest remaining body of ice in the Northern Hemisphere is the Greenland Ice Sheet. This ice sheet has a surface area of approximately 1.7 million km^2 although the margins of the ice sheet are rapidly constricting amid concerns of the impact of human-induced global warming. Should the entire mass of the Greenland Ice Sheet melt, it would result in a global sea-level rise of about 7.2m.

What causes Ice Ages?

One of the most obvious questions is why glaciers and ice sheets have been able to grow so extensively during the Quaternary, and less frequently throughout other parts of the geological record. The precise answer to this question has baffled climate scientists for several decades. The consensus view is that the Quaternary and other geological episodes where 'Ice Ages' have been commonplace are unique in combining a specific set of geological and geographic 'circumstances' that accentuate a longer-term pacemaker that regulates global and regional climate.

This climatic pacemaker relates to long-term changes in the shape and nature of the earth's orbit around the sun. Such 'astronomical' phenomena have forced earth climate throughout geological time and have operated over a range of temporal time scales. Critical to our 'Ice Age' story are millennial-scale changes in the earth's orbit that follow regular and predictable cycles. These cycles are often referred to as 'Milankovitch Cycles' and are named after the Serbian astrophysicist who identified them. They correspond to subtle changes in the elliptical shape of the Earth's orbit around the sun ('eccentricity') that occur over 100,000 year cycles, and slight tilts ('obliquity') and wobbles ('precession') of the Earth's axis that occur over 41,000 and 21,000 year time-scales respectively. In simple terms, these cycles impact upon both the amount of radiation that the earth receives, and its spatial and temporal distribution over the earth surface through the seasons – in other words, seasonality.

Whilst this 'astronomical forcing' exerts a dominant control on the background 'global climate', a range of regional to local scale geographical and geological controls are also required to enable ice sheets to develop and grow. One of the most important controls is the global configuration of the continents, due to the way it controls oceanic and atmospheric circulation, and in-turn, the distribution of heat and moisture around the planet. Land is also required in high and mid-latitude areas to enable ice to form into ice sheets and glaciers.

By way of an example, we mentioned earlier that ice sheets developed on Antarctica far earlier than in the Northern Hemisphere. This occurred when the continent of Antarctica detached from South America about 34 million years ago and drifted southwards into the Southern Ocean by processes of continental drift. This led to the opening of the Drake Passage and the surrounding of the Antarctic continent by cold ocean currents – Antarctica literally froze, and the Antarctic Ice Sheet soon developed.

The story from the northern hemisphere appears to have been more complex. Many scientists believe that the critical factor was the closing of the Central American Seaway that linked the tropical waters of the Pacific and Atlantic, and the formation of the Isthmus of Panama about 5 Ma. The reason why this is critical is that oceanic circulation – a global-scale conveyor belt that circulates water around the worlds' oceans, is principally driven by salinity differences between the two oceans. With the Central American Seaway open, the transfer and mixing of warm tropical surface-waters from the Pacific and Atlantic oceans largely balanced the salinity differences between the two oceans. By contrast, closure of the seaway created a greater salinity imbalance between the two oceans leading to enhanced oceanic circulation and the more effective transfer of heat and moisture around the globe.

For northwest Europe and the UK, the Gulf Stream plays a key role in keeping our climate more temperate than places such as Labrador and Newfoundland that lie at similar latitudes. Closure of the Central American Seaway led to the Gulf of Mexico becoming more saline driving greater rates of heat and moisture circulation into higher northern latitudes via the Gulf Stream. As these warm saline surface waters are transferred northwards, they cool, increase in density and sink. From the Greenland Sea, these bottom-waters then flow back southwards via the Labrador Sea, drawing-in even more warm water into the conveyor. Moisture is not only essential in nourishing ice sheets, but also contributed large amounts of cold freshwater into the Arctic Ocean either directly or by rivers from northern Eurasia. Introducing this cold freshwater into the Arctic Ocean made the surface ocean waters much colder and less salty, making it possible for the regular development of seasonal and continuous sea ice. Extending like a blanket across the oceans in high latitude polar areas, this sea ice also played an important role in reflecting incoming solar radiation back into space. This process is known as the 'albedo affect' and is self-perpetuating – the more sea-ice, the greater reflection of solar radiation, the colder it gets, which encourages greater formation of sea-ice…and so-on.

Together the 'astronomical' and 'regional' scale mechanisms regulate climate but interact with local geographic factors such as elevation and latitude to control temperature, and whether precipitation falls as rain or snow. These factors in-turn drive the 'mass balance' of an ice sheet or glacier – namely, the relative balance between snow fall and conversion to ice ('accumulation') that make glaciers grow, and the loss of ice volume to melting and iceberg calving ('ablation') which makes glaciers shrink. Thus, for an ice sheet to form and grow rapidly, the rate of 'accumulation' has to far exceed the 'ablation' rate. By contrast, if the rate of 'ablation' is far higher than 'accumulation' then either an ice sheet won't form or an existing ice sheet will shrink.

Cool Britannia

Until recently, geologists believed that Britain and Ireland remained ice free for much of the Quaternary with only two extensive glaciations occurring **(Figure 2)**. The first of these was the Anglian Glaciation which occurred between 0.48-0.43 Ma. This was the largest glaciation to affect us during the Quaternary with ice extending across two-thirds of Britain and Ireland down to Oxfordshire and north London, and laterally to the edge of the continental margin from western Ireland around to Norway. Both the North Sea and Irish Sea were land and occupied by glacier ice. In the Midlands, Pennine Ice deposited the Thrussington Till as it moved west to east across the region. Later, British North Sea ice extended westwards across the Lincolnshire Wolds into the Midlands depositing the chalky Oadby Till. The second glaciation was the Late Devensian glaciation with a maximum ice sheet extent – referred to as the Last Glacial Maximum, achieved at around 27ka ago. Again, glacier ice occupied much of the North and Irish Sea basins with ice extending southwards from Scotland into northern and northern England. British North Sea ice reached the Wash but there is no direct evidence for ice ever reaching into the East Midlands or beyond. Instead, the area that lay beyond the Last Glacial Maximum ice limit, as with other glacial limits, was subjected to intense cold with large areas of frozen ground **(Figure3)**.

Together, this evidence suggests that Britain and Ireland had a limited glacial history during the Quaternary. It implies that ice sheets and glaciers were only sporadically active within our landscape. This is somewhat puzzling, especially when the position of Britain and Ireland relative to an abundant moisture source (the North Atlantic) and the Polar Front is considered. Indeed, new scientific data and re-examined information, suggests that Britain and Ireland may have been glaciated on many separate occasions. The evidence for these extra glaciations is often very discrete and even open to different scientific interpretations. Equally, determining their precise is age has proved very problematic. In the sections that follow, we review all of the evidence and paint a picture of numerous Ice Ages **(Figure 4)**. Broadly speaking, we can divide our Ice Age history into 3 separate phases – each relating to different scales and / or frequencies of glaciation.

2.6 – 1.2 million years ago

The climate in Britain and northwestern Europe during this time-interval was driven by the short-term 'precession' and 'obliquity' orbital cycles producing numerous episodes of climate change albeit of small magnitude and duration. Several scientists have speculated that this global climatic backdrop was probably insufficient to generate permanent ice caps over highland areas of Britain such as Wales, the Lake District and Scottish Highlands, such that when glaciations did occur, they were of limited spatial and temporal extent.

Several lines of evidence have been discovered that support this assertion. On the Hebrides Margin, located to the northwest of the Hebrides, a large submarine fan called the Sula Sgeir fan extends outwards from the edge of the continental shelf. Sediment cores obtained from the fan reveal that the earliest Quaternary deposits contain fragments of rock derived from northwest Scotland. It is believed that they were transported to the shelf edge by icebergs before they melted and dropped the rock fragments. The source for these icebergs is likely to be glaciers that extended from highland parts of western Scotland into coastal areas, where they eroded and entrained the rock material, before calving and releasing the icebergs. Further south in Southern and Eastern England, a number of far-travelled erratics from North Wales – some of which possess glacial striations, have been found within ancient deposits of the River Thames. These deposits relate to a period during the early part of the Quaternary when the upper reaches of the River Thames lay within Wales, far to the west and north of their current location in the Cotswolds. The erratics are considered to have been transported within blocks of ice by melt-water streams that eventually flowed into the Thames. Further downstream, the blocks of ice grounded, whereupon they melted and deposited the erratics – a minimum of ten separate restricted glaciations in North Wales have been speculated.

Recently, new evidence from the Porcupine Basin – located on the continental margin to the southwest of Ireland, has led scientists to radically reconsider the notion that ice sheets were limited in temporal and spatial extent during this time interval. Sediment cores reveal no less than 16 major pulses of IRD derived from western Britain and Ireland between 2.6-1.7 million years ago. Each of these IRD pulses records separate occasions where glacier ice extended into coastal waters, with thin layers of ice-rafted sediment deposited across the continental shelf and margin from melting icebergs. It suggests that in places in western Britain and Ireland, ice caps were likely to have existed for prolonged phases during this period.

1.2-0.48 million years ago

This second period of time takes us upto our biggest glaciation – the Anglian glaciation. It spans a period where global climate was in state of transition from climate change driven by the smaller, more frequent, 'precession' and 'obliquity' orbital cycles, to the higher magnitude 100ka 'eccentricity cycles'. The effect of this 'Mid-Pleistocene Transition' - as it has become known, was to make Britain, Ireland and other parts of northwest Europe far colder during 'cold stages' and reduce 'seasonality'. It pushed the Polar Front further southwards and for much longer periods of time leading to parts of Britain becoming arctic tundra with the ground frequently becoming either permanently or seasonally frozen (permafrost). River systems, such as the Thames mentioned previously, and others that flowed through Central and Southern Britain became much more active and dynamic. Not only did they possess a stronger seasonal flow due to melting permafrost and snow, but periglacial slope processes acted to supply them with much greater volumes of sediment. Rivers became more efficient at recycling larger volumes of material along the length of their catchments and over shorter periods of time. There is also good evidence for an increase in the size and frequency of glaciation. Rather than simply being restricted to highland parts of Britain and adjacent coastal areas, ice also extended into more lowland parts of Central England and the Thames Basin, and further eastwards into the North Sea Basin. Evidence from the North Sea and adjacent parts of East Anglia includes several generations of tills and meltwater-incised valleys, iceberg plough surfaces and ice-rafted erratics.

0.48 million – 11 thousand years ago

This time period spans the two big glaciations to affect Britain and Ireland – the Anglian and Late Devensian glaciations, and the final decay of our last great ice sheet. Globally, the 100ka ‘eccentricity’ orbital cycle dominates and drives big oscillations in climate between warm temperate interglacial stages and cold glacial stages - in total six major cold glacial stages and five major interglacial stages have been recognised. During cold stages, the effect of this climate forcing is to promote the rapid build-up of ice volume within high and mid-latitude areas. Cores and offshore seismic data from around our continental margin demonstrate the presence of glacier ice on the continental shelf during each of the major cold stages. On land, evidence for glaciation is largely confined to the Anglian and Late Devensian glaciations already referred to. During the Anglian Glaciation (480-430 thousand years ago) the Midlands was extensively glaciated with the region located some 175km up-ice (northwards) of the maximum ice sheet extent. The effect of the glaciation on the landscape of our region has been marked. Many of the old pre-glacial river systems were overridden and destroyed although their host valleys can still be identified buried beneath the modern landscape. Widespread bedrock erosion occurred with vast quantities of sediment removed and deposited by ice either as till (boulder clay) or by meltwaters issuing from the ice margin.

Late Devensian ice, although extensive in northern and western Britain and Ireland, the North Sea and Irish Sea, lay just to the west, north and east of the Midlands and didn’t directly affect the region. River terrace deposits within the Trent Valley that relate to this glacial episode contain ice wedge casts which show that whilst glaciers didn’t reach the Midlands, the climate within the region was extremely cold and arid enabling the development of frozen ground or permafrost. The maximum extent of the British-Irish ice sheet was reached about 27,000 years ago with ice extending to the continental margin offshore from northwest Scotland, and southwards to the Isles of Scilly within the Irish Sea. Progressive wasting and collapse of the ice sheet followed with ice all but absent from marine areas by 17,000 years ago. The final ‘glaciation’ to affect Britain and Ireland was a short-lived glacial event called the Younger Dryas which occurred about 12,900-11,500 years ago, when northwestern Europe was gradually emerging from the prolonged cold arid climates of the Late Devensian. It resulted in the growth of the Loch Lomond Stadial Ice Cap in highland areas of Britain and the expansion of small glaciers. The cause of this short, sharp glacial event is believed to relate to the sudden influx of freshwater from Lake Agassiz into the North Atlantic and the collapse of the North American Laurentide Ice Sheet. Scientists believe that this influx of freshwater disrupted oceanic circulation in the North Atlantic causing the Gulf Stream to shut down and plunging Britain into the deep freeze.

Whether additional glaciations occurred between the Anglian and Devensian glaciations is unclear. Part of the problem surrounds the interpretation of deposits traditionally assigned to the Anglian and Late Devensian glaciations that may in reality, equate to glaciations that took place between the two. Resolving this issue has proved challenging, due both to different interpretations of the same geological information using different techniques, and the general paucity of materials that can be dated using geochronological techniques.

The wider context…

Rather than possessing a limited record for glaciation during the Quaternary as many scientists have previously considered, the geology of Britain and Ireland reveals a complex history of ice sheets and Ice Ages **(Figure 4)**. Whilst the precise timing of many of these glaciations cannot reliably be constrained by absolute dating techniques, their broad relative timing and chronology can be determined via biostratigraphy, and their relationship to other geological sequences that possess a crude chronology. The long-term evolution of these events provides a basis with which we can understand the sensitivity of the British and Irish land-masses to climate change throughout the Quaternary.

Prior to 1.2 Ma, there is abundant evidence for the development of ice caps and localised glaciation in highland parts of western Britain and Ireland, and at times, they extended onto the continental shelf. In many respects this unsurprising considering the abundant supply of moisture from the north Atlantic which in theory would enable ice volume to build-up relatively quickly. However, these small orbitally-forced climate changes ('precession' and 'obliquity') do not generally promote the development of permanent to semi-permanent ice caps in mid-latitude areas - especially the maintenance of a moderate 'seasonality'. In this respect, the inference that ice caps were either permanent or semi-permanent over parts of western Britain and Ireland is unique and not replicated in areas such as mid-latitude western Norway. It suggests that the Polar Front lay further to the south than it does today, and / or the moisture input into western Britain and Ireland was sufficient for the glaciers to maintain a largely positive mass-balance despite more moderate 'seasonality'.

From 1.2 Ma onwards, the progressive switch to the longer-term high-magnitude orbital 'eccentricity' cycles pushed Britain and Ireland into the deep freeze during cold stages. The spatial scale of glaciation increased with ice extending occasionally into more lowland and mid-basin areas. It demonstrates that ice masses in Britain and Ireland were able to build-up larger ice volumes more quickly – unsurprising given the reduced 'seasonality'. A similar picture emerges from ice sheets in Scandinavia, the Barents Sea region and in Greenland and North America which all experience more widespread and frequent glaciation. For example, the first shelf-edge expansion of the Scandinavian Ice Sheet and the first known existence of a major ice stream off western Norway occurs at around 1.2 Ma.

By the time of the Anglian Glaciation between 0.48-0.43 million years, global climate was driven by the high magnitude 'eccentricity' cycles. The glaciation generally equates to the maximum extent of global ice coverage during the Quaternary. Putting this into a context, if you happened to have been standing in where is now Nottingham, not only would you have been extremely cold, but your were probably standing on over a kilometre of ice! Furthermore, if you started walking eastwards, you would have kept walking across glacier ice until you reached eastern Siberia! From this glaciation onwards, ice sheets possessed an even greater ability to rapidly build ice volume due to low 'seasonality'. In Britain and Ireland, the precise number of glaciations we have had since the Anglian remains contentious.

Together, all of the evidence presented demonstrates that Britain and Ireland possesses a long history of Ice Ages and glaciations that spans much of the Quaternary. The scales of these glaciations appear to increase towards the present-day with a series of marked steps in a similar manner to other ice sheets that bordered the North Atlantic. It shows that our land-mass was highly sensitive to Climate Change, and that glaciers quickly became established in highland areas when climate deteriorated.

Acknowledgements

This article has been written as a follow-up to the lecture given by the author to the East Midlands Geological Society in January 2011. The scope of the article is aimed at a non-expert general science audience, and as such I have omitted references to the numerous scientific papers that have been used. However, I wish to place on record a formal acknowledgement of their contributions to what is a fascinating aspect of the recent history of the British Isles and Ireland. In particular I wish to acknowledge a number of individual who have directly influenced my thoughts and views on this matter especially Freek Busschers, Ian Candy, Chris Clark, Richard Hamblin, Brian Moorlock, Jim Rose, Hans Petter Sejrup and Mieke Thierens. Steve Booth and Andrew Finlayson are thanked for the constructive and thought provoking reviews.

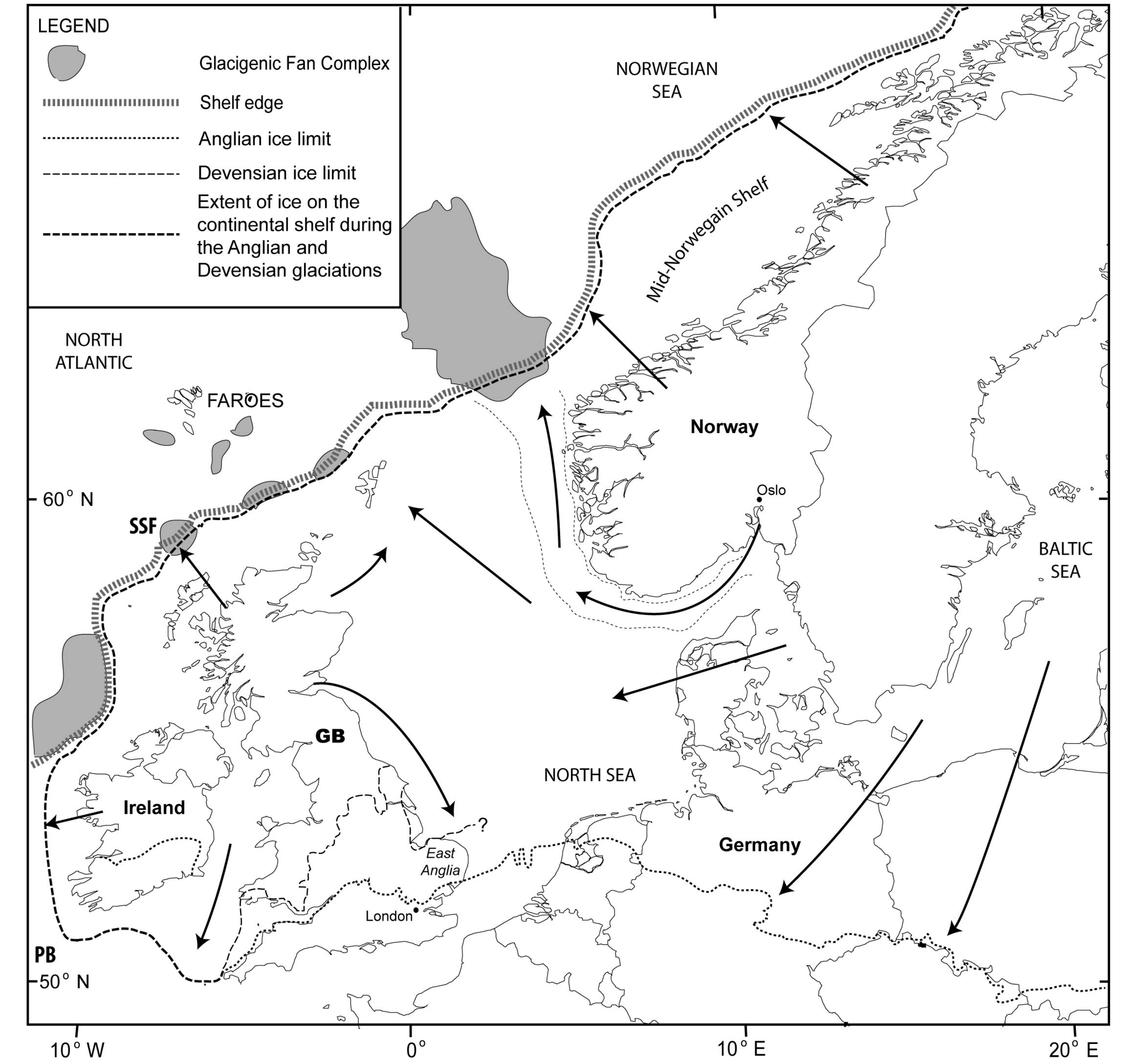
Figure Captions

Figure 1. Icebergs such as these at Jökulsárlón (Southern Iceland) are common where an ice margin terminates within a marine or lacustrine basin. Within the geological record, they can produce plough marks where they are dragged over the sea or lake bed. When the icebergs melt, the rock debris falls through the water column and is deposited. Sometimes this includes large erratic blocks, or smaller more discrete layers of sediment called Ice Rafted Detritus (IRD).

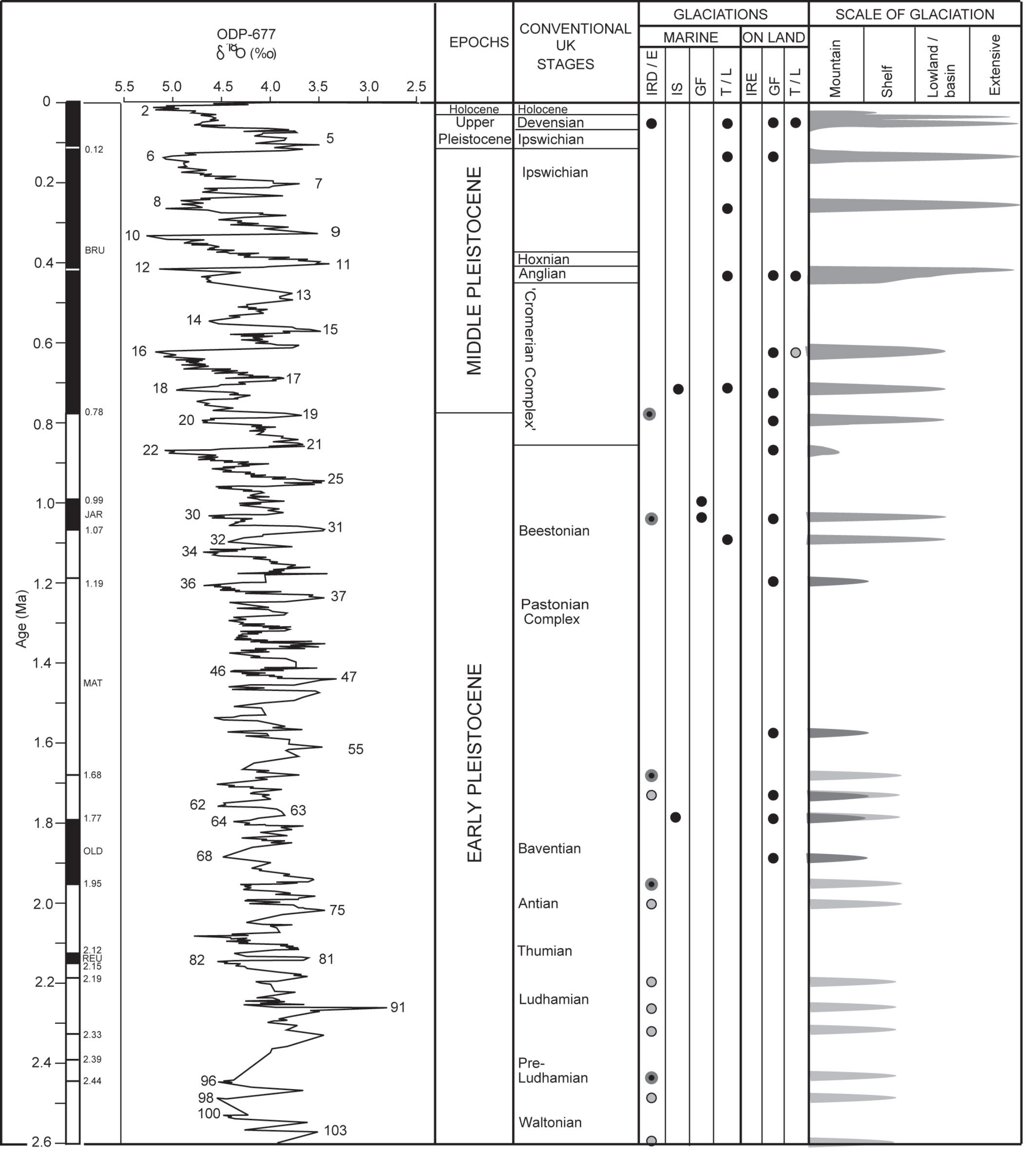
Figure 2. Map showing the main Quaternary ice limits in Britain and Ireland and their extension into Europe. Also shown are the main flow paths of elements of the British-Irish and Scandinavian ice sheets. PB – Porcupine Basin; SSF – Sula Sgeir Fan.

Figure 3. There were lots of periods of intense cold during the Quaternary. Some of these resulted in the growth of ice sheets and glaciers that extended across the landscape. In areas that weren't glaciated, vast expanses of cold arctic tundra existed complete with an exotic array of animal life. This picture could be what the southern part of the North Sea looked like 24,000 years ago.

Figure 4. Summary table showing the evidence for glaciations within Britain, Ireland and adjacent marine areas. The line on the left of the diagram shows an oxygen isotope curve which provides a crude global yard-stick for the volume of glaciation relative to sea-level. Peaks to the left show high global ice volume / low global sea-levels (i.e. 'glacials') whereas peaks to the right show 'interglacials' with low global ice volume and high sea-levels. Abbreviations: IRD / E – Ice Rafted Detritus / erratics; IS – iceberg scours and plough marks; GF – glacifluvial deposits; T / L – till and / or landforms.



LEGEND
Glacigenic Fan Complex
Shelf edge
Anglian ice limit
Devensian ice limit
Extent of ice on the continental shelf during the Anglian and Devensian glaciations
NORWEGIAN SEA
Mid-Norwegain Shelf
NORTH ATLANTIC
FAROES
Norway
Oslo
60° N
SSF
BALTIC SEA
GB
NORTH SEA
Ireland
?
East Anglia
Germany
London
PB
50° N
10° W
0°
10° E
20° E


ODP-677
δ¹⁸O (‰)
5.5 5.0 4.5 4.0 3.5 3.0 2.5
Age (Ma)
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6
0.12
BRU
0.78
0.99
JAR
1.07
1.19
MAT
1.68
1.77
OLD
1.95
2.12
REU
2.15
2.19
2.33
2.39
2.44
EPOCHS
Holocene
Upper Pleistocene
MIDDLE PLEISTOCENE
EARLY PLEISTOCENE
CONVENTIONAL UK STAGES
Holocene
Devensian
Ipswichian
Ipswichian
Hoxnian
Anglian
'Cromerian Complex'
Beestonian
Pastonian Complex
Baventian
Antian
Thumian
Ludhamian
Pre-Ludhamian
Waltonian
GLACIATIONS
MARINE
IRD / E
IS
GF
T / L
ON LAND
IRE
GF
T / L
SCALE OF GLACIATION
Mountain
Shelf
Lowland / basin
Extensive