The Plymouth Student Scientist - Volume 10 - 2017 The Plymouth Student Scientist - Volume 10, No. 2 - 2017

2017

A glaciologic and palaeoclimatic reconstruction of Younger Dryas conditions using geomorphic evidence from selected sites in the Fforest Fawr, Brecon Beacons National Park

Irvine, H.

Irvine, H. (2017) 'A glaciologic and palaeoclimatic reconstruction of Younger Dryas conditions using geomorphic evidence from selected sites in the Fforest Fawr, Brecon Beacons National Park', The Plymouth Student Scientist, 10(2), p.224-264.
http://hdl.handle.net/10026.1/14167

The Plymouth Student Scientist
University of Plymouth

*The Plymouth Student Scientist, 2017, **10** (2), 224-264*

A glaciologic and palaeoclimatic reconstruction of Younger Dryas conditions using geomorphic evidence from selected sites in the Fforest Fawr, Brecon Beacons National Park

Henry Irvine

Project Advisors: Stephanie Mills and Caroline Clason, School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth, PL4 8AA

Abstract

During the Younger Dryas the climate in southern Wales enabled topographically constrained glaciers to develop within high elevation areas of the Brecon Beacons. Previous studies in this area have attributed numerous basin-floor ridge systems to both glacial and non-glacial origins. An approach considering viability based upon reconstructed dynamics has been found to yield results comparable with contemporary analogues, reducing reliance upon subjective interpretation of field evidence. Due to the sensitivity of cirque glaciers to changes in climate, palaeoglacial modelling may provide insight into past environmental conditions. This study contributes to published literature by undertaking glaciologic and palaeoclimatic reconstructions at four previously uninvestigated sites in the Fforest Fawr, using a recently released ArcGIS toolbox. Geomorphic evidence at these sites was considered likely to be of Younger Dryas age due to similarity with landforms dated nearby. Modelled cirque glaciers at Fan Gyhirych, Blaen Senni, Fan Bwlch Chwyth and Craig Cwm-du occupied a total area of 0.335km^2 at a calculated average Equilibrium Line Altitude of 496m ASL. The resulting palaeoclimatic reconstructions appear to suggest an environment with greater annual precipitation than today. Solar radiation modelling of the June-August ablation season indicates partial shading of all sites due to aspect and topography, aiding ice preservation by minimising surface mass loss. Analysis of the potential for mass balance contribution from avalanches and windblown snow accumulation was also considered, with Fan Bwlch Chwyth and Fan Gyhirych yielding high prevailing wind snowblow factors of 5.2 and 2.1 respectively. Finally, calculation of glaciological dynamics suggests relatively inactive yet viable glaciers to have existed at Fan Gyhirych, Fan Bwlch Chywth and Craig Cwm-du, while geomorphic features at Blaen Senni are rejected as being of glacial origin due to the dimensions of modelled ice extent.

Section 1: Introduction, aims and objectives

Introduction

Following the Last Glacial Maximum (LGM) circa. 21 ka cal. BP ice recession occurred non-uniformly across much of northern Europe (Chiverrell & Thomas, 2010). The British-Irish Ice Sheet receded and broke in to several smaller ice masses, including the Welsh Ice Cap, which itself was short lived (Patton et al., 2013). By c. 12.9 ka cal. BP warming trends had subsided and glacial conditions returned, lasting approximately 1.2 ka (Lowe et al., 2008). This period, known as the Younger Dryas or Loch Lomond stadial, is characterised by strong seasonality particularly in the northern hemisphere, and is related to a reduction in thermohaline circulation (Ruddiman & MacIntyre, 1981). Ice masses readvanced with new glaciers developing in upland areas of the British Isles, including the Brecon Beacons, south Wales (Hubbard et al., 2009). Much of this information is derived from geomorphic and sedimentological analysis and is used to reconstruct the dynamics and characteristics of former glaciers. Wider climatic records for this period originate from a range of proxy data such as ice cores (e.g. Dansgaard, 1989), foraminifera and coleoptera (e.g. Atkinson et al., 2007). This study attempts to expand upon research of Younger Dryas glaciation in the Brecon Beacons by looking at several areas not yet studied in detail.

Aims and objectives

Within the study area, this research aims to:

- Use mapped geomorphological evidence to reconstruct the extent and glaciological dynamics of former cirque glaciation
- Establish local climatic conditions during the Younger Dryas
- Consider factors that may have influenced spatially confined accumulations of glacial ice

These will be achieved by completing the following objectives:

- Map relevant depositional and erosional features in the study area to construct a geomorphological map using ArcGIS
- Reconstruct 3D glacial form and ice surface contours using the GlaRE GIS toolbox (Pellitero et al., 2016)
- Calculate local Equilibrium Line Altitudes (ELA's) for each study site and infer climate at each
- Assess the viability of Younger Dryas glaciation at each site by evaluating calculated glaciological characteristics
- Establish the possible influence of solar radiation, snowblow and avalanching upon the spatial distribution of ice accumulation

Section 2: Study area overview

Study area

The Brecon Beacons are a range of mountains situated in South Wales, in the vicinity of the market town of Brecon. In the context of this study, the Brecon Beacons are referred to as the area covered by the Brecon Beacons National Park, which includes the Black Mountains to the east and the Black Mountain

to the west. The national park covers 1,344km^2 and is characterised by large expanses of mountainous upland (Brecon Beacons National Park Authority, 2012). The highest peak is Pen Y Fan, 886m ASL, part of a central group of six major mountains.

Figure 1: Reference map showing the location of the Brecon Beacons National Park within Wales. Author: Self; Data: Edina, 2016; Brecon Beacons National Park Authority, 2015.

Within the Brecon Beacons National Park this study focuses on four mountains within the Fforest Fawr upland area between the A4067 and A470 roads. The sites were selected because they have not been properly studied before but have similar apparent characteristics to nearby locations with confirmed evidence of Younger Dryas glaciation (e.g. Shakesby, 1996; Carr, 2001).

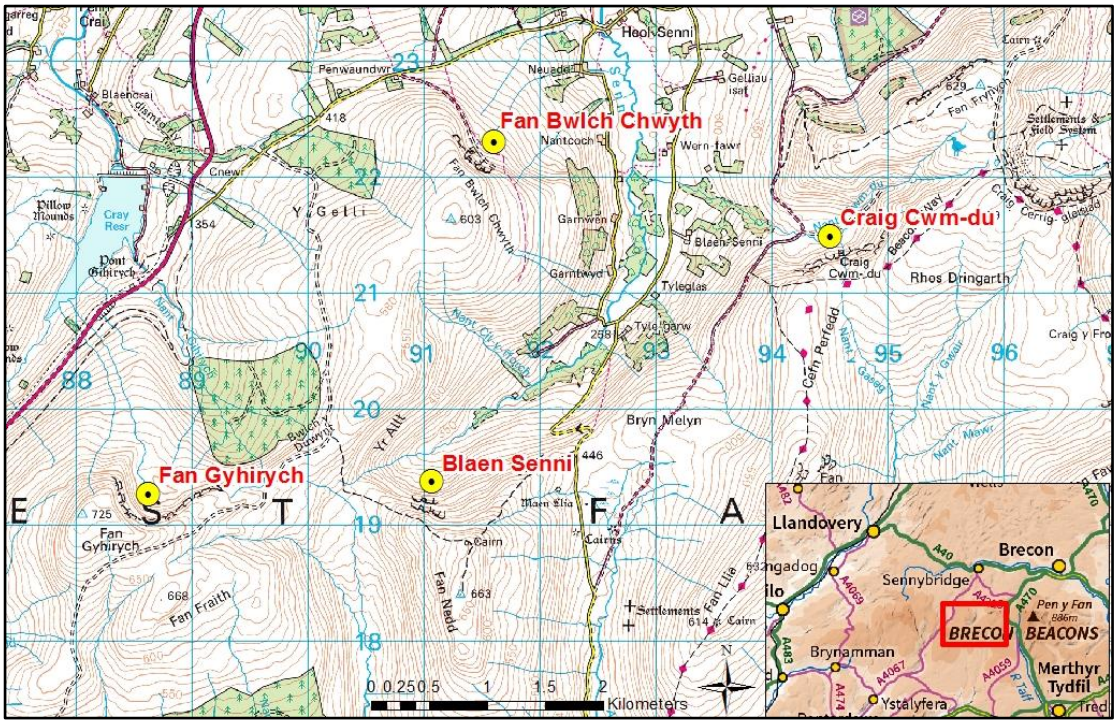

Figure 2: Map showing the locations of sites studied. Author: Self; Data: Edina, 2016 (originally Ordnance Survey).

Geomorphology

The Brecon Beacons are predominantly grassy mountains forming large areas of upland plateau. These mountains commonly have steep north/east aspects and more gently sloping south/west aspects. The orientation of this is primarily a reflection of geology, with repeated glaciation during the Quaternary further defining the north/east aspects (Coleman & Carr, 2008).

A number of regionally important rivers rise from within the National Park, including the Usk and the Wye. As is evident from many erosional and depositional features in the park, fluvial processes play a significant role in shaping the landscape (Brecon Beacons National Park Authority, 2012).

Geology

The park contains varied geology, reflecting a dynamic history. Devonian Old Red Sandstone occupies the greatest lateral expanse of bedrock, approximately two thirds of the national park area. This was formed under desert conditions, reflecting significant past tectonic movement and explaining the characteristically red soil of the area. Folding largely as a result of the Variscan Orogeny has led to this strata dipping southwards, manifested morphologically as gently sloping southern mountain aspects and steep northern scarp faces (Humpage, 2007, p. 12).

In the northwest, Ordovician rocks can be found flanking the River Towy. These are abutted to the south by Silurian strata such as the Raglan Mudstone Formation (Fmn). The Lower Devonian St Maughans Fmn and Brownstones & Senni Beds overlie these, occupying most of the north of the park, including Brecon and Sennybridge. The highest peaks, Pen y Fan and Corn Du, are capped by Upper Devonian Plateau Beds, which have greater

resistance to weathering than those below. In the south, Carboniferous limestone forms a thin band running E-W, with scattered pavements exposed at the surface. Along the southern margin of the park, the Carboniferous Coal Measures provide a large economic resource of national importance (Humpage, 2007, pp. 2-12).

Glacial history

Moraine evidence from the Last Glacial Maximum suggests that ice was at its southern Welsh limit by 23 ka BP (Phillips et al., 1994), decoupling from ice covering Ireland from 20 ka BP onwards (Foster, 1970) and retreating from the southern Welsh coast. This was established using cosmogenic dating techniques (Phillips et al., 1994). By 18 ka BP the British-Irish Ice Sheet had receded to the extent whereby a separate Welsh Cap Ice remained, which itself likely disappeared by 16 ka BP (Clark et al., 2012). This is largely supported by Patton et al. (2013) who's modelling suggests that ice cover receded from the Brecon Beacons around 19 ka BP.

During the LGM ice flow in the vicinity of the Brecon Beacons was from northwest to southeast (Boulton, 1977), which Jannson & Glasser (2008) suggest to have had a far greater impact upon landscape evolution in the Brecon Beacons than any subsequent local glaciation. However, this view is contested by Shakesby & Matthews (2009) because it appears to neglect a range of pre-existing field data suggesting many of the features Jannson & Glasser considered to date to the LGM are in fact related to Loch Lomond Stadial cirque glaciation. The problem of accurately determining the age of features in the Brecon Beacons is commonly documented, with only a limited number of sites having undergone radiometric dating (e.g. Walker, 1980; Robertson, 1989). Nevertheless, the data from these upland sites points towards Loch Lomond Stadial formation and so other studies widely infer this age as being correct for similar features (e.g. Shakesby & Matthews, 1993; Carr, 2001). In the absence of specific data for the sites in this study it will also be assumed that this is the case.

The Younger Dryas/Loch Lomond Stadial cooling event occurred rapidly in the North Atlantic c. 12.9 ka cal. BP and is suggested to have been triggered by a combination of a weakened Atlantic Meridional Overturning Circulation, negative radiative forcing and altered atmospheric circulation (Renssen et al., 2015). In the UK a characteristic of this is the growth of ice in upland areas, the greatest extent of which in Scotland. In South Wales ice accumulation was confined to cirque and valley areas beneath high peaks. Here, year-round temperatures were sufficiently cool due to topographic shading and altitude, with orographic precipitation and windblown snow accumulation feeding mass balance. Research thus far indicates that the Equilibrium Line Altitudes of all of these glaciers were above 400m ASL. This places a significant constraint upon feasible locations for new investigation, as there is unlikely to be substantial deviation from this.

Section 3: Literature review

Glacial reconstruction techniques

As changes in present day glaciers offer a clear metric for the study of climate change, the reconstruction of past glaciation offers insight in to palaeoclimatic conditions at a range of scales. Ice masses exist and change within known physical parameters, established using a range of empirical evidence. By reconstructing past glaciation it is possible to better understand the fundamental relationship between ice and climate, which can be used to inform the study of current climate change (Benn & Evans, 2010). The focus of this review is to examine literature relating to the reconstruction of upland cirque glaciation in the UK and its relationship with climate at a regional scale. By better understanding past climatic conditions in the Brecon Beacons, accurate reconstruction of glacial dynamics can be inferred. This in turn will feed a more detailed picture of climatic conditions at the time.

Mapping of geomorphological features with the aim of reconstructing past glaciation has improved significantly in recent decades. Technological advances such as the advent of LiDAR data have in part facilitated this by aiding more definitive determination of ice margin position. This is a problem early researchers such as Sissons (1974) acknowledged when undertaking field mapping. His work to reconstruct a late-glacial ice cap in the central Grampian Mountains has influenced many more recent studies, but widely uses professional judgement to infer ice margin position where evidence is ambiguous or non-existent. The need for correct geomorphological interpretation is of pivotal importance when reconstructing former glaciers, for failure to distinguish between features of glacial and non-glacial origin can have significant inferential implication for palaeoenvironmental reconstruction attempts (Carr et al., 2010). By determining the likely extent of the Gaick ice cap, Sissons calculated the altitude where total accumulation and ablation were balanced when ice extent was at its maximum, often referred to as the Equilibrium Line Altitude ('ELA'). From this, using a curve of ablation season mean temperature developed by Ahlmann (1948) on glaciers in Norway, Sissons estimated mean summer temperature by assuming precipitation was likely in the region of 80% of today. This was in general agreement with pollen and coleoptera proxy data from the English Midlands for this time.

Mass movement and periglacial processes are capable of producing features within cirques similar to those of glacial origin. Carr (2001) suggested that these could be differentiated from glacial evidence by adopting an approach less reliant on human interpretation of geomorphological origin. He proposed a method using glaciological parameters to model ice mass dynamics at five locations in the Brecon Beacons. This approach was useful in deducing the origin of small depositional features such as cirque basin ridges, offering an alternative methodology to Sissons (1974). Data yielded by this approach includes; basal shear stress at ELA, mass flux, average velocity at ELA and contribution of basal slip as a % of total velocity. These figures can be compared between study sites and modern analogues to determine the feasibility of modelled ice.

Calculating the ELA is a fundamental concept in establishing palaeoglacial dynamics and making climatic evaluations (Carr & Coleman, 2007). In modern glaciers, strong links have been found between ELA position, snowfall and local climate (Osmaston, 1975). Changes to the ELA most frequently occur due to fluctuations in summer temperature or amount of snow accumulation, with an increase in the former contributing to a higher ELA while an increase in the latter lowering the ELA (Benn & Evans, 2010). There are four widely recognised techniques used to determine the ELA of former glaciers, summarised by Benn et al. (2005), these are; accumulation area ratio ('AAR'), area altitude balance ratio ('AABR'), maximum elevation of lateral moraines ('MELM') and terminus-to-head altitude ratio ('THAR'). ELA estimation by glaciation threshold or cirque-floor altitude is omitted from this discussion as they are deemed to be methods yielding lower-accuracy, especially in small-scale studies such as this. Each approach normally produces different values and so a mean of several methods is regarded as best practice for reconstructive studies (Benn et al., 2005), although this may propagate inherent errors within specific methods through the research. Details of each technique are discussed in Section 4. Differences in the ELA of characteristically and climatically similar glaciers are typically due to topographical differences affecting solar radiation, wind transportation of snow ('snowblow') or avalanching (Carrivick & Brewer, 2004). These differences can be modelled and are discussed in Section 4.

In the last decade significant advances have been made to aid glacial reconstruction and reduce reliance upon personal interpretation of evidence when determining the position of a former ice surface. Benn & Hulton (2010) introduced *Profiler*, an Excel™ spreadsheet able to model glacier long-profile using the concept of perfect ice plasticity when mapped landform and bed topography data are inputted. Recently, Pellitero et al. (2016) further increased the utility of palaeoglacial 3D surface reconstruction by presenting GlaRE, a semi-automated ArcGIS toolbox. GlaRE requires a minimum of two input datasets, a raster DEM of bed topography and at least one palaeoglacial flowline. In order to improve the outcome of the modelling process, extent parameters can be set using mapped features and likely hydrologic catchment. Once shear stress is defined, ice thickness along the flowline is calculated and interpolated across the entire glacier. Under testing using two geomorphically dissimilar extant glaciers, Pellitero et al. (2016) found GlaRE to be highly accurate in reproducing ice surface and extent.

Upon successful 3D ice surface reconstruction, ELA can be calculated using methods previously described. In addition to the GlaRE toolbox, Pellitero et al. (2015) designed an additional toolbox to aid this process. AAR and AABR can be calculated and overlaid on the reconstructed ice surface, with the ability to enter multiple calculation ratios so that a mean of possible scenarios can be determined, as indicated best practise.

Glacial reconstruction in the Brecon Beacons

Recent studies using techniques discussed above have demonstrated the existence of nine Younger Dryas niche/cirque glaciers in the Brecon Beacons. The first comprehensive glacial reconstruction in recent decades was

undertaken at Craig Cerrig-gleisiad (Shakesby & Matthews, 1996), building upon previous work (e.g. Lewis, 1968; Ellis-Gruffydd, 1977) in order to clarify the origin of depositional features. These had previously been attributed to multiple late Devensian ice advances, but were demonstrated to have formed by a combination of landsliding and a subsequent single Younger Dryas glaciation event. This work again highlights the need to accurately distinguish the origin of deposited sediment.

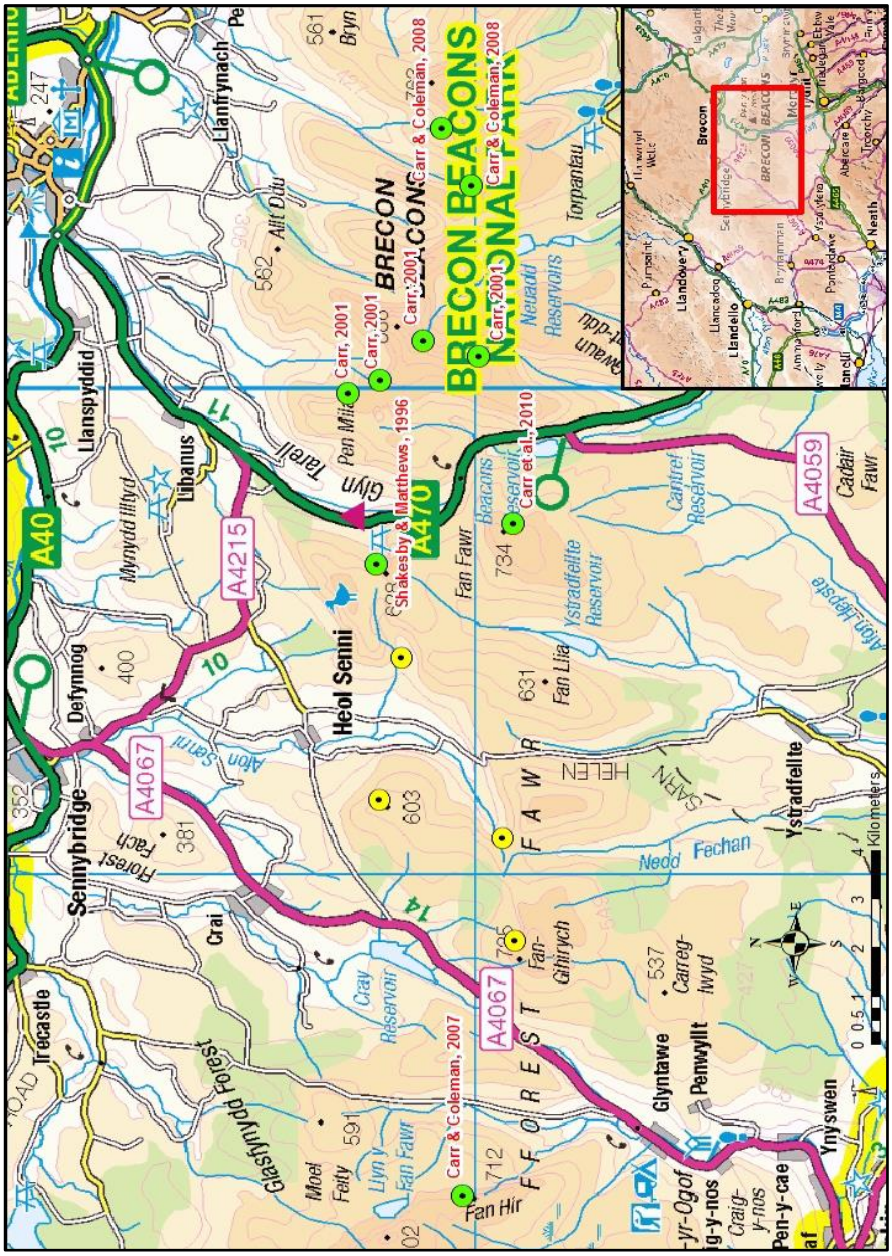

Figure 3: Map of previously studied sites in the Brecon Beacons (green) and the sites investigated in this study (yellow). Author: Self; Data: Edina, 2016 (originally Ordnance Survey).

In 2001 Carr used a glaciological approach to examine apparent Loch Lomond Stadial landforms at five sites, four of which were deemed to have had origins within this period while one was rejected as being a product of earlier glaciation. Carr used the same approach as Sissons (1974) to

delineate the downslope extent of ice, mapping at 1:5000, but recognised that defining the upper margins was largely impossible due to the absence of features such as trimlines and role subsequent paraglacial slope activity. With this in mind, an inferential approach adopted by Gray (1982) was used, placing the upper margins 20-30m below the confining scarp. This is based upon the likely depth of snow-firn-ice transformation, as derived from modern examples. Gray's method of ice contour placement was also adopted; with a straight contour at the mean ice altitude but lines becomingly increasingly concave/convex near the uphill and downhill margins respectively. From the derived mass-balance characteristics it was recognised that Cwm Crew, Cwm Llwch, Cwm Milan and Cwm Gwaun Taf had similar ELA basal shear stress and ice deformation velocities to small slow-moving modern glaciers in southern Norway (Paterson, 1994). The fifth, Cwm Cul, had a modelled basal slip component of 99.8% and a maximum ice thickness of only 21m, excluding a glacial origin.

Reconstructing climate

During the Lateglacial, ca. 15,000-11,500 cal yr BP, the climate in Western Europe was susceptible to rapid fluctuations. These were driven by complex forcing mechanisms as global transition to present day interglacial conditions occurred (Vandenberghe et al., 2011). Climatic data from this period is manifested in a wide range of proxies, affording the most recent insight in to a significant period of instability in the global climate system. This is an important tool in gaining an understanding of present day climate change, especially in understanding interactions between earth and atmosphere in both temporal and spatial contexts (Lowe & Walker, 1997).

In Britain, research initiatives such as the National Environmental Research Council's TIGGER II programme (Oliver et al., 1999) have led to the development of a geographically diverse network of high-resolution study sites. Many of these locations are former lacustrine settings naturally exposed in section or by human excavation. A range of evidence such as pollen, plant macrofossil, coleopteran, geochemical and stable-isotope data can be extracted and used in conjunction with other data such as that of the GRIP Greenland ice core to establish Lateglacial climatic conditions (Walker et al., 1993). Nearest to the Brecon Beacons a site at Llanilid, c.25km south of the park at an altitude of 60m OD, is an opencast coal-working underlain by shales of the Carboniferous Lower Coal Measures. From eight sequential monoliths the full range of proxy types mentioned above were extracted and analysed. These showed that during the Loch Lomond/Younger Dryas Stadial the area experienced mean July sea-level temperatures of 10-11°C (Walker et al., 2003). This is in agreement with other sites in the UK and is c. 10°C cooler than present-day climate (Met Office, 2010).

Section 4: Methodology

Mapping and fieldwork

Initially, an outline of geomorphic features at each location was produced from satellite imagery in Google Earth Pro (Google, 2015). Next, a 1:7500 scale topographic base map was produced from Ordnance Survey data using

Digimap (Edina, 2016). Using a handheld GPS, and an additional handheld GPS for accuracy monitoring, the positions of geomorphic features were ground truthed, with any additional features added. It is recognised that this method relies significantly on an element of professional judgement, an example of which includes determining the point at which a ridge crest ends as it gradually becomes more ambiguous. By plotting any plausible moraine-like feature without debating its origin in the field, it's hoped that the approach of this investigation will differentiate between glacial and non-glacial origin.

Palaeoclimatic interpretation

Using a mean July sea-level temperature of 10.5°C as established at nearby Llanilid by Walker et al. (2003) it is possible to derive mean 3-month summer sea-level temperature. This enables extrapolation to mean summer temperature at the calculated ELA of each glacier and is vital in subsequent glaciological analysis. Mean July sea-level temperature was translated to 3-month summer sea-level temperature using the following equation, presented by Benn & Ballantyne (2005).

$$T_3 = 0.97T_j$$

Where:
T_3 = Mean 3-month summer temperature (°C)
T_j = Mean July sea-level temperature (°C)

Therefore: T_3 = 10.19°C

An environmental lapse rate can then be used to extrapolate T_3 to temperature at the ELA. Lapse rates of 0.006°C m^{-1} and 0.007°C m^{-1} are widely regarded as valid averages based upon climate analysis of a global set of contemporary glaciers (Ohmura et al., 1992) with subsequent use for palaeoglacial reconstruction in the UK by Ballantyne (2002), Benn & Ballantyne (2005), Bendle & Glasser (2012) and others. For this reason calculations were based upon a lapse rate of 0.0065°C m^{-1}.

Upon establishing mean 3-month summer temperature annual precipitation at the ELA can be calculated. This is based upon a strong relationship between the two variables, as recognised in modern analogues by Ohmura et al. (1992). Temperature is used as the input variable because data on palaeoprecipitation is less abundant and difficult to test.

$$P_a = 645 + 296T_3 + 9{T_3}^2$$

(Standard error = ±200mm)

Where:
P_a = Annual precipitation at the ELA (mm)
T_3 = Mean 3-month summer temperature (°C)

Glacial extent reconstruction

Mapped geomorphic evidence formed the basis for inferring past glacial extent. However, in all cases this was only useful in determining maximum downslope position due to an absence of lateral or upslope evidence. The

crest line of the most distal terminal material was considered to mark the snout of the glacier during its maximum.

Lateral extent was inferred from topography since all of the study sites are topographically confined. As suggested by Gray (1982), the upper ice margin was considered to be 25m below the confining headwall. A problem with both of these assumptions is that they neglect possible changes in morphology since the Loch Lomond Stadial. An example is the quarrying of the headwall at Fan Bwlch Chwyth. To attempt to overcome this map contours were adjusted using surrounding topography to infer previous form.

Three-dimensional surface modelling

Using ArcGIS to compile mapped spatial extent data the GlaRE toolbox (Pellitero et al., 2016) could then be applied to model ice thickness. An Ordnance Survey Terrain 5 DTM raster (Edina, 2016) was used as the input DEM for the modelling, as it was the highest resolution available for the study area. Due to the simple single-cirque nature of the selected study sites a single flowline was constructed by eye, the direction of which was based upon interpretation of present day slope morphology. Next, shear stress was defined along the length of the flowline with a value of 100kPa (discussed in Section 4.9). Using this, the Glacier Reconstruction toolset then modelled ice thickness along the flowline and interpreted it across the mapped extent of the glacier using a 'topo to raster' method with 20 iterations. Glacier constraints were inputted as a single polygon accounting for mapped moraine features and feasible lateral limits. Sideways flowline altitude propagation was determined from this as being equal to glacier width, ensuring the best distribution of interpolated data points.

ELA calculation

Once ice surface position has been modelled, calculation of the equilibrium line altitude can be achieved via a number of means, as discussed below. A mean of the three AAR, two AABR values and single THAR value were used to derive ELA position. AAR and AABR were calculated using the ELA calculation GIS toolbox (Pellitero et al., 2015) with the ratios specified below.

AAR

Accumulation area ratio assumes that the zone of accumulation occupies a fixed proportion of the total area of the glacier, under steady state conditions (Benn et al., 2005). AAR values for mid to high latitude glaciers range from 0.5-0.8, typically 0.55-0.65 (Porter, 1975). These values vary with latitude, with tropical glaciers tending to have steeper ablation gradients and less steep accumulation gradients as a result of climate, yielding a higher AAR (Kaser & Osmaston, 2002). Debris cover can also influence AAR value, lowering it by increasing the ablation area required to counter accumulation (Kern & László, 2010). For the Brecon Beacons, Carr (2001) and Carr & Coleman (2007) used an AAR value of 0.65 for their calculations. Recent (Kern & László, 2010) analysis of 46 cirque and valley glaciers worldwide showed that for glaciers with a surface area of 0.1-1km^2 an AAR of 0.44 was best applied, while for glaciers 1-4km^2 a value of 0.54 was optimal. As a result, AAR values of 0.44, 0.54 and 0.64 were selected for this study.

AABR

Area altitude balance ratio is argued to be the best technique available for palaeoglacial ELA reconstruction (Benn & Lehmkuhl, 2000). Unlike the AAR method it additionally accounts for glacier hypsometry, the distribution of area with altitude. This may provide a more accurately calculated ELA. Studying modern data from around the world, Rea (2009) found that mid-latitude maritime glaciers exhibit an AABR value of 1.9±0.81. The glaciers of western Norway, perhaps the most similar to those reconstructed in the Brecon Beacons, had an AABR of 1.5±0.4. This figure has already been applied in the reconstruction of Fan Fawr (Carr et al., 2010) and would appear to be in general agreement with the mean calculated ELAs of other nearby sites. Consequently, AABR values of 1.5 and 1.9 were selected for this study.

THAR

Terminus-to-head altitude ratio can be used to infer ELA position by means of the distance between the headwall and terminal moraines. This method is convenient in providing a rapid approximation that can be done in the field however it fails to account for climatic factors, changes in headwall position (e.g. Fan Bwlch Chwyth) and non-uniform glacier hypsometry. As such, Porter (1981) concluded that the THAR method is best used on small, geometrically regular glaciers.

Porter, 2001:

$$ELA = A_t + THAR \times (A_h - A_t)$$

Where:

A_t = Altitude of terminus

A_h = Altitude of headwall

A THAR value of 0.4 would indicate that the ELA lay at an altitude 40% of the elevation range higher than the position of terminal moraines. This correlates well with an AAR of 0.6 (Meierding, 1982), often considered ‘normal’ for alpine glaciers (Meier & Post, 1962).

Osipov & Khlystov (2010) consider most glaciers to have a THAR value between 0.35 and 0.45, for this reason a value of 0.40 has been selected for this study.

Solar radiation

Given the mountainous nature of the study area, topographic shading and solar insolation are likely to have been key factors affecting glacier formation and mass balance (Coleman et al., 2009). In the northern hemisphere, solar radiation is strongest during the months of June, July and August, as days are longest and sun-earth angle of incidence is largest. For this reason the effect of solar radiation upon glacier ablation is most pronounced during these summer months, when clear sky conditions also most commonly occur meaning shortwave radiation dominates surface-energy balance (Oerlemans, 1992). To assess solar radiation the ArcGIS Solar Radiation tool was used to create a solar radiation map for each of the study site areas averaged over the three-month period. This tool used the same Ordnance Survey Terrain 5 DTM (Edina, 2016) as in Section 4.4, with sky size kept on the default value of

200 as indicated most suitable for with day intervals >14 with whole DEMs (ESRI, 2016).

Snowblow and avalanching

Following precipitation, topography and wind are useful tools in the redistribution of snow in mountainous areas. This can have a pronounced effect upon glacial accumulation; with windblown snow often collecting in the same topographic depressions where moving ice might be expected to form (Benn & Evans, 2010). All ground above the ELA of a glacier and sloping towards it may be considered to have the potential to contribute wind transported snow to glacier mass balance (Mitchell, 1996), possibly altering ELA position. In addition, wind is capable of transporting snow uphill on slopes up to 10° (Coleman et al., 2009) and so all areas of land sloping towards the modelled glaciers or away up to this angle should be accounted for. To calculate this, areas matching these criteria were marked in ArcGIS using slope analysis of the input DEM. Potential areas were then split in to quadrants by compass direction, centred upon the intersection of glacier ELA and centreline, enabling the significance of wind direction to be examined. The role of avalanching upon glacial accumulation was considered in the same regard, the potential of which was deemed confined to slopes exceeding 20° surrounding each glacier (Sissons & Sutherland, 1976).

Upon calculating the size of snowblow and avalanche areas within each quadrant, potential mass balance contribution may be described as a ratio of glacier area (Sissons & Sutherland, 1976). To further refine this so that distal areas are not considered as having the same potential contribution as glacier margins a ‘factor’ can be derived from the square root of the ratio (Sissons, 1980).

Glacial dynamics

To determine the viability of the palaeoglacial reconstructions and test the interpretation of geomorphic evidence it is necessary to calculate the glaciological dynamics that the modelled ice masses would exert. This allows their characteristics to be compared with other local study sites and with modern glaciers. In order to initially model the 3D palaeoglacial surface using the GlaRe GIS toolbox, which in turn provides data to feed these calculations, an approximation of basal shear stress was required. Paterson (1994) suggests a value of 100kPa to be typical of a glacier, a value used as the default in the GlaRe toolbox. Subsequent calculations of basal shear stress using the equation below (Hooke, 2005) may provide comparison with the original figure used.

$$\tau_b = \frac{(\rho g H \sin \alpha)}{100{,}000}$$

Where:

τ_b = Basal shear stress (Bars)

ρ = Glacial ice density (910kg m^3) (Paterson, 1994)

g = Acceleration due to gravity (9.81 m/s^2)

H = Thickness of ice at ELA (m)

α = Angle of ice surface at ELA (degrees)

Temperature and accumulation at the ELA are intrinsically related, as demonstrated by Ohmura et al. (1992) in recognising that this association changes for differing climatic regions. Therefore, results of the palaeoclimatic interpretation underpin calculations of glacial dynamics. Carr & Coleman (2007) noted that summer precipitation contributes little to glacier mass balance and dynamics, therefore the first step in understanding possible glacial activity at the study sites is to calculate winter accumulation at the ELA, a figure deemed to represent ELA mass loss.

$$b_w = 13.285{T_3}^2 + 229.81T_3 + 453.23$$

Where:
b_w = Winter accumulation at the ELA (m/a^{-1})
T_3 = Temperature at ELA (°C)

Using this, the ablation gradient for each glacier may be calculated (Carr & Coleman, 2007). This describes changes in ablation resulting from altitude.

$$a_z = 0.7809{P_a}^2 - 0.5681P_a + 3.3342$$

Where:
a_z = Ablation gradient (mm/m^{-1})
P_a = Mass loss at ELA (m a^{-1}) i.e. b_w

Following the methods of Carr & Coleman (2007) the ablation gradient calculated may be used to determine cumulative ablation for each contour interval below the ELA of the reconstructed glacier, allowing total ablation to be understood (m^3 water-equivalent). This figure can be divided by ice density (assumed as 910 kg/m^3) to deduce total ice volume discharge (m^3) at the ELA, also known as mass flux. Using this, average balance velocity may be calculated.

$$U_s = \frac{Q_{ELA}}{A'_{ELA}}$$

Where:
U_s = Average balance velocity (m/a^{-1})
Q_{ELA} = Total ice volume discharge at ELA (m^3)
A'_{ELA} = Cross-sectional area at ELA

Lastly, glacier motion can be derived by first calculating ice deformation. This is based upon Glen's Flow Law (Glen, 1952) but was adapted for glacial ice by Carr & Coleman (2007).

$$V_c = (2A{\tau_b}^n H)/(n+1)$$

Where:
V_c = Ice centre-line deformation (m/a^{-1})
A = 0.167. A temperature dependent flow-law constant
n = 3. An exponential flow-law constant
τ_b = Basal shear stress (Bars)
H = Thickness of ice at ELA (m)

To estimate basal motion from this, V_c may be subtracted from U_s (average balance velocity) and converted in to a percentage of total glacier motion.

Section 5: Geomorphological Evidence

Fan Gyhirych - SN 885 192

A prominent large cirque abounds the north-northeasterly aspect of Fan Gyhirych, dropping from the summit plateau (725m ASL) to 545m. The mouth of the basin is approximately 500m wide and overlooks the Cray Reservoir. From the cirque floor a large but gently sloping moraine extends for 335m with up to 10m relief on the headwall side. Its shape is perhaps unusual in that it is semi-arcuate but curving to mimic the backwall instead of in opposition to it. Enclosed by this is an expanse of flat boggy ground with a stream draining between the north-westerly end of the moraine and the headwall. For this reason, it could be inferred that the moraine would likely have extended all the way to the lateral margin, however fluvial erosion has since dissected this.

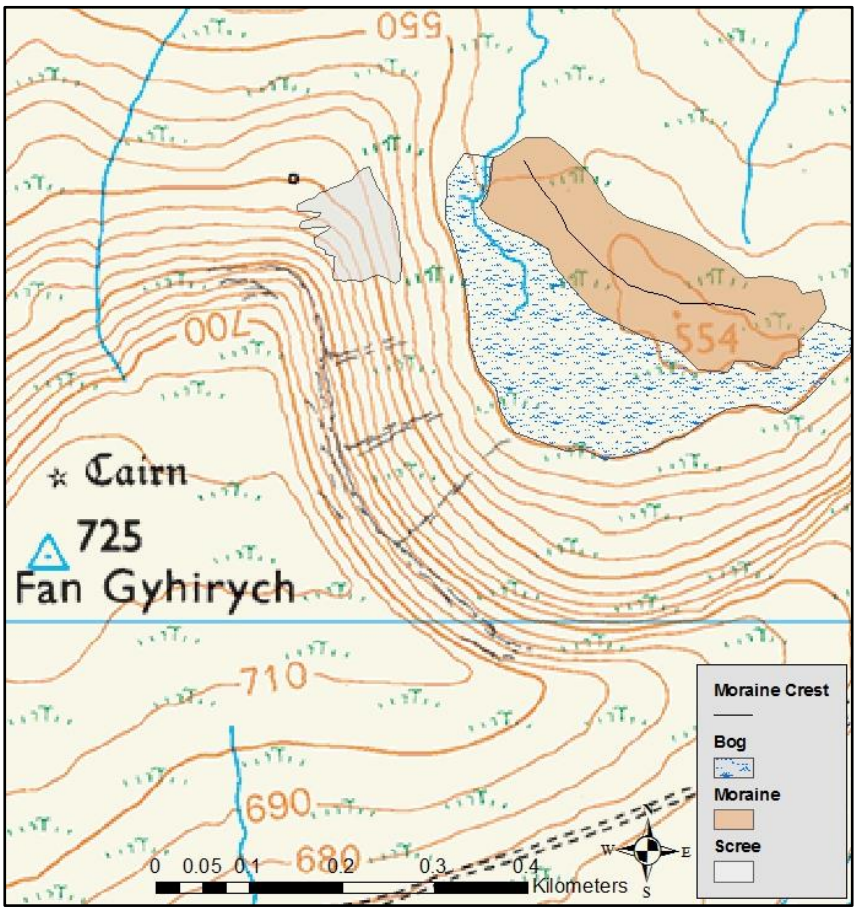

Figure 4: Geomorphological map including possible glacial features near Fan Gyhirych. Author: Self; Data: Self & Edina, 2016 (originally Ordnance Survey).

Blaen Senni - SN 909 193

The steep sided Senni Valley runs southwest to northeast, forming a drainage of the River Usk. On the northerly aspect of its furthest reaches a relatively indistinct arcuate moraine-like feature occupies a slight break in slope at 380-400m ASL. Stretching for 170m with an average relief of only c.1m it encloses steeply sloping ground heavily shaded by craggy terrain above. As can be

seen in Figure 5, in order to show the feature in the context of surrounding terrain the thickness of the symbolised ridge is not to scale.

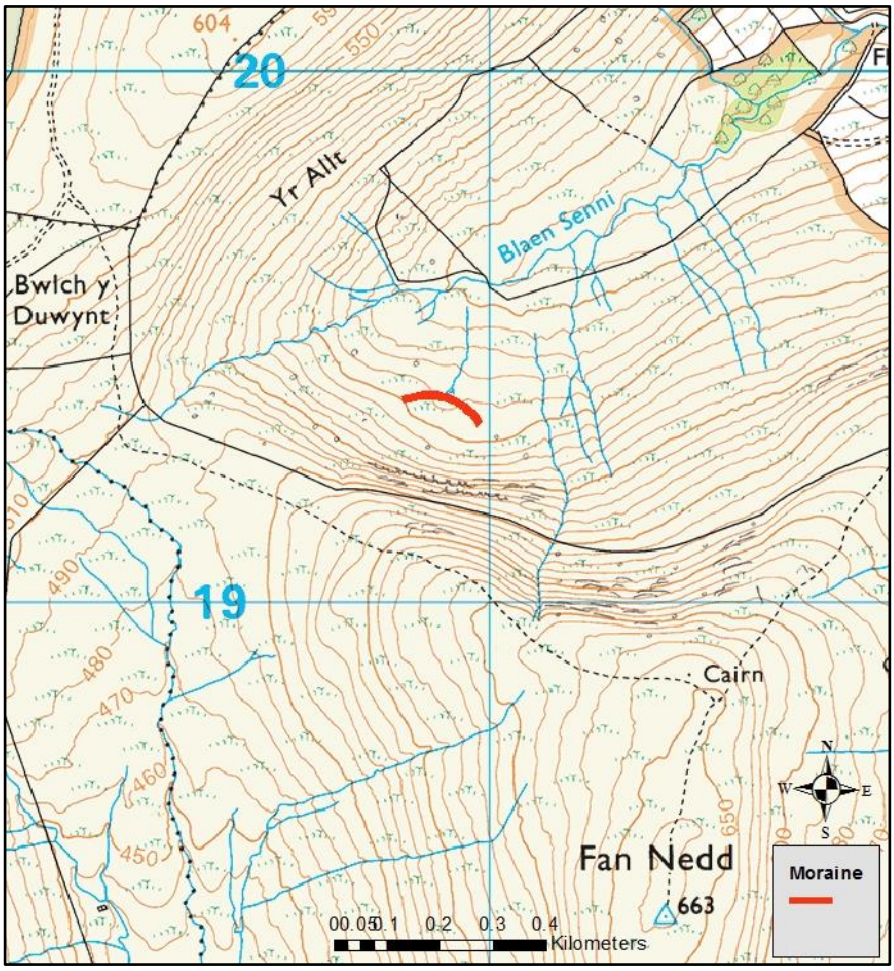

Figure 5: Geomorphological map including possible glacial features near Blaen Senni. Author: Self; Data: Self & Edina, 2016 (originally Ordnance Survey).

Fan Bwlch Chwyth – SN 915 221

The headwall of this northeast-facing cirque has been heavily altered by human extraction of materials, however it rises approximately 120m to just below the summit plateau (603m ASL). Two conspicuous arcuate ridges of moraine enclose an area of marshy ground drained by numerous streams. The outer ridge is the largest, extending for c.400m and broken only by fluvial erosion and human activity in support of quarrying here in the late 19th & 20th centuries. It has 10-12m relief over the ground beyond it and has a very well defined crest line. The inner line of moraine is closer to 200m in length and runs roughly parallel to the larger distal moraine, with a relief of only a few metres. On the crest line of one of the ridges a hollow approximately 50cm wide and 40cm deep was found, this was thought to represent a kettle hole, a view supported by Shaskeby (2002).

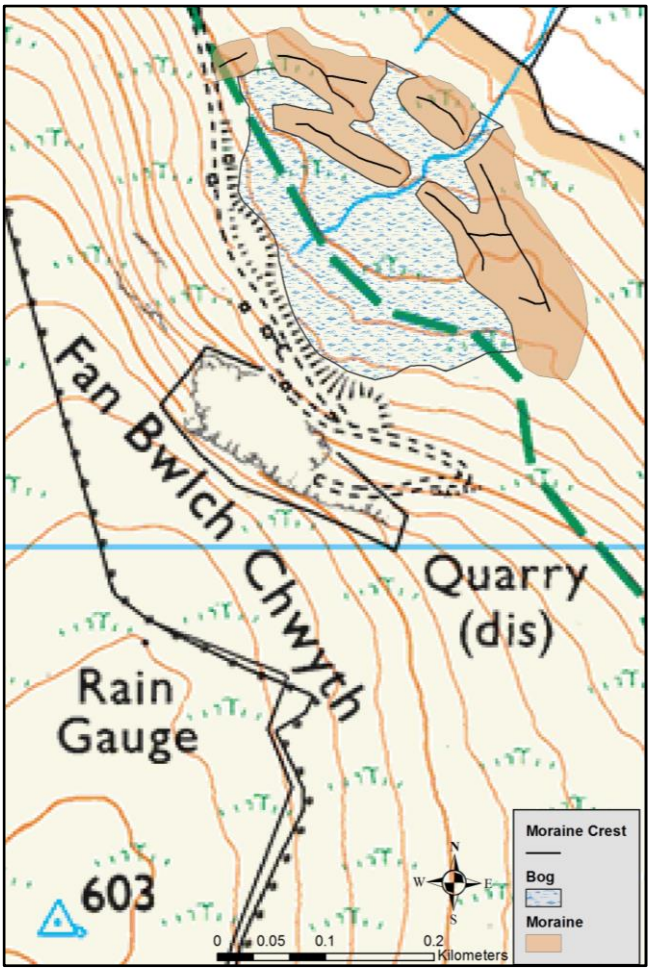

Figure 6: Geomorphological map including possible glacial features near Fan Bwlch Chwyth. Author: Self; Data: Self & Edina, 2016 (originally Ordnance Survey).

Craig Cwm-du – SN 943 214

The mouth of this valley runs west to east before narrowing, steepening and turning upstream to the northeast. The relatively linear escarpment of Craig Cwm-du has a northwest aspect rising 170m above the valley floor, littered with several talus cones. In the basin, numerous indistinct depositional features such as hummocks and ridges can be identified, but many have been significantly altered by fluvial erosion. Several former river channels and terraces can be seen, as well as the current position of the Nant Cwm-du River, which cuts through the most prominent moraine feature just downstream of the bridge. The crest line of this is oriented SW-NE and extends to abut the lower slopes of the headwall, indicating the lateral extent of any former glacier. Another faint ridge curves around from this in a WNW-ESE direction, and could be interpreted as the terminus of a small glacier nestled against the headwall, only c.120m from the base of the slope.

On the other side of the river, some 300m North of the base of the escarpment, two distinct hummocks lie with their crest lines oriented E-W. A further wide ridge lies c.200m west of these, oriented SW-NE. This would appear to be at odds with the interpretation of the proximal moraine as demarcating the glacier's terminus. Via this scenario of a much larger glacial area and extent it's clear that the Nant Cwm-du River would have at some

stage been dammed. Shakesby (2002) supports this, having analysed sediments exposed in the riverbank near the bridge to find finely layered lake deposits.

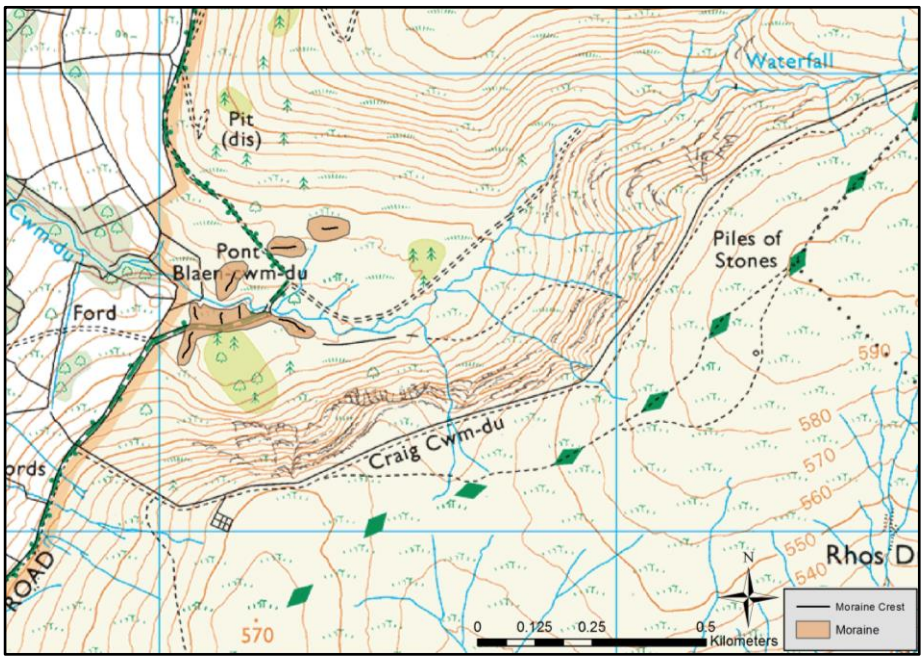

Figure 7: Geomorphological map including possible glacial features near Craig Cwm-du. Author: Self; Data: Self & Edina, 2016 (originally Ordnance Survey).

Section 6: Palaeoclimatic Conditions

Table 1 below uses methods discussed in Section 4.1 to extrapolate mean summer temperature and annual total accumulation at the ELA of each reconstructed glacier. It is important to note that calculated annual total accumulation (Ohmura et al., 1992) seeks to encompass accumulation via all means; including snowblow, avalanching and precipitation. For this reason it does not give an accurate representation of atmospheric conditions but is useful in calculating glaciological dynamics.

Table 1: Extrapolation of Younger Dryas sea level climate data (Walker et al., 2003) to calculate mean summer temperature and annual accumulation for each study site.

Location, calculated ELA and environmental lapse rate used for sea-level temperature extrapolation	Derived mean 3-month summer temperature (°C)	Calculated annual total accumulation (mm)
Fan Gyhirych 611m ASL 0.0065°C m^{-1}	6.2	2834
Blaen Senni 432m ASL 0.0065°C m^{-1}	7.4	3321
Fan Bwlch Chwyth 502m ASL 0.0065°C m^{-1}	6.9	3127
Craig Cwm-du 440m ASL 0.0065°C m^{-1}	7.3	3298
Average	7.0	3145

Section 7: Palaeoglacial reconstruction

Reconstructing glacial extent and morphology

Using evidence gathered to compile Section 5, past ice extent and form could be modelled using the GlaRE and ELA calculation ArcGIS toolboxes (Pellitero et al., 2015 & 2016) explained in Sections 4.4 and 4.5. For each study site ice extent was determined by terminal moraine position and surrounding topography. For sites such as Fan Bwlch Chwyth and Craig Cwm-du (Figures 10 & 11) it is highly likely that multiple ice advances occurred, given the existence of several moraine ridges. These were not modelled as due to a lack of dating evidence this was deemed beyond the remit of the study.

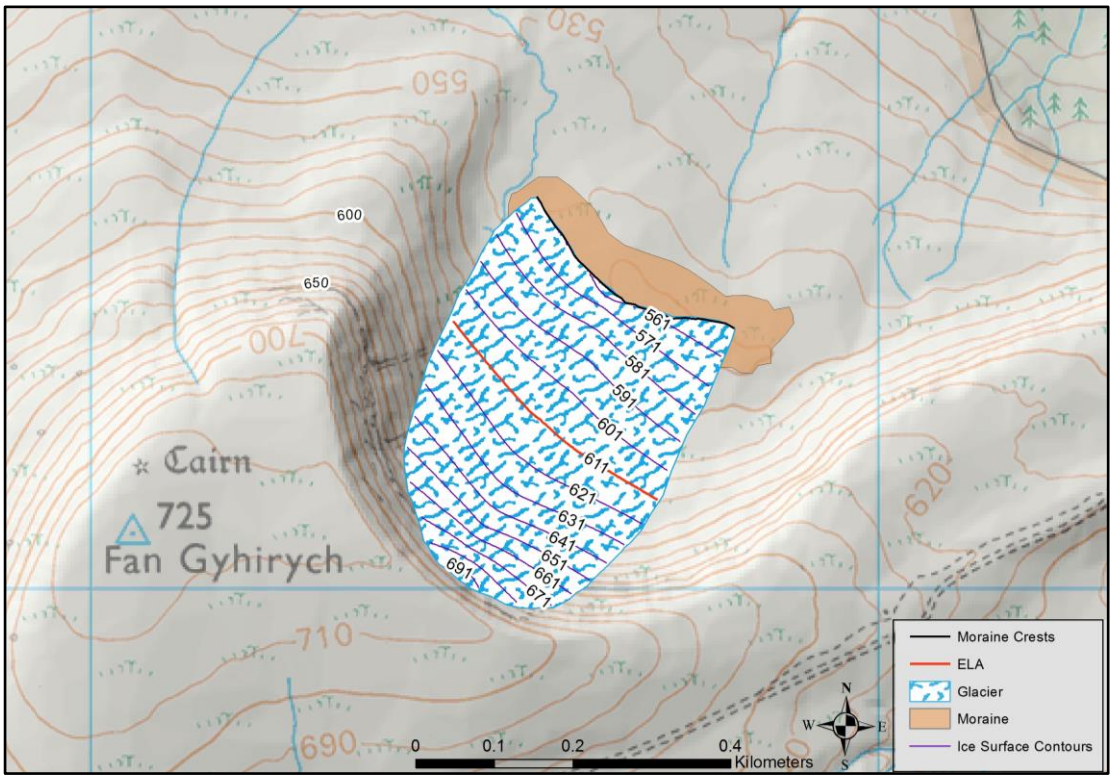

Figure 8: Map of modelled ice at Fan Gyhirych. Author: Self; Data: Self & Edina, 2016 (originally Ordnance Survey).

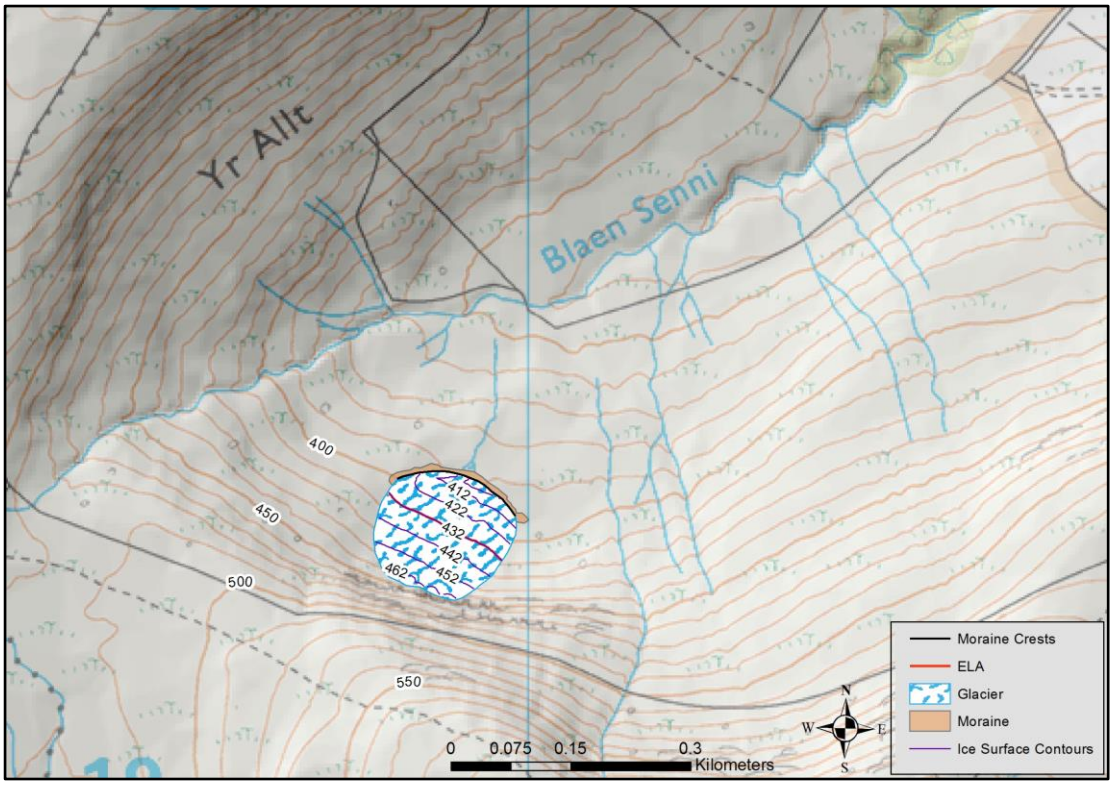

Figure 9: Map of modelled ice at Blaen Senni. Author: Self; Data: Self & Edina, 2016 (originally Ordnance Survey).

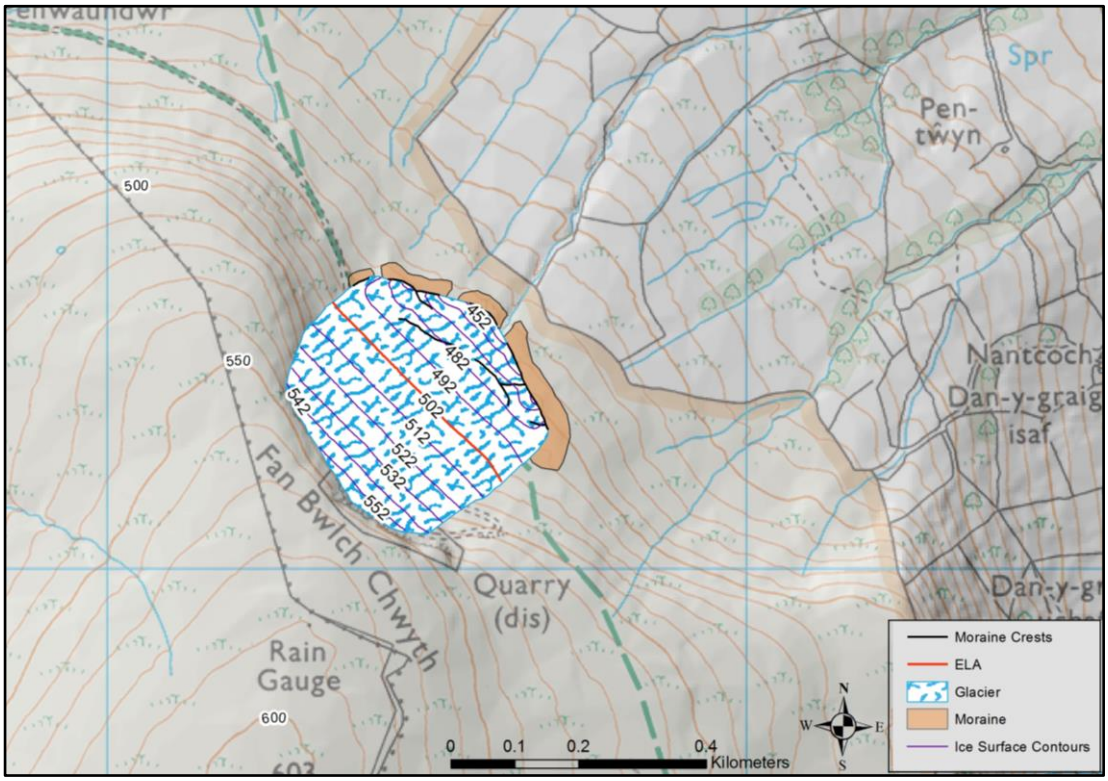

Figure 10: Map of modelled ice at Fan Bwlch Chwyth. Author: Self; Data: Self & Edina, 2016 (originally Ordnance Survey).

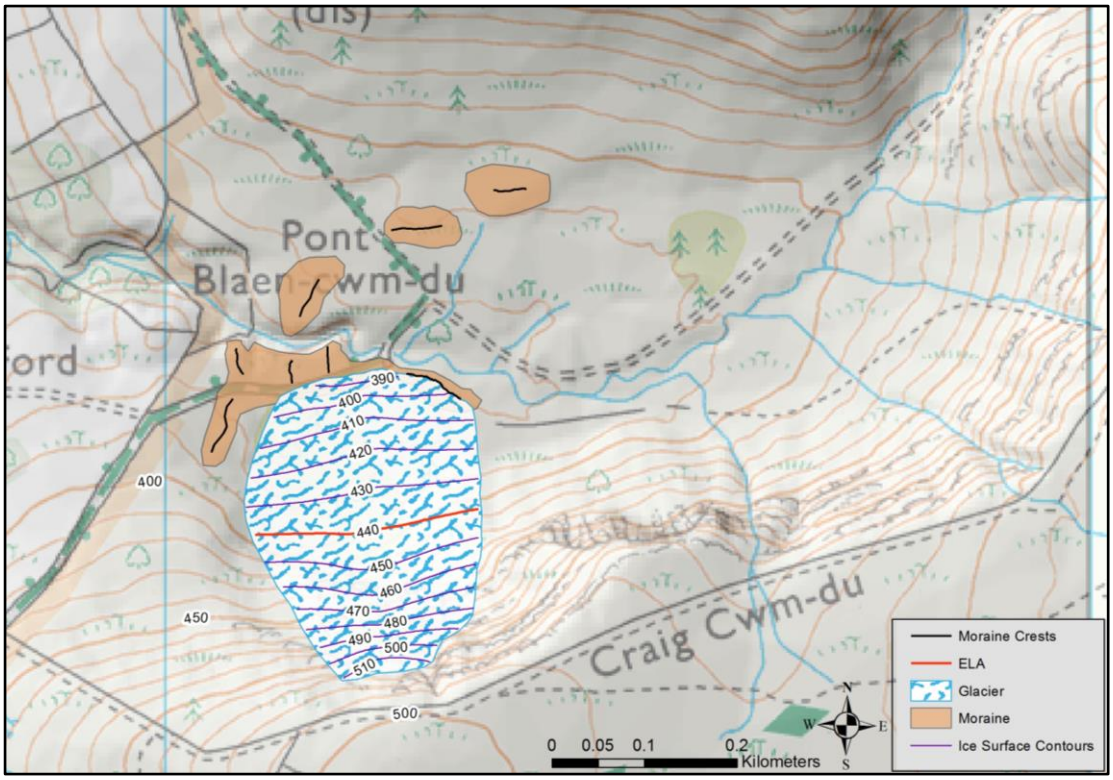

Figure 11: Map of modelled ice at Craig Cwm-du. Author: Self; Data: Self & Edina, 2016 (originally Ordnance Survey).

Ice surface profiles

Upon modelling ice extent and form a longitudinal profile for each glacier could be established. This aided in assessing the viability of each reconstruction by providing a visual representation of changes in ice thickness over distance. Each profile was drawn along the main flowline of the glacier.

In general, it could be expected that ice thickness would increase moving towards the ELA from both the snout and the headwall. This is widely demonstrated in Figures 12 to 15, however the profile of each reconstruction varies. Figures 12 and 15 exhibit thin ice cover for a relatively large horizontal distance from the headwall before thickness increases, whereas Figures 13 and 14 appear to thicken more rapidly. The modelled ice surface in Figure 13 appears not to join up with the bed near the headwall of the glacier. This could be due to the output resolution of the modelled ice surface compared to the small size of the glacier.

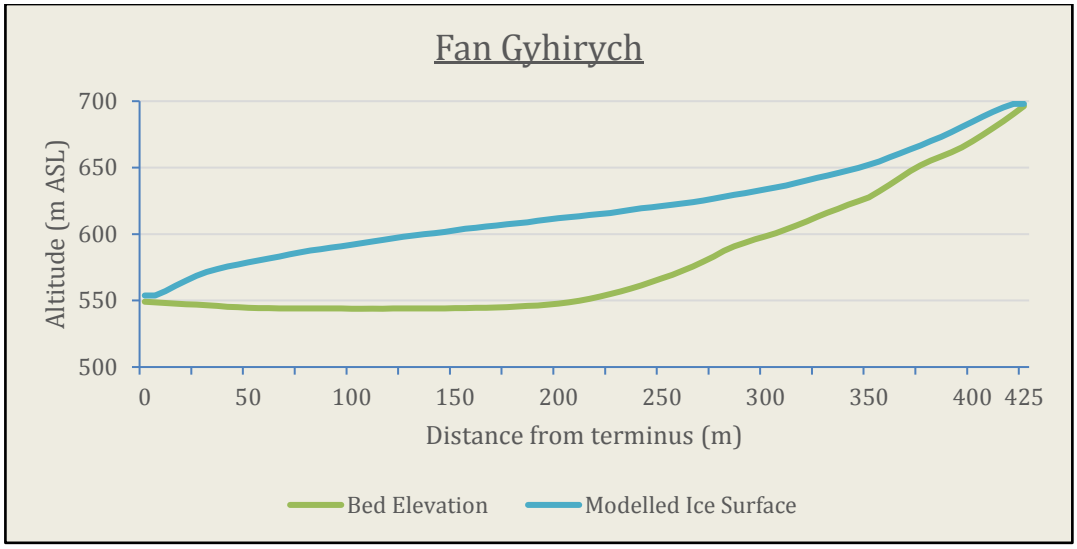

Figure 12: A longitudinal profile of modelled ice at Fan Gyhirych. Author: Self.

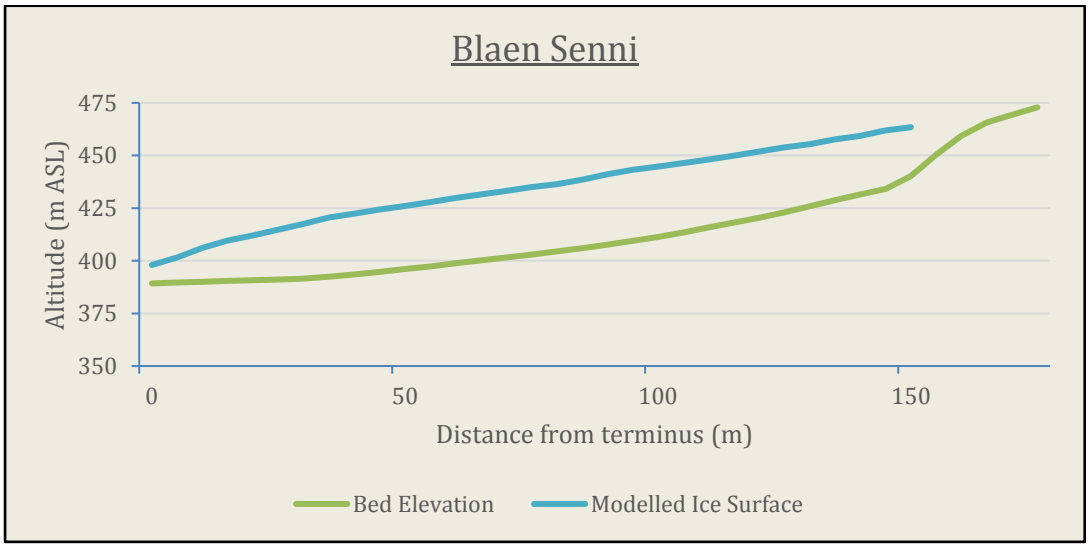

Figure 13: A longitudinal profile of modelled ice at Blaen Senni. Author: Self.

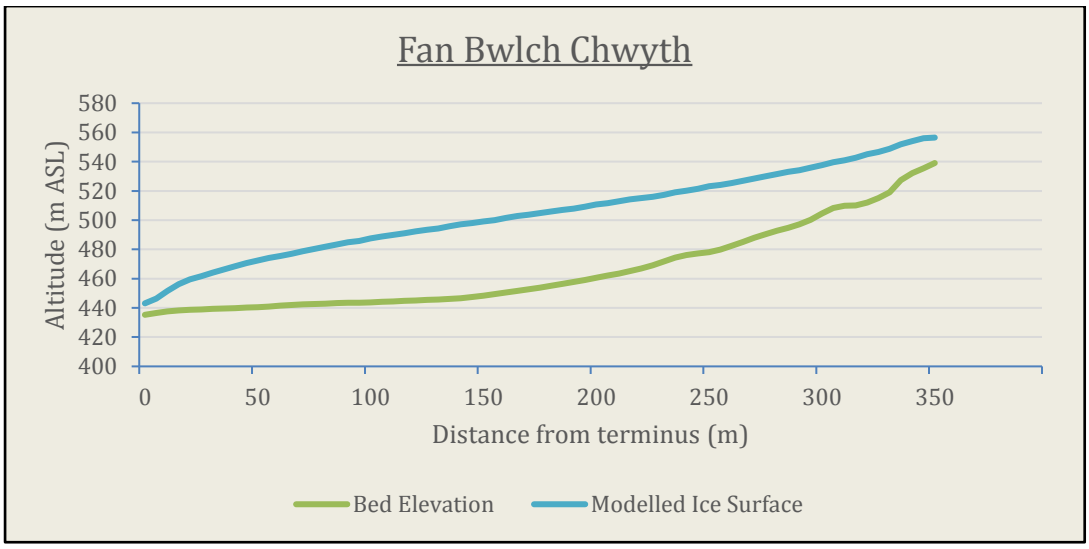

Figure 14: A longitudinal profile of modelled ice at Fan Bwlch Chwyth. Author: Self.

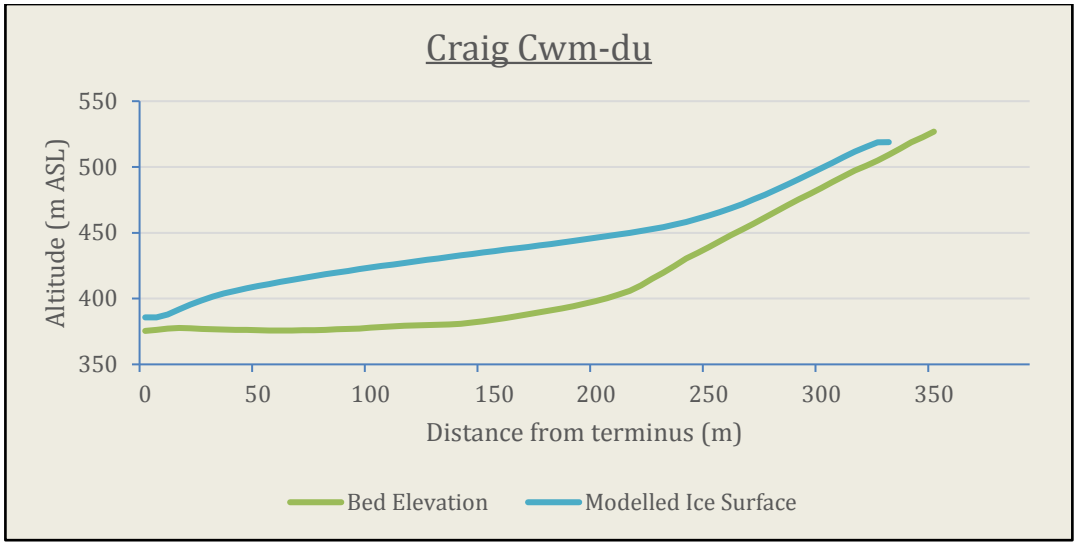

Figure 15: A longitudinal profile of modelled ice at Craig Cwm-du. Author: Self.

Calculation of Equilibrium Line Altitudes

Utilising the data contained within the models shown in Figures 8 to 11, the ELA for each glacier could be calculated via an average of the methods described in Section 4.5. The altitude of each calculated ELA shown in Table 2 appears to correlate strongly with the overall surface area of ice. Whether this is coincidental or relates to causation is not entirely clear but it would seem logical that lower temperatures resulting from increased elevation would enable the formation of larger ice masses.

Table 2: Calculated ELA values using methods described in Section 4.5. The ELA of each reconstructed glacier was considered to be the mean of the six approaches.

Location	Ice surface area (km^2)	AAR (0.44)	AAR (0.54)	AAR (0.64)	AABR (1.5)	AABR (1.9)	THAR (0.4)	Average (m asl)
Fan Gyhirych	0.133	627m	617m	607m	607m	607m	603m	611m
Blaen Senni	0.022	448m	438m	438m	428m	428m	414m	432m
Fan Bwlch Chwyth	0.112	515m	515m	505m	505m	495m	479m	502m
Craig Cwm-du	0.068	448m	448m	438m	438m	438m	429m	440m

Section 8: Other Factors

Solar radiation

As mentioned in Section 4.6, due to the nature of topography in mountainous areas insolation is not evenly distributed across the landscape. This is clearly shown by the spatial variation of modelled solar radiation in Figures 16 to 18.

Slope angle and aspect can create areas shaded from direct sunlight, which the upper reaches of the four reconstructed glaciers appear to exhibit the ablation season, protecting against mass loss and potentially catalysing ice accumulation. An average of the three months June-August was deemed most useful as changes between these months modelled individually appeared almost imperceptible. The result of modelling at Fan Bwlch Chwyth (LH side of Figure 18) should be carefully considered because human alteration of the headwall could not be eradicated from the input DEM.

At Fan Gyhirych (Figure 16) it would appear that virtually all ground above the reconstructed ELA is well shaded, whereas only the very uppermost reaches of the other three study sites are well shaded. However, this model does not account for changes in solar radiation as a result of ice forming on the landscape, which could feasibly have increased solar radiation upon these areas by raising the surface relative to the surrounding topography. Furthermore, seasonality during the Younger Dryas was likely more pronounced than today (Borisova, 1997) meaning insolation during the summer months would have been higher than as modelled, due to a reliance upon present day values. While this would probably not have had much effect upon well-shaded cirques it may have influenced albedo.

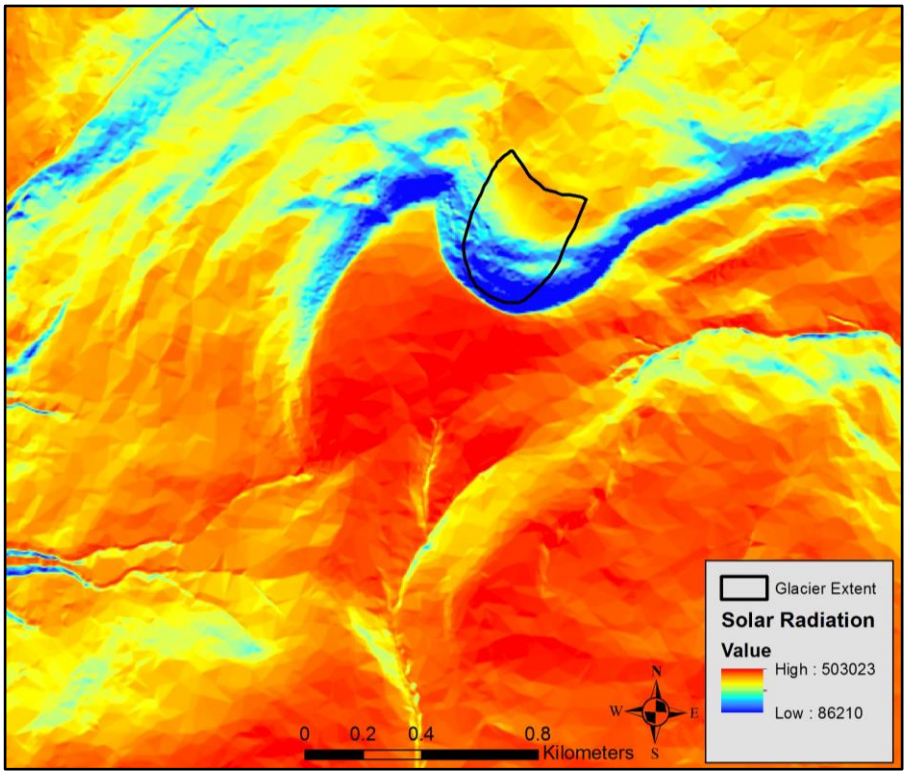

Figure 16: A model of solar radiation for Fan Gyhirych for the June-August ablation season. Author: Self; Data: Edina, 2016 (originally Ordnance Survey).

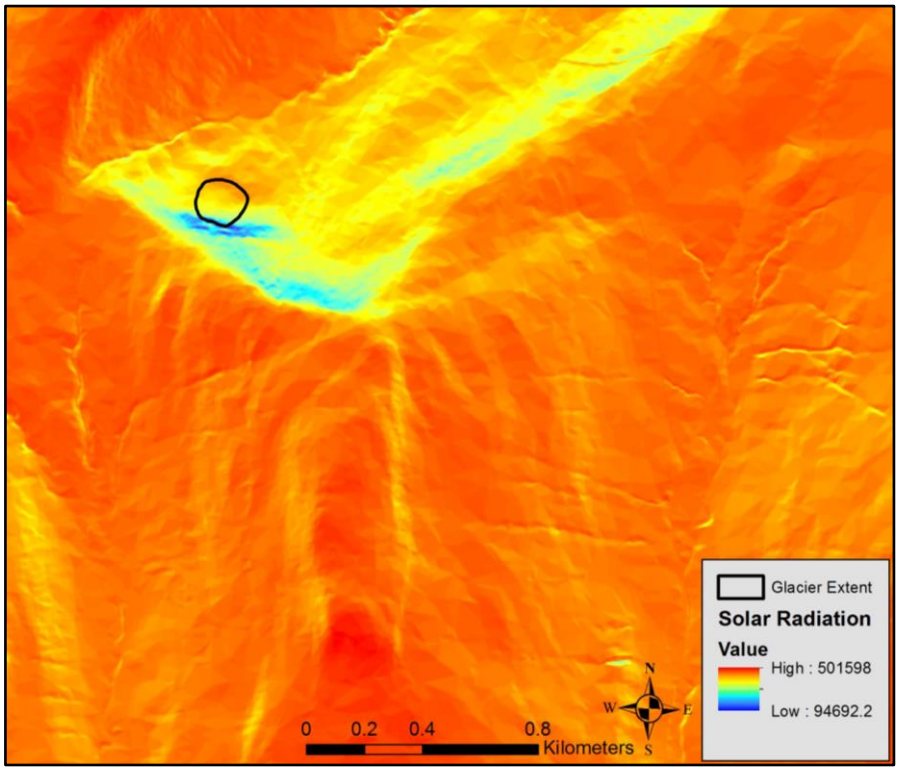

Figure 17: A model of solar radiation for Blaen Senni for the June-August ablation season. Author: Self; Data: Edina, 2016 (originally Ordnance Survey).

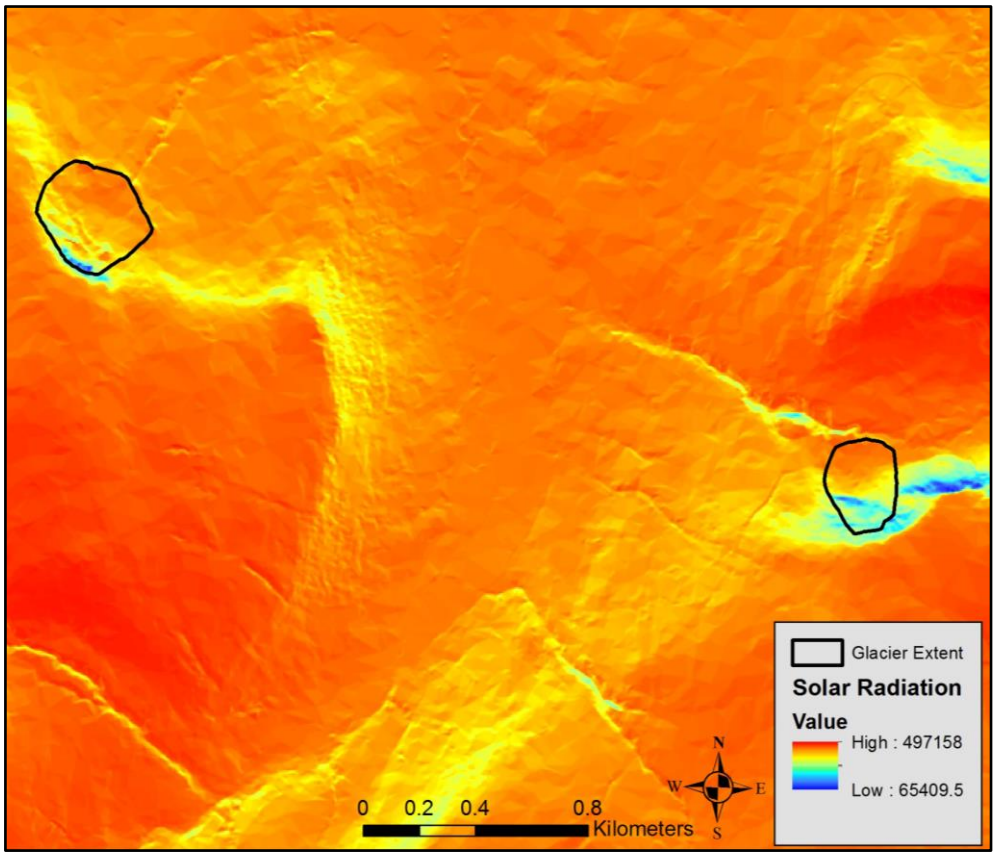

Figure 18: A model of solar radiation for Fan Bwlch Chwyth (left) and Craig Cwm-du (right) for the June-August ablation season. Author: Self; Data: Edina, 2016 (originally Ordnance Survey).

Snowblow and avalanching

When coupled with solar radiation information, assessing the role of snowblow and avalanching upon a cirque can be crucial in determining whether modelled dynamics are viable. It may also be useful in explaining how some glaciers can form at lower altitudes than nearby counterparts, or how very small glaciers may be sustained (Mitchell, 1996). Figures 19 to 22 show areas deemed to have the potential to contribute wind blown or avalanched snow on to the modelled glaciers, as described in Section 4.7.

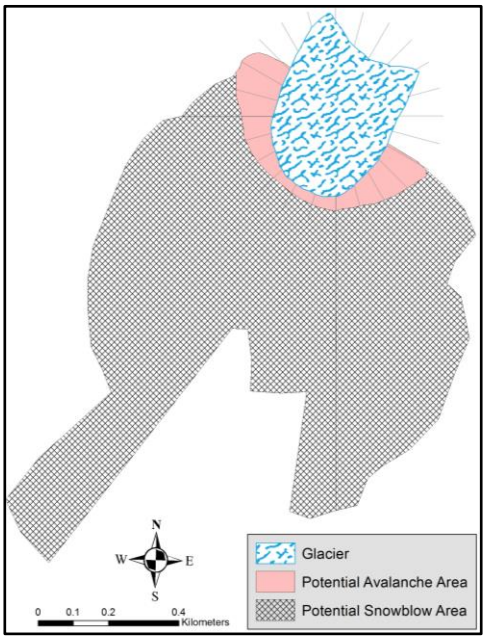

Figure 19: A map showing the potential area of contribution of snowblow and avalanching for the Fan Gyhirych palaeoglacier. Author: Self.

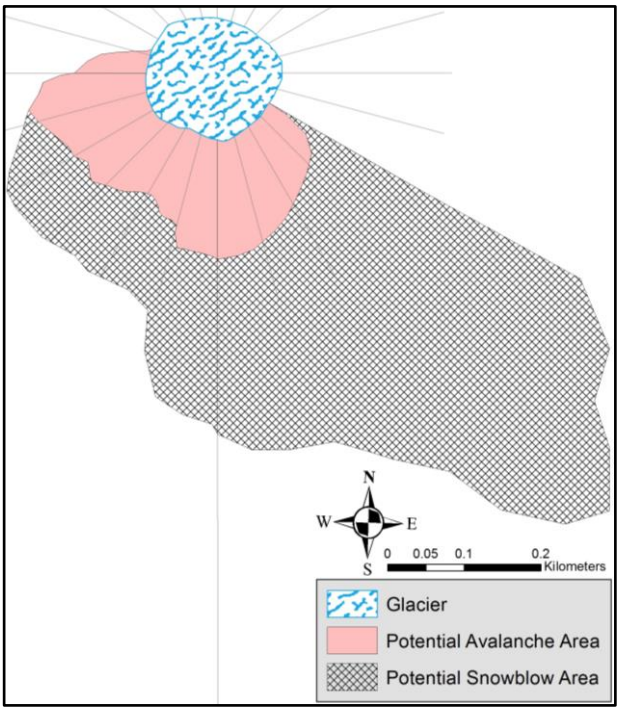

Figure 20: A map showing the potential area of contribution of snowblow and avalanching for the Blaen Senni palaeoglacier. Author: Self.

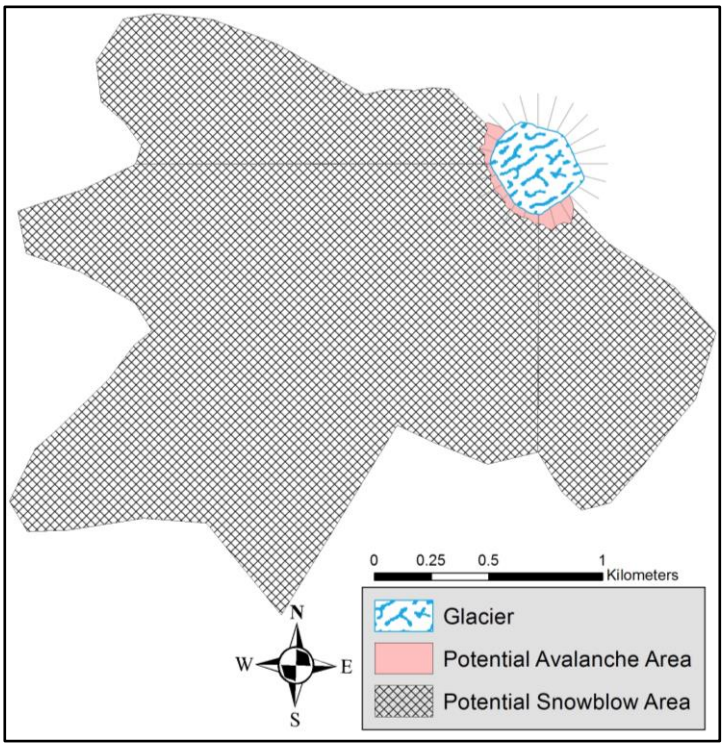

Figure 21: A map showing the potential area of contribution of snowblow and avalanching for the Fan Bwlch Chwyth palaeoglacier. Author: Self.

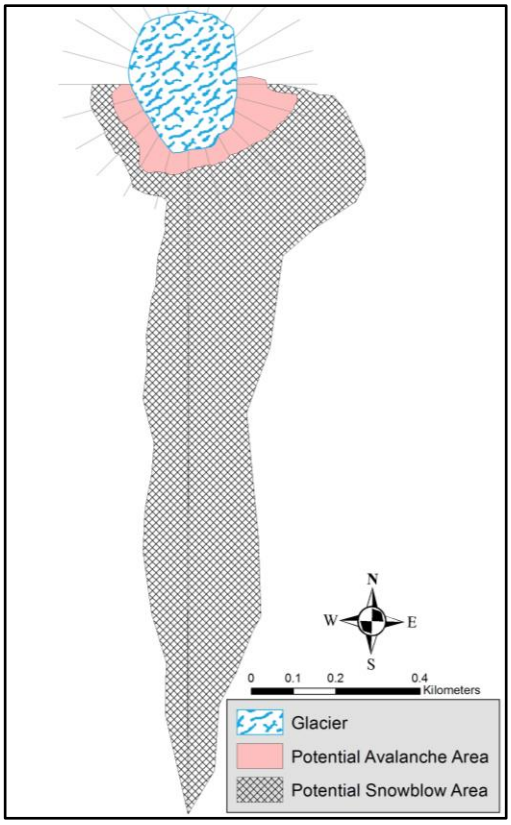

Figure 22: A map showing the potential area of contribution of snowblow and avalanching for the Craig Cwm-du palaeoglacier. Author: Self.

Tables 3 and 5 aim to calculate the total area of possible contribution via snowblow or avalanching as shown in Figures 19-22. This is broken in to compass quadrants to enable factors such as wind direction to be considered. During the Younger Dryas it is suggested that in the British Isles the prevailing wind came from southerly to westerly directions, much as today (Benn & Ballantyne, 2005; Bendle & Glasser, 2012). Table 3 shows that Fan Bwlch Chwyth has a significantly larger area of possible contribution via snowblow than the other study sites, with most of this area falling within the southwest quadrant. Table 5 would appear to indicate that the area potentially prone to avalanching surrounding the Craig Cwm-du glacier is much larger than the other sites.

Tables 4 and 6 provide more objective comparison between the sites using factor analysis. Considering the prevailing wind direction, Table 4 further demonstrates Fan Bwlch Chwyth to be most open to windblown snow accumulation, while due to the orientation of the valley that the Craig Cwm-du reconstructed glacier lies within wind scouring could have been a detrimental factor. On the other hand Table 6 indicates that avalanching would have been a positive factor affecting Craig Cwm-du mass-balance.

A noted shortcoming of the factors assessed in this Section is that while this method is useful in demarcating potential source areas it does provide assertions as to volumetric contribution.

Table 3: Area of possible contribution to glacier mass balance via snowblow. Quadrant of likely prevailing wind (SW) shown in **bold**.

Location	ELA altitude ASL	Area of modelled ice (km^2)	Snowblow area by compass quadrant (km^2) % of total snowblow area				Total area of possible snowblow contribution (km^2)
			NE	SE	SW	NW	
Fan Gyhirych	611m	0.133	0.000 0	0.286 31.5	**0.590** **65.0**	0.032 3.5	0.908
Blaen Senni	432m	0.022	0.000 0	0.187 70.8	**0.075** **28.4**	0.002 0.8	0.264
Fan Bwlch Chwyth	502m	0.112	0.000 0	0.692 15.4	**3.047** **67.6**	0.768 17.0	4.507
Craig Cwm-du	440m	0.068	0.001 0.2	0.320 69.1	**0.142** **30.7**	0.000 0	0.463

Table 4: Calculation of 'snowblow factor' to account for diminishing likelihood of contribution with increasing distance from each glacier. Quadrant of likely prevailing wind (SW) shown in **bold**.

Location	Area of modelled ice (km^2)	Total snowblow area (km^2)	Ratio (snowblow area/ice area)	Snowblow factor ($\sqrt{Ratio}$)	Snowblow factor by compass quadrant			
					NE	SE	SW	NW
Fan Gyhirych	0.133	0.908	6.827	2.612	0	1.47	**2.11**	0.49
Blaen Senni	0.022	0.264	12.000	3.464	0	2.92	**1.85**	0.30
Fan Bwlch Chwyth	0.112	4.507	40.241	6.344	0	2.49	**5.22**	2.62
Craig Cwm-du	0.068	0.463	6.809	2.609	0.12	2.17	**1.45**	0

Table 5: Area of possible contribution to glacier mass balance via avalanching.

Location	ELA altitude ASL	Area of modelled ice (km^2)	Avalanche area by compass quadrant (km^2)				Total area prone to avalanching (km^2)
			NE	SE	SW	NW	
Fan Gyhirych	611m	0.133	0.000	0.022	0.017	0.021	0.060
Blaen Senni	432m	0.022	0.000	0.017	0.030	0.002	0.049
Fan Bwlch Chwyth	502m	0.112	0.000	0.014	0.011	0.001	0.026
Craig Cwm-du	440m	0.068	0.001	0.022	0.016	0.000	0.237

Table 6: Calculation of 'avalanche factor' to account for diminishing likelihood of contribution with increasing distance from each glacier.

Location	Area of modelled ice (km^2)	Total avalanche area (km^2)	Ratio (avalanche area/ice area)	Avalanche factor ($\sqrt{ratio}$)	Avalanche factor by compass quadrant			
					NE	SE	SW	NW
Fan Gyhirych	0.133	0.060	0.451	0.672	0.00	0.41	0.36	0.40
Blaen Senni	0.022	0.049	2.227	1.492	0.00	0.90	1.17	0.30
Fan Bwlch Chwyth	0.112	0.026	0.232	0.482	0.00	0.35	0.31	0.09
Craig Cwm-du	0.068	0.237	3.485	1.867	0.12	0.57	0.49	0.00

Section 9: Glacial dynamics

In order to determine the viability of the reconstructed glaciers, quantification of their modelled dynamics is necessary for comparison between sites and with the literature. Table 7 summarises this information for discussion in Section 10.6.

Table 7: Calculated glaciological dynamics for each study site.

	Fan Gyhirych	Blaen Senni	Fan Bwlch Chwyth	Craig Cwm-du
ELA (m asl)	611	432	502	440
Temperature at ELA (°C)	6.2	7.4	6.9	7.3
Winter accumulation/mass loss at ELA (m/a)	2.396	2.874	2.683	2.852
Ablation gradient (mm/m^{-1})	6.5	8.2	7.4	8.1
Ablation (m^3 water-equivalent)	10,259.9	938.1	6,316.0	6,520,5
Mass flux (m^3)	11,274.6	1,030.7	6,940.6	7,165.4
ELA ice thickness (m)	64	31	50	50
ELA cross-sectional area (m^2)	19,140	4,814	15,923	11,675
ELA balance velocity (m/a^{-1})	0.6	0.2	0.4	0.6
ELA surface slope (degrees)	11	19	15	13
ELA basal shear stress (Bars)	1.1	0.9	1.2	1.0
Ice deformation (m/a^{-1})	6.9	1.8	6.4	4.2
Basal motion as % of total velocity	0(-1075)	0(-738)	0(-1377)	0(-589)

Section 10: Discussion

Geomorphological evidence

At Fan Gyhirych, the crest line of the large moraine is subtle and much less pronounced than other nearby examples (e.g. Craig Cerrig-gleisiad), however its distance of around 200m from the escarpment makes interpretation as a pronival rampart unlikely. This is in agreement with Shakesby (2002), who notes that for a snowbed to extend as far as the ridge it would have to have had a surface angle of only 19° for 400m. On the escarpment an area of scree extends from the valley floor to 600m, however no erratics or discernible features of glaciation were detected upon inspection. In contrast to the shape of the Fan Gyhirych moraine, the smaller but better defined ridge at Blaen Senni curves in a fashion consistent with movement away from the headwall. Jansson and Glasser (2008) attempted to explain the shape of the moraine feature at Fan Gyhirych by suggesting post-LGM up-valley ice sheet flow, however this view has been contested by Shakesby and Matthews (2008) due to its failure to acknowledge a wealth of evidence for cirque glaciation from nearby sites.

The variety in distribution, morphology and orientation of depositional features at Craig Cwm-du is suggestive of multiple phases of glaciation, as discussed in Section 5.4 and supported by Shakesby (2002). Placing temporal

constraints upon these will require dating of sediments extracted from features but may aid in establishing a clear timeline of events at this site. This sentiment is echoed at Fan Bwlch Chwyth, where comparison between the most prominent terminal moraine and an inner moraine ridge, possibly representing a recessional moraine, could yield a better understanding of glacial activity on relatively small timescales.

Palaeoclimatic conditions

On the southerly margin of the national park at an elevation of 324m ASL the Tredegar weather station provides the nearest contemporary climate data to the study area (Met Office, 2010). Here, average annual precipitation from 1981-2010 of 1674.2mm compares with a calculated average of 3145mm for the study sites during the Younger Dryas (Section 6). With an average reconstructed ELA of 496m between study sites there is clearly a large difference in elevation between the modern climate data quoted and historic calculations, making direct comparison hard to draw. However, given the role of orographic precipitation climate at the study sites is undoubtedly wetter than at Tredegar. Considering that average precipitation for the same period 1981-2010 at St Athan (Met Office, 2010), a weather station on the coast of south Wales (49m ASL), is 998.9mm it could be suggested that precipitation during the Younger Dryas was higher than today. Even though trends in precipitation with altitude are more complex than a linear relationship precipitation today for the average ELA elevation is likely less than 3000mm a^{-1}. This inference that precipitation was likely higher during the Younger Dryas is supported by Ballantyne (2002) using evidence from the Isle of Mull, however it is also contested by Bendle and Glasser (2012) whom suggest using a different methodology that in northern Snowdonia precipitation was lower than today.

Equilibrium Line Altitudes

The ELA of Fan Gyhirych (611m) falls well within the range of other viable reconstructed Younger Dryas glaciers in the area (Figure 3) such as Fan Hir (623m ASL ELA) (Carr & Coleman, 2007). Fan Bwlch Chwyth (502m) is at the low end of this spectrum, however sites such as Cwm Milan (548m) (Carr, 2001) would appear to indicate that glaciation at this elevation was possible and the role of snowblow was likely a significant factor in ice formation here (Section 10.5).

The calculated ELAs of Blaen Senni (432m) and Craig Cwm-du (440m) are below the values of widely accepted sites, with the origin of features at similar altitudes on Craig y Fro (436m) contested. At Craig y Fro, Carr et al. (2007) concluded that depositional features at the site were the result of paraglacial rock slope failure following the LGM. On the other hand, more recent evidence presented by Shakesby and Matthews (2009) argues that this conclusion is incorrect. Drilling of the peat basin in the cirque revealed no pre-Younger Dryas basal sediment and numerous striated, edge-rounded clasts were found within the moraine ridges. This perhaps supports the possibility of ice formation at Blaen Senni and Craig Cwm-du.

Solar radiation

Modelling in Figures 16-18 primarily illustrates a marked difference between incoming solar radiation on north and south facing aspects, indicating the NE facing Fan Chwyth Bwlch glacier would have received greater sunlight than the other study sites, most of this likely coming in the morning. On the other hand, the slightly NW facing Craig Cwm-du glacier would appear exposed to late afternoon sunlight but still well shaded from the strongest insolation during the middle of the day. Almost the entire accumulation area of the reconstructed Fan Gyhirych glacier would seem to lie in shade during the ablation season, likely enabling an extremely low yield of surface meltwater and preserving winter ice accumulation since most of the energy used in melt production is derived from incoming solar radiation (Hock et al., 2006). This could also have reduced basal lubrication by restricting moulin discharge.

Snowblow and avalanching

Using Tables 4 and 6 comparisons may be drawn with the nearby sites of Cwm Oergwm and Cwm Cwareli where similar factor analysis has been undertaken (Coleman et al., 2009). Overall, the sites presented within this study yielded snowblow and avalanche factors within the range established, however comparison isn't easily drawn because the results are presented using eight quadrants instead of four. In general, the results in Tables 4 and 6 would appear favourable for glacier formation with both factors enabling an increase in snow accumulation on the glacier surface. While wind transportation of snow around the landscape is an important factor in accumulation, by this nature it must also be a scouring agent. With the likely prevailing wind during the Younger Dryas (Benn & Ballantyne, 2005; Bendle & Glasser, 2012) falling within the SW quadrant of snowblow calculation (Table 4), this should be given the greatest consideration for aiding accumulation. A large plateau area to the SW of Fan Bwlch Chwyth (Figure 21) and few nearby north facing depressions mean that accumulation via snowblow was likely a critical factor in the development of a glacier at this site, especially considering the relatively low ELA. Accumulation via avalanching (Table 6) can be considered a minor factor, as the morphology of the flanking hillside is not widely steep enough to initiate this process. At Fan Gyhirych avalanching was likely a more prominent glacier input, with a large and expansive cirque headwall enclosing the glacier on three sides. Due to the significant elevation difference between the cirque basin and ridgeline (c.180m) avalanches could potentially also have entrained more snow than at other nearby sites with lower relief. By contrast, a less pronounced plateau to the SW of the summit of Fan Gyhirych likely meant that accumulation via snowblow was low.

The results of modelling at Blaen Senni and Craig Cwm-du yielded avalanche factors more than twice as high as at the sites discussed above, while snowblow factor within the SW quadrant was considerably smaller. Low angled ground to the S and SE of these study sites raised the overall snowblow factor in Table 4, perhaps misleadingly. At Craig Cwm-du (Figure 22) a relatively narrow ridgeline stretching southwards for c.500m was included in snowblow assessment, however the utility of this area to provide snow to the study site in all but due southerly winds is questionable. High avalanche factor results may be reasoned to result from the valley setting of

the reconstructed ice masses, affording c.180° of potential input. Slope angle was also a factor in yielding high results, with a large expanse of ground surrounding the Blaen Senni reconstruction site (Figure 20) sloping at angles of 20-25° to yield a proportionally larger avalanche area than the steeper gradients of Fan Gyhirych.

Glacial dynamics

Examining Table 7, a wide range of information can be derived regarding how an ice mass at each site would have behaved. Ablation gradients range from 6.5 to 8.2 mm/m^{-1}, the steepness of which are in agreement with a generalised figure of >5 mm/m^{-1} for mid-latitude glaciers (Benn & Evans, 2010) and a range of 5.01-8.3 mm/$^{m-1}$ for previously studied sites in the Brecon Beacons (Carr & Coleman, 2007; Coleman & Carr, 2008) using the same methods. Values of basal shear stress (0.9-1.2 bars) were also coherent with the default input of 100 kPa used in the GlaRE toolbox and the research of Paterson (1994), who noted contemporary glaciers typically exert 0.5-1.5 bars. On the other hand, the ELA balance velocities (0.2-0.6 m/a^{-1}) were much lower than the previously studied sites, suggesting very slow ice movement.

A striking aspect of Table 7 is that at all of the sites modelled, basal motion as a % of total velocity is zero. While Carr & Coleman (2007) suggest a threshold of 90%, above which it is unlikely that a viable glacier could have existed, values so low are not widely discussed. However, this does not indicate that the ice modelled was in fact cold-based, only that internal deformation was significant enough to transport ice downslope without basal sliding. Given the low calculated balance velocities this remains a possibility, but would indicate glaciers that were not significant geomorphic agents.

At Blaen Senni, an ELA ice thickness of only 31m is close to the suggestion of Gray (1982) for snow-ice transformation in this environment (20-30m). This, coupled with an ELA balance velocity of 0.2m/a^{-1} and very small cross-sectional area at an altitude of 432m would seem to suggest that glacial ice at this location was not viable. An ELA slope angle of 19° could suggest that the feature mapped in Figure 5 was instead a product of non-glacial processes, such as a pronival rampart. Sedimentological analysis would be required to confirm this proposition and to temporally constrain its formation.

Greater ELA ice thicknesses and cross-sectional areas at Fan Gyhirych, Fan Bwlch Chwyth and Craig Cwm-du are more consistent with glacial ice formation and similar to previously constructed sites such as Fan Hir (Carr & Coleman, 2007). These sites still differ significantly to others in their modelled ELA basal motion, however basal shear stress values of 1.1, 1.2 and 1.0 bars respectively may account for the generation of significant ice deformation at slow speeds. When combined with favourable solar radiation, snowblow and avalanche characteristics these study sites were considered glaciologically viable.

Limitations and review of error

During the course of this investigation, several potential limitations and sources of error have been introduced, which must be considered when evaluating the study findings. Many critical assessments of methods and findings have already been made, however this aims to raise further considerations that may propagate error through the study. Initially, while mapping features in the field some subjective interpretation had to be used to infer ice margin position from indistinct evidence. While combining satellite imagery and ground truthing helped to overcome this, the precision of moraine-crest placement cannot be guaranteed. Following this, upon digitisation in ArcGIS and before the GlaRE toolbox could be implemented, ice margin position was drawn by eye using mapped evidence and interpreted surrounding topographic constraints. This led to a number of possible glacial extents being modelled with only the most viable being presented, which could introduce bias when considering glaciological viability. The GlaRE toolbox is also a very recent publication (2016), so limited reference data on palaeoglacial reconstruction exists. This method neglected to consider possible advance, retreat and readvance stages at each site, which considering the cycling of contemporary glaciers is highly likely.

Perhaps the most significant limitation of this study was a lack of dating evidence to constrain the mapped features to being of Younger Dryas origin. Unfortunately, due to significant grass cover on the moraines surface exposure dating using resources such as a Schmidt Hammer were not possible and seeking permission to excavate was advised against. Finally, an issue specific to the Fan Bwlch Chwyth study site which may have influenced studying findings is recent quarrying activity. While efforts such as historic contour interpretation were made to try to account for this it is unlikely that these were entirely accurate.

Section 11: Conclusion

This study expanded upon the research of Younger Dryas glaciation in the Brecon Beacons by considering four study sites that had not before been reconstructed. It also contributed the first application of the GlaRE ArcGIS toolbox (Pellitero et al., 2016) in the region. Within this process the research aims established in Section 1.2 have been successfully achieved and discussed, these were:

- Use mapped geomorphological evidence to reconstruct the extent and glaciological dynamics of former cirque glaciation
- Establish local climatic conditions during the Younger Dryas
- Consider factors that may have influenced spatially confined accumulations of glacial ice

At Fan Gyhirych, excellent shading at an altitude similar to other locally reconstructed palaeoglaciers was an initial indicator of possible past glacial formation. Upon modelling a mass of ice that was agreeable with the restrictions of surrounding topography, glaciological calculations formed a key component in determining a glacial origin. Notably, an ELA ice thickness of 64m at a very low slope angle of 11° was considered to explain a lack of

basal motion due to significant ice deformation. The broad and indistinct morphology of the terminal moraine mapped in Figure 4 would appear to suggest a glacier that was relatively inactive, in agreement with the observations of Shakesby (2002).

Interpretation of modelled ice at the Blaen Senni study site as being non-glacial in origin is based upon several key factors. An extremely small surface area (0.022km^2) coupled with low altitude (432m ELA) initially questioned its viability. This, compounded by relatively low potential for snowblow accumulation under prevailing wind conditions, does not make the calculated glaciological dynamics (Table 7) seem feasible. Even given shading from cliffs above, which in turn provide high avalanche potential, westerly winds breaching the head of the Senni Valley would likely have scoured this slope.

An extremely large source area for snowblow accumulation from prevailing winds (3.047km^2) would likely have provided the main input for ice accumulation at Fan Bwlch Chwyth. Excellent geomorphic evidence in the form of well-preserved arcuate ridges at distances from the headwall significant enough to rule out non-glacial origin made initial interpretation of this site relatively straightforward. However, attempts to model this palaeoglacier using ArcGIS were more difficult due to widespread alteration of the cirque headwall by quarrying. Even though efforts were made to overcome this, glaciological calculations should be viewed with caution.

The array of apparently glacial material (Shakesby, 2002) at Craig Cwm-du would indicate a convoluted timeline of events since the LGM. The dissimilar orientation of the mapped moraine used to constrain terminal ice extent for this study (Figure 11) appeared to suggest the past existence of a small discrete glacier. Due to the low altitude of the study site this was considered to have the greatest likelihood in being of Younger Dryas age, while it is surmised that other larger moraine features reflect earlier glaciation. Though smaller than the Fan Bwlch Chwyth study site, its greater calculated mass flux and balance velocity are perhaps a product of significant input via avalanching. While correct interpretation of geomorphic evidence has been pivotal in reaching a conclusion of glacial origin, this site perhaps represents the lowest elevation of reconstructed cirque glaciation in the Brecon Beacons.

Although this research has sought to address a gap in the literature the need for further scientific study in this area remains. Widespread absolute dating of features is necessary to move beyond inference of Younger Dryas origin based upon geomorphological similarity to a small number of dated local sites. Additional modelling of multiple ice extent phases is also necessary to establish a specific timeline of events. Though efforts have been made to consider factors that may have influenced ice accumulation, scope exists for other important glaciological considerations such as debris cover to be modelled.

Acknowledgements

Thank you to my tutor for most of the course of this piece of work, Dr Stephanie Mills, whom through several meetings and many emails guided me

from project inception to near completion. Thank you also to Dr Caroline Clason for helping me upon Stephanie's departure. Finally, thank you to my friends in South Wales for looking after me during my time undertaking fieldwork, regularly providing cups of tea and food after sodden days in the mountains.

Bibliography

Ahlmann, H. W., (1948) Glaciological research on the North Atlantic coasts. *Royal Geographical Society Research Series,* 1, 84.

Atkinson, T. C., Briffa, K. R., Coope, G. R., (1987) Seasonal temperatures in Britain during the past 22,000 years, reconstructed using beetle remains, *Nature,* 325, 587-592.

Ballantyne, C. K., (2002) The Loch Lomond Readvance on the Isle of Mull, Scotland: glacier reconstructions and palaeoclimatic interpretations, *Journal of Quaternary Science,* 17 (8), 759-771.

Bendle, J. M., Glasser, N. F., (2012) Palaeoclimatic reconstruction from Lateglacial (Younger Dryas Chronozone) cirque glaciers in Snowdonia, *Proceeding of the Geologists' Association,* 123, 130-145.

Benn, D. I., Ballantyne, C. K., (2005) Palaeoclimatic reconstruction from Loch Lomond Readvance glaciers in the West Drumochter Hills, Scotland, *Journal of Quaternary Science*, 20 (6), 577-592.

Benn, D. I., Evans, D. J., (2010) *Glaciers and Glaciation.* 2nd edn. Abingdon: Routledge.

Benn, D. I., Hulton, N., (2010) An Excel™ spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps, *Computers & Geosciences,* 36, 605-610.

Benn, D. I., Lehmkuhl, F., (2000) Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments, *Quaternary International,* 65-66*,* 15-29.

Benn, D. I., Owen, L. A., Osmaston, H. A., Seltzer, G. O., Porter, S. C., Mark, B., (2005) Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glacier, *Quaternary International,* 8 (21), 138-139.

Borisova, O. K., (1997) Younger Dryas landscape and climate in Northern Eurasia and North America, *Quaternary International*, 41/42, 103-109.

Boulton, G. S., (1977) A multiple till sequence formed by a late Devensian Welsh Ice Cap: Glanllynnau, Gwynedd, *Cambria,* 4, 10-31.

Brecon Beacons National Park Authority (2012) *Brecon Beacons National Park Landscape Character Assessment.* Available at: http://www.beacons-

npa.gov.uk/wp-content/uploads/5.0_Story-of-the-BB-Landscape_final_120930.pdf (Accessed: 29 October 2016).

Brecon Beacons National Park Authority (2012) *Facts about the National Park.* Available at: http://www.beacons-npa.gov.uk/wp-content/uploads/basic-facts-about-the-brecon-beacons-national-park.pdf (Accessed: 29 October 2016).

Brecon Beacons National Park Authority (2015) *GIS Datasets.* Available at: https://data.gov.uk/publisher/brecon-beacons-national-park-authority (Accessed: 23 December 2016).

Carr, S. J., (2001) A glaciological approach for the discrimination of Loch Lomond Stadial glacial landforms in the Brecon Beacons, South Wales, *Proceedings of the Geologists' Association,* 112, 253-262.

Carr, S. J., Colemen, C. G., (2007) An improved technique for the reconstruction of former glacier mass-balance and dynamics, *Geomorphology,* 92, 76-90.

Carr, S. J., Coleman, C. G., Evans, D. J. A., Porter, E. M., Rea, B. R., (2007) 'An alternative interpretation of Craig y Fro based on mass-balance and radiation modelling', in Carr, S. J., Coleman, C. G., Humpage, A. J., Shakesby, R. A. (ed.) *Quaternary of the Brecon Beacons Field Guide*. London: Quaternary Research Association.

Carr, S. J., Lukas, S., Mills, S., (2010) Glacier reconstruction and mass-balance modelling as a geomorphic and palaeoclimatic tool, *Earth Surface Processes and Landforms,* 35, 1103-1115.

Carrivick, J. L., Brewer, T. R., (2004) Improving local estimations and regional trends of glacier equilibrium line altitudes, *Geografiska Annaler Series A Physical Geography,* 86 (1), 67-79.

Chiverrell, R. C., Thomas, G. S. P., (2010) Extent and timing of the Last Glacial Maximum (LGM) in Britain and Ireland: a review, *Journal of Quaternary Science,* 25 (4), 535-549.

Clark, C. D., Hughes, A. L. C., Greenwood, S. L., Jordan, C., Sejrup, H. P., (2012) Pattern and timing of retreat of the last British-Irish Ice Sheet, *Quaternary Science Reviews*, 44, 112-146.

Coleman, C. G., Carr, S. J., (2008) Complex relationships between Younger Dryas glacial, periglacial and paraglacial landforms, Brecon Beacons, South Wales, *Proceedings of the Geologists' Association,* 119, 259-276.

Coleman, C. G., Carr, S. J., Parker, A. G., (2009) Modelling topographic controls on palaeoglaciers: implications for inferring palaeoclimate from geomorphic evidence, *Quaternary Sciences Reviews,* 28, 249-259.

Dansgaard, W., White, J. W. C., Johnsen, S. J., (1989) The abrupt termination of the Younger Dryas climate event, *Nature*, 339, 532-534.

Edina (2016) *Digimap.* Available at: https://digimap.edina.ac.uk/ (Accessed: 30 September 2016).

Ellis-Gruffydd, I. D., (1977) Late Devensian glaciation in the upper Usk basin, *Cambria a Welsh geographical review,* 4, 46-55.

ESRI, (2016) *ArcGIS for Desktop: Area Solar Radiation – Help*. Available at: http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/area-solar-radiation.htm (Accessed: 12 December 2016).

Foster, H. D., (1970) Establishing the age and geomorphological significance of sorted stone stripes in the Rhinog Mountains, North Wales, *Geografiska Annaler,* 52A, 96-102.

Google (2015) *Google Earth Pro* (Version 7.1.5) [Computer program). Available at: https://www.google.co.uk/earth/download/gep/agree.html (Downloaded: 20 May 2015).

Gray, J. M., (1982) The last glaciers (Loch Lomond advance) in Snowdonia, N. Wales, *Geological Journal,* 17, 111-133.

Hock, R., Rees, G., Williams, M. W., Ramirez, E., (2006) Contribution from glaciers and snow cover to runoff from mountains in different climates, *Hydrological Processes*, 20 (10), 2089-2090.

Hooke, R. Le. B., (2005) *Principles of Glacier Mechanics*. 2nd edn. Cambridge: Cambridge University Press.

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M., (2009) Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British-Irish ice sheet, *Quaternary Science Reviews,* 28, 758-776.

Humpage, A. J., (2007) 'The bedrock geology of the Brecon Beacons and Usk Valley', in Carr, S. J., Coleman, C. G., Humpage, A. J., Shakesby, R. A. (ed.) *Quaternary of the Brecon Beacons Field Guide*. London: Quaternary Research Association.

Jansson, K. N., Glasser, N. F., (2008) Modification of peripheral mountain ranges by former ice sheets: The Brecon Beacons, Southern UK, *Geomorphology*, 97, 178-189.

Kaser, G., Osmaston, H., (2002) *Tropical Glaciers.* Cambridge: Cambridge University Press.

Kern, Z., László, P., (2010) Size specific steady-state accumulation-area ratio: an improvement for equilibrium-line estimation of small palaeoglaciers, *Quaternary Science Reviews,* 29, 2781-2787.

Lewis, C. A., (1968) The glaciations of the Brecknock Beacons Wales, *Brycheiniog,* 14, 97-120

Lowe, J. J., Rasmussen, S. O., Björck, S., Hoek, W. Z., Steffensen, J. P., Walker, M. J. C., Yu, Z. C., (2008) Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group, *Quaternary Science Reviews,* 27 (1-2), 6-17.

Lowe, J. J., Walker, M. J. C., (1997) *Reconstructing Quaternary Environments.* 2nd edn. London: Addison Wesley Longman.

Meier, M. F., Post, A. S., (1962) Recent variations in mass net budgets of glaciers in western North America, *International Association of Scientific Hydrology Publications,* 58, 63-77.

Meierding, T. C., (1982) Late Pleistocene Glacial Equilibrium-Line Altitudes in the Colorado Front Range: A Comparison of Methods, *Quaternary Research,* 18, 289-310.

Met Office (2010) *St-Athan climate.* Available at: http://www.metoffice.gov.uk/public/weather/climate/gcjs3tzpf (Accessed: 16 November 2016).

Met Office (2010) *Tredegar climate.* Available at: http://www.metoffice.gov.uk/public/weather/climate/gcjww0udy (Accessed: 04 January 2016).

Mitchell, W. A., (1996) Significance of snowblow in the generation of Loch Lomond Stadial (Younger Dryas) glaciers in the western Pennines, northern England, *Journal of Quaternary Science,* 11, 233-248.

Oerlemans, J., (1992) Climatic sensitivity of glaciers in southern Norway: application of an energy balance model to Nigardsbreen, Hellstugubreen and Alfortbreen, *Journal of Glaciology,* 38, 223-232.

Ohmura, A., Kasser, P., Funk, M., (1992) Climate at the Equilibrium Line of Glaciers, *Journal of Glaciology,* 38 (130), pp. 397-411.

Oliver, H. R., Chaloner, W. G., Rose, J., (1999) Geology in the Terrestrial Initiative in Global Environmental Research Programme TIGGER, *Journal of the Geological Society,* 156, 341-448.

Osipov, E. Y., Khlystov, O. M., (2010) Glaciers and meltwater flux to Lake Baikal during the Last Glacial Maximum, *Palaeogeography, Palaeoclimatology, Palaeoecology,* 294, 4-15.

Osmaston, H. A., (1975) 'Models for the estimation of firnlines of present and Pleistocene glaciers', in Peel, R. F., Chisholm, M. D. I., Haggett, P., (eds.) *Processes in Physical and Human Geography*. Bristol: University of Bristol Press, pp. 218–245.

Paterson, W. S. B., (1994) *The Physics of Glaciers.* 3rd edn. Oxford: Pergamon.

Patton, H., Hubbard, A., Glasser, N. F., Bradwell, T., Golledge, N. R., (2013) The last Welsh Ice Cap: Part 1 – Modelling its evolution, sensitivity and associated climate, *Boreas,* 42, 471-490.

Pellitero, R., Rea, B. R., Spagnolo, M., Bakke, J., Hughes, P., Ivy-Ochs, S., Lukas, S., Ribolini, A., (2015) A GIS tool for automatic calculation of glacier equilibrium-line altitudes, *Computers and Geosciences,* 82, 55-62.

Pellitero, R., Rea, B. R., Spagnolo, M., Bakke, J., Ivy-Ochs, S., Frew, C. R., Hughes, P., Ribolini, A., Lukas, S., Renssen, H., (2016) GlaRe, a GIS tool to reconstruct the 3D surface of palaeoglaciers, *Computers & Geosciences*, 94, 77-85.

Phillips, F. M., Bowen, D. Q., Elmore, D., (1994) Surface exposure dating of glacial features in Great Britain using cosmogenic chlorine-36: preliminary results, *Mineralogical Magazine,* 58A, 722-723.

Porter, S. C., (1975) Equilibrium line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand, *Quaternary Research,* 5, 27-47.

Rea, B. R., (2009) Defining modern day Area-Altitude Balance Ratios (AABRs) and their use in glacier-climate reconstructions, *Quaternary Science Reviews,* 28, 237-248.

Renssen, H., Mairesse, A., Goosse, H., Mathiot, P., Heiri, O., Roche, D. M., Nisancioglu, K. H., Vales, P. J., (2015) Multiple causes of the Younger Dryas cold period, *Nature Geoscience,* 8, 946-949.

Robertson, D. W., (1989) *Aspects of the Late-Glacial and Flandrian environmental history of the Brecon Beacons, Fforest Fawr, Black Mountains, South Wales, with emphasis on the Late-Glacial and early Flandrian periods.* PhD thesis. University of Wales.

Ruddiman, W. F., McIntyre, A., (1981) The mode and mechanism of the last deglaciation: Oceanic evidence, *Quaternary Research*, 16 (2), 125-134.

Shakesby, R. A., (2002) *Quaternary of the Brecon Beacons: Field Guide.* Sheffield: Geographical Association.

Shakesby, R. A., Matthews, J. A., (1993) Loch Lomond Stadial glacier at Fan Hir, Mynydd Du (Brecon Beacons), South Wales: Critical evidence and palaeoclimatic implications, *Geological Review,* 28, 69-69.

Shakesby, R. A., Matthews, J. A., (1996) Glacial activity and paraglacial landsliding activity in the Devensian Lateglacial: evidence from Craig Cerrig-gleisiad and Fan Dringarth, Fforest Fawr (Brecon Beacons), South Wales, *Geological Journal,* 31, 143-157.

Shakesby, R. A., Matthews, J. A., (2009) Comments on Jansson, K.N. and Glasser, N.F. (2008) "Modification of peripheral mountain ranges by former ice sheets: The Brecon Beacons, southern UK," Geomorphology 97, 178–189, *Geomorphology*, 110, 217-225.

Sissons, J. B., (1974) A Late-Glacial Ice Cap in the Central Grampians, Scotland, *Transactions of the Institute of British Geographers*, 62, 95-114.

Sissons, J. B., Sutherland, D. G., (1976) Climatic inferences from glaciers in the Southeast Grampian Highlands, Scotland, *Journal of Glaciology,* 17, 325-346.

Sissons, J. B., (1980) 'Palaeoclimatic inferences from Loch Lomond advance glaciers', in Lowe, J. J., Gray, J. M., Robinson, D. E. (eds.), *Studies in the Lateglacial of North West Europe*. Oxford: Pergamon, pp. 31-43.

Vandenberghe, J., Renssen, H., Isarin, R. F. B., (2001) The last deglaciation: climate modelling and data analysis, *Global and Planetary Change,* 30, 1-165.

Walker, M. J. C., (1982) The Late Glacial and early Flandrian deposits at Traeth Mawr, Brecon Beacons, South Wales, *New Phytologist,* 90, 177-194.

Walker, M. J. C., Coope, G. R., Lowe, J. J., (1993) The Devensian (Weichselian) Lateglacial palaeoenvironmental record from Gransmoor, East Yorkshire, England, *Quaternary Science Reviews,* 12, 659-680.

Walker, M. J. C., Coope, G. R., Sheldrick, C., Turney, C. S. M., Lowe, J. J., Blockley, S. P. E., Harkness, D. D., (2003) Devensian Lateglacial environmental changes in Britain: a multi proxy environmental record from Llanilid, South Wales, UK, *Quaternary Science Reviews,* 22, 475-520.