Rapid thinning of the Welsh Ice Cap at 20–19 ka based on 10Be ages

Hughes, Philip D.; Glasser, Neil; Fink, David

Published in:
Quaternary Research

DOI:
10.1016/j.yqres.2015.11.003

Publication date:
2016

Citation for published version (APA):
Hughes, P. D., Glasser, N., & Fink, D. (2016). Rapid thinning of the Welsh Ice Cap at 20–19 ka based on 10Be ages. *Quaternary Research*, *85*(1), 107-117. https://doi.org/10.1016/j.yqres.2015.11.003

Elsevier Editorial System(tm) for Quaternary Research
Manuscript Draft

Manuscript Number:

Title: Rapid thinning of the Welsh Ice Cap at 20-19 ka based on 10Be ages

Article Type: Research Paper

Keywords: Welsh ice cap; nunatak; 10Be; cosmogenic exposure dating; Rhinogs; Moelwyns; Arenigs

Corresponding Author: Dr. P.D. Hughes, PhD

Corresponding Author's Institution: University of Manchester

First Author: P.D. Hughes, PhD

Order of Authors: P.D. Hughes, PhD; Neil F Glasser, PhD; David Fink, PhD

Abstract: Nine new 10Be ages from the summits of the Rhinogs, Moelwyns and Arenigs, North Wales, reveal a very similar timing for the exposure of these summits as the Welsh Ice Cap thinned after the Last Glacial Maximum. The regional extent of the three sites and equal exposure ages over a 320 m vertical range (824 to 581 m altitude) show that ice cap thinning was very rapid and spatially uniform. Using the same production rate and scaling scheme, we recalculated published 10Be exposure ages from the nearby Arans, which also covered a similar elevation range from 608 to 901 m. The average exposure age of all 15 accepted deglaciation ages is 19.21 ± 1.07 (5.6%, 1σ). The complete dataset for the all 15 samples from North Wales provides very strong evidence indicating that these summits became exposed as nunataks at ~19.5 ka, after the global Last Glacial Maximum and the rate of surface lowering of the Welsh Ice Cap was relatively rapid at about 300 metres within 1-2 ka. Subsequently, the mountain summits would have been subject to periglacial processes for at least 4 ka as the ice cap continued to thin and was replaced by valley glaciers.

Suggested Reviewers: Simon Cook PhD
Lecturer, Geography & Environmental Management, Manchester Metropolitan University
s.j.cook@mmu.ac.uk
Simon is an expert on glacial erosion and has worked extensively in Wales.

Chris Clark PhD
Professor, Geography, University of Sheffield
C.Clark@Sheffield.ac.uk
Chris Clark leads the BRITICE_CHRONO project which is dating the retreat of the last ice sheet over the British Isles.

Danny McCarroll PhD
Professor, Geography, University of Swansea
d.mccarroll@swansea.ac.uk
Professor McCarroll is an expert on the glaciations of Wales.

Opposed Reviewers:

MANCHESTER
1824

The University
of Manchester

School of Environment and
Development
The University of Manchester
Oxford Road
Manchester M13 9PL

+44(0)161 306 1220
www.manchester.ac.uk

Wednesday 3rd May, 2015

Dear Editors,

We have submitted a manuscript entitled "**Rapid thinning of the Welsh Ice Cap at 20-19 ka based on ^{10}Be ages**" to be considered for publication in *Quaternary Research*.

This paper provides new evidence for the timing of the down-wasting of the last Welsh ice cap in the British Isles. The paper presents 10Be exposure ages in collaboration with David Fink at the Australian Nuclear Science and Technology Organisation (ANSTO), a leading cosmogenic isotope analysis facility. The paper is likely to be well-cited because there is a parallel and complementary project underway (BRITICE CHRONO) that is investigating the timing of the retreat of the British-Irish ice sheet. This is independent of our research. Thus, the Welsh data is very timely and shows rapid ice cap thinning soon after the global LGM.

We believe that this paper will be of interest to many Quaternary Scientists, glaciologists and Earth Scientists in general.

We look forward to the comments of the reviewers and the opinion of the Editors on the suitability of this paper for publication in *Quaternary Research*.

Yours Sincerely

P. Hughes

Dr. Philip Hughes
Senior Lecturer in Physical Geography

philip.hughes@manchester.ac.uk

Quaternary Research

Rapid thinning of the Welsh Ice Cap at 20-19 ka based on ^{10}Be ages

Philip D. Hughes[1*], Neil F. Glasser[2], David Fink[3]

[1] *Geography, School of Environment and Development, The University of Manchester, Manchester, M13 9PL, England, UK.*
[2] *Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, SY23 3DB, Wales, UK*
[3] *Australian Nuclear Science and Technology Organisation, PMB1, Menai, NSW 2234, Australia.*

ABSTRACT

Nine new ^{10}Be ages from the summits of the Rhinogs, Moelwyns and Arenigs, North Wales, reveal a very similar timing for the exposure of these summits as the Welsh Ice Cap thinned after the Last Glacial Maximum. The regional extent of the three sites and equal exposure ages over a 320 m vertical range (824 to 581 m altitude) show that ice cap thinning was very rapid and spatially uniform. Using the same production rate and scaling scheme, we recalculated published ^{10}Be exposure ages from the nearby Arans, which also covered a similar elevation range from 608 to 901 m. The average exposure age of all 15 accepted deglaciation ages is 19.21 ± 1.07 (5.6%, 1σ). The complete dataset for the all 15 samples from North Wales provides very strong evidence indicating that these summits became exposed as nunataks at ~19.5 ka, after the global Last Glacial Maximum and the rate of surface lowering of the Welsh Ice Cap was relatively rapid at about 300 metres within 1-2 ka. Subsequently, the mountain summits would have been subject to periglacial processes for at least 4 ka as the ice cap continued to thin and was replaced by valley glaciers.

1. Introduction

The Welsh Ice Cap has been the subject of research for over 150 years. The thickest part of the ice cap in Wales was situated over the Arenig Mountains, a fact that has long been known (e.g. Fearnsides 1905). Whilst the exact location of the ice divide varies in the literature, it is clear that the thickest part of the Welsh Ice Cap was positioned over the Arenigs and nearby Aran mountains, with ice moving westwards from these areas towards the Cardigan Bay (Foster, 1970a,b) and eastwards towards the borderlands of England (Travis, 1944).

The Welsh Ice Cap was largely independent of the British Irish Ice Sheet which had its thickest centres over Ireland, England and Scotland. Whilst the Welsh Ice Cap and the British Irish Ice Sheet were separate and autonomous, there were some incursions of Irish Sea ice into Wales, such as in the Vale of Clwyd (Rowlands, 1971) and across Anglesey and the Lleyn Peninsula (Thomas and Chiverrell, 2007). In North Wales the British Irish Ice Sheet subsumed the Welsh Ice Cap (Clark et al., 2012) whilst in Mid and South Wales the Welsh Ice Cap did not coalesce with the British Irish Ice Sheet. The timing of retreat of the various sectors of the British Irish Ice Sheet has been the subject of intense research (e.g. Ballantyne 2010; Chiverrell et al., 2013; Everest et al., 2013). However, the history of the Welsh Ice Cap has not been the focus of recent geochronological investigations despite there being very little known about the timing of ice cap retreat. More recent studies have provided new insight into the pattern of ice dynamics in this region using satellite imagery and ice cap modelling (Jansson and Glasser, 2005; Patton et al. 2013a, b). Most of the geochronology that does exist is based on dating the lateral retreat of ice margins (see A.L. Hughes et al., 2010a,b for a review of ages for both the Welsh Ice Cap and the British Irish Ice Sheet). Despite the lack of dating control, the geomorphology of the landscape produced by the last Welsh Ice Sheet is well understood (e.g. Jansson and Glasser 2005). The geomorphological evidence provides the basis for recent modelling simulations (e.g. Patton et al., 2013a, 2013b) which are constrained by a limited geochronology from only a few areas.

Glasser et al. (2012) provided eight paired $^{26}Al/^{10}Be$ exposure ages from the Aran ridge mountain summits in Wales in order to establish the vertical exposure history of the Welsh Ice Cap. This study aimed to test both the timing of exposure and whether there was any evidence of complex exposure history. The results indicated that the summits were exposed at c. 20-17 ka (subject to recalculation using new production rates in this paper – see later) and that there was no evidence of complex exposure history. Six out of the eight exposure ages overlapped within error suggesting near complete zeroing of the cosmogenic nuclide signal by prior glaciation and a simple exposure history following ice retreat. Two samples were old outliers and suggest inheritance and localised patches of reduced erosion on the summit ridge.

Glasser et al. (2012) demonstrated that the Welsh Ice Cap was thinning at c. 20 ka, after the Last Glacial Maximum (LGM) which is often defined within the interval 26-21 ka (Clark et al. 2006; Shakun and Carlson 2010). The definition of the LGM is discussed by Hughes and Gibbard (2014) who argue that it should be defined as an ‘event’ in the ice core stratigraphy, coeval with Greenland Stadial 3 (27.5-23.4 ka). They suggest that Heinrich 2 terminated the LGM at c. 23 ka and thus ice cap thinning after this time is consistent with this. However, in order to achieve a regional picture of ice cap thinning, exposure ages are needed from the independent mountain ranges believed to have been submerged by the ice cap in order to test whether ice cap thinning occurred locally or regionally soon after Heinrich Event 2. Furthermore, new exposure ages are calculated using revised production rates (e.g. Fenton et al., 2011; Balco et al., 2009; Putnam et al., 2010, Briner et al., 2012; Young et al., 2013) with previously published ages such as those from the Arans (Glasser et al., 2012), have been recalculated accordingly.

This paper presents evidence from three mountains ranges in central Snowdonia, North Wales: the northern Rhinogs, the Moelwyns and the Arenigs (Fig. 1). The northern Rhinogs culminate at Moel Ysgyfarnogod (623 m), the Moelwyns at Moelwyn Mawr (770 m) and the Arenigs at Arenig Fawr (854 m). The mountains are strategically important for understanding ice cap dynamics because these areas were close to the thickest centre of the last Welsh Ice cap (Fearnsides 1905; Greenly 1919; Foster 1968, 1970a,b; Addison 1997; Jansson and Glasser 2005; Glasser et al., 2012; Patton et al. 2013a, b). Terrestrial cosmogenic nuclide exposure ages have never been published from these three sites. This study exploits the quartz-rich lithologies of these areas to provide a new cosmogenic exposure chronology for the mountain summits. The primary aim is to establish the exposure ages of the summits of the northern Rhinogs, the Moelwyns and the Arenigs and compare this with the recently-obtained paired $^{26}Al/^{10}Be$ exposure ages from the nearby Arans (Glasser et al. 2012). This will provide a time constraint for understanding the vertical thinning of the last Welsh Ice Cap at the end of the last cold stage. In addition, the timing of ice cap thinning over Wales will also provide interesting comparison with deglaciation geochronologies from the wider British-Irish Ice Sheet (e.g. Chiverrell et al. 2013; Ballantyne and Stone 2015).

2. Study area

The study area spans a narrow latitudinal and longitudinal range from 52.8763 to 52.9819°N and -4.0013 to -3.7432°E. The Rhinogs are formed in Cambrian sandstones and mudstones of the Rhinog Formation and sandstones of the Hafotty Formation. The latter rock type forms the summit areas of most of the northern Rhinogs. Ordovician microgabbro intrusions also occur in this area emplaced into the Cambrian rocks. The Moelwyns are formed in Ordovician siltstones (slates) and volcanics. We targeted quartz veins which are widely found in both. The volcanics comprise of an unnamed intrusive rhyolite and tuffite of the Moelwyn Volcanic Formation. The Arenigs are formed in Ordovician volcanics dominated by felsic tuffs and quartz-latite intrusions. The tuffs form the summit ridges with tuffs of the Aran Fawddwy Formation predominant with a small area of tuffs belonging to the Benglog Volcanic Formation. All geological terminology for these areas was obtained from EDINA Geology Digimap (2014).

3. Methods

3.1. Geomorphology

This project focused on the evidence of glaciation on the summits of the Rhinogs, Moelwyns and Arenigs. Glacial erosional features are widely evident, such as striations, roche moutonees whalebacks and rock pavements, and these were targeted for cosmogenic dating. Perched boulders resting on ice-polished bedrock were also noted as evidence of ice overriding summits. The main focus of the project was to establish the exposure history of the summits of the three mountain areas. Thus, samples were taken from rock surfaces at or close to the apex of the watersheds in these mountain areas. Regional patterns of ice flows were established using topographic maps and satellite imagery as well as utilising field evidence from a number of previous research studies (e.g. Foster, 1970b; Rowlands, 1979).

3.2. Geochronology

Eight samples were taken from ice-moulded striated bedrock on the summit watersheds of the northern Rhinogs (1 sandstone and 1 quartz-vein sample), Moelwyns (3 quartz vein samples) and Arenigs (3 quartz vein samples). Glacially-abraded surfaces can yield reliable exposure ages when erosion by ice from the most recent ice advance has been sufficient to remove the accumulated in-situ cosmogenic signal from all previous exposures This has been shown to be a reliable approach (Dielforder and Hetzel, 2014) yet bedrock is often overlooked in favour of boulders since the prevailing pattern of sampling favours erratics on the assumption that transported erratics are more likely to have minimal inheritance and there is no way of detecting inheritance prior to sampling (Balco, 2011). The expansive ice-overridden summit regions in this work are characterised by exposed, gently sloping polished bedrock sheets on which are perched erratics and cobbles of various sizes. Unlike the short transit times for boulders in typical alpine glacial systems prior to deposition at terminal moraine locations, the erratics on these open summit bedrock watersheds may well have resided sub-aerially for a considerable period prior to ice cap thinning and final glacial retreat. Hence it was not a priori assumed that erratics would provide the best target and one glacially-transported boulder was also sampled (sandstone) immediately adjacent to a bedrock sample (quartz vein) in the Rhinogs to form a bedrock-boulder pair. Details of all 9 samples are provided in Table 1.

Samples were crushed, sieved and cleaned with aqua regia at the University of Manchester Geography Laboratories. The 250-500 micron fraction (~100-200 g) was added to 1L glass beakers, mixed with Aqua Regia [60ml of conc. HNO_3 and 180ml of conc. HCl], then left to stand for 24 hours and stirred twice in this period. The Aqua Regia was then decanted and replaced until the solution was clear (1-2 washes). After Aqua Regia treatment the sample was rinsed in water (~6 times, wash and decant), then 100-200 ml of NaOH was added, stirred, then left for 2-4 hours. Samples were then washed with water and dried. Samples were then sent for further preparation and AMS measurement at the Cosmogenic Geochemistry Laboratories at the Australian Nuclear Science and Technology Organisation (ANSTO). Here, quartz separation and purification was achieved by hot phosphoric acid etching (Mifsud et al., 2013) and elution of the ^{10}Be fraction (Child et al., 2000). Instead of selective hydrofluoric acid etching to separate quartz (Kohl and Nishiizumi 1992) repeated treatments of hot ortho-phosphoric acid (H_3PO_4 85% w/w) at 250ºC were used to remove non-quartz mineral species followed by one or two cycles of HF (2%) etch. The hot H_3PO_4 method does not attack quartz as severely as HF, making it preferable when the quartz grain size is very small, such as in silcretes, chert and other quasi-amorphous silicates or when the quartz concentration in the bulk is very low. The samples were all quartz-rich and initial rock masses used for processing (in the 250-500 micron fraction) ranged from ~100 to 200 grams, with yields of about 40-95% of acceptable quartz following treatment described above. Following quartz dissolution in 50% w/w HF and addition of a ^{9}Be carrier (~0.32 mg) all samples were carefully fumed with the addition of 5ml of $HClO_4$. Dowex anion and cation resins (1X-8 and 50W-X8) were used for ion chromatography separation to eliminate matrix contaminations (Fe, Ca, Ti etc.). Following pH-adjustment $Be(OH)_2$ was precipitated, carefully dried and calcined at 800ºC. The final BeO material (0.5 to 1.0 mg oxide) was mixed with a Nb binder (BeO : Nb=1:4) (Fink et al. 2000) and then pressed into target cathodes for AMS measurement.

AMS targets were measured for ^{10}Be at the ANTARES AMS Facility at ANSTO (Fink and Smith, 2007). $^{10}Be/^{9}Be$ ratios (see Table 2) were normalised against the NIST-4325 standard reference material ($^{10}Be/^{9}Be$ ratio of 27,900 x 10^{-15}). All isotopic ratios were corrected using full chemistry procedural blanks prepared from dissolved and purified beryl crystal with a measured $^{10}Be/^{9}Be$ ratio of (5.66 ± 0.62) x10^{-15} (n=4, 2 targets) and with a ^{9}Be concentration of 1080±11 ug/g. Background corrections ranged between 1.7-2.8% of the measured AMS $^{10}Be/^{9}Be$ ratio (Table 1). Repeat measurements of individual samples were combined as weighted means with the larger of the mean standard error or total statistical error. Final analytical errors in the 10Be concentration (^{10}Be/g-quartz) were derived from the quadrature addition of the 1σ spread in repeat measure of AMS standards (1.5%), final statistical error in the AMS ratio, and a 1% error in Be-spike assay resulting in a combined analytical error ranging from 2.8 to 3.6% (Table 2). Site spallation and muon production rates were scaled independently from seal-level and high altitude (SLHL) following the prescription given by Stone (2000). A range of reference production rates (ie rates defined for SLHL) can be used to calculate exposure ages and there remain uncertainties over suitable values for Wales. In order to compare with other published data, we adopt the same ^{10}Be reference production rate used for west Wales and the Irish Sea area by Chiverrell et al. (2013) of 4.20 ± 3.6% atoms g^{-1} a^{-1} based on a calibrated dataset from northwest Scotland (Ballantyne and Stone, 2012). . We choose a SLHL surface ^{10}Be muon total production rate of 0.1 at/g/y (ie ~2.5% of total production (Stone, 2000) (see Table 2) and a ^{10}Be decay constant of 4.99 x10^{-7} a^{-1}, based on the half-life value of 1.387 ± 0.012 Ma (Chmeleff et al., 2010; Korschinek et al., 2010). Glasser et al., (2012) have previously published ^{10}Be ages from the neighbouring Aran mountains and to enable a direct comparison, we have recalculated these ages using identical methods as described above.

Reduced paleo-geomagnetic dipole strengths result in increased time-integrated production rates compared to present day (or early Holocene) estimates. Hence apparent exposure ages based on a non-varying geomagnetic field intensity (ie constant site production rate) usually will overestimate the true age. For this study, at the high northern latitude of ~52 N, production rate corrections for a time varying geomagnetic field become marginal and also rather insensitive to choice in scaling or paleomagnetic record. Direct comparison of age calculations based on Dunai scaling with a time varying geomagnetic field (Dunai 2002) results in ages < 1% younger than those based on time invariant Dunai calculations. Corrections to site specific production rates due to horizon topographic shielding of cosmic rays were negligible apart from one sample (MW02; 0.96) whereas corrections for sample thicknesses (~3-5 cm) ranged from ~0.95-0.97 (thickness corrections were carried out by integrating the effective comsic ray flux over the given depth using Λ= 150 g/cm^2 and ρ= 2.7 g/cm^3). Corrections for seasonal snow cover were not included as we believe that little summer snow accumulates due to the open and flat expanses of the bedrock summits. Age correction due to surface weathering becomes progressively more important with increasing zero-erosion minimum age. For example, a reasonable erosion rate of 1 mm/ka for quartz vein samples would amount to <0.5 ka increase in age over a 20 ka exposure period. Hence with the above uncertainties, choice in relative muon production contribution (see Braucher et al 2012) and scaling schemes (Balco et al 2007), our conclusions regarding the exposure age determinations for these Welsh summits are not altered.

4. Rhinogs

4.1. Geomorphology

The northern Rhinogs contain extensive rock pavements, striated whalebacks and roche moutonees with several small glacial lakes occupying bedrock hollows on the watershed (Fig. 2). The rock pavements are littered with perched boulders. The sandstone rocks are heavily fractured in this area and perched rocks appear to have been plucked off bedding planes and then transported up to several hundreds of metres. Whilst local in origin the boulders are often subrounded or subangular and display evidence of significant glacial abrasion. Striations were recorded on the bedrock at the sample sites (see below) and have an east-west lineation (85/265 to 110/290°) which is consistent with ice movement from the east (Foster, 1970) (Fig. 2).

4.2. Geochronology

Three samples were taken from the watershed of the northern Rhinogs between the peaks of Clip (598 m) and Moel Ysgyfarnogod (623 m). The first sample (RH01) was taken from a striated bedrock whaleback (Fig. 3) a short distance (~100 m) NE of Clip summit near Bwlch Gwilym. This sample gave an exposure age of 19.4 ± 0.7 ka (analytical error will be used for each sample noted in the following). The second sample (RH02) was taken from a quartz vein on a striated rock pavement between Llyn Du and Moel Ysgyfarnogod (Fig. 3). This gave an exposure age of 20.3 ± 0.6 ka. The third sample (RH03) was taken from the top of a large subangular sandstone boulder (2.50 x 1.80 x 1.20 m) perched on striated bedrock pavement of the same lithology. This sample is just 20 metres to the south of bedrock sample RH02 (Fig. 3) and yielded an exposure age of 17.9 ± 0.5 ka. We note that this is the only erratic in the data set and has the lowest exposure age which is ~ 2-3 sigma from the mean based on the remaining 8 bedrock samples. The resultant mean age for this site (using all 3 samples) is 19.2 ± 1.2 ka.

5. Moelwyns

5.1. Geomorphology

The northern summit area of Moelwyn Bach (710 m) is characterised by extensive rock pavements, formed in tuffite of the Moelwyn Volcanic Formation, with occasional perched boulders of local origin. The southern (and highest) summit area is formed in metamorphosed siltstones (slates) (Nant Ffrancon Subgroup) with quartz veins. Again these slates form smoothed pavements, whalebacks and roches moutonnées. All of these rock features exhibit features (such as streamlining, local boulders plucked from bedrock joints, grooves and occasional striae on the finer grained siltstones) consistent with ice moulding from the east to west (Fig. 4).

To the north of Moelwyn Bach the ridge of Craigysgafn leads on to Moelwyn Mawr (770 m) (Figs. 4 and 5). This ridge is formed in rhyolite and tuffite with numerous quartz veins, and in some case extensive quartz outcrops (Fig. 6). The rocks of this ridge are smoothed with numerous whalebacks and roches moutonnées . As with the summit of Moelwyn Bach this is consistent with ice moulding. The ice-moulded features on Craigysgafn are aligned east-west. However, the eastern face of Craigysgafn is the steeper face (Fig. 4 and 5), although this is not indicative of ice direction over the ridge (i.e. through lee-side plucking). Instead, this steeper eastern face is the result of localised glaciation in Cwm Stwlan after the ridge top was abraded by ice – probably during the Younger Dryas since moraines are present in this cwm (partly concealed by the raised hydroelectric lake level).

5.2. Geochronology

Three samples from were taken from the Moelwyns for ^{10}Be analysis (Fig. 5 and 6). One sample was taken from a quartz vein in siltstone bedrock near the summit of Moelwyn Bach (MW01) at an altitude of 700 m and yielded an exposure age of 19.5 ± 0.7 ka. Two samples were also taken from Craigysgafn. the first (MW02) from a prominent smooth and polished section of the quartz outcrop on the south side of this ridge (Fig. 6) at an altitude of 650 m on the ridge crest and gave an exposure age of 19.4 ± 0.6 ka. A second sample (MW03) was taken from the higher part of this ridge, at an altitude of 670 m between the subsidiary summit of Craigysgafn

(689 m) and the slope leading up to Moelwyn Mawr (770 m). This sample was taken from a quartz vein in ice moulded rhyolite bedrock (Fig. 6) and yielded an exposure age of 19.5 ± 0.6 ka. The resultant mean age for this site is 19.5 ± 0.02 ka (using weighted mean and standard error).

6. Arenigs

5.1. Geomorphology

The summit ridge of Arenig Fawr (Fig. 7) is characterised by bare rock surfaces formed in volcanic tuffs with occasional quartz veins. Evidence of glacier abrasion is best displayed in the north near Simdde Ddu (697 m a.s.l.). Further south towards the higher peak of Arenig Fawr (854 m a.s.l.) the bedrock surface is broken and often deeply fractured, producing tor-like features, suggesting significant frost action (Hughes, 2002a). However, some areas of bedrock exhibit evidence of ice-moulding and perched boulders occur along the summit ridge. It is clear that ice has overridden the highest parts of Arenig Fawr at some point in the past. Hughes (2002a, b) argued the temporal relationship between the ice-moulding and superficial frost weathering requires testing using cosmogenic exposure dating.

The evidence for ice overriding the summit of Arenig Fach is clearer than on Arenig Fawr. Several large (> 1x1x1 m) perched subrounded and subangular boulders are present on the summit near the cairn of Carnedd y Bachgen. Whilst these are locally-derived tuffs, they are clearly ice-transported. Perched boulders can be traced in a westerly direction from the summit cairn. Few perched boulders exist east of the summit cairn. This is consistent with ice movement from the west (to east) with boulders being dragged up the obstacle of Arenig Fach (in a similar way to the classic sites described by Darwin 1848). Roches moutonnées, whalebacks and rock pavements are also present on the summit plateau of Arenig Fach and the entire summit area exhibits clear evidence of glaciation. The geomorphology of the lower slopes is also consistent with ice movement from west to east (Rowlands 1979).

5.2. Geochronology

Three samples from were taken from the Arenigs for ^{10}Be analysis: two from Arenig fach and one from Arenig Fawr (Fig. 8). On Arenig Fach, one sample was taken from a quartz vein in tuff bedrock 50 m SE of the summit cairn (ARENIG 1) at an altitude of 680 m. This sample yielded an exposure age of 18.4 ± 0.7 ka. Another sample (ARENIG 2) taken from a quartz vein on top of a bedrock whaleback NE of the summit cairn, at an altitude of 650 m a short distance (~50 m) from the cliff edge, gave an exposure age of 18.0 ± 0.6 ka. On Arenig Fawr, a sample (ARENIG 3) from a quartz vein in ice-moulded bedrock tuff a short distance north of the summit yielded an exposure age of 19.4 ± 0.6 ka (Fig. 8. The resultant mean age for this site is 18.6 ± 0.7 ka (1σ).

7. Discussion

Ice-moulded bedrock and perched boulders on the summit areas of the northern Rhinogs, Moelwyns and Arenigs indicate that all three mountains were overridden by ice during the Pleistocene. This indicates that the Welsh Ice cap exceeded the highest summits (854 m) by an undetermined margin. The geomorphological evidence from the Rhinogs, Moelwyns and Arenigs is consistent with Smith and George (1936) who argued that the surface of the last Welsh Ice Cap must have been at an altitude of least 915 m. Smith and George (1936) and later Rowlands (1979) argued that the ice divide must have been west of Arenig Fawr and Arenig Fach. Erratic boulders on the summits of the Arenigs are entirely of local origin and appear to have been transported short distances from west to east. Similarly, on the Rhinog watershed, perched boulders are all of local origin. Nevertheless, Rowlands (1979) correctly placed the ice divide just a few kilometres west of the Arenig watershed (see Fig. 1) since tills on the eastern flank of the Rhinogs do, however, contain clasts of

Arenig origin (Foster 1970b). This, and the clear evidence of ice-movement from east to west across the Rhinogs therefore supports an ice divide in the Arenigs as suggested by Rowlands (1979)

Evidence of glacial erosion is most striking in the Rhinogs. The excellent preservation of ice-moulded bedrock is helped by the nature of the very resistant Cambrian sandstones in this area. In parts of the Moelwyns, such as on Craigysgafn, glacial erosional landforms are also very well preserved and again this is because of the very resistant rhyolite bedrock. In the Arenigs, glacial erosional features are less obvious, most probably related to the fact that the Arenigs are formed in volcanic tuffs, which weather more easily than the very hard sandstone and rhyolite of the Rhinogs and Moelwyns. A few kilometres south-east of our sampled ranges, the nearby Arans are also formed in tuffs and as with the Arenigs, the glacial erosional landforms are not as clear as in the Rhinogs and Moelwyns. However, in addition to the lithological controls on glacial erosional landforms, the Arenigs and Arans were subject to slower ice velocities than the Rhinogs and Moelwyns during the maximum thickness of the last ice sheet (Patton et al., 2013b, their Fig. 8). Both the sampled areas of the Rhinogs and Moelwyns lay to the south-west and north-west of the ice divide, respectively, and both areas had elevated ice velocities with the greatest ice velocities occurring in the Dwyryd Valley that separates these two areas (Fig. 5).

All our new ^{10}Be ages reported in this work indicate that summits of the Rhinogs, Moelwyns and Arenigs emerged simultaneously through a decreasing ice cap thickness at 19.5 ka. Within the resolution of the cosmogenic dating technique and taking into account age differences using different input constants, this occurred over a ~1-2 ka period. Mean exposure ages from the Rhinogs, Arenigs and Moelwyns overlap within their respective 1σ standard deviations (i.e. Rhinogs, 19.2 ± 1.2 ka (n = 3); Moelwyns, 19.5 ± 0.4 ka (n = 3); Arenigs, 18.6 ± 0.7 ka (n = 3)) mean = 19.68 ka, st dev: 0.76 ka). These ages are very similar to those from the Aran ridge in southern Snowdonia (Table 2) reported by Glasser et al. (2012) and re-calculated here using an identical procedure. The mean Aran exposure age of 19.41 ± 1.45 ka (7.5%, n=6, 1σ) is indistinguishable from the combined mean age from the Rhinogs, Moelwyns and Arenigs. As described in Glasser et al. (2012), we have also excluded two samples (AB02, 36.2 ± 1.3 ka and AB03, 29.3 ± 1.1 ka) which are clearly older outliers considered to have an inherited nuclide signal. The combined mean exposure age from all four areas (Rhinogs, Moelwyns, Arenigs and Arans) is 19.2 ± 1.1 ka (n=15, analytical error only, 5.6% 1σ).

The highest bedrock samples from the new dataset obtained from the Rhinogs, Moelwyns, Arenigs, are from 824 m close to the summit of Arenig Fawr and from 700 m near the summit of Moelwyn Bach. These yielded exposure ages of 19.4 ± 0.6 ka (ARENIG3), and 19.5 ± 0.7 ka (MW01) whilst the lowest bedrock samples from 581 and 589 m in the northern Rhinogs yielded effectively identical exposure ages of 19.4 ± 0.7 ka and 20.3 ± 0.6 ka (RH01 and RH02). The only boulder sampled yielded an exposure age that was about 2 ka younger than the mean of all 8 of the bedrock samples. Whilst the bedrock surfaces are on different mountains and on different lithologies, it would require removal of at least ~3 m bedrock to reduce a previous exposure history to result in a residual inherited concentration of a few percent of the 20 ka exposure measured in the bedrock samples. For example, assuming a bedrock pre-exposure concentration equivalent to 50 ka, we would require more than 3.5 metres bedrock removal such that the residual signal is less than half the 1.5 ka difference between boulder RH03 age at 17.9 ka and the mean bedrock age of 19.4 ka. The fact that the bedrock signals are tightly clustered can readily be explained by the negligible difference made by bedrock removal ranging from 2-4m. Thus there remains a small possibility that the bedrock ages could be slightly too old. This may indicate an inherited cosmogenic nuclide signal in the bedrock samples in the Rhinogs, Moelwyns and Arenigs and that the real age of exposure of these summits is closer to 17.9 ka (the age of the only sampled boulder). In order to test for inheritance, future sampling should target both bedrock and boulders, ideally as paired samples in close proximity. Given the problems of exhumation and toppling with boulder samples, in addition to the inheritance issues in bedrock, this would be the favoured approach.

No clear correlation appears between individual exposure ages from all 4 sites (max range of ~3.5 ka and elevation (maximum range of ~320m). However, a reasonable estimate can be made if we assume these maxima follow a linear trend resulting in a vertical retreat of the Welsh Ice Cap of ~100 m/ka at the commencement of deglaciation following the global LGM. Alternatively, using an age spread based on the 2σ error in mean age for all samples (i.e. ~2.2 ka) this would give a retreat rate of 150 m/ka. Within the limits of the age resolution of our cosmogenic dating method, these estimates support a rapid decrease in ice cap volume.

Exposure of the summits of the Welsh mountains at ~ 20-19 ka as the ice cap thinned is consistent with glaciological evidence from the Irish Sea to the west. Here, the Irish Sea Ice Sheet expanded south into the Celtic Sea area between 34.0 and 25.3 ka, reaching maximum limits at 25.3-24.5 ka, based on several geochronological techniques (radiocarbon, cosmogenic isotope exposure ages and optically stimulated luminescence, see Chiverrell et al., 2013). Retreat of Irish Sea Ice Sheet exposing Holyhead Mountain in Anglesey, NW Wales had occurred by 18.8-21.4 ka (Chiverrell et al 2013). All of this evidence is consistent with a maximum extent and thickness of both the Irish sea Ice Stream and the adjacent Welsh Ice Cap during Greenland Stadial 3, which Hughes and Gibbard (2015) proposed is coeval with the global LGM. It is apparent that retreat of the Welsh Ice Sheet was synchronous with that of the Irish Sea Ice Sheet and moreover rather rapid as shown by our new cosmogenic data.

There is ample geomorphological evidence of still-stands (or readvances) of large valley glaciers as the Welsh Ice Cap thinned and retreated. A series of frontal moraines are preserved in the Dee Valley, to the east of the Arenigs (Travis 1944) whilst similar moraines can be found in the many outlet valleys of the Arenigs. Several moraine assemblages are found close to the watershed (Rowlands, 1979) with some cirque moraines of Younger Dryas age (Hughes 2002a). Though, the timing and dynamics of deglaciation are not dated in this area the other valley moraines must represent younger retreat phases of the last Welsh Ice Cap

Moraines of large valley glaciers are also present to the west of the Rhinogs (Foster 1968, 1970a). The ages of these moraine systems are also unknown. Most attention has focused on the deglaciation history of the adjacent Irish Sheet Ice Sheet (e.g. Brown et al., 1967; Foster 1970a; b, Chiverrell et al 2013). Whilst a recent paper by Patton et al. (2013c) has investigated the geomorphological relationships between the Irish Sea Ice Stream and the adjacent Welsh Ice Cap, the timing of ice dynamics in the latter is still unresolved. Nevertheless, the new evidence from the mountain summits presented here helps to constrain the ages of Alpine-style valley glaciation in Wales. Based on the exposure ages from the watersheds presented in this study it is clear that the Welsh Ice Cap had thinned to below 600 m a.s.l. by 20-19 ka. Thus, the valley glacier moraines (which lie at altitudes from c. 400 down to below sea level) mentioned above must post-date this period of ice cap retreat. This is important because it means that a period of glacier advance or stabilisation occurred when the mountain peaks stood above as nunataks.

Radiocarbon dates from Llyn Gwernan on the northern side of the mountain Cadair Idris (892 m a.s.l.), a few kilometres to the south of the Rhinogs, indicate that valley glaciers had retreated in this area by 13.20 ± 0.12 ^{14}C ka BP (15.82 ± 0.39 cal. ka BP; calibrated using Calib 7.0, Reimer et al., 2013). All the mountain summits display evidence of periglacial weathering, superimposed onto the ice-moulded bedrock (Foster 1970b; McCarroll and Ballantyne 2002; Hughes 2002c, Glasser et al., 2012) and this is consistent with a sustained period of intense periglacial activity on these summits after Late Pleistocene deglaciation. This means that there was potentially a period of 4 ka when glacier stabilised or advanced as Alpine-style valley glaciers, a time period more than three times as long as the Younger Dryas. This has important implications for the development of periglacial features that are present on the mountain summits of this study area. However, the age and history of the periglacial features found on the summits of higher summits in Snowdonia (Ball and Goodier, 1970; Addison 1997; McCarroll and Ballantyne 2000) remains an interesting question and further research is underway by the authors to examine the exposure history of the summits in the Snowdon and Glyder areas.

8. Conclusions

The summits of the Rhinogs, Moelwyns and Arenigs in North Wales were covered at the last maximum in ice volume of the Welsh Ice Sheet and display evidence of ice moulding and transport of glacial boulders. The ice moulding is particularly pronounced in the Rhinogs and Moelwyns. Eight new ^{10}Be ages from ice-moulded bedrock and one from a perched boulder indicate that the mountain tops above ~ 600 m were exposed by 19.5ka, shortly after the LGM. Combined with a further 6 published ages from the Aran ridge (Glasser et al. 2012 (excluding two old outliers) there are now 15 ^{10}Be ages constraining the vertical dynamics of the last Welsh Ice Cap. In this combined dataset 15 of these ages give a mean exposure age of 19.2 ± 1.1 ka (n=15, analytical error only, 5.6% 1σ). . These ages show that ice cap thinning was very rapid and exposure ages are statistically indistinguishable over a 320 m vertical range (581-901 m.a.s.l.). This dataset is consistent with rapid thinning of the Welsh Ice cap after the global Last Glacial Maximum (27.5 to 23.3 ka, based on the definition of Hughes and Gibbard, 2012) with the summits of the Rhinogs, Moelwyns, Arenigs and Arans all revealed more-or-less simultaneously as nunataks at c. 20-19 ka. The new insights into the timing of the vertical thinning of the last Welsh Ice Cap will help constraint numerical ice cap models and link in with evidence from the lateral margins (moraines, outwash etc.) of the retreating ice cap.

Acknowledgements

This research was funded by The University of Manchester School of Environment and Development Research Stimulation Fund. Laurence Totelin assisted in Moelwyns, Isabel Brown on Arenig Fach, and John Balfour, Mike Hambrey, Patrick Robson in the Rhinogs. We would also like to thank Stewart Campbell, Earth Science Officer at Natural Resources Wales, for advice on permissions and protocols for working in the study areas.

References

Addison, K., (1997) Classic Landforms of Snowdonia. Classic Landforms Guides. Geographical Association. 60 pp.

Balco, G., 2011. Contributions and unrealized potential contributions of cosmogenic-nuclide exposure dating to glacier chronology, 1990-2010. Quaternary Science Reviews 30, 3-27.

Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schäfer, J.M., 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. Quaternary Geochronology 4, 93-107.

Ball, D.F., Goodier, R., 1970. Morphology and distribution of features resulting from frost-action in Snowdonia. Field Studies 3, 193-218.

Ballantyne, C.K., 2010. Extent and deglacial chronology of the last British-Irish Ice Sheet: Implications of exposure dating using cosmogenic isotopes. Journal of Quaternary Science 25, 515-534.

Ballantyne, C.K., Stone, J.O. 2015. Trimlines, blockfields and the vertical extent of the last ice sheet in southern Ireland. Boreas 44, 277-287.

Briner, J.P., Young, N.E., Goehring, B.M., Schäefer, J.M., 2012. Constraining Holocene ^{10}Be production rates in Greenland. Journal of Quaternary Science 27, 2-6.

Child, D., Elliott G., Misfud, C., Smith, A.M., Fink, D., 2000. Sample Processing for Earth Science Studies at ANTARES Nuclear Instruments and Methods B172 856-860.

Chiverrell, R.C., Thrasher, I.M., Thomas, G.S.P., Lang, A., Scourse, J.D., van Landeghem, K.J.J., McCarroll, D., Clark, C.D., Cofaigh, Ó., Evans, D.J.A., Ballantyne, C.K., 2013. Bayesian modelling of the retreat of the Irish Sea Ice Stream. Journal of Quaternary Science
28, 200-209.

Chmeleff, J., von Blanckenburg, F., Kossert, K., Jakob, D., 2010. Determination of the ^{10}Be half-life by multicollector ICP-MS and liquid scintillation counting. Nuclear Instruments and Methods in Physics Research B 268, 192-199.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The Last Glacial Maximum. Science 325, 710-714.

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.

Darwin, C. 1848. On the Transportal of Erratic Boulders from a lower to a higher level. Quarterly Journal of the Geological Society 4, 315-323.

Dielforder, A., Hetzel, R., 2014. The deglaciation history of the simplon region (southern Swiss Alps) constrained by ^{10}Be exposure dating of ice-molded bedrock surfaces. Quaternary Science Reviews 84, 26-38.

EDINA Geology Digimap. 2014. British Geological Survey (BGS) data.http://edina.ac.uk/digimap/index.shtml

Everest, J.D., Bradwell, T., Stoker, M.S., Dewey, S. 2013. New age constraints for the maximum extent of the last British-Irish Ice Sheet (NW Sector). *Journal of Quaternary Science* 28, 2-7.

Fearnsides WG. 1905. On the Geology of Arenig Fawr and Moel Llyfnant. Quarterly Journal of the Geological Society 61: 608–640.

Fenton, C.R., Hermanns, R.L., Blikra, L.H., Kubik, P.W., Bryant, C., Niedermann, S., Meixner, A., 2011. Regional ^{10}Be production rate calibration for the past 12 ka deduced from the radiocarbon-dated Grøtlandsura and Russenes rock avalanches at 69°N, Norway. Quaternary Geochronology 6, 437-452.

Fink, D., Smith, A., 2007. An inter-comparison of ^{10}Be and ^{26}Al AMS reference standards and the ^{10}Be half-life, Nuclear Instruments and Methods B259, 600-609.

Fink, D., McKelvey, B., Hannan, D., Newsome, D. 2000, Cold rocks, hot sands: In-situ cosmogenic applications in Australia at ANTARES: Nuclear Instruments and Methods in Physics Research B172, 838–846.

Foster, H.D. 1970a: Sarn Badrig, a submarine moraine in Cardigan Bay, north Wales. *Zeitschrift für Geomorphologie 14*, 473–486.

Foster, H.D., 1970b. Establishing the Age and Geomorphological Significance of Sorted Stone-Stripes in the Rhinog Mountains, North Wales. Geografiska Annaler 52, 96-102.

Glasser, N.F., Hughes, P.D., Fenton, C., Schnabel, C., Rother, H., 2012. ^{10}Be and ^{26}Al exposure-age dating of bedrock surfaces on the Aran ridge, Wales: evidence for a thick Welsh Ice Cap at the Last Glacial Maximum: Journal of Quaternary Science 27, 97-104.

Greenly, E. (1919) The Geology of Anglesey. *Memoirs of the Geological Survey of Great Britain*. HMSO: London.

Hughes, A.L.C, Greenwood, S.L. and Clark, C.D. (2011a) Dating constraints on the last British-Irish Ice Sheet: a map and database, Journal of Maps, v2011, 156-183. 10.4113/jom.2011.1145.

Hughes, A.L.C, Greenwood, S.L. and Clark, C.D. (2011b) Published Map. In Hughes, A.L.C, Greenwood, S.L. and Clark, C.D. (2011) Dating constraints on the last British-Irish Ice Sheet: a map and database, Journal of Maps, v2011, 156-183. 10.4113/jom.2011.1145.

Hughes, P.D. 2002a. Loch Lomond Stadial glaciers in the Aran and Arenig Mountains, North Wales, Great Britain. *Geological Journal* 37, 9-15.

Hughes, P.D. 2002b. Nunataks and the surface altitude of the last ice-sheet in southern Snowdonia, Wales. *Quaternary Newsletter* 97, 19-25.

Hughes, P.D. 2002c. Nunataks and the surface altitude of the last ice-sheet in southern Snowdonia, Wales: a reply to McCarroll and Ballantyne (2002). *Quaternary Newsletter* 98, 15-17.

Hughes, P.D., Gibbard, P.L. 2014. A stratigraphical basis for the Last Glacial Maximum (LGM). Quaternary International. DOI: 10.1016/j.quaint.2014.06.006

Jansson KN, Glasser NF. 2005. Palaeoglaciology of the Welsh sector of the British–Irish Ice Sheet. Journal of the Geological Society, London 162: 25–37.

Kohl, C.P., Nishiizumi, K., 1992. Chemical isolation of quartz for measurement of in situ-produced cosmogenic nuclides. Geochimica Cosmochimica Acta 56, 3583-3587.
Lal D. 1991. Cosmic ray labelling or erosion surfaces: *in situ* nuclide production rates and erosion models. *Earth and Planetary Science Letters* 104: 424-439.

Korschinek G, Bergmaier A, Faestermann T, Gerstmann UC, Knie K, Rugel G, Wallner A, Dillmann A, Dollinger G, Liese von Gostomski Ch, Kossert K, Maiti M, Poutivtsev M, Remmert A. 2010. A new value for the half-life of ^{10}Be by heavy-ion elastic recoil detection and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research* B 268: 187-191.

McCarroll, D., Ballantyne, C.K., 2000. The last ice sheet in Snowdonia. Journal of Quaternary Science 15, 765-778.

McCarroll, D., Ballantyne, C.K., 2002. Nunataks and the surface altitude of the last ice-sheet in southern Snowdonia, Wales: A comment on Hughes (2002). *Quaternary Newsletter* 98, 10-14.

Patton, H., Hubbard, A., Glasser, N.F., Bradwell, T., Golledge, N.R., 2013a. The last Welsh Ice cap: part I – Modelling its evolution, sensitivity and associated climate. Boreas 42, 471-490.

Patton, H., Hubbard, A., Glasser, N.F., Bradwell, T., Golledge, N.R., 2013b. The last Welsh Ice Cap: Part 2 – Dynamics of a topographically controlled ice cap. Boreas 42, 491-510.

Patton, H., Hubbard, A., Bradwell, T., Glasser, N.F., Hambrey, M.J., Clark, C.D., 2013c. Rapid deglaciation: asynchronous retreat dynamics between the Irish Sea Ice Stream and terrestrial outlet glaciers. Earth Surface Dynamics 1, 53-65.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and MARINE13 radiocarbon age calibration curves 0-50000 years cal BP. Radiocarbon 55(4). DOI: 10.2458/azu_js_rc.55.16947

Rowlands, B.M., 1971. Radiocarbon evidence of the age of an Irish Sea Glaciation in the Vale of Clwyd. Nature 230, 9-11.

Shakun, J.D., Carlson, A.E., 2010. A global perspective on Last Glacial Maximum to Holocene climate change. Quaternary Science Reviews 29, 1801-1816.

Smith B., George T.N. 1961. *North Wales*. British Regional Geology, HMSO: London; 96 pp.

Stone, J.O., 2000. Air pressure and cosmogenic isotope production. Journal of Geophysical Research-Solid Earth 105, 23753-23759.

Thomas, G.S.P., Chiverrell, R.C., 2007. Structural and depositional evidence for repeated ice-marginal oscillation along the eastern margin of the Late Devensian irish Sea Ice Stream. Quaternary Science Reviews 26, 2375-2405.

Travis, C.B., 1944. The glacial history of the Berwyn hills, North Wales. Proceedings of the Liverpool Geological Society 19: 14–28.

Whittow, J.B., Ball, D.F., 1970. North-west Wales. In The Glaciations of Wales and Adjoining Areas, Lewis CA (ed.). Longman: London. p. 21–58.

Young, N.E., Schäefer, J.M., Briner, J.P., Goehring, B.M., 2013. A ^{10}Be production-rate for the Arctic. Journal of Quaternary Science 28, 515-526.

Table 1. Sample information, AMS cosmogenic $^{10}Be/^{9}Be$ results and analytical errors.

Sample name	Alt (m)	Latitude (N)	Longitude (W)	Quartz mass (g)	^{9}Be spike mass [(1)] (mg)	$^{10}Be/^{9}Be$ ($\times 10^{-15}$) [(2)]	$^{10}Be/^{9}Be$ error (%)	Sample thickness (cm)	Horizon shielding correction [(3)]	Thickness correction [(3)]
Rhinogs										
RH-01	589	52.8763	-4.0013	80.511	0.321	535.4	2.65	3	1.000	0.975
RH-02 [(4)]	581	52.8889	-3.9970	87.317	0.321	602.8	2.11	3	1.000	0.975
RH-03	581	52.8887	-3.9971	90.041	0.320	539.8	1.74	5	1.000	0.959
Moelwyns										
MW-01	700	52.9748	-3.9941	91.752	0.323	658.1	2.54	5	1.000	0.959
MW-02	650	52.9792	-3.9973	90.209	0.325	591.5	2.30	5	0.960	0.959
MW-03	670	52.9819	-3.9987	90.254	0.325	627.5	2.36	5	1.000	0.959
Arenigs										
ARENIG-01	680	52.9585	-3.7569	70.569	0.324	469.3	2.77	5	1.000	0.959
ARENIG-02	655	52.9590	-3.7538	47.079	0.325	304.2	2.70	3	1.000	0.975
ARENIG-03	824	52.9185	-3.7432	90.271	0.326	719.1	2.29	4	1.000	0.967

(1) ^{9}Be spike mass from beryl crystal solution prepared at the ANSTO Cosmogenic Laboratory with 1080 ± 11 µg ^{9}Be/g solution.
(2) Final AMS $^{10}Be/^{9}Be$ ratio from weighted mean of repeat measurements. All AMS ratios corrected for full chemistry procedural blank and calibrated against NIST-4325 AMS $^{10}Be/^{9}Be$ standard reference material with a nominal value of 27,900 x 10^{-15}. Beryl chemistry $^{10}Be/^{9}Be$ blank (2 cathodes, n=4) of (5.66 ± 0.62) x 10^{-15}.
(3) Horizon shielding calculated using m=2.65; thickness correction using rock density of 2.7 g/cm^3 and Λ =150 g/cm^2
All samples are from bedrock quartz veins apart from RH02, a boulder of dimension 2.5 x1.8 m and 1.2 m in height.

Table 2. ^{10}Be cosmogenic concentrations and calculated exposure ages.

Sample name	Alt (m)	^{10}Be conc. & analytical error (atoms/gram) (x 10^3) (1)	Scaling factor (2)	Total site production rate (atoms/g/y) (3)	^{10}Be exposure age (ka) (4)	Exposure age error (absolute) (ka)	Exposure age error (analytical) (ka)
Rhinogs							
RH-01	589	142.6 (4.9)	1.761	7.3911	19.39	0.97	0.69
RH-02	581	147.9 (4.5)	1.748	7.340	20.26	0.96	0.64
RH-03	581	128.4 (3.6)	1.748	7.218	17.86	0.81	0.52
arith mean (± 1σ) = 19.17 ± 1.21 (6.3%) ka. Reduced χ2 = 4.7							
Moelwyns							
MW-01	700	154.9 (5.2)	1.938	8.002	19.45	0.94	0.66
MW-02	650	142.3 (4.6)	1.857	7.359	19.43	0.88	0.60
MW-03	670	151.0 (4.9)	1.889	7.799	19.46	0.93	0.64
arith mean (± 1σ) = 19.45 ± 0.02 (0.1%) ka. Reduced χ2 = <1							
Arenigs							
ARENIG-01	680	144.2 (5.1)	1.905	7.866	18.41	0.92	0.66
ARENIG-02	655	140.3 (4.9)	1.865	7.828	18.00	0.90	0.64
ARENIG-03	824	173.2 (5.5)	2.153	8.963	19.42	0.93	0.63
arith mean (± 1σ) = 18.61 ± 0.7 (3.9%) ka. Reduced χ2 = 1.4							
Aran Ridge (recalculated from Glasser et al 2012)							
AB0-1	878	175.2 (6.4)	2.252	9.453	18.62	0.95	0.69
AB0-6	608	145.5 (6.7)	1.790	7.513	19.46	1.13	0.90
AF0-1	818	168.2 (6.4)	2.142	9.065	18.64	0.98	0.72
AF0-2	880	195.1 (7.2)	2.256	9.236	21.24	1.07	0.78
AF0-3	901	197.9 (7.7)	2.296	9.479	20.99	1.09	0.81
AF0-4	638	133.5 (6.1)	1.837	7.647	17.53	1.00	0.80
arith mean (± 1σ) = 19.41 ± 1.45 (7.5%) ka. Reduced χ2 = 3.5							

(1) ^{10}Be concentration derived from final mean ^{10}Be/^{9}Be ratio (see table 1). Total analytical error in ^{10}Be concentration based on final AMS ^{10}Be/^{9}Be error, 1% error ion 9Be spike value and 2% reproducibility error based on the standard deviation from long term repeat measure of the NIST-4325 primary standard.

(2) Total spallation and muon scaling factor for sample site and normalized to sea-level and high latitude derived using the same formalism as from Stone (2000).

(3) Site production rate based on a reference sea-level high latitude spallation production rate from Chiverell et al , (2012) of 4.20 ± 0.15 ^{10}Be atoms/g/y (see text) and an assumed total SLHL muon contribution of 0.11 at/g/y scaled independently as described by Stone (2000) and corrected for shielding and sample thickness as given in Table 1 (and Glasser et al 2012 for Aran Ridge)

Figures

Figure 1. Location map of the field areas and sample sites denoted by grey shaded squares. The ice flow directions are primarily based on field observations in this study and also evidence presented Smith and George (1961), Foster (1970b), Whittow and Ball (1970), Rowlands (1979), Addison (1997), Jansson and Glasser (2005), Glasser et al. (2012) and Patton et al. (2013a,b). The ice divide in the Arenig area is based on Rowlands (1979). In some areas the ice flow patterns are disputed, such as in the Snowdon-Glyders area (see McCarroll and Ballantyne 2000) but the general patterns indicated above are agreed by most workers.

Figure 2. The Rhinogs showing the main ice flow directions and sample sites for ^{10}Be exposure dating. Location is marked on Figure 1.

Figure 3. Sample sites in the Rhinogs.

Figure 4. The Moelwyns showing the main ice flow directions and sample sites for ^{10}Be exposure dating. Location is marked on Figure 1.

Figure 5. The Moelwyns showing the sample sites for ^{10}Be exposure dating. This photograph is taken from Moelwyn Mawr looking south over Craig Ysgafn and Moelwyn Bach. Sample site MW02 is behind the summit of Craig Ysgafn.

Figure 6. Sample sites in the Moelwyns.

Figure 7. The Arenigs showing the main ice flow directions and sample sites for ^{10}Be exposure dating. The location of the ice divide is based on Rowlands (1979) as well as observations made in this paper. Location is marked on Figure 1.

Figure 8. Sample sites in the Arenigs

Figure 1

Click here to download high resolution image

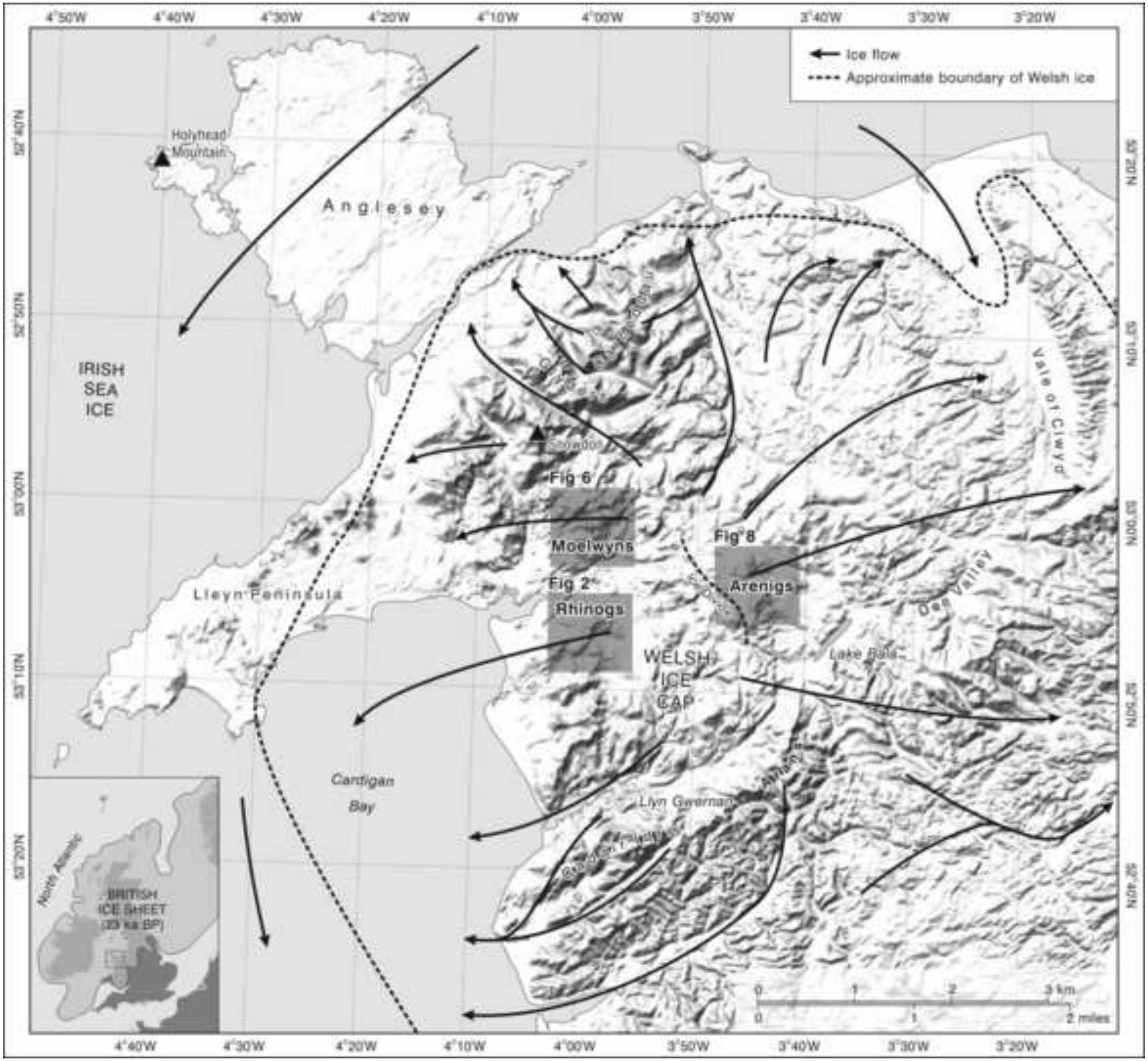

Figure 2

Click here to download high resolution image

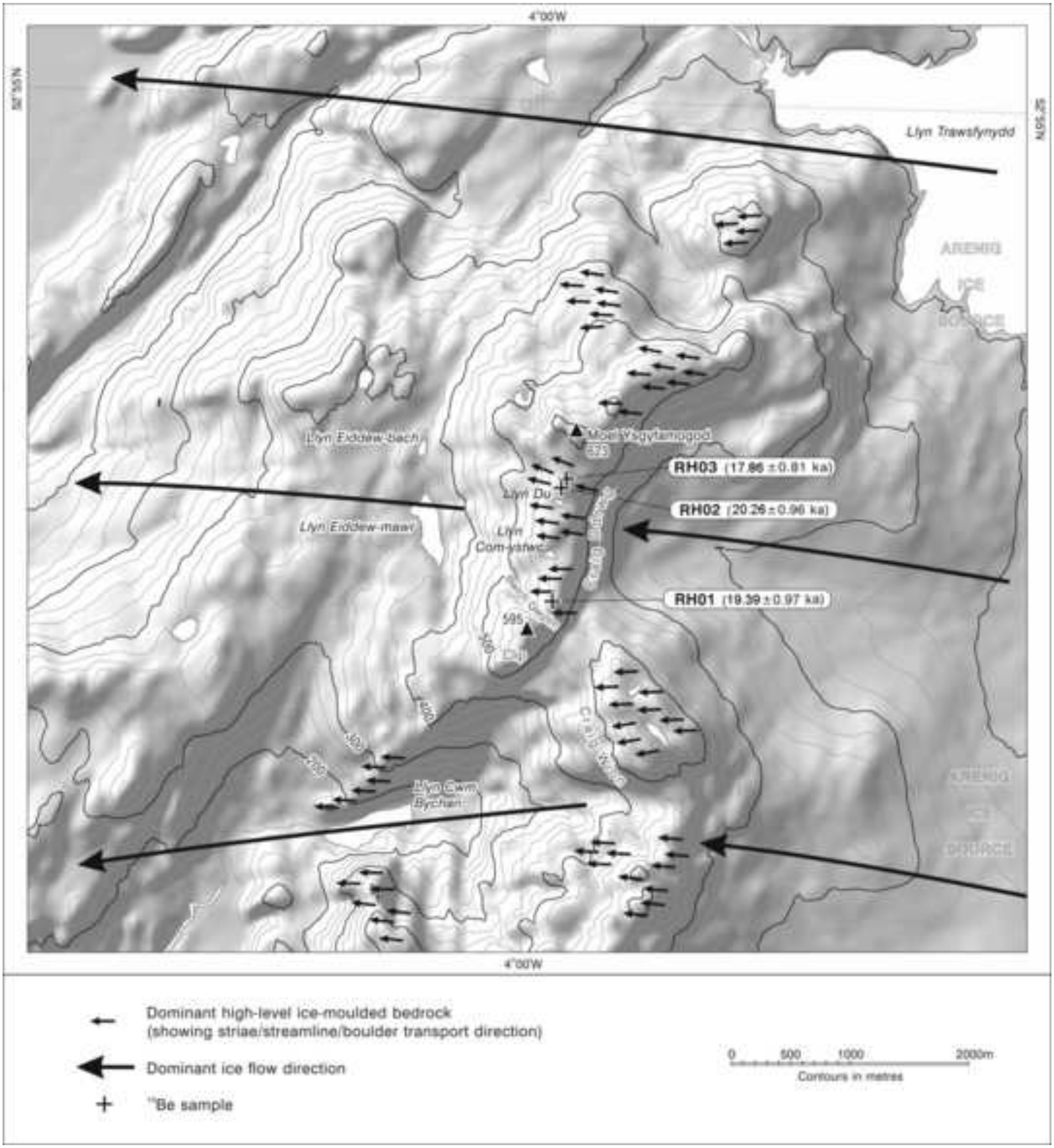

Figure 3
Click here to download high resolution image

Figure 4

Click here to download high resolution image

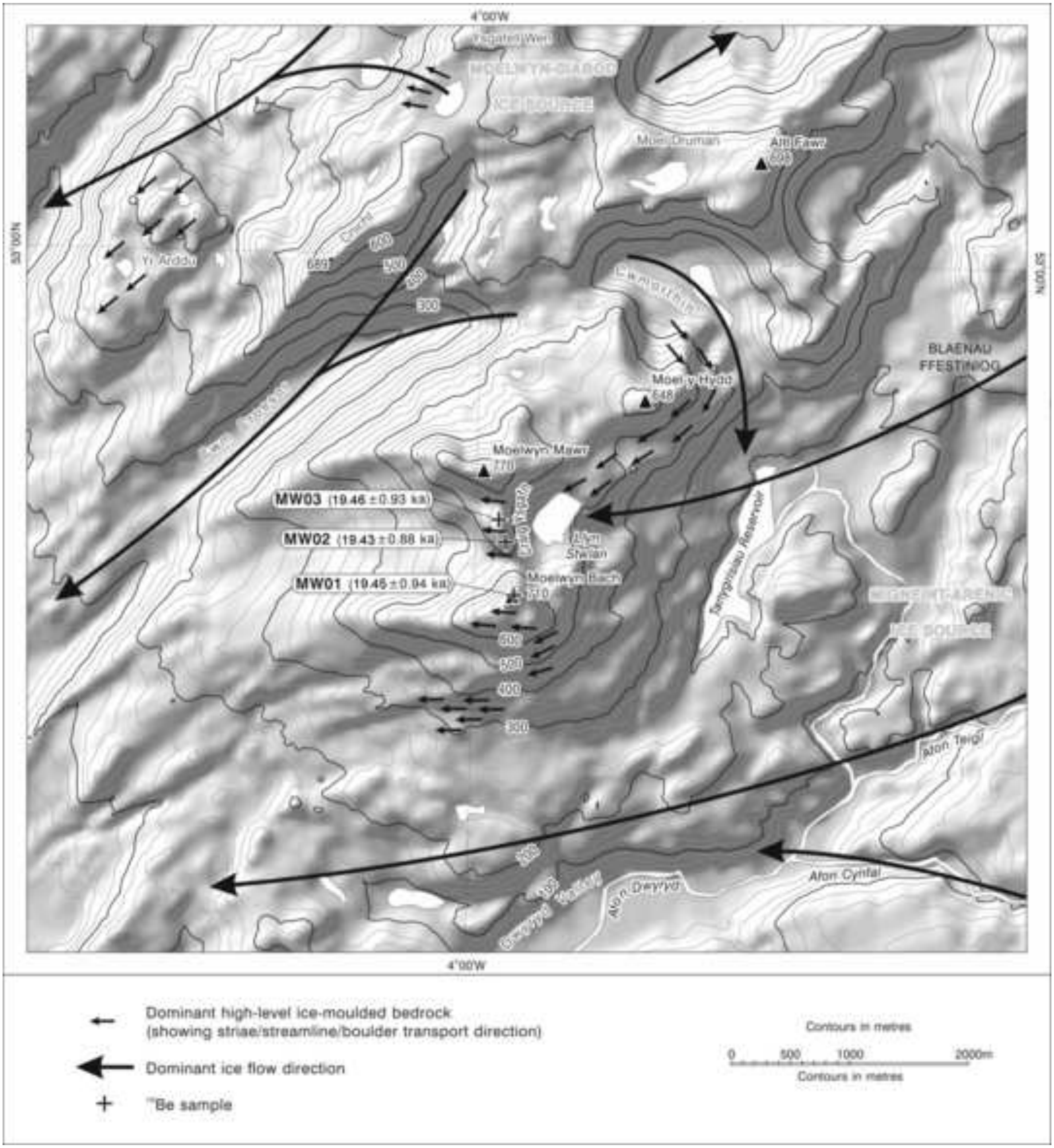

Figure 5
Click here to download high resolution image

Figure 6
Click here to download high resolution image

Figure 7

Click here to download high resolution image

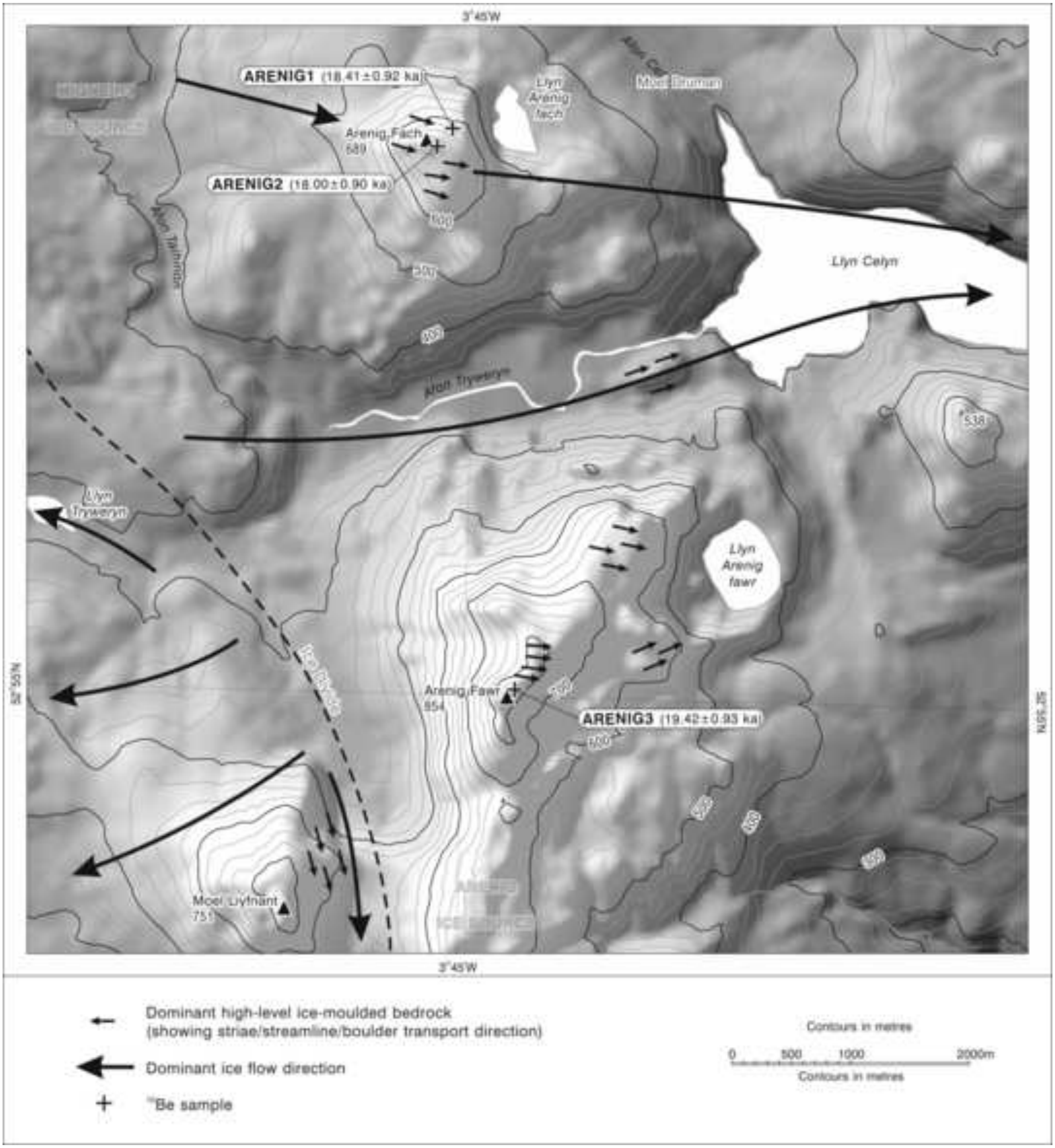

Figure 8

Click here to download high resolution image