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Late Devensian deglaciation of south-west Wales from luminescence and cosmogenic isotope dating

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ABSTRACT: The Welsh Ice Cap was a dynamic component of the last British–Irish Ice Sheet at the Last Glacial Maximum, but there are few chronological constraints on the pace and timing of deglaciation. This paper presents new geomorphological and geochronological evidence that constrains the timing of the separation of the Welsh Ice Cap from the Irish Sea Ice Stream and the subsequent deglaciation of south-west Wales; and allow these to be assessed in the context of late Pleistocene climatic events. Luminescence ages from glacial outwash sediments south of Cardigan demonstrate that the Irish Sea Ice Stream was receding by ~26.7 ka. The subsequent recession of the Welsh Ice Cap is documented by cosmogenic ages from landforms and sediments in the Aeron and Teifi valleys and upland areas. Deglaciation of the Cambrian Mountains was underway by ~19.6 ka. Cross-valley moraines and associated deglaciation deposits show that minor re-advances interrupted the recession of the Aeron Glacier twice, and the Teifi Glacier on at least 12 occasions. By ~14.9 ka, the Aeron valley was probably ice-free, but the northwards withdrawal of the Teifi glacier had halted in the Tregaron area. The final rapid recession of this glacier into the uplands of central Wales was completed during the Windermere Interstadial (13.5 cal ka BP) when, in common with much of the UK, the whole of Wales is believed to have become ice-free. There is no evidence that the Cambrian Mountains contained ice-free enclaves at the Last Glacial Maximum, as has been previously suggested. The new ages presented here support suggestions that there was rapid change in the configuration of the Welsh Ice Cap between 20 and 17 ka as upland areas became exposed and there was increasing topographic control on patterns of ice discharge. © 2018 The Authors. Journal of Quaternary Science Published by John Wiley & Sons Ltd.

KEYWORDS: cosmogenic isotopes; deglaciation; Irish Sea Ice Stream; luminescence dating; Welsh Ice Cap.

Introduction

Both modelling studies and observations show that the last British–Irish Ice Sheet (BIIS) was a dynamic and rapidly changing ice mass (Hubbard et al., 2009; Chiverrell et al., 2013; Patton et al., 2013a,b,c; Clark et al., 2018). Scourse et al. (2009) also interpreted dynamism, and rapid response to millennial-scale forcing, in their analysis of the continuous ice-rafterd detritus record from the adjacent deep sea. This dynamism was largely due to its relatively small size, which was constrained by the continental shelf break, and proximity to the warm North Atlantic Current, part of the Atlantic Meridional Ovorture Circulation (Clark et al., 2012). Early numerical simulations of the BIIS (e.g. Boulton et al., 1977, 1985, 1991; Lambbeck, 1993, 1995) suggested that it was an uncomplicated feature, largely centred over the Scottish Highlands, and with gradually decreasing ice-surface elevation across the rest of the country. However, this view differs from that derived from empirical geomorphological and geochronological evidence, which indicates that at the Last Glacial Maximum (LGM), the BIIS was composed of several small, semi-independent ice caps or ice-dispersal centres (McCarroll and Ballantyne, 2000; Golledge et al., 2008; Hubbard et al., 2009; Hughes et al., 2014; Figure 1). The Welsh Ice Cap was one such centre and the timing of recession of this and other sectors of the BIIS are also debated (e.g. Ballantyne, 2010; Chiverrell et al., 2013; Everest et al., 2013; Hughes et al., 2011). We use here the global LGM definition of Peltier and Fairbanks (2006), which places it around 26 ka.

Several workers have attempted to develop a chronology for recession of the Irish Sea Ice Stream and the Welsh Ice Cap (e.g. Ballantyne, 2010; Chiverrell et al., 2013; Patton et al., 2013a,b), but uncertainties remain. Initial work using cosmogenic nuclide ages along the coast implied that decoupling of the two ice masses and deglaciation of the southern Irish Sea Basin was well underway by 23–22 ka (McCarroll et al., 2010) despite some age estimates of 33–100 ka being obtained (Ballantyne, 2010). Although the geomorphology of the landscape produced by the Welsh Ice Cap is reasonably well documented (e.g. Etienne et al., 2005; Jansson and Glasser, 2005), little is known about its recession history. Recent geochronology in Snowdonia (Glasser et al., 2012; Hughes et al., 2016; Figure 2A) corroborates modelling simulations (e.g. Patton et al., 2013a,b) that show a previously extensive ice cover evolving into a series of valley glaciers. These individual glaciers receded progressively up-valley into accumulation areas in the Cambrian Mountains and Snowdona. Significantly, the new exposure ages from Snowdenia point to a rapid change in ice-mass configuration between 20 and 17 ka accompanied by transition from an ice cap to a thinning highland ice field with nunataks (Hughes et al., 2016). Before the current study, this apparent rapid change had not been revealed elsewhere in Wales, leaving questions about rates of deglaciation and deglacial dynamics of the Welsh sector of the BIIS.
Clark et al. (2012, 2018) and Hughes et al. (2011, 2014) provided comprehensive reviews of the geochronological evidence for the glaciation in the British Isles and concluded that the BIIS reached its maximum extent at different times in different sectors. In many parts of Britain, Ireland and the North Sea, ice had reached its maximum extent by 27 ka. For example, the earliest maximum advances recognized by Clark et al. (2012) occurred by 27 ka in the North Sea and off the coast of NW Scotland. More recently, the maximum southern extent of the Irish Sea Ice Stream on the Isles of Scilly has been dated to 26–25 ka (Smedley et al., 2017a). According to Chiverrell et al. (2013), the maximum extent of Devensian ice was delayed until 25.3 and 24.5 ka near our study area in Wales. A large-scale review by Ballantyne (2010) also suggests a glacial maximum in this area between 26 and 21 ka.

During the early stages of the Devensian Glaciation, the Welsh Ice Cap developed as a separate and autonomous feature and the mountainous areas of North Wales provide constraints on ice-surface elevation (Glasser et al., 2012; Hughes et al., 2016). Most evidence points to the Snowdon massif as a major centre of ice dispersal, with either small domes situated above satellite massifs or a continuous ice divide running broadly north to south (Jansson and Glasser,
The thickest part of the ice cap was positioned over the Arenig and Aran mountains (Fearsides, 1905; see Fig. 2 for locations named in the text), with ice flowing westwards from these areas towards Cardigan Bay (Foster, 1970a,b) and eastwards towards the border with England (Travis, 1944). To the north and west, the ice cap interacted and coalesced with a southwards-moving ice mass sourced from northern sectors of the BIIS, which occupied the site of the current Irish Sea Basin (Fig. 1). The distinctive deposits of this Irish Sea Ice Stream mark its maximum extent (McCarroll et al., 2010; Chiverrell et al., 2013).

Where it was unimpeded, the Irish Sea Ice Stream spread across the Cheshire Plain into north-east Wales, the northern Vale of Clwyd (Rowlands, 1971; Thomas, 1985, 1989; Davies et al., 2004), Anglesey and the Llŷn Peninsula (Thomas and Chiverrell, 2007) as part of its southwards progress into Cardigan Bay and across the coastal tract of south-west Wales (Fig. 1). In all these areas, the landward advance of Irish Sea ice was halted by the expanding Welsh Ice Cap so that at the time of the LGM a complex interface existed between the two competing ice masses. The deposits and landforms that locate this zone of interaction have been identified in north Wales (Thomas, 1989; Davies et al., 2004) and in south-west Wales (Davies et al., 2006b). The southward progress of the Irish Sea Ice Stream into south-west Wales was halted locally by the uplands of the Preseli Mountains, which it failed to overtop even at the time of the LGM (Burt et al., 2012). The large ice-dammed glacial Llyn (Lake) Teifi, once thought to have formed during ice recession (e.g. Charlesworth, 1929; Jones, 1965), is now known to have developed between the two converging ice masses during their Late Devensian advance into the Teifi Valley (Waters et al., 1997; Fletcher and Siddle, 1998; Hambrey et al., 2001; Etienne et al., 2006).

Here we present new luminescence and cosmogenic isotope (surface exposure) ages obtained for the coastal tract and river catchments of south-west Wales and the southern Cambrian Mountains. These new ages, when interpreted in the context of associated glacial landforms and deposits, provide insight into the post-LGM behaviour of the Welsh Ice Cap, notably its separation from the Irish Sea Ice Stream, and subsequent history and pattern of deglaciation.

Study area: geology and geomorphology

This paper focuses on the Teifi, Aeron and Ystwyth river catchments and the flanking upland regions of the southern Cambrian Mountains and Mynydd Bach (Fig. 2). This region was covered by the Welsh Ice Cap and its confluence with the south-eastern margin of the Irish Sea Ice Stream (Fig. 1). South of the Ystwyth valley, the deeply dissected Cambrian Mountains plateau widely achieves elevations above 450 m with a maximum elevation near the headwaters of the Teifi of 594 m. The more westerly Mynydd Bach plateau, on which the River Aeron rises, and which widely exceeds 300 m in elevation, overlooks the lower ground that forms the Cardigan Bay coastal tract. In the far south of the study area, the prominent rock tors of the Preseli Mountains rise to elevations over 460 m. The bedrock of the area principally comprises...
interbedded mudstone, sandstone and localized conglomerate deposited by turbidity currents and other mass-flow processes. Most are of Silurian age, but Ordovician rocks that also include volcanic and intrusive igneous units occur in the south and west (e.g. Davies et al., 1997, 2006a,b; Burt et al., 2012). NE–SW-trending bedrock lineaments reflect the dominant geological structural trend imposed by late Caledonian orogenesis (e.g. Davies et al., 1997). However, the modern drainage systems only locally reflect this structural grain with major ENE–WSW-trending cross faults also influential. Before the Cenozoic capture of its headwaters by the rivers Rheidol and Ystwyth the source of the previously much larger River Teifi was located on the flanks of the Plynlimon (Pumlumon) Dome. Broad glaciated hollows indicate the abandoned former course of this palaeo-River Teifi in the north of the study area. Waters et al. (1997) recognized the current river as a misfit within the sector of the original catchment it still occupies.

The form and distribution of glacially transported and deposited materials present throughout the area have been established by the British Geological Survey’s (BGS) mapping programme in the region (e.g. BGS, 1989, 1993, 1994, 2003, 2006a,b, 2007a,b, 2008, 2010). These materials include widespread diamicton of subglacial origin (till) and, principally along valley bottoms, extensive deposits of glaciofluvial and glaciodeltaic sand and gravel, and glaciallacustrine silt and clay. The presence of exotic igneous, metamorphic and sedimentary rock clasts, as well as common shell fragments and Cenozoic lignite particles, allow sediment derived from the catchment region of Irish Sea ice to be distinguished from Welsh ice-sourced materials that contain clasts only of the regional Lower Palaeozoic bedrock (e.g. Davies et al., 2003). Several studies (e.g. Waters et al., 1997; Hambrey et al., 2001; Glasser et al., 2004; Etienne et al., 2006; Davies et al., 2006b; Patton and Hambrey, 2009) have charted the advance of the Irish Sea Ice Stream into western parts of the Teifi and Aeron catchments and the evolution of pro- and sub-glacial drainage features and spillways as the Ice Stream impounded and then displaced glacial Llyn Teifi. Locally extensive sand and gravel deposits, as worked for example at Trefignin, Pantgwyn and Penparc quarries (Fig. 2B), are interpreted as outwash formed during the subsequent recession of Irish Sea ice from this region (see below). Conversely, the distribution of Devensian deposits of Welsh Ice Cap provenance confirms that much of the area away from the coastal tract lay within the reach of the Welsh Ice Cap. The co-incidence of the inland, eastern limit of abundant Irish Sea erratic material and the western extent of Welsh ice-contact deposits indicate that the two ice masses converged. However, Waters et al. (1997; see also Jones, 1965 and Davies et al., 2006b) suggested that, at the time of the LGM, there remained an ice-free enclave along the main Teifi valley; and the reconstructions of Etienne et al. (2006) and Wilby et al. (2007) show this as the northern point of an extensive and widening region to the south that escaped Late Devensian glaciation (see below).

The southern Cambrian Mountains and the valleys of the Teifi (including its major tributary, the River Dulas) and the Aeron were the loci for regional ice discharge (Fig. 2; Jansson and Glasser, 2005; Sahlin et al., 2007; Sahlin, 2010). The deposits and landforms formed during recession in these river catchments were assessed during the BGS mapping of the region (Davies et al., 1997, 2006a,b; Waters et al., 1997; Ross, 2006; Wilby et al., 2007; Burt et al., 2012). Mounds and hummocks of poorly stratified and poorly sorted ice-contact sand and gravel record the location of cross-valley and lateral moraines marking the retreat of discrete valley glaciers that occupied these valleys during Devensian deglaciation. Valley floor exposures and boreholes show that, during glacier withdrawal, the recessional moraines in both catchments impounded pro-glacial lakes in which clay, silt and glaciodeltaic deposits accumulated (Merrin, 1999; Davies et al., 2006a,b). In the Teifi valley, the lake dammed by the northernmost of these moraines evolved into Tregaron Bog (Cors Caron in Welsh) – one of the largest raised peat bogs in the UK (Godwin and Mitchell, 1938; Davies et al., 1997). Radiocarbon dating at this site by Hibbert and Switsur (1976) (10,200±220 cal BP) confirms that organic-rich sediments began to accumulate above barren, grey, lacustrine clays soon after the climatic amelioration that signalled the end of the Younger Dryas Stadial and the onset of the Holocene.

In upland and interfluve areas, glacially streamlined bedrock ridges show a strong structural bedrock control. Deposits of head and nivation scree (head gravels) testify to the periglacial conditions that prevailed as Devensian ice withdrew from the region. Landslides, alluvial fans and river terraces record periglacial adjustment of the landscape that preceded the establishment of the area’s modern drainage system and modern alluvial deposition (Davies et al., 1997, 2006a).

**Sampling strategy and sample details**

**Irish Sea Ice Stream deglaciation**

Four sediment samples were obtained for luminescence dating from two sand and gravel quarries located to the south of the Teifi valley, SW of Cardigan: two samples from Pantgwyn Quarry (MW05 and MW07; 52.048°N, 4.735°E) and two samples from Trefignin Quarry (MW08 and MW09; 52.057°N, 4.718°E) (Fig. 3). Sample details are provided in Tables 1 and 2. Both quarries work ridges of poorly sorted gravel and coarse to fine sand, in which abundant cross-stratification testifies to deposition by southerly flowing, braided rivers (Fig. 3) (Owen, 1997). Clast assemblages and abundant shell fragments confirm an Irish Sea Ice Stream source. Extensive faulting (Fig. 3b) seen in the quarry faces has been interpreted by Hambrey et al. (2001) as evidence of collapse of the sediment pile following the decay of flanking ice buttresses. Fining-upwards successions at both sites further support their interpretation as remnants of a once more extensive spread of glacial outwash formed during the withdrawal of the Irish Sea Ice Stream from the area (e.g. Davies et al., 2003). Significantly, both quarries are located several kilometres to the north of the Preseli Mountains, which formed the local southern limit of the Irish Sea Ice Stream advance into the region.

**Welsh Ice Cap deglaciation**

The absence of glacially transported boulders on the surface of recessional moraines in the Teifi and Aeron valleys precluded dating of these features using cosmogenic isotope techniques. However, 10 samples were collected for cosmogenic nuclide exposure dating from glacially transported boulders and ice-scoured bedrock sites located in the adjacent uplands and interfluvies (Table 3; Fig. 4). Following the sampling guidelines of Gosse and Phillips (2001), Dunai (2010) and Balco (2011), samples were collected from the upper surfaces using a hammer and chisel and all samples were ≤4 cm thick. Detailed site descriptions were made for each sample. Skyline measurements were recorded using an Abney level where the angle to the horizon was >15°. Sample coordinates were collected using a handheld GPS with a horizontal accuracy of ±4 m. The cosmogenic nuclide
samples fall into two broad geographical groups: (i) those associated with the deglaciation of the Cambrian Mountain plateau and the eastern side of the Afon Teifi catchment (seven samples); and (ii) those associated with the deglaciation of the Afon Aeron catchment and the Mynydd Bach plateau (three samples). Sample locations are indicated on Fig. 2B, and further information relating to samples can be found in Tables 3 and 4.

Methods and results

Geomorphological mapping

Extensive geomorphological mapping was undertaken by BGS and its collaborators as part of their field investigations in the region (e.g. Waters et al., 1997; Hambrey et al., 2001; Glasser et al., 2004; Etienne et al., 2006; Davies et al., 2006b) and incorporated the results of earlier studies (e.g. Jones, 1965; Watson, 1969). Landforms and sediments were identified according to their size, shape, composition and texture using field observations, including section logging and hand augering, colour stereo aerial photography, borehole records and site investigation reports (see McMillan and Powell, 1999; Hubbard and Glasser, 2006).

Luminescence dating

Samples were taken for luminescence dating by hammering opaque tubes into the sedimentary section to prevent exposure to sunlight during sampling. External beta dose-rates were determined for optically stimulated luminescence (OSL) dating using inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectroscopy (ICP-AES), and the external gamma dose-rates were determined using in situ gamma spectrometry (Table 1). To isolate coarse-grained quartz for OSL analysis, each sample was first treated with a 10% (v/v) dilution of 37% HCl and with 20% (v/v) of H2O2 to remove carbonates and organics, respectively. Dry-sieving then isolated grains 180–212 μm in diameter, and density-separation using sodium polytungstate provided the 2.62–2.70 g cm⁻³ (quartz-dominated) fractions. The quartz grains were etched for 1 h in 40% hydrofluoric (HF) acid to remove the outer portion of the quartz grains that was affected by alpha irradiation and also remove any contaminating grains of feldspar. After the HF etching, grains were washed in a 10% solution of HCl to remove any fluorides that may have been produced. Grains were finally mounted into 10 mm-diameter holes in a 9.8-mm-diameter aluminium single-grain disc for analysis.

Table 1. Environmental dose-rates determined for OSL dating of single grains of quartz using ICP-MS analysis and field gamma spectrometry. The chemical concentrations are presented in the decimal points relevant for the detection limit. The dose-rates were calculated using the conversion factors of Guerin et al. (2011) and beta dose-rate attenuation factors of Guérin et al. (2012). Water-contents (17 ± 5%) were estimated considering the field and saturated water contents, and the environmental history for each sample; these values are expressed as a percentage of the mass of dry sediment. Cosmic dose-rates were determined after Prescott and Hutton (1994), using a depth of 3 ± 2 m for all samples. Dose-rates were calculated using the dose rate and age calculator (DRAC; Durcan et al., 2015). All samples have a laboratory prefix code (Aber210).

| Sample  | K (%) | Rb (ppm) | U (ppm) | Th (ppm) | Beta dose-rate (Gy ka⁻¹) | Gamma dose-rate (Gy ka⁻¹) | Cosmic dose-rate (Gy ka⁻¹) | Total dose-rate (Gy ka⁻¹) |
|---------|-------|----------|---------|----------|--------------------------|--------------------------|---------------------------|---------------------------|
| MW05    | 0.8 ± 0.1 | 35.7 ± 3.6 | 1.15 ± 0.12 | 3.6 ± 0.4 | 0.66 ± 0.06 | 0.37 ± 0.03 | 0.14 ± 0.01 | 1.19 ± 0.07 |
| MW07    | 1.1 ± 0.1 | 46.2 ± 4.6 | 1.09 ± 0.11 | 4.1 ± 0.4 | 0.85 ± 0.08 | 0.45 ± 0.03 | 0.14 ± 0.01 | 1.46 ± 0.09 |
| MW08    | 1.1 ± 0.1 | 47.5 ± 4.8 | 1.21 ± 0.12 | 4.4 ± 0.4 | 0.87 ± 0.08 | 0.61 ± 0.04 | 0.14 ± 0.01 | 1.63 ± 0.09 |
| MW09    | 0.8 ± 0.1 | 34.3 ± 3.4 | 0.88 ± 0.09 | 3.2 ± 0.3 | 0.63 ± 0.06 | 0.40 ± 0.03 | 0.14 ± 0.01 | 1.18 ± 0.07 |
All luminescence measurements were performed using a Riso TL/OSL DA-15 automated single-grain system equipped with a $^{88}$Sr/$^{86}$Y beta source (Bøtter-Jensen et al., 2003) as described by Smedley et al. (2017a,b). A preheat plateau test performed on 5-mm aliquots was used to determine the preheat temperature used (200°C) with a cut-off temperature of 160°C for the single aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2003). Five screening criteria were applied to the resulting data throughout the analyses unless otherwise specified. Grains were screened based upon whether (i) the test dose response was greater than three sigma above the background, (ii) the test dose uncertainty was <20%, (iii) the recycling and OSL-IR depletion ratios were within the range of ratios 0.8–1.2, (iv) recuperation was <5% of the response from the largest regenerative dose (150 Gy) and (v) the single-grain equivalent dose ($D_e$) values were not from a population of very low doses that were identified by the finite mixture model (FMM) to be inconsistent with the geological context of the sample (i.e. <1 ka). The associated uncertainties were taken into account when applying the screening criteria. $D_e$ values were then calculated for all grains that passed the screening criteria, incorporating the uncertainty from instrument reproducibility of 2.5% (Thomsen et al., 2005). Dose-recovery experiments were performed on Samples MW05 (overdispersion = 16 ± 1%), MW07 (overdispersion = 22 ± 1%) and MW09 (overdispersion = 15 ± 1%) and suggested that the SAR protocol was appropriate for OSL dating. The single-grain $D_e$ values determined for each sample are shown (Fig. 5) and included in Appendix 1.

### Luminescence dating results

The single-grain $D_e$ distributions for Samples MW07 and MW08 were not asymmetrical and so the sediments were deemed to have been well bleached before burial; thus, the central age model (CAM) was used to determine $D_e$ values for these samples (Table 2). The single-grain equivalent dose ($D_e$) values were then divided by the environmental dose-rates to determine OSL ages (Table 2). The weighted mean and standard error (e.g. 21 and 22 in Aitken and Alldred, 1972) of the two OSL ages at both Pantgwyn and Trefigin were 26.7 ± 1.8 and 26.7 ± 1.6 ka, respectively; consistent with their proximity to one another, these ages appear to confirm that outwash accumulation at both sites was broadly synchronous.

### Cosmogenic nuclide dating

Samples were processed in the Natural Environment Research Council (NERC) Cosmogenic Isotope Laboratory Facility, at the Scottish Universities Environmental Research Centre (SUERC). After the mechanical procedures and chemical etching to separate the quartz from other minerals and remove the meteoric $^{10}$Be, the pure quartz was spiked with $^{10}$Be (approx. 0.2 mg $^{10}$Be) and $^{27}$Al (to total up ~1500 mg $^{27}$Al) and dissolved. The beryllium and aluminium isotopes were extracted following chemical procedures adapted from Child et al. (2000). Prepared BeO and AlO targets were subsequently mixed with Nb and Ag, respectively, and pressed into copper cathodes. Target measurements were performed using the 5-MV accelerator mass spectrometer at the SUERC AMS Laboratory (Xu et al., 2010). Measured $^{10}$Be/$^{9}$Be ratios and $^{26}$Al/$^{27}$Al ratios were converted to nuclide concentrations in quartz and exposure ages were calculated using the Cronus Earth online calculator v.2.3 (hess.ess.washington.edu; Balco et al., 2008). The calculated age uncertainties are expressed as ±1σ (Table 4). Internal uncertainties are quoted when describing our results and the external uncertainties are quoted when comparing our results to previously published data sets. A range of $^{10}$Be production rates can be used to calculate exposure ages and there remain uncertainties over suitable

| Sample | Orientation | Longitude | Altitude (m) | Thickness (cm) | Density (g cm$^{-2}$) | Shielding (factor) |
|--------|-------------|-----------|--------------|----------------|----------------------|-------------------|
| AV1201 | 52.28832    | 4.04284773| 339          | 2              | 2.65                 | 1                 |
| AV1202 | 52.249909   | 4.04780323| 347          | 2              | 2.65                 | 1                 |
| BB1201 | 52.180370   | 3.889437  | 370          | 2              | 2.65                 | 1                 |
| BB1202 | 52.189138   | 3.902756  | 466          | 2              | 2.65                 | 1                 |
| CT1201 | 52.114032   | 3.977533  | 371          | 2              | 2.65                 | 1                 |
| MP1201 | 52.063093   | 4.087965  | 392          | 2              | 2.65                 | 1                 |
| TP1203 | 52.293819   | 3.76683368| 435          | 2              | 2.65                 | 1                 |
| TV1201 | 52.288467   | 3.91515499| 290          | 2              | 2.65                 | 1                 |
| YST1201| 52.340828   | 3.7616162 | 497          | 3              | 2.65                 | 1                 |
| YST1202| 52.340809   | 3.7616395 | 495          | 4              | 2.65                 | 1                 |
Figure 4. Photographs of selected sites sampled for cosmogenic dating (see Fig. 2 and Table 3 for location details): (a) Sample AV12/01, Hafod Ithel, Mynydd Bach (map case is 30 cm); (b) close up of quartz and feldspar granules at sampled point on a; (c) Sample CT 12/01, Craig Twrch, Cambrian Mountains; (d) Sample BB12/01, Blaenbrefi, Cambrian Mountains (max. length of boulder 1.8 m); (e) Sample BB12/02, Bryn Rhud, Cambrian Mountains (open compass is 18 cm long); (f) Sample TP12/03, Teifi Pools, Cambrian Mountains (GPS is 16 cm long); (g) Sample YST12/02, Banc Hir, Cambrian Mountains (hammer is 28 cm long); (h) TV12/01, Drysgol, region of Aeron-Teifi interfluve. Internal uncertainty values are shown for each sample.
The ratios ranged between 3.20/C2/CYST1202 b7915 a2234 115 985/C6/CYST1201 b7914 a2233 97 649/C6/TV1201 b7913 a2232 85 159/C6/TP1203 b7912 a2231 102 808/C6/CT1201 b7909 a2228 118 715/C6/BB1202 b7908 a2227 118 894/C6/BB1201 b7907 a2226 98 822/C6/AV1201 b7903 a2224 117 152. The 10Be ages were calculated based on a calibrated dataset from north-west Scotland to explore the possibility of multiple exposure histories on the Exposure ages (Table 4) were calculated using a 10Be decay using the Lal (1991)/Stone (2000) production rate model. The 26Al concentrations are corrected for the procedural blank values of 2.65/C2/

Exposure ages (Table 4) were calculated using a 10Be decay using the Lal (1991)/Stone (2000) production rate model. The 26Al concentrations are corrected for the procedural blank values of 2.65/C2/10Be/9Be taken as 2.79/C2/10Be/C2. Nishiizumi, 2004). The 26Al concentrations are corrected for the procedural blank values of 2.65/C2/10Be/9Be taken as 2.79/C2/10Be/C2. Nishiizumi, 2007). Exposure ages calculated using Cronus-Earth 10Be–26Al exposure age calculator v.2.3 (hess.ess.washington.edu). They assume zero erosion, scaling factors according to Stone (2000) and a spallation production rate of 4.49/C0.12 Myr (Chmeleff et al., 2010; Korschinek et al., 2013) to calculate ages:

 Welsh Ice Cap deglaciation in the Teifi Valley and Cambrian Mountains

Most of this sample set came from the eastern side of the Afon Teifi catchment, along the western flanks of the Cambrian Mountains plateau (Figs 2 and 6). These dates provide evidence for the age and pattern of the Welsh Ice Cap withdrawal across this upland region. The ages and locations of Samples CT12/01 (19.3 ± 0.7 ka), BB12/01 (16.1 ± 1.3 ka), BB12/02 (17.7 ± 0.6 ka), TP12/03 (15.7 ± 0.5 ka) and YST12/02 (17.1 ± 0.5 ka) tell a broadly consistent story. They suggest that ice withdrew from some of the most prominent upland ridges at c. 19 ka in the south of the region, exemplified by Criag Tyrch. This was preceded by a more widespread westwards retreat of the ice cap from the southern Cambrian Mountains towards the Teifi Valley, which was largely complete by c. 16–17 ka (Fig. 6).

Sample MP12/01 (13.8 ± 0.8 ka) is the most southerly sample of the Teifi Valley/Cambrian Mountains set. This sample, collected at a higher elevation (392 m) than others to the north, implies that the withdrawal of ice from this site was delayed until around 13.8 ka (Fig. 6). Whereas the other samples of this set provide a fairly consistent picture for the timing and pattern of ice retreat from the western flanks of the Cambrian Mountain plateau (see below), the date obtained for Sample MP12/01 appears to be an outlier. The mean exposure age provided by the northernmost sample, YST12/01 (14.3 ± 0.4 ka), in being significantly younger (~2.9 kyr) than that obtained for the nearby Sample YST12/02, also appears aberrant. For MP12/01 and YST12/01, the wide discrepancies between the Be and Al exposure data imply that both these samples may record a more complex exposure
history than other locations. The sample sites for MP12/01 and YST12/01 both exhibit features consistent with periglacial heaving and post-glacial downslope movement, which may explain this discrepancy.

**Welsh Ice Cap deglaciation in the Aeron Valley and Mynydd Bach**

The ages obtained for Samples AV12/01 (19.6 ± 0.6 ka) and AV12/02 (19.1 ± 0.6 ka) testify to the early emergence of the highest part of the Mynydd Bach plateau and indicate withdrawal of the Welsh Ice Cap from the whole of this upland region was complete by c. 19–20 ka. Sample TV12/01 (14.9 ± 0.4 ka) implies that, in common with much of the Cambrian Mountains, the interfluve between the Teifi and Aeron catchments was similarly ice-free by c. 15 ka.

**Integrating the geomorphological and geochronological evidence**

In Figs 6 and 7 we present a putative chronology and palaeogeographical model for the deglaciation of southwest Wales in the context of late Pleistocene climate events including those identified by the Greenland-based ‘INTIMATE’ project (e.g. Björck et al., 1998; Blockley et al., 2014). The regional maximum limits of the Irish Sea Ice Stream and Welsh Ice Cap in the region are based, with only minor modification, on published accounts (e.g.

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**Figure 5.** Abanico plots showing the single-grain $D_e$ values determined for OSL dating, where the grey shading marks the CAM or MAM $D_e$ value ($\pm\sigma$).
suggesting that benches of sand and gravel near Pentre-
Greenland-based INTIMATE climate events (Figs 6 and 7). A
new cosmogenic exposure ages provide a basis for a
chronology for these events remains difficult to tie down, the
valleys provides evidence of a longer period of ice occupa-
succession of landforms seen along the Teifi and Dulas
around this time (Fig. 6). Glacier recession from the Aeron
(Y1) and Rheidol (R1) valleys was also in progress from
that occupied the lower reaches of the Aeron (A1), Ystwyth
suggest that withdrawal of the Welsh Ice Cap outlet glaciers
of this process in the Teifi Valley. Comparable landforms
and the early retreat moraine T1 had formed and been
westwards withdrawal of ice from the upland plateau towards
the axis of the Teifi Valley, Sample TV12/01 indicates that by
14.9 ka ice had also withdrawn from the region of the Aeron–
Teifi interfluve and it is likely that the whole of the western
sector of the study area including the Aeron Valley may then
have been ice-free (Fig. 6).

Glacial landforms between Llandysul and Tregaron Bog
reveal a staged northwards recession of the Teifi glacier along
this 45-km-long reach of the valley (Figs 6 and 7). Recession
of the ice from the Teifi valley probably commenced soon
after the decoupling of Irish Sea ice from the Welsh Ice Cap,
ongoing before 19 ka (see above). The chronology of its
subsequent retreat is constrained ostensibly by the MP12/01
exposure age (13.8±0.8 ka) in the south and, in the north,
by the onset of early post-glacial deposition at Tregaron Bog
(10.2 ka). However, Late Devensian ice is widely assumed to
have disappeared from Wales, as throughout much of the UK,
during the early part of the Windermere Interstadial c. 13.5 cal
ka (Clark et al., 2012). Even the maximum interval these
figures allow (c. 1700 years) appears too short to generate the
complex suite of recessional landforms and deposits preserved
to the south of Tregaron Bog. Such analysis underlines the
probability that the cosmogenic isotope values obtained for
Sample MP12/01 may not accurately reflect the date of ice
withdrawal from this locality (see above).

The exposure age obtained for Sample TV12/01 (c. 14.9 ka)
offers an alternative, more realistic chronology arguably more
consistent with other data. Its proximity to Tregaron Bog
implies that the withdrawal of ice from this sample site can
be linked to the recession of the Teifi glacier into the area
currently occupied by the bog and to the formation of its
associated recessional moraines (T11 and T12; Fig. 6). Hence,
and contrary to MP12/01, it suggests that much of the 45-km
northwards retreat of the Teifi Valley Glacier into the
Tregaron area spanned a period of over 5000 years (Fig. 7).

The succession of cross-valley moraines and impounded lake
deposits formed during this interval undoubtedly testify in
some way to the impact of climatic variations associated with the
INTIMATE GS-2.1a-b interval. However, the dynamic
nature of the glacier probably meant that its response to these
events was neither synchronous nor simplistic.

The absence of recessional moraines to the north of
Tregaron Bog appears to signal a marked change in ice
behaviour and that the final phase of ice withdrawal from the
upper reaches of the modern and palaeo-Teifi valleys was
rapid and uninterrupted. This must have occurred between c.
14.9 ka and c. 13.5 ka in response to the climatic ameliora-
tion associated with the Windermere Interstadial (= INTI-
MATE GI-1) (Fig. 7). The undated lacustrine clays present
beneath the organic-rich Holocene sediments at Tregaron
Bog may include material laid down during this period of
warming or the subsequent, short-lived, cold period (Loch
Lomond Stadial/Younger Dryas; INTIMATE event GS-1), as at
other sites in mid-Wales (e.g. Walker et al., 2001).

The 10 cosmogenic nuclide exposure age samples from
these valleys provide the first chronological control on land-
forms related to the terrestrial deglaciation of south-west
Wales. They indicate that deglaciation was well underway by
19 ka and that discrete outlet glaciers subsequently occupied
and receded up the Aeron and Teifi valleys. By 15 ka these
glaciers had retreated into the uplands of Wales and the
lower reaches of these valleys were ice-free. Glasser et al.
(2012) and Hughes et al. (2016) presented 10Be exposure
ages from mountain summits in the Aran Mountains, the
northern Rhinogydd, the Moelwyns and the Arenigs of North
Wales and used these to establish the vertical exposure
history of the Welsh Ice Cap. Their exposure ages indicate a
Figure 6. Integrated geomorphological and deglaciation model for the Welsh Ice Cap and Irish Sea Ice Stream in south-west Wales showing putative ice fronts at the Last Glacial Maximum (LGM) and at stages during their retreat, based on published maps of glacial deposits (see text) and the new OSL and cosmogenic isotope ages presented in this paper. Notes: 1. Some geomorphological features have been extrapolated to show their likely extent before later Pleistocene and Holocene deposition and erosion. 2. Only the most seaward of the retreat moraines present in the Ystwyth and Rheidol valleys are shown. 3. Only the largest proglacial lakes are named; many of the others were probably short-lived features that drained rapidly as their moraine dams were breached soon after ice withdrawal. 4. ‘Unglaciated’ refers only to the Late Devensian the Preseli Mountains were over-ridden during earlier, more extensive episodes of Pleistocene ice advance. 5. Ice-front positions incorporate and update those proposed in the area by Davies et al. (1997, 2006b), Waters et al. (1997), Etienne et al. (2006), Wilby et al. (2007) and Burt et al. (2012). 6. Bedrock prominences indicate those areas that were the first to emerge from under the Welsh Ice Cap (WIC) during thinning. 7. As independently evolving ice masses, the maritime Irish Sea Ice Stream and the land-based WIC need not have achieved their maximum extents in the region at the same time (e.g. Patton et al., 2013c). The WIC may have continued to advance westwards along the Afon Teifi valley, and to the south, for some time after the Irish Sea Ice Stream had attained its maximum limit in the region. 8. The new ages and their interpretation imply that the maximum advance of the Irish Sea Ice Stream into south-west Wales occurred before 26.7 ka and that this ice mass had fully decoupled from the WIC and withdrawn from the region before c. 20 ka. 9. Dates obtained for Samples MPI 2/01 and YST 12/01 are not considered to represent maximum exposure ages — see text for full explanation.
Figure 7. Timeline for the deglaciation of south-west Wales as suggested by the dating results of this study (see Tables 1–4 and Fig. 6) in the context of late Pleistocene climatic intervals including the Greenland Ice Sheet INTIMATE events (see text). Notes: 1. See Fig. 6, note 6. 2. Dates obtained for these samples are not considered to represent maximum exposure ages — see text. 3. Sample of Hibbert and Switsur (1976) that dates the onset of post-glacial, organic-rich sediment accumulation at Tregaron Bog. 4. See Hambrey et al. (2001). Dotted, dashed and solid vertical arrows are used to imply increasing significance of process or landform. Abbreviations: ISIS = Irish Sea Ice Stream; WIC = Welsh Ice Cap.
clear pattern demonstrating that, following a period of rapid thinning, mountain summits in North Wales became exposed as nunataks between 19 and 20 ka. Our samples from the Cambrian Mountain are farther south and at lower elevations than those collected in North Wales. Nevertheless, our \(^{10}\text{Be}\) exposure ages appear to confirm that there was a period of significant thinning around 20 ka, that bedrock prominences became emergent around this time, and that deglaciation of the south-west portion of the Welsh Ice Cap was then dominated by a series of increasingly discrete outlet glaciers that receded progressively up-valley. Numerical ice-sheet models show a similar recessional pattern, with dynamic outlet glaciers occupying valleys during deglaciation as the ice cap receded into the interior of Wales (Patton et al., 2013a,b,c).

These new data from the south-west of the Welsh Ice Cap are also relevant to the debate about the extent of the ice cap at the LGM. In a series of papers, Watson (1965, 1969) argued that this area of mid-Wales is predominantly a periglacial landscape, lacking evidence of glaciation. Watson argued that, where they exist, glacial deposits are buried beneath periglacial landforms and sediments implying that there was a period of prolonged or intense periglacial activity following glaciation. However, our geomorphological mapping and associated \(^{10}\text{Be}\) exposure ages indicate that upland areas in south-west Wales share a similar deglaciation history to mountainous regions in North Wales, that valley glaciers remained active in the region until c. 15 ka, and that their subsequent recession into upland source areas and final down-wasting pre-dated the Windermere Interglacial. Evidence for a regionally widespread or significantly more protracted Late Devensian periglacial phase is therefore lacking.

**Conclusions**

i. Using luminescence and cosmogenic isotope dating, we have produced the first detailed chronological framework for Late Devensian glacial events in south-west Wales and the southern Cambrian Mountains.

ii. Luminescence ages for ice-contact sand and gravel deposits at Pantgwyn and Trefign is 26.7 ± 1.8 and 26.7 ± 1.6 ka, respectively, indicate that the Irish Sea Ice Stream was undergoing active recession from the coastal fringes of south-west Wales at that time and, consequently, that the maximum advance of the Irish Sea Ice Stream into south-west Wales occurred before this.

iii. Deglaciation of the south-western area of the Welsh Ice Cap was marked by a progression from ice cap conditions to valley glaciation as the ice cap thinned and its outlet glaciers became increasingly constrained by the local topography.

iv. Deglaciation of the Welsh Ice Cap probably commenced immediately after the LGM. Bedrock prominences were the first features to emerge from the ice cover. By 19 ka, the adjacent upland regions were ice-free and outlet glaciers occupied, and had begun to recede up, the Aeron and Teifi valleys. By this time, the Irish Sea Ice Stream had fully decoupled from the Welsh Ice Cap and both ice masses had probably withdrawn from the coastal tract of south-west Wales.

v. Cross-valley recessional moraines and glacial lake and outwash sediments chart multiple periods of stagnation or re-advance of the Teifi and Aeron glaciers. By c. 15 ka, the whole of the Aeron catchment and much of the Cambrian Mountains plateau were ice-free and the Teifi glacier had receded into the Tregaron area.

vi. A period of rapid deglaciation followed, which saw the Teifi glacier retreat into its upland source areas in the Cambrian Mountains prior to final down-wasting before the onset of the Windermere Interglacial around 13.5 ka. The deglaciation geochronology for south-west and south-central Wales matches that of parts of North Wales, confirming that the Welsh Ice Cap underwent a period of marked thinning and reconfiguration around 17–20 ka.

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**Abbreviations.** BIIS, British–Irish Ice Sheet; CAM, central age model; DR, dose-recovery; DRAC, dose rate and age calculator; FMM, finite mixture model; HF, hydrofluoric; ICP-AES, inductively coupled plasma atomic emission spectroscopy; ICP-MS, inductively coupled plasma mass spectrometry; ISIS, Irish Sea Ice Stream; LGM, Last Glacial Maximum; MAM, minimum age model; OD, overdispersion; SUERC, Scottish Universities Environmental Research Centre; WIC, Welsh Ice Cap.

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