Was there a low-altitude Younger Dryas Stadial glacier in south-east Wales? Re-interpretation of landforms and palaeo-climatic inferences

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ABSTRACT

A glacial origin for cirque-like hollows cut into the western escarpment of the UsK valley near Abergavenny, south Wales has become widely accepted. Associated supposed extensive moraine 'festoons' have been depicted merging and contemporaneous with Last Glacial Maximum (LGM) deposits formed by ice occupying the adjacent Usk valley. We re-interpret these festoons as the product mainly of rock slope failures (RSFs) emanating from the hollows. A cirque glacier origin is preferred to account for a compact double-ridge feature in one of the hollows. The Equilibrium-line Altitude (ELA) of the reconstructed glacier (357 m) is >60 m lower than all similarly small, presumed Younger Dryas Stadial (YDS; c. 12.9 – 11.7 ka) glaciers elsewhere in south Wales. To test whether this glacier nevertheless might date from the YDS, we apply three approaches to reconstruct annual palaeo-precipitation amounts at the ELA, two based on relationships between accumulation and ablation for modern glaciers and the third on a simple degree-day model (DDM) using likely climatic characteristics for this event. The DDM can be tailored to represent the recognised large-amplitude YDS annual temperature range rather than the much smaller one experienced by modern glaciers, making it our preferred approach. Although conditions along the Usk valley escarpment during the LGM would have been well suited to cirque glacier formation, the DDM approach, using the large-amplitude annual temperature ranges, suggests that a YDS age might also be possible. The results have implications for re-assessing the likely ages of some former small glaciers in south Wales.

Keywords: Wales; rock slope failure; glaciation; Younger Dryas Stadial; equilibrium-line altitude; palaeo-climatic reconstruction

1. Introduction

There has been wide acceptance for more than 50 years of Late Glacial (Younger Dryas Stadial (YDS); 12.9-11.7 ka) glaciers in Bannau Brycheiniog (Brecon Beacons) National Park, south Wales but, with only a few exceptions, research has been confined to the Fforest Fawr (central) and Mynydd Du (western) areas (e.g. Ellis-Gruffydd, 1977; Shakesby and Matthews, 1993, 1996; Carr, 2001; Carr et al., 2007; Coleman et al., 2009). The exceptions (e.g. Lewis, 1970; Barclay, 1989; Robertson, 1989) have described depositional landforms presumed to be of this age in the north-east of the park in the Black Mountains. In contrast, in the literature this age has been mostly rejected for undulating depositional fans, lobes and mounds believed to be extensive 'festoons' of glacial moraines associated with three pronounced, small cirque-like hollows cut into the western flank of the

Mynydd y Garn-fawr - Blorenge (Blorens) upland in the extreme south-east of the Park (Fig. 1). Instead, these landforms have been assigned a last glaciation age by, for example, Williams (1968) and Thomas and Humpage (2007), these authors regarding them as contemporaneous and closely associated with 'kame-moraine' and sandur sediments linked to the large terminal tongue of Last Glacial Maximum (LGM, c. 25-21 ka; Clark et al., 2012) ice in the adjacent Usk valley (Fig. 1). Without dating evidence, the suggested age for these upland deposits has rested largely on their relatively low altitudinal range, lower than any presumed YDS moraines elsewhere in Bannau Brycheiniog, and the proposed commingling of two of the extensive supposed cirque moraine sequences with Usk valley last glaciation deposits (cf. Barclay, 1989).

Previous interpretations of the landforms (e.g. Williams, 1968; Barclay, 1989; Thomas, 1997; Lewis and Thomas, 2005) would have been hampered by a thick vegetation cover and sunken roads, many with dense hedgerows, and the dearth of accessible sediment exposures. Airborne LiDAR (Light Detection and Ranging) imagery of the sites, however, suggests the need for a re-interpretation of the erosional forms and associated deposits and their origins. In this paper, we re-assess, first, the likely origins of both the hollows and their associated depositional landforms from their geological, and morphological settings and with reference to features elsewhere in Bannau Brycheiniog. Second, evidence of a possible former small cirque glacier in one of the hollows is discussed. Third, implications of the palaeoclimatic data derived from the Equilibrium-line Altitude (ELA) of the reconstructed glacier are evaluated with respect to its possible age.

2. Background

2.1 Setting

There are four sites of interest located along the steep eastern margins of the Mynydd y Garn-fawr and Blorens (Blorenge) plateaux on the western side of the Usk valley near Abergavenny (Fig. 1). The plateaux reach maximum altitudes, respectively of 503 m and 559 m. The sites comprise the following three hollows with associated depositional landforms: The Punchbowl (SO117282), Craig-yr-hafod – Cwm-mawr (SO275102 – SO280097) and Graig-Y-Cwm (SO285092). The fourth site, Cwm Craf (SO277125), lacks significant depositional landforms and is only briefly considered. The eastern margin of the plateaux comprisesteep escarpments dominated by a thick sequence of Devonian sandstones and conglomerates (Old Red Sandstone), with much of it comprising Brownstones, overlain by a relatively thin sequence of Early Carboniferous Limestone and Dolomite, containing more than 240 km of cave passages (Farrant and Simms,2011; Farrant et al., 2014). Capping these strata are Late Carboniferous sandstones, conglomerates and mudstones of the Marros Group (formerly Millstone Grit) and South Wales Coal Measures. The regional dip is c. 8-12° to the west-south-west.

2.2 Glacial history: previous research

With some exceptions (e.g. Williams, 1968; Lewis, 1970; Barclay, 1989; Crimes et al., 1992; Humpage 1992; Thomas 1997; Lewis and Thomas 2005; Thomas and Humpage 2007), there has been comparatively little detailed research into or reference to the glacial geomorphology and chronology of the area and particularly of the escarpment where the study sites are located. The LGM ice limit is represented by the Usk valley ice tongue, which terminated in a well-defined piedmont lobe near the town of Usk (Fig. 1). Some authorities (e.g. Lewis and Thomas, 2005; Thomas and Humpage, 2007) have followed Williams (1968, p. 223) in accepting that small glaciers occupied the three cirque-like hollows during the last glaciation and that associated debris fans with two of them formed "*festoons of morainic deposits … linking up with marginal deposits of the main* [i.e.

Usk] *glacier along the scarp foot*”. According to this view, therefore, the LGM valley ice tongue could not have extended into any of the hollows. Barclay (1989), however, referred briefly to formation in only one of the hollows (Craig-yr-hafod) of a cirque glacier of probable YDS rather than LGM age, which he thought had varied considerably in size during its short existence. In Graig-Y-Cwm, he identified ‘nivation ridges’ (i.e. pronival or protalus ramparts) but no moraine. Farrant et al. (2014), however, apparently viewed the ‘festoons of morainic deposits’ as part of the debris deposited by the Usk valley ice tongue, which they showed reaching the headwalls of the hollows. They considered that there would have been insufficient time during the last glaciation for development of small glaciers in any of the hollows. The present landscape was in their opinion created by the end of the Anglian Glaciation (c. 478-424 ka; Marine Isotope Stage (MIS) 12), during which a valley glacier occupied the Afon (River) Lwyd valley, west of the study sites causing temporary reversal of water flow eastwards through the extensive limestone cave system underlying the Mynydd y Garn-fawr and Blorens (Blorenge) plateaux. Lastly, according to modelling of LGM ice by Patton et al. (2013), the plateaux would have been covered by thin cold-based ice.

3. Methods

3.1 LiDAR Digital Terrain Model and field reconnaissance

The LiDAR Digital Terrain Model (DTM, Fig. 2) reveals otherwise unattainable details of the form of the escarpment and particularly of the associated depositional landforms. Because of obstructed views on the ground, we focused particularly on visiting suspected moraines identified on the DTM. The DTM comprises elevation values for the ground surface beneath any tree canopy, which would otherwise obscure the landforms. A simple hillshade view of the DTM data highlights escarpments, slope breaks and even subtle ridges and hollows.

3.2 Glacier reconstruction and palaeo-climatic inferences

To derive palaeo-climatic inferences from a reconstructed glacier, first, the Equilibrium-line Altitude (ELA) needs to be determined. We used four established methods: (1) the area-weighted mean altitude (AWMA) (Sissons, 1974; Sutherland, 1984); (2) the accumulation area ratio (AAR) (Porter, 1975); (3) the toe-to-headwall (THAR) altitude ratio (Meierding, 1982); and (4) the accumulation area balance ratio (AABR) (e.g. Furbish and Andrews, 1984; Benn and Ballantyne, 2005; Ballantyne, 2007a, 20007b; Golledge et al., 2010; Oein et al., 2021).

To explore the possibility of a YDS glacier in one of the hollows, three methods providing estimates of palaeo-precipitation or annual snowmelt based on the ELA have been applied: they are (1) a simple degree-day model (DDM) (Brugger, 2006; Braithwaite, 2008; Hughes and Braithwaite, 2008); (2) two variants (Ohmura et al., 1992; Rea et al., 2020) of a regression equation derived from an empirical relationship between summer mean temperature (June-August) and summer precipitation and winter balance for modern glaciers; and (3) a curvilinear relationship between the mean ablation-season (May-September) temperature and mean winter precipitation for ten modern Norwegian glaciers (Sutherland, 1984).

The DDM is based on the annual sum of daily melting of snow as a function of air temperature. It requires construction of a sinusoidal curve of annual temperature:

$$Td = Aysin(2\,\Pi d/\lambda - \varphi) + Ta \qquad (1)$$

Where T_d is the mean daily temperature, A_y is the annual temperature amplitude (i.e. half the annual temperature range), *d* the ordinal day, φ the phase angle (taken as 1.93 radians, since January is the coolest month) and T_a the mean annual temperature. We applied a daily mean temperature threshold for melting of 0°C (e.g. Barr et al., 2017), although others have preferred 1°C (e.g. Golledge et al., 2010). To calculate the snow depth melted per day >0°C, a degree-day factor (DDF) is required. We selected two values from the literature of 2.6 and 4 mm d^{-1} °C^{-1}. The latter has been widely adopted in studies of British YDS glaciers (e.g. Braithwaite et al., 2006; Hughes, 2009) and the former was proposed by Barr et al. (2017) and thought to represent better YDS continental conditions caused by extensive North Atlantic sea ice (e.g. Atkinson et al., 1987; Denton et al., 2005; Jost et al., 2005; Thomas et al., 2008). Annual snowmelt was calculated separately for annual temperature sinusoidal curves with annual ranges of 30 and 34 °C adopted by different authors (e.g. Golledge et al., 2010; Barr et al., 2017) and a 10.5 °C mean July temperature based on a multi-proxy record from south Wales (Walker et al., 2003). The two annual temperature ranges were applied to examine whether the difference caused any significant differences in palaeoclimatic inferences.

The second method uses a regression equation developed from an empirical relationship between summer temperature and precipitation input. The original equation (Ohmura et al., 1992) uses data from more than 70 modern glaciers in the North American Cordillera and Scandinavia and is expressed as:

$$P = 645 + 296T + 9T^2 \qquad (2)$$

Where *P* is the winter balance and summer precipitation (in m of water equivalent (m w.e.)) and *T* is the mean summer temperature (June-August) in °C. Based on data for 122 Europe-wide dated YDS glaciers, Rea et al. (2020) modified equation 2 as:

$$P = 691.83 + 294.31T + 7.7171T^2 \qquad (3)$$

The third method, proposed by Sutherland (1984), is based on a strong curvilinear relationship between mean ablation-season (May-September) temperature and mean winter precipitation for ten modern Norwegian glaciers, expressed as:

$$A = 0.915e^{0.339T} \qquad (4)$$

Where A Is the mean winter precipitation and T is the mean ablation-season temperature.

To assess the potential for windblown and avalanche snow input, a snowblow ratio was calculated (e.g. Sissons and Sutherland, 1976; Mitchell, 1988; Dahl et al., 1997), defined here as the ratio between the areas of ground sloping towards the accumulation zone and the accumulation zone itself.

4. Results and discussion

4.1 Description of the hollows and depositional landforms

The largest hollow lies east of the c. 1.2-km long, NNW-SSE-aligned Craig-yr-hafod – Cwm-mawr stretch of escarpment, which curves gradually to the east at its southern end, but more acutely at its northern Craig-yr-hafod end. The steep headwall marks the escarpment edge of the Mynydd y Garn-fawr plateau and reaches a height of c. 460 m. It shelters a hollow with a marshy flat floor at c. 320 m. The plateau and escarpment both decline gently southwards (Fig. 1). Above the headwall is an abandoned small-scale early nineteenth-century limestone quarry face, which supplied rock, first to a small limekiln north of Craig-yr-hafod, but later the hewn rock was made to fall down the escarpment to be transported via a crude small tramway that ran along the escarpment foot (Fig. 2; Phil Jenkins, pers. comm.; www.industrialgwent.co.uk/f21-rural/index.htm).

The Graig-Y-Cwm and Punchbowl hollows, with lower floors at c. 240 and 290 m, respectively, are smaller, but well-formed features. They have low-angled floors and similar plan-form dimensions, respectively of the order of 420 and 360 m in width and 640 and 380 m in length, measured from the tops of the steep headwalls. Graig-Y-Cwm has the most pronounced form of the features, followed in turn by Craig-yr-hafod – Cwm-mawr and the Punchbowl.

The detailed morphology of the depositional landforms emanating from the Graig-Y-Cwm, Craig-yr-hafod – Cwm-mawr and Punchbowl escarpment hollows is shown in Figure 2. These landforms constitute fans with slightly ramparted margins that have abrupt outer slopes, more pronounced at the latter than the former site. For Graig-Y-Cwm, the fan broadens to c. 530 m beyond the hollow confines, and extends c. 1200 m from the headwall summit. Beyond this fan, a small, comparatively narrow, less distinct lobe is apparently partly overlain by it. The Craig-yr-hafod – Cwm-mawr fan is wider (up to c. 1100 m) and extends some 1020 m from the headwall summit, its northern margin being less pronounced than the southern one and its eastern terminus more uneven and generally lower than on the Graig-Y-Cwm fan. It also has short, distinct, intermittent, more or less north-south-aligned mounds. Both fans have single entrenched stream channels. Upslope of the Craig-yr-hafod fan is a c. 10-m high, near-linear, compact, double-ridge depositional complex (Figs 2 and 3) some 330 m from the headwall summit, and it forms the eastern boundary of the marshy floor of the hollow. The ridges possibly link to low, indistinct mounds at the headwall foot. The few sandstone and conglomerate boulders and cobbles found on the surface were subangular and subrounded, which would be more typical of glacial rather than slope action (e.g. Lukas et al., 2013). The coarse surface texture and surface weathering of the clasts meant that any striations would not have been preserved.

The Punchbowl hollow is cut into the south-eastern margin of the Blorenge (Blorens) plateau (Fig. 2) and its floor has a small lake, dammed by a low artificial ridge. The imagery suggests the deposits downslope of the ridge are relatively thick, but dense vegetation hinders confirmation on the ground. Cwm Craf (Fig. 2), farther north, has a much less pronounced form than the other three and has little surface debris and is not considered further.

4.2 Was excavation of the escarpment hollows carried out by cirque glaciers or Rock Slope Failures?

Evans (2006) classified the three hollows as either 'definite' or 'well defined' glacial cirques and this would probably not be questioned by most other researchers, possibly attributing them with a developmental sequence, from 'proto-cirque' (Cwm Craf), to classic cirque forms (Graig-Y-Cwm and Punchbowl) to a long-eroded form (Craig-yr-hafod – Cwm-mawr), possibly resulting from the merger of two well developed, smaller features. Certainly, the features lie within a typical size range for cirques (e.g. Turnbull and Davies, 2006) and, other than Cwm Craf, they have the classic features of steep headwalls, relatively low-angled floors and easterly aspects favouring snow-drift by prevailing westerly winds. Accepting that the hollows escaped inundation by the LGM ice tongue in the Usk valley (Fig. 1), they could conceivably have been excavated incrementally over several Pleistocene glacial events.

The DTM hillshade model of the associated deposits, however, indirectly supports an alternative non-glacial origin for the hollows, particularly the Graig-Y-Cwm deposits, which have little in common with typical moraine sequences. Instead, by spreading beyond the lateral confines of the small hollow, lacking transverse, arcuate ridges (Fig. 2), having ramparted margins to a smooth undulating surface and abrupt margins, a Rock Slope Failure (RSF) origin is indicated. For the main fan and minor lobe combined, an approximate calculation suggests that an average thickness of c. 30 m would match the estimated 10.4 mill. m^3 of rock removed from the hollow. Even if, conservatively, the combined average thickness of the fan and minor lobe were assumed to be half this amount, it would mean that a substantial quantity of the rock was removed from the hollow in two phases. Good preservation implies recent formation (i.e. no older than the last glaciation). There is some support for a RSF origin from two sources: Barclay (1989) who regarded the Graig-Y-Cwm hollow as possibly produced in part by 'rotational landslipping' and D. Jarman (pers. comm.) who regards all three as clear RSFs. Such a non-glacial origin for cirques has been championed elsewhere by, for example, Turnbull and Davies (2006) and Coquin et al. (2019). Even Evans (2021), challenging this view, acknowledges that a RSF origin for cirques may be possible where there is an "escarpment of bedded sediments" (p. 41), as in this study.

The Craig-yr-hafod – Cwm-mawr depositional landforms show many similarities to those associated with Graig-Y-Cwm, but with a few differences. They too form a fan, in this case originating from a much broader hollow, they have a similar mostly smooth surface with some parts of the inner margins ramparted and an entrenched stream channel, but they seem to have a greater thickness near the southern than northern margin. This would be accountable by some lateral downslope movement of the RSF deposits southwards as well as eastwards, reflecting the influence of the local topography, and the parallel mounds probably echoing the underlying bedrock structure.

The morphology of the Punchbowl deposits is different. Downslope of the artificial dam, the undulating downslope-elongated lobes display no moraine-like characteristics and are regarded as shaped by stream dissection. A RSF origin, therefore, seems fitting. The Cwm Craf feature is considered too shallow to have been excavated by a glacier and also tentatively assigned a RSF origin, slope processes perhaps responsible for efficient evacuation of debris from the relatively steep floor, unless this was achieved by the Usk valley glacier tongue.

Although Wilson and Jarman (2022) suggest a pre-LGM date for RSFs in the Lake District, good preservation of the features in this study makes a LGM or, less likely, a Heinrich 1 Event (c. 16.8 ka) age more probable. Seismic activity during deglaciation triggering the RSFs (cf. Jarman and Harrison, 2019) seems unlikely given the marginal location with respect to thick LGM ice, leaving enhanced pore water pressure as the most likely cause. Significantly, Thomas (1959, p. 117) argued that "*Brownstone formations with alternating bands of massive well-jointed sandstones and incompetent marls are particularly susceptible to major landslides. Large catchment areas provide an abundance of vadose water, with flow concentrated along bedding planes towards the base of individual sandstone band.*" This view is supported by similar associations recorded in the Lake District (Wilson and Jarman, 2022). Caves in the overlying limestone may have played a role.

4.3 Craig-yr-hafod glacier characteristics and probable moraine

An artificial origin for the compact double-ridge feature as an unusual spoil heap or embankment for transport of quarried rock can be ruled out because of its scale and location well removed from the quarrying activities (see Fig. 2). There are three other possible origins. First, the feature might be considered a pronival rampart formed by frost-shattered rock fragments weathered from the headwall bouncing, sliding or avalanching down the surface of a snowbed occupying the hollow and accumulating at the foot of the snowbed. This is unlikely because of the large headwall-to-feature distance (>300 m), the relatively modest snowbed surface angle (estimated at <20°) and restricted momentum for transport of debris dropping a short distance onto the snowbed from what would have remained as exposed headwall above the snowbed (see Shakesby 1997). Second, the feature could be part of the RSF. However, the smooth undulating nature of the major part of the depositional landform emanating from the Craig-yr-hafod- Cwm-mawr hollow, its run-out distance of >1 km and clear signs of the underlying bedrock structure indicating the thinness of much of the RSF suggest that there was little resistance to movement up to the terminus. An unlikely significant difference in bed resistance would be needed to arrest some of the RSF debris to form the double-ridge feature. Third, a more plausible origin is that the feature represents a terminal moraine formed by a cirque glacier some time after the RSF had occurred, for which there is a precedent with dating support at Craig Cerrig-gleisiad in central Bannau Brycheiniog (Walker 1980; Shakesby and Matthews 1996; Bowen 1999). This, therefore, differs from the interpretation of the RSF and proposed moraine by Barclay (1989) who considered that both were formed by a glacier that varied considerably in extent. Formation of the moraine complex during the LGM by an outlet glacier draining thin cold ice on the plateau and spilling into the hollow is rejected on the grounds of the lack of both gullies etched into the headwall and moulded rock surfaces (e.g. McCerery and Woodward, 2022) and, significantly, no evidence of active 'back-wasting' of the glacier, which would be reflected in multiple moraines formed over some distance (McDougall, 1998).The presence of surface subangular and subrounded clasts lends some support to a glacial origin interpretation for the feature. Glacier reconstruction indicates a maximum ice thickness of c. 40 m, which is considered sufficient for conversion of snow to ice (e.g. Gray, 1982). The reconstructed glacier area at 0.12 km^2 (Table 1; Fig. 4) is small, but not exceptionally so, exceeding as it does, for example, four out of the five glaciers in north Wales investigated by Hughes (2009). The snowblow ratio is comparatively high (Table 1), reflecting a relatively large area upslope of the glacier from which wind-drifted snow and avalanches could have reached the accumulation area. If high ground to the west sloping away from the glacier at 10° or less were also included (e.g. Mitchell, 1996; Chandler and Lukas, 2017), the calculated ratio would be even larger.

5. ELA and palaeo-climatic reconstructions of the Craig-yr-hafod glacier

There are only small differences in ELA calculations for the proposed Craig-yr-hafod glacier (Table 1), attributable mainly to its small size and limited altitudinal range. The AWMA method produced the highest altitude (364 m), a recognised tendency of this method (Hughes, 2011), but the remaining three methods produced similar results (352-358 m). Although AABR has grown in popularity in recent years (e.g. Osmaston, 2005; Rea, 2009; Chandler and Lukas, 2017), largely supplanting the formerly popular AAR method (e.g. Nesje and Dahl, 1992), they both gave the same result (357 m), when using an appropriate balance ratio of 2.0 with the AABR method (e.g. Hughes, 2009). This ELA is 69 m lower than all cirque glaciers elsewhere in south Wales listed by Hughes (2009). The next lowest ELA is that calculated for Craig y Fro in the central Fforest Fawr area which is 426 m according to Robertson (1989) (though considerably higher according to Rea et al. (2020)).

Results for the three methods used to assess annual palaeo-precipitation and annual snowmelt derived from the ELA (Table 2) show that calculation of the mean annual winter precipitation (3432-4150 mm) produced the highest values followed by the two versions of the regression equation of winter balance and summer precipitation (3125-3153 mm), with the lowest range of values found for the DDM results (1768-2907 mm) for the two selected annual temperature ranges and two DDFs.

Of these three methods, like a number of other researchers reconstructing YDS glaciers (e.g. Hughes, 2009; Bendle and Glasser, 2012; Barr et al., 2017), we prefer the DDM as we consider it is likely to be the most realistic, first, because the other two approaches are based on data from modern glaciers experiencing considerably smaller annual temperature ranges than is widely accepted for the YDS in Britain where the range is thought to have been some 19-22°C larger than today (Isarin et al. 1998). Calculations based on modern glaciers experiencing relatively small annual temperature ranges would effectively rule out glacier formation anywhere along the Mynydd y Garn-fawr - Blorenge escarpment during the YDS because an improbably large snowblow and avalanche input would be needed to counter the high ablation rate. A large annual temperature range, however, could mean that topographically-advantaged sites judged too low previously might have nurtured glaciers, with less snow accumulation being needed for glacier formation (Golledge et al., 2010). The DDM, therefore, can provide a realistic annual snowmelt amount as it is process-based and depends on calculations from sinusoidal curves of the large annual range of daily mean temperatures considered representative of YDS conditions. A second reason is that palaeo-climatic inferences drawn from the other two approaches require assumptions about the likely contribution of summer precipitation to accumulation.

Decisions do, however, need to be made regarding the selection of two input variables to the DDM: the threshold for daily melting (typically taken as 0 or 1°C) and the DDF (in the case of this paper, 2.6 or 4.0 mm d^{-1} $°C^{-1}$). Although the steep rising and falling 'limbs' of the two generated annual temperature sinusoidal curves mean that cumulative daily snowmelt amounts differ little, 0°C was selected as this gives a marginally higher and therefore less favourable snowmelt total as regards assessing the viability of the glacier. The choice of DDF, however, does have a significant effect (Table 2).

To assess which DDF is more appropriate, consideration is needed of the likely YDS and modern annual precipitation amounts. Past YDS glacier reconstructions in the Brecon Beacons (e.g. Shakesby and Matthews, 1993, 1996; Coleman et al., 2009) have assumed similar palaeo- to estimated modern annual precipitation amounts (c. 2400 mm). In a review of YDS climate across Europe based on reconstructed former glacier ELAs, Rea et al. (2020; Figs 1 and 2) provided contoured maps showing an approximate mean annual precipitation for south-east Wales of c. 2250 mm and an interpolated south-east Wales regional ELA of c. 550-600 m. Using an altitudinal precipitation gradient of 3 mm m^{-1} (Brunsdon et al., 2001), the YDS annual precipitation at the Craig-yr-hafod glacier ELA (357 m) would be 1671-1521 mm, derived from the estimated palaeo-precipitation amount and ELA range provided by Rea et al. (2020). This precipitation estimate is lower than both that calculated using a DDF of 2.6 mm d^{-1} $°C^{-1}$ (Table 2) and the modern estimated precipitation amount of c. 1800-2050 mm at 357 m extrapolated from nearby weather stations using the same precipitation gradient. This would imply that the Craig-yr-hafod glacier could have existed during the YDS without requiring a snowblow input. Since, in view of the recognised marginality of the Brecon Beacons for YDS glaciers, there is strong evidence of the significance of a snowblow input to YDS glaciers throughout the area, both the annual precipitation according to Rea et al. (2020) and those amounts derived using a DDF of 2.6 mm d^{-1} $°C^{-1}$ (1768 and 1890 mm) are considered less likely than the higher palaeo-precipitation calculations using a DDF of 4 mm d^{-1} $°C^{-1}$ (2720 and 2907 mm; Table 2), which indicate a third or more of snow accumulation needed from snowblow or avalanching to maintain the glacier. The large snowblow ratio calculated for the glacier (Table 1) and the extensive plateau surfaces to the west from which snow might also have been removed, mean that there would have been potentially an ample supply of drifted snow carried by westerly winds into the Craig-yr-hafod hollow, and this topic is a focus for our ongoing research. If this reasoning is accepted, a YDS date for the Craig-yr-hafod glacier is plausible. Why there is no evidence of glacier development at the other two sites is not entirely clear, but may reflect marginal but critical differences in snowblow and topographic conditions.

5.1 Sequence of events

Since, in contrast to other similar sites in this region, it appears that the hollows and associated deposits avoided being affected by the LGM-age Usk valley glacier tongue, a broad range of potential ages of the various erosional and depositional landforms needs to be evaluated. As discussed, however, an Anglian or even earlier date (Farrant et al., 2014) seems unlikely because of their 'fresh' appearance and lack of any other preserved depositional landforms of this age in the British Isles. Consequently, a LGM or even younger date is preferred. The Craig-yr-hafod glacier could date from the LGM, as suggested for small glaciers in south-west England (Harrison et al. 1998, 2001, 2015). This assumes the Usk valley ice tongue did not reach the site, which is generally accepted, but our results open the possibility of an alternative sequence of events.

(1) During the LGM (though alternatively, conceivably, the Heinrich 1 Event), enhanced pore water pressure in fissures and joints in the Brownstone Formation strata, possibly assisted by water from the overlying limestone caverns, triggered collapse of vulnerable parts of the Usk valley western escarpment and downslope deposition of debris fans. For Graig-Y-Cwm, this apparently occurred in two phases to explain the separate fan and lobe.

(2) Following ice sheet wastage and temperate Windermere Interstadial conditions (c. 14.7-12.9 ka), the subsequent return to cold YDS conditions characterised by large annual temperature ranges could have been suitable for development of the Craig-yr-hafod glacier. Very low winter temperatures might have caused it to be polythermal (but see Bickerdike et al., 2018), its margins frozen to the substrate thereby restricting much of the glacier movement to deformation, perhaps explaining the near-linear plan form of the moraine and the minimal fluctuation of the snout implied by the closeness of the ridges. Alternatively, the moraine form might simply reflect limited movement of this small glacier over its lifetime.

(3) Holocene temperate conditions from c. 11.7 ka would probably have led to little significant landform change, other than stream channel entrenchment and continued alluvial fan accumulation onto LGM deposits in the Usk valley (Fig. 1). During the nineteenth century, quarrying modified the slopes above the Craig-yr-hafod headwall.

In the future, dating of suitable basal organic material in the marshy sediment on the floor of Craig-yr-hafod could help determine the minimum age of the deposits.

6. Conclusions

Previous origins and likely dates assigned to erosional and depositional landforms in Graig-Y-Cwm, Cwm-mawr – Craig-yr-hafod and Punchbowl and glacier development in south-east Wales during the Younger Dryas Stadial (YDS) might benefit from reconsideration. The following points summarise our main conclusions.

(1) The three featured cirque-like hollows were more likely formed mainly by rock slope failure (RSF) than by glacial erosion. The Graig-Y-Cwm, Cwm-mawr – Craig-yr-hafod features have spreads of debris with undulating smooth surfaces, ramparted margins and abrupt outer limits, which are more characteristic of RSFs than glacial moraine sequences. The Punchbowl deposits are also assigned a RSF origin, the relatively steep slopes beyond the hollow floor thought to have impeded fan development. Factors conducive to rotational RSF initiation include escarpment steepness and a sequence of gently-dipping, backward-tilting, well-jointed permeable sandstone and incompetent layers prone to collapse when subjected to raised pore water pressure.

(2) Following RSF formation, a small east-facing cirque glacier is thought to have occupied the Craig-yr-hafod hollow, shown by the well-preserved, compact double-ridge moraine. If glaciers occupied any of the other hollows, they left no clear evidence. An estimated Equilibrium Line Altitude (ELA) of 357 m for the reconstructed glacier is lower than those of any other identified small YDS glaciers in south Wales.

(3) The estimated annual palaeo-precipitation for YDS climatic scenarios in which annual temperature ranges of as much as 30 or 34°C were experienced indicates the possibility during the YDS of sufficient snow accumulation both from direct snowfall and snowdrift from the west to maintain the proposed Craig-yr-hafod glacier despite its low altitude, implying that ages of small glaciers assigned pre-YDS ages elsewhere in the region because of a perceived impossibly large snow input during the YDS might now require re-assessment.

(4) The most likely date for RSF formation at the three sites is the last glaciation (or possibly the later Heinrich I Event), and not earlier, given the good preservation of both the escarpment hollows and associated deposits.

(5) The degree-day model is process-based and can be tailored to model any selected likely annual temperature range and daily snowmelt amount and should therefore be the preferred method for assessing climatic conditions from reconstructions of former glaciers. Methods based on modern glaciers that have commonly been used in many previous studies, and make the assumption that modern annual temperature ranges are similar to those in the YDS, should be abandoned. Using such methods may result in significant errors in palaeo-precipitation amounts and the evaluation of the viability of glacier formation in marginal locations.

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Table 1

Selected characteristics of the reconstructed Craig-yr-hafod glacier

Table 2

Palaeo-climatic characteristics at the ELA (357 m) of the reconstructed Craig-yr-hafod glacier using different methods. To test the feasibility of a YDS age, a mean July sea-level temperature of 10.5°C

Area (km^2)	**Aspect (°)**	**Ice depth at ELA of 357 m (m)**	**Snowblow ratio***	**ELA (THAR**) (m)**	**ELA (AWMA) (m)**	**ELA (AAR ± 0.05) (m)**	ELA (AABR)*** (m)
0.12	81	c. 40	2.9	358	364	357 ± 2	357

THAR = toe-to-headwall ratio, AWMA = area-weighted mean altitude, AAR = accumulation area ratio, AABR = accumulation area balance ratio
*Ratio of upslope catchment area potentially contributing wind-blown and avalanched snow to accumulation area,**Altitude ratio of 0.4, *** Balance ratio of 2.0

and mean annual temperature ranges of 30°C and 34°C have been used where applicable

Method	**Assumptions/equation**	**Accumulation /precipitation (mm w.e.)**	**Author(s)**
Degree-day model. Annual accumulation	30°C annual range, 7.0°C ELA mean summer (JJA) temperature	2907* *1890***	Brugger (2006)
	34°C annual range, 6.8°C ELA mean summer (JJA) temperature	2720* *1768***	
Mean annual winter precipitation	30°C annual range, 4.5°C ELA mean ablation-season (MJJAS) temperature	4150	Sutherland (1984)
	34°C annual range, 3.9°C ELA mean ablation-season (MJJAS) temperature	3432	
Regression of winter balance + summer precipitation	$P = 645 + 296T + 9T^2$	3153	Ohmura *et al.* (1992)
	$P = 691.83 + 294.31T + 7.7171T^2$	3125	Rea *et al.* (2020)

* Calculated using a degree-day factor of 4 mm d^{-1} $°C^{-1}$
** Calculated using a degree-day factor of 2.6 mm d^{-1} $°C^{-1}$
Lapse rate of 0.6°C per 100 m used
w.e. = water equivalent; P = annual precipitation; T = mean summer (JJA) temperature
N.B. Different definitions of summer (JJA) and ablation-season (MJJAS) adopted in the methods

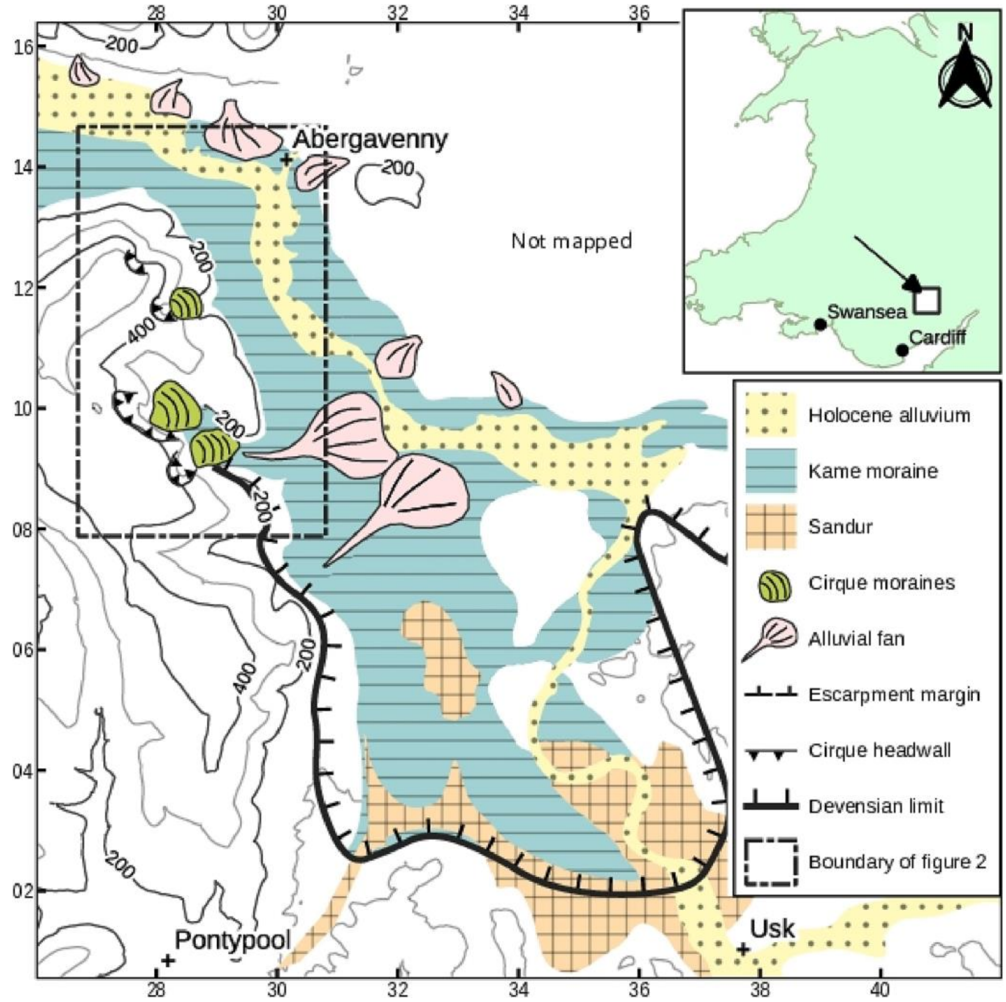

Figure 1 Location of the study area near Abergavenny, south-east Wales. The landforms described in this paper occur along the western escarpment of the Usk valley and lie within the box, which indicates the area shown in Figure 2. Previous interpretations of the escarpment hollows as glacially-eroded cirques, two sets of what have been termed 'festoons of moraine ridges' shown commingling and therefore coeval with last glaciation (Devensian) sediments are compiled from earlier research (Williams, 1968; Thomas, 1997; Lewis and Thomas, 2005). Our interpretation is different. National Grid two-figure Northings and Eastings at 2 km intervals are shown along the margins.

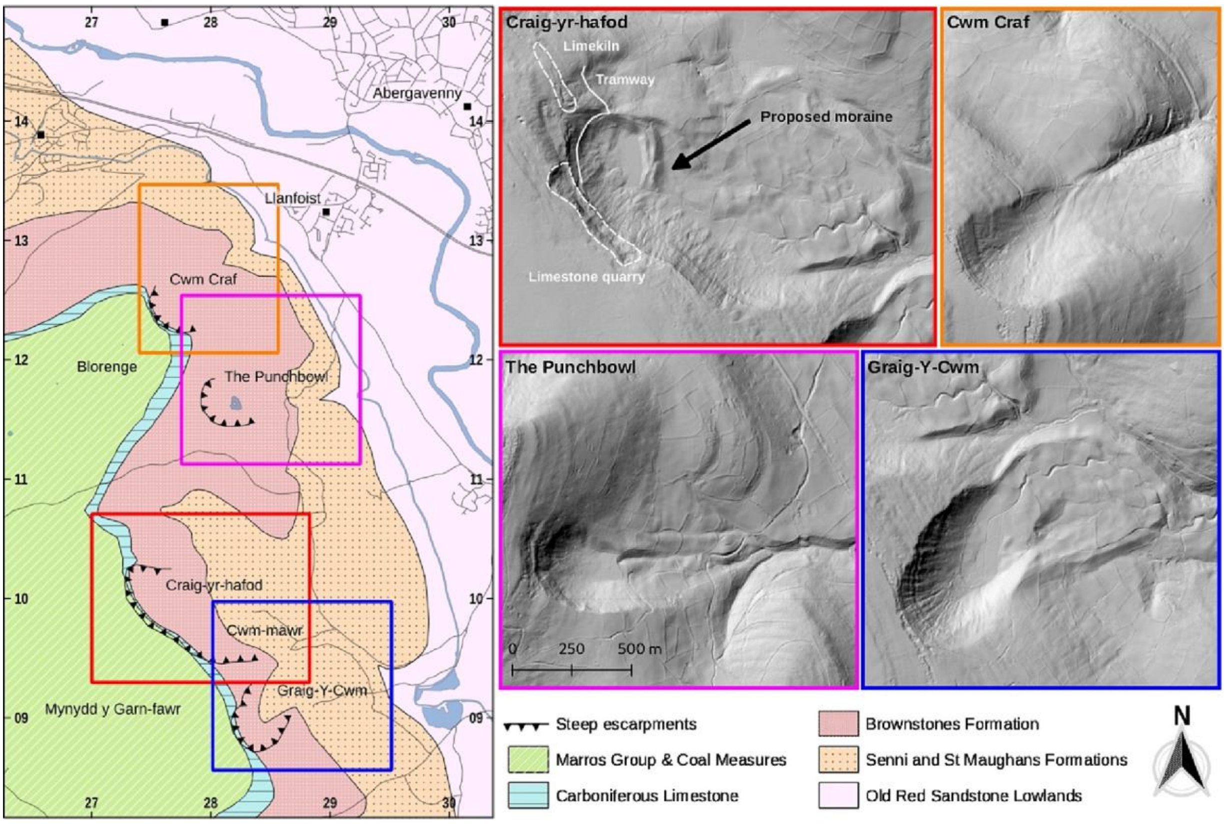

Figure 2 Simplified geology of the study area (left) and Digital Terrain Models (2 m resolution) of the four escarpment hollows and associated sediments (right). In the Craig-yr-hafod hollow, the double-ridge moraine is arrowed and evidence of past quarrying activity identified. National Grid two-figure Northings and Eastings at 1 km intervals are shown along the margins of the map. © Environment Agency. *Contains public sector information licensed under the Open Government Licence v3.0 (*http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/*)*

Figure 3 View looking southwards along the inner of the two ridges forming what is interpreted as a probable moraine complex deposited by a small glacier that occupied the Craig-yr-hafod cirque-like hollow. The proximal part of the outer ridge can be seen at the extreme left of the image partly obscured by trees. The marshy floor of the hollow lies to the right. Note the figure (arrowed) for scale. See Figure 2 for location of the ridges.

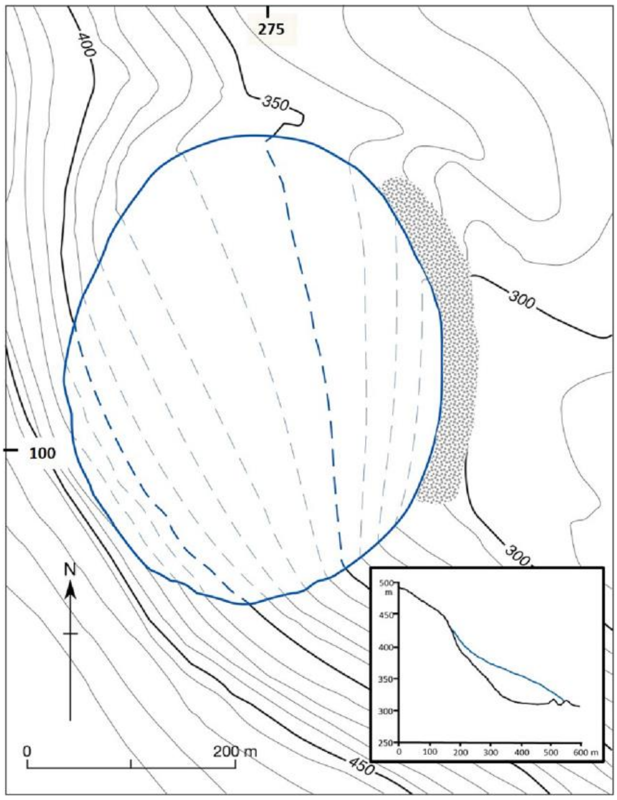

Figure 4 A reconstruction of the proposed Craig-yr-hafod glacier and its moraine. The contours have been interpolated to represent the pre-quarrying form of the upper headwall. The inset shows the long profile of the glacier at its maximum extent. Note the vertical exaggeration. Selected National Grid three-figure Northings and Eastings are shown. See also Figure 2 for location.