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The southernmost Quaternary niche glacier system in Great Britain

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ABSTRACT: Until recently, the scientific consensus has been that the uplands of southwest Britain remained unglaciated throughout the Quaternary, with glacial ice sheet limits lying to the north of the southwest Peninsula. However, recent work has shown that small glaciers and ice caps existed in the uplands of Exmoor and Dartmoor during the late Quaternary demonstrating that the consensus of an unglaciated southwest Britain requires considerable revision. Here we report geomorphological and sedimentary evidence supported by glacier-climate modelling for a Quaternary nichel glacier from west Cornwall, southwest England. This niche glacier represents the southernmost such system from mainland Great Britain, and provides evidence for the presence of extra-glacial niche glaciers probably during the Last Glacial Maximum (LGM) of the Devensian glaciation, and well outside of the limits of the main British-Irish Ice Sheet.

KEYWORDS: Niche glaciers; Cornwall; Quaternary; Glacier modelling; Palaeoclimate.

Introduction

Perennial snowbanks (or snowpatches) and niche glaciers represent the initial stages of glacier development, and can be found well outside of the limits of present-day glaciers and ice caps in climatically-favourable positions such as the shaded and lee sides of mountain tops where wind-blown snow accumulates (Rapp, 1984; Lewkowicz and Harry, 1991; Allen, 1998; Kariya, 2002; Palacios *et al*., 2003; Brenning and Trombotto, 2006). The strong topographic and climatic controls on glacier occurrence has been used as a guide to suggest locations where perennial snowbanks and niche glaciers may have been present in the past, outside of the known limits of the late Quaternary British-Irish Ice Sheet (BIIS) during the Last Glacial Maximum (LGM) or Younger Dryas (YD) cooling event (Ballantyne, 1985; Carr, 2001; Coleman *et al*., 2009; Mills *et al*., 2009; Margold *et al*., 2011). Although niche glaciers usually leave a detectable erosional and depositional imprint on the landscape (Carr, 2001; Coleman *et al*., 2009), the geomorphological and sedimentary processes and signatures of large perennial snowbanks – which are transitional to niche glaciers – are not well known. The generally non-erosive nature of large snowbanks or small niche glaciers, their short-lived timeframe and restricted capacity for sediment transport except in a passive mode through the formation of protalus (better termed 'pronival') ramparts means that such palaeo-features are under-reported in the literature relative to the frequency with which they are found in contemporary mountainous and extra-glacial environments (Brown and Ward, 1996; Shakesby, 1997). Furthermore, pronival ramparts are very variable in terms of their morphology and sedimentology depending on geological setting and sediment supply, which is mainly by backwall weathering (Christiansen, 1998; Anderson *et al*., 2001; Palacios *et al*., 2003; Margold *et al*., 2011), and are likely to occur as polygenetic features formed in several phases (Ballantyne and Benn, 1994; Ballantyne, 1985; Nyberg, 1991; Caine, 1992, 1995). Identifying palaeo-snowbanks and niche glaciers in the geological record based on morphosedimentary evidence is therefore problematic (Henderson, 1956; Ballantyne, 1985; Shakesby, 1997). This identification can be made, however, from the presence of fronting ridges composed of pre-existing weathered materials, which can be easily moved by even small glacionival features.

Geological evidence has often been used to calculate the difference in mean annual air temperature (MAAT) required to sustain these snow and ice forms, based on calculated equilibrium line altitudes (ELA) of small niche or cirque glaciers (Carr, 2001). However, wind-blown snow is a significant and poorly-constrained factor in maintaining such small snow and ice forms (Mitchell, 1996; Hughes, 2002), and thus calculations of palaeo-ELAs are also problematic and not suitable for all situations. Palaeo-snowbanks and niche or small cirque glaciers of presumed LGM or later age have been reported from outside of the margins of the late Devensian BIIS, for example on Exmoor and Dartmoor(Harrison *et al*., 1998, 2001; Harrison, 2001; Evans *et al*., 2012; Evans and Harrison 2014) , and YD-age features have also been reported within BIIS limits(Mitchell, 1996; Anderson et al., 1998; Carr, 2001; McDougall, 2001). The relatively low elevation ranges of the sites on Exmoor and Dartmoor a (around 300-400 m and 370-410 m asl respectively) and their locations well outside of late Devensian limits suggest that these glaciers were of LGM age, which is also supported by the decrease in MAAT required to yield the calculated ELA values (Harrison, 2001). The discovery of these niche glacier sites in southwest Britain has led to renewed investigations of other possible niche glaciers or perennial snowbanks, here collectively termed glacionival features.

We report evidence for a significant glacionival feature in extreme west Cornwall in southwest Britain, located some 120 km southwest from Dartmoor and directly adjacent to the Bristol Channel (Fig. 1). This is the southernmost and westernmost extent of such a glacionival feature on the British mainland. It shows that these features were likely to have been more numerous during the LGM than was previously thought, and has implications for reconstruction of LGM ice extent and climate in areas previously considered to be extra-glacial. In this paper, we first contextualize the late Devensian history of west Cornwall, and present detailed geomorphological and sedimentary evidence from Rosemergy in the West Penwith region of west Cornwall, that shows the presence of a significant glacionival feature. We discuss the geomorphological processes associated with the formation of the Rosemergy glacionival feature, and apply a glacier model to test the hypothesis that the conditions required to sustain the late Devensian ice sheet were conducive to glaciation in west Cornwall. We then discuss implications for the regional palaeoclimate and the nature of late Quaternary ice masses outside the limits of the Quaternary ice sheets.

The late Devensian climate history of west Cornwall

Mainland Cornwall is thought never to have been glaciated during the Quaternary ice ages (Bowen, 1994; Cullingford, 1998; Clark *et al*., 2004). Instead, it is assumed that arid periglacial conditions prevailed throughout the Quaternary, with the formation of tors, altiplanation terraces, extensive solifluction sheets and aeolian loess and coversands (te Punga, 1956; Scourse, 1996). Some luminescence dates from loess deposits suggest arid and windy conditions during the LGM (Wintle, 1981). Radiocarbon ages from organic lenses that have been buried and deformed by later solifluction, suggest cool, vegetated land surfaces around 30 kyr BP during marine oxygen isotope stage (MIS) 3 (Scourse, 1996). There is geomorphological, sedimentary and geochronological evidence for Irish Sea ice impinging on the Scilly Isles, located west of mainland Cornwall (Hiemstra *et al*., 2006), but no ice or snow masses have been previously reported on the mainland, although in east Cornwall Cullingford (1998) identified some rounded hollows with dry valley heads where snowbanks may have accumulated. The southernmost extent of the BIIS during the Quaternary was not thought to have reached the north Cornwall coast, even during the Anglian stage (Stephens, 1970; Bowen, 1986), although it may have impounded marginal lakes and deposited outwash gravels on some north coast estuaries in Devon and Cornwall (Mitchell and Orme, 1967; Stephens, 1970). Recent work suggests, however, that an ice margin reached Lundy Island offshore from north Devon during MIS 4 (Rolfe *et al*., 2012). The previously presumed absence of glaciation throughout the Quaternary has meant that periglacial weathering has been viewed as a dominant geomorphological process during this time (Cullingford, 1998), seen in particular in the formation of tors developed on the granite uplands (Linton, 1955). The high sediment yield due to periglacial weathering has resulted in thick lowland solifluction sequences, particularly around coasts (James, 1981; Scourse, 1987, 1991; Gerrard, 1988; Murton and Lautridou, 2003; Knight, 2005).

Much previous research has emphasized the role of long-term landscape evolution under warm Tertiary climates, in particular the role of high sea levels in land surface planation and deep tropical weathering in the formation of tors (Linton, 1955; Eden and Green, 1971). More recent work, however, suggests that repeated periglacial cycles during the Quaternary have had a stronger landscape imprint, and that tors formed mainly under Quaternary periglacial climates and processes (Palmer and Neilson, 1962; Waters 1964; Bowen, 1994; Murton and Lautridou, 2003). This work suggests that Quaternary landscape evolution may have been more significant for the geomorphology of southwest England than hitherto realized (Cullingford, 1998).

Study site

The field site is located on the moors of west Cornwall in the far southwest corner of Great Britain at Rosemergy (UK national grid reference SW14220566; 50°10’19”N, 5°36’36”W), 8 km northwest of Penzance in the West Penwith region of west Cornwall (Fig. 1) and between the settlements of Morvah and Zennor. The area is underlain by Land’s End granite, which is a biotite granite associated with extensive metamorphism and mineralization (Mitropoulos, 1984). A broad hollow (around 650 m long, 430 m wide) is present on the northeast-facing side of Watch Croft, which is the highest point in west Cornwall at 252 m asl (Fig. 2A). The geomorphology of the study area (Fig. 1), in particular tors, ridge forms and boulder structures was mapped using stereo air photos at 1:10,000 scale and verified in detail in the field. The properties, structures and clast fabrics of sediments exposed in gully sections were investigated. Spoil heaps resulting from past mining activity in the area were identified in order to distinguish these from non-anthropogenic landforms.

Description of field evidence

The hollow at Rosemergy is broad and shallow with a floor at around 140 m asl, and faces towards the NW (to 330^{o}). Tor-topped hills are located on both lateral margins of the hollow. The col at the head of the hollow has a much lower elevation (21-34 m difference) than the lateral margins. These margins extend for 630 m distance from the head of the hollow, and terminate at 680 m distance from the contemporary cliff edge at Bosigran (120 m high) on the adjacent Celtic Sea coast. The hollow is asymmetric in cross profile (see Figs. 1, 2A). The northeast-facing side of the hollow is steeper (1:1.25) than the southwest-facing side (1:2.1). This valley-side asymmetry is typical across extra-glacial southern England (Ollier and Thomasson, 1957; Cullingford, 1998). Specific landforms interpreted as glacionival in origin are now described from locations around the hollow.

Geomorphology

Erosional and depositional periglacial and glacionival landforms are present around the hollow at Rosemergy. Tors on either side of the hollow are well developed. These tors rise 5-20 m above the surrounding landscape (Fig. 2B, C) and are composed of weathered and joint-defined *in situ* and detached granite bedrock blocks that are strongly controlled by pre-existing joint patterns. Tor peaks are not concordant and are spaced up to 30 m apart. Fractures in the *in situ* bedrock can be identified to a depth of 2-3 m.

Surface-parallel and vertical fractures in the granite bedrock have created weathered blocks that are up to 5 m in width. Blocks are edge rounded, tabular to equant in shape, and may show a stacked morphology where dissociated from rockhead. Detached blocks are present both around tor tops and on adjacent slopes where they form a clitter of variable thickness in which non-touching boulders are scattered across the land surface, or interact with each other by processes of stacking and slope-controlled imbrication forming accumulations of more than one block thickness. Variations in block distribution can be mapped from field and air photo observations. Blocks are present in particular on the easternmost side of the hollow, on the flanks of the tor Carn Galver. Blocks are not uniformly distributed across this hill flank, but are concentrated across-slope declining in elevation seaward (Fig. 2B). Blocks are more common on the eastern than on the western sides of the hollow. Despite this, the western (northeast-facing) side of the hollow is much steeper than the eastern side (Fig. 2C).

The eastern flank of Carn Galver is also block-covered, but here blocks are non-uniformly distributed and form boulder lobes that extend downslope and have overlapping margins. These boulder lobes are up to 30 m wide, 40 m long and have steep, lobate margins and convex upper surfaces. Blocks comprising the boulder lobes are up to 1.6 m in dimension, subrounded in shape, and all show the same degree of surface weathering including lichen cover. The blocks are openwork, interlocking and with occasional up-slope imbrication and are estimated to attain a thickness of 4 m above rockhead. No outsized blocks are observed ahead of lobe margins. A prominent boulder lobe (Fig. 1A) is located immediately downslope of a break in the tor long profile.

Sedimentology

Four sections (A–D) are described from the gully cut into coastal cliff sections to the west of Bosigran cliff (Fig. 3). Throughout, clasts are wholly derived from the underlying granite and its surrounding metamorphic aureole. No exotic clasts have been observed that may be indicative of long-distance glacial transport or deposition, coastal longshore drift, or storm/tsunami overwashing from the Bristol Channel and Celtic Sea located to the northwest. Two generalized units are identified. The lowermost unit 1 comprises facies that are considered to be consistent with sedimentation at or directly in front of an ice margin (Dmm, Dms/Gms, Ss/Sm facies; Eyles 1983; Evans and Benn 2004). Evidence for this comes from the diamicton units being overconsolidated and the presence of striated bullet-shaped clasts. Unit 2 comprises facies that are considered to be deposited by solifluction mass and debris flows (Dmm/Gmm, Dms/Gcs, Ss) and corresponding to post-LGM slope relaxation.

Section A (4 m high) is composed of massive to vaguely planar stratified gravelly diamicton (Dmm to Dms facies; unit 2). Stratification where seen is marked by the presence of larger flat-lying and non-touching clasts (20-40 cm diameter). Pebbles (5-8 cm diameter) dominate within a coarse granule matrix composed of quartz and plagioclase crystals weathered from the granite country rock.

Section B (2 m high), which is located farther downslope than Section A but is considered to be stratigraphically equivalent, shows massive to planar stratified gravelly diamicton beds (Dmm/Dms/Gms facies; unit 2) which are arranged in laterally continuous layers 10-20 cm thick. Bed boundaries, where apparent, are demarcated by concentrations of larger clasts (10-12 cm diameter) compared to the middle of beds which are massive and clast supported by pebbles (2-4 cm diameter).

Section C (3 m high), which is located downslope from sections A and B, shows interbedded gravelly diamicton (Dmm/Gmm facies) and sand units (Ss facies) that are highly variable in grain size and degree of sediment sorting and stratification (Fig. 3). Sand units are expressed as discontinuous and flat-lying, occasionally deformed, lenses and interbeds (<10 cm thick, 40 cm long) that have welded margins and which are internally laminated. At the base of the profile, and stratigraphically below the gravelly diamictons of sections A and B, is what appears to be an overconsolidated diamicton (Dmm/Dms facies; unit 1) separated from the overlying gravelly diamicton by a deformed sand lens composed of laminated medium sand (Ss/Sm facies) which is located above a prominent planar north-going shear (Fig. 4A). Within the overconsolidated diamicton are bullet-shaped and facetted clasts (e.g. Fig. 4B) that are morphologically similar to those described from glaciated terrain (Benn and Evans, 2010). Short (few cm) and very narrow (sub-mm-scale) linear features on the edges of the clasts could be interpreted as striations. Located above these diamicton units and separated by an erosional contact are poorly stratified but planar beds (20-50 cm thick) of gravelly diamicton (Dmm/Gmm to Gsc facies; unit 2). These beds are not internally sorted.

Section D (7 m high) is dominated by two major facies types. Massive to planar stratified gravelly diamicton (Dmm/Dms facies; unit 2) which is variably clast- to matrix-supported overlies matrix-dominated sandy units that contain gravelly interbeds (unit 1). These interbeds (10-40 cm thick) are tabular and laterally continuous. Within gravel-rich beds at the top of the section, cryoturbation involutions demarked by variations in clast long axis alignment can be identified. These involutions are up to 0.5 m across and deep.

Clast morphology and fabrics were evaluated from three diamicton beds (samples 1-3 on Fig. 3). All three samples show very similar patterns, with a similar spread of clast morphologies when shown on clast form ternary plots (Benn and Ballantyne, 1994) and clast fabrics 1–3 that cluster in the northwestern quadrant which is in a downslope direction (Fig. 3). The moderately strong clast fabrics are consistent with 'lodgement till' (Dowdeswell and Sharp, 1986), but it is also to be noted that the sediments are deposited on a steep bedrock slope (bedrock outcrops intermittently within the Bosigran ravine). Consideration of C_{40} ratios (Benn and Ballantyne, 1994) shows that all three samples plot within the domain of typical sediments found within moraines.

Interpretation of field evidence

The presence of clasts that appear to be glacially facetted and bearing striae at the base of section C within unit 1 (Fig. 4B) strongly suggests that subglacial processes of clast erosion and transport have been operating in this location, delivering glacially-transported clasts directly to an ice margin. However, the dominance of gravelly diamicton beds within unit 2 at the top of all the described sections that are variably clast- to matrix-supported, planar stratified and with sandy interbeds suggests that downslope reworking of ice-contact sediments was the major mechanism of sediment transport and emplacement (Curry, 1999). The dominant downslope fabric of sediments within unit 2 confirms that gravity-driven reworking in the form of sheet solifluction, mass flows and possibly debris flows was directed into a pre-existing bedrock valley (which is likely of a previous interstadial in age) (e.g. Harrison *et al.*, 2010). This dominance of the post-LGM slope sediment reworking is very likely given the steep bedrock slopes throughout the north Cornwall coast region (e.g. Scourse, 1996) and this must have occurred prior to the last phase of periglacial cryoturbation which has affected the topmost sediments in section D. It is likely that the ridge morphology seen immediately adjacent to the Bosigran section at Rosemergy farm (Fig. 4C) is part of a previously more extensive terminal moraine from which the Bosigran sediments were derived, and this is supported by the presence of hummocky topography immediately outside of this ridge. This may represent a paraglacial slope response to deglaciation in this setting, strongly mediated by the steep nature of the proglacial environment (e.g. Curry, 1999)

Glacier-climate modelling

To test the hypothesis that palaeoclimatic conditions during the Late Devensian were sufficient to sustain a niche glacier at our field site, we applied a 2-D glacier-climate model to the study area. The glacier model (Plummer and Phillips, 2003) is particularly suitable for the investigation of small glaciers where topography and solar position exert a strong control on mass balance.

Model design

The topography of the model domain was described using the NEXTMap Britain digital terrain model (DTM) that has a 5-m grid spacing. Energy-balance calculations were made using a description of present-day climate from the Met Office regional datasets for South Wales and Southwest England for a 30-year period (1981-2010) and solar position for the LGM (21 ka). Maximum slope in the study area is 27 degrees, but as only 2% of the study area is steeper than 20 degrees we did not include a calculation for the redistribution of snow by avalanching. As the dominant wind direction is southwesterly (Kosanic et al. 2014) we would expect wind-blown snow to increase the amount of snow accumulation at the study site. We do not directly model the wind redistribution of snow (*cf.* Harrison et al., 2014), but instead tested this variable by making energy balance calculations where the amount of snow delivered to the catchment was increased by 5% of the total snowfall for each month. This resulted in a slightly more extensive simulated glacier (Fig. 5 inset) although the resulting difference in ice volume is within the uncertainty of the model application as described below.

The simulated mass balance and the DTM topography were input to a 2-D ice flow calculation implementing the shallow ice approximation to determine the steady-state ice thickness in the catchment. Ice flow was described by assigning equal weighting to internal deformation and basal sliding using values well within the range commonly applied in studies of present-day glaciers (Cuffey and Paterson, 2010). Results were considered acceptable when the integrated mass balance was within 0.1% of steady state. Palaeoclimatic uncertainty in the application of this glacier model has been quantified for present-day and Holocene glaciers in the Southern Alps of New Zealand as equivalent to a difference in MAAT of 0.25°C (Rowan et al., 2014). In the current study, under LGM conditions the change in glacier volume resulting from a difference in precipitation amount of ±10% was offset by a difference in MAAT of ±0.25°C, which is the value assigned to the palaeoclimatic uncertainty in the model application. Parameter values used in these simulations are given in Table 1.

Conditions during the LGM were likely to have been colder and drier than present, with increased temperature seasonality. However, constraining the difference in climate between the present day and the last glacial is challenging due to the variation in palaeoclimatic conditions represented by proxy records. We tested a range of plausible values for differences in MAAT (ΔT) and precipitation amount (P), and made a conservative estimate of LGM seasonality of 3°C compared to the present day, giving a mean LGM temperature of 7°C for July and –10°C for January (Table 1). A slightly higher value for LGM wind speed (10 m s^{-1}) than are currently observed in southwest England (mean monthly values of 6 m s^{-1}) was used to represent inferred windier conditions. The LGM palaeoclimate was simulated using a range of scenarios with ΔT of between –8.0°C and –10.0°C in increments of 0.5°C, and P of between 40% and 100% of present-day values (Fig. 5). Simulations made using the present-day climate and solar position produced no glacier ice or perennial snow in the study area and are not presented.

Glacier-climate reconstructions

Our simulations demonstrate that a niche glacier could have formed in the hollow on the northeast-facing side of Watch Croft under conditions within the range of the regional LGM, equivalent to Δ*T* of –9.5°C accompanied by *P* of 60% compared to present-day values (Fig. 5 and 6). Summer temperatures at least 7°C cooler than present were required to form this glacier. The palaeoclimate could have varied by ±0.5°C and in precipitation amount by ±10% around these values and still produced conditions favourable to glaciation. This envelope of palaeoclimate that could form and sustain a niche glacier is consistent with LGM palaeoclimate modeled for the North Atlantic region (Otto-Bliesner et al. 2006; Arpe et al. 2011), and simulations of the LGM BIIS (Hubbard et al. 2009). The LGM niche glacier had an area of 0.44 km^2, a maximum ice thickness of 51 m, a mean ice thickness of 29 m, and an ELA of 184 ± 17 m. Response times for these simulations are long (over 500 years for Δ*T* of –0.5°C), indicating that it is unlikely that marginal niche glaciers such as this did maintain steady state, and were instead likely to have been short-lived features that may only have reached the extent described in this study briefly when the palaeoclimate was favourable.

Discussion

Valleys that are asymmetric in cross-profile have been previously reported from glacial and periglacial settings (e.g. Currey, 1964; Crampton, 1977; Naylor and Gabet, 2007). Valley asymmetry is most commonly attributed to different microclimates and weathering and slope sediment transport rates on valley sides with different facing directions (Ollier and Thomasson, 1957; Burnett *et al*., 2008; Pawelec, 2011). At Rosemergy we argue that the different lines of independent evidence suggest that a niche glacier occupied the hollow on the northeast-facing side of Watch Croft at times during the late Quaternary. Surrounding hillsides were affected by severe periglacial processes, and this is evidenced by the landform-sediment association of frost-shattered tors, clitter spreads, solifluction deposits and boulder lobes on hillsides (cf. Evans *et al*., 2012). The elevation of block clusters on the west-facing slope of Carn Galver may indicate the elevation of the former ice surface which declines down-ice and, at its maximum elevation, may indicate an ice mass up to 30 m thick, consistent with the modeled mean ice thickness.

We infer that the Rosemergy glacionival system is of late Quaternary, specifically LGM age for three main reasons; (1) The climatic conditions inferred using the glacier model required to produce a niche glacier at this relatively low elevation (200-250 m asl) best matches with the proposed palaeoclimate in west Cornwall during the LGM (Hubbard *et al*., 2009), (2) Uppermost sediments exposed within Bosigran cliff show some evidence for periglacial cryoturbation, thus suggesting active layer development during late sedimentation stages following sediment deposition under a glacionival regime, (3) Niche glaciers of likely LGM age have been described from upland areas of Exmoor (Harrison *et al*., 1998, 2001) and Dartmoor (Evans *et al*., 2012), 185 km northeast and 125 km east of Rosemergy respectively. It is likely that Rosemergy forms part of a regional-scale archipelago of small glacionival systems developed in locations where topoclimatic controls favoured a sustained positive mass balance during the LGM. A YD age for Rosemergy is discounted on the basis that temperatures and therefore ELAs were not low enough, and that any YD system would have occupied the same locations of any larger LGM systems.

An inversion approach can be usefully used to reconstruct larger-scale synoptic weather patterns, including the role of wind-blown snow on snowbank accumulation and maintenance. Development as niche glaciers from perennial snowbanks has also not been widely investigated. The geomorphological distinction between these two forms is also unclear and may be simply a matter of scale, although this hypothesis has not been tested. Niche glaciers are generally thin (< 10 m thickness) and thus do not experience rotational gravity-driven ice flow that allows for bed excavation and overdeepening. As such, niche glaciers may show little or no evidence for active subglacial abrasion, plucking and sediment transport, although the basal ice thermal condition is likely a considerable control on rock weathering by suppressing freeze-thaw action.

Conclusions

We have presented geomorphological and sedimentological evidence to suggest that a north-facing shallow hollow in west Cornwall was occupied by a small glacier, probably during LGM times when the southerly margin of the BIIS lay just offshore of the present Cornish coast. This finding is supported by glacier-climate modeling which shows that a reduction in MAAT of between –9°C and –10°C accompanied by a reduction in precipitation of up to 50% was sufficient to form and sustain a niche glacier in the hollow. This niche glacier represents the southernmost such system from Great Britain, and provides evidence for the presence of extra-glacial niche glaciers outside of the limits of the main ice sheet. This work adds to the suggestion that glacial ice in the uplands of southwest

Britain beyond the southern margins of the British-Irish Ice Sheet may well have been extensive during cold phases of the late Quaternary.

Table and figure captions

Table 1. Glacier model parameters used in the simulations described in this study. For the climatological parameters, annual and 6-month summer (April to September) and winter (October to March) are given. All values used in these simulations were monthly means apart from where only annual values are given. Values given here describe the present-day climate, except where LGM temperatures are given. Precipitation totals describe the amount of precipitation falling within the model domain.

Figure 1. Location and geomorphology of the study site in west Cornwall, including (A) site geomorphology, and (B) location of sediment logs shown in Fig. 3. In (A), CG is Carn Galver hilltop, and elevation in m.

Figure 2. Views of the site location and geomorphology (A) The hollow from the north, showing its size (it is 430 m wide) and its asymmetric profile. (B) Looking towards Carn Galver from Watch Croft. (C) Photograph looking from Carn Galver towards the northwest. Rosemergy farm in the distance on the green fields.

Figure 3. Sedimentology of sections A-D from the gully at Bosigran cliff (shown in Fig. 1B).

Figure 4. Photographs of sediments and landforms at Rosemergy. (A) Consolidated diamicton exposed at the base of section C, (B) Facetted and weakly striated bullet-shaped clast found in Section C whose form and shape is characteristic of subglacial erosion and transport, (C) Hummocky drift ridges near Rosemergy Farm.

Figure 5. Glaciers simulated under a range of palaeoclimates. In each case, the ice thickness (blue shading) is drawn to the same scale, and draped over a shaded relief map of the DTM (pink to green shading). Inset shows the simulated glaciers and difference in ice thickness resulting from a 5% increase in snowfall under LGM conditions attributed to the wind redistribution of snow.

Figure 6. Perspective view looking southeast towards Watch Croft from near Rosemergy showing (a) the study area, and (b) the reconstructed glacier produced with $\Delta T = -9.5$°C and $P = 60\%$. The catchment boundary used to define the model domain is shown by the solid red line. The imagery is the Tellus 1-m grid spacing digital surface model overlain with aerial photography. Note that the

glacier surface is shown in (b) rather than the ice volume, such that this surface appears to float above the topography to the right of the image, and that the vegetation shown here is not present in the NextMap DTM used as the model domain.

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