

Loch Lomond Stadial glaciers in the Aran and Arenig Mountains, North Wales, Great Britain

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Geomorphological evidence for four former local glaciers has been mapped in the Aran and Arenig Mountains, North Wales. Former glacial extent was deduced from the distribution and assemblage of end and lateral moraines, hummocky moraine, boulder limits, drift limits and periglacial trimlines. Comparison of infilled lake sediment stratigraphies inside and outside of the former glacier limits suggests a Loch Lomond Stadial (Late Devensian) age of the former glaciers (*c.* 12.9–11.5 cal. ka BP). This finding is also supported by periglacial–landform contrasts between the land inside and outside of the glacier limits. Reconstruction of the four glaciers illustrates a mean equilibrium line altitude (ELA) of *c.* 504 m. From the reconstructed ELAs and the combination of precipitation and snowblow input for total accumulation, by analogy with Norwegian glaciers, a mean sea-level July temperature is calculated at 8.4°C. Copyright © 2002 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The Aran and Arenig Mountains lie in the southern part of the Snowdonia National Park in North Wales (Figure 1). They both form the western watershed of the River Dee catchment basin and contain the largest natural lake in Wales, Llyn Tegid (commonly known as Bala Lake). The geology of the Arenig region is dominated by Ordovician volcanic strata comprising tuffs, ignimbrites, intercalated andesites, lavas and associated andesitic intrusions, which have given rise to the major peaks of Arenig Fawr and Arenig Fach by differential erosion (Rowlands 1979). Northeastward of the main Arenig peaks, around Cwm Gylchedd, these volcanic rocks are flanked by Ordovician mudstones, grits and sandstones. The main ridge of the Aran Mountains is also dominated by Ordovician volcanic strata and is flanked to the east by Ordovician slates and shales.

Localized cirque glaciation of Loch Lomond Stadial (Late Devensian) age (12.9–11.5 cal. ka BP) has been recognized in several areas of the Welsh uplands including north Snowdonia (Gray 1982), Cadair Idris (Lowe 1993) and the Brecon Beacons (Ellis-Gruffydd 1977; Walker 1980; Shakesby and Matthews 1993). The Aran and Arenig Mountains have received scant attention in the literature relating to glacial advance during the Loch Lomond Stadial. Gray *et al.* (1981) mention briefly the moraines at Llyn Arenig Fach. Also, Lowe (1993) identified evidence for two former glaciers at Llyn Arenig Fach and Llyn Lliwbran in his PhD thesis dealing with the Late-glacial and Early Flandrian of southern Snowdonia, although the details of these glaciers are unpublished.

Cirques are well developed, particularly on the eastern flank of the Aran Ridge, the northeast faces of Arenig Fawr and Arenig Fach and the northern slopes of Carnedd-y-Filiast. Within these cirques, localized moraines are evident and are accompanied by several geomorphological features suggestive of local glacier occupation. These former glaciers represent the last glaciation of the Aran and Arenig Mountains and are the focus of this study.

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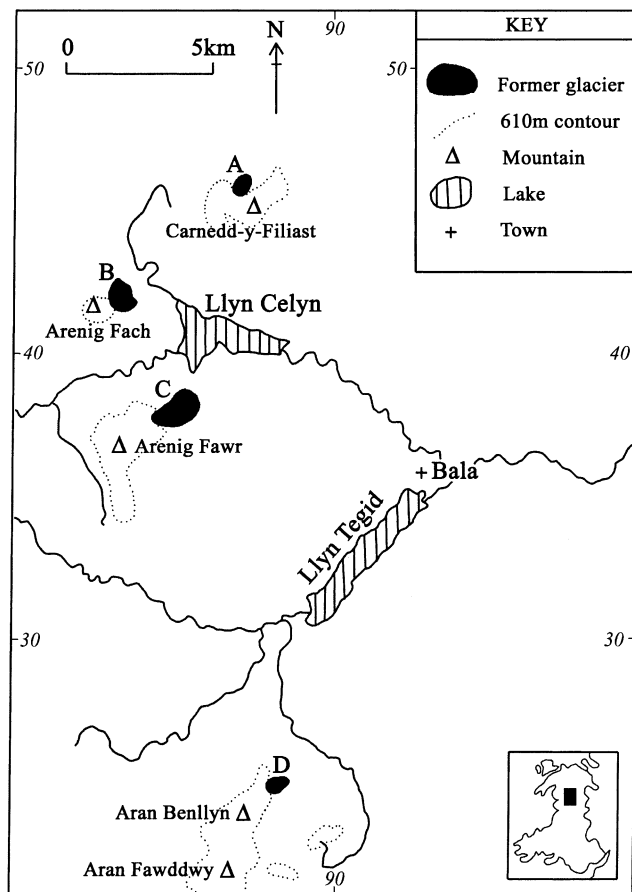


Figure 1. Location map of the Aran and Arenig Mountains showing the sites of the former glaciers. Site key: A, Cwm Gylchedd glacier; B, Llyn Arenig Fach glacier; C, Llyn Arenig Fawr glacier; D, Llyn Lliwbran glacier.

2. METHODS OF INVESTIGATION

The maximum limits of four former local glaciers were mapped in the field using base maps. These were at Llyn Lliwbran (SH 875255) in the Aran Mountains and at Llyn Arenig Fawr (SH 845380), Llyn Arenig Fach (SH 827417) and Cwm Gylchedd (SH 866455) in the Arenig Mountains. Field mapping was aided using evidence derived from 1:15 000 scale aerial photographs. The field evidence was mapped onto transparent overlays that allowed accurate redrawing for presentation and reconstruction purposes. Features mapped in the field included end moraines, hummocky moraine, drift and boulder limits, fluted moraine, periglacially disturbed ground and periglacial trimlines.

3. GEOMORPHOLOGICAL EVIDENCE

3.1. Cwm Gylchedd (SH 866455)

The maximum extent of the former Cwm Gylchedd glacier is marked by a well-defined drift limit which is dissected at its approximate mid-point by a clear meltwater channel (Figure 2A). Within the drift limits and

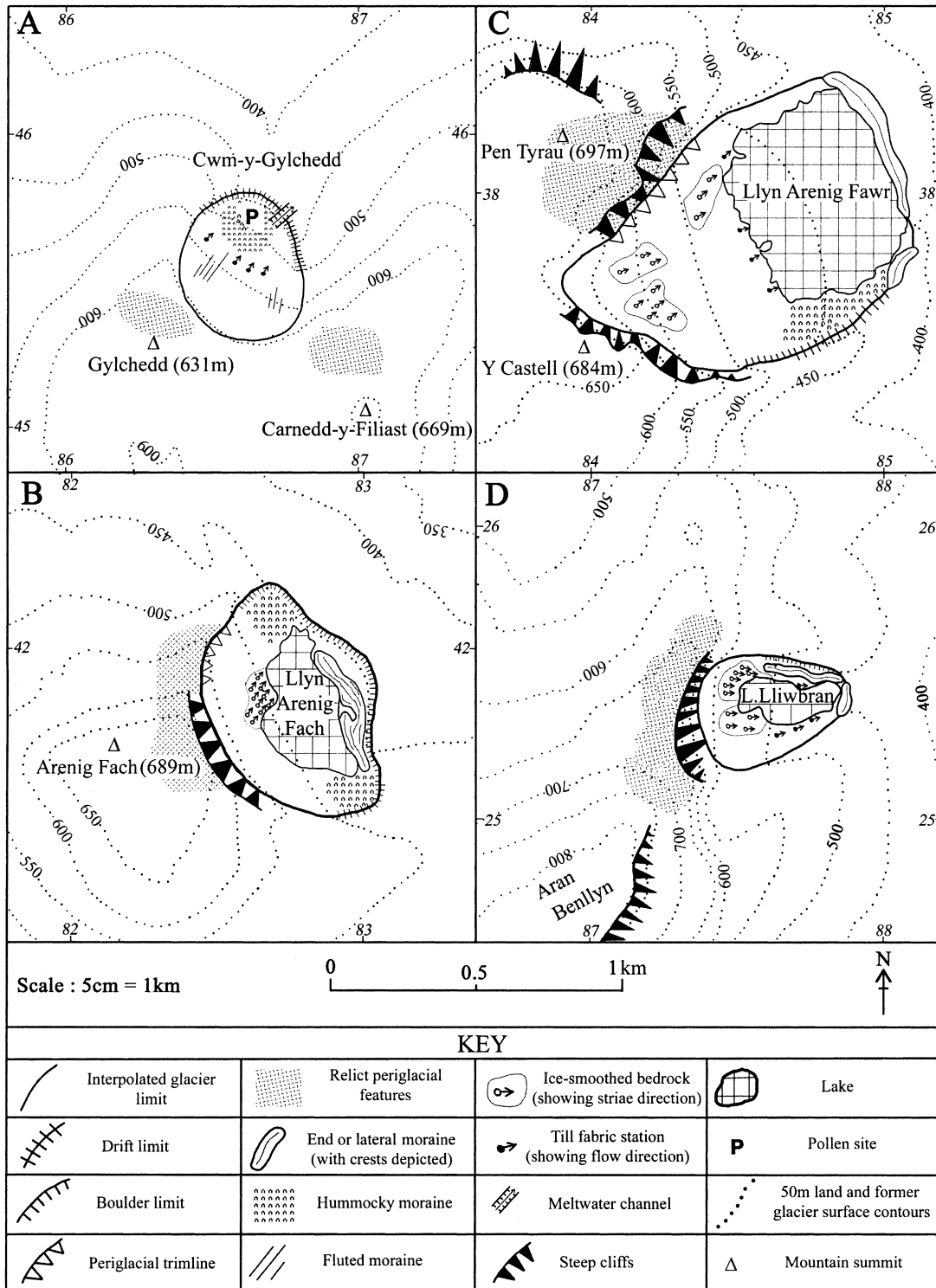


Figure 2. Geomorphological maps of the former glacier sites. A, Cwm Gylchedd glacier; B, Llyn Arenig Fach glacier; C, Llyn Arenig Fawr glacier; D, Llyn Lliwbran glacier.

interpolated glacier limit, hummocky moraine is evident whilst linear ridges are evident on the steeper slopes up-valley of the hummocky moraine. They are interpreted as fluted moraine. Till-fabric analysis showed that ice flow was in a northeasterly direction which is consistent with the assemblage of features described above.

3.2. *Llyn Arenig Fach (SH 827417)*

This site displays very impressive readvance features, in particular along the eastern shores of Llyn Arenig Fach (Figure 2B). Here, a series of very clear morainic ridges bound the lake for *c.* 500 m from north to south. However, the maximum limit of the former glacier is represented by a boulder limit nearly 100 m beyond these ridges. The upper limit of the former glacier cannot be easily deduced, although a periglacial trimline is evident north of the backwall cliffs.

3.3. *Llyn Arenig Fawr (SH 845380)*

The lake Llyn Arenig Fawr is impounded by a broad ridge (Figure 2C) which, though of disputed origin (Rowlands 1970), is morphologically consistent with an end moraine defining the limit of a small glacier to the southwest. Further evidence of localized glacier occupation is provided by a clear boulder limit marking the southern limit of the former glacier and the presence of hummocky moraine inside of this limit. The northwestern limit of the former glacier is marked by a periglacial trimline. The results of striae direction measurements and till-fabric analyses suggest east to northeasterly ice movement which is consistent with the position of the end moraine at the front of the glacier.

3.4. *Llyn Lliwbran (SH 875255)*

The maximum extent of the glacier that occupied the basin containing Llyn Lliwbran is marked by an end moraine 10 m long and up to 4 m high that bounds the easternmost part of the lake (Figure 2D). The northern limit of the former glacier is marked by a well-defined lateral moraine. The actual glacier limit is mapped slightly north of this limit, in parts, because it is likely that the moraine has moved downslope from its original position by paraglacial mass movement. The southern limits are unclear on the ground, although they can be confidently interpolated given the tight closure of the cirque morphometry. With little evidence for ice extent up the headwall, the common practice of assuming glacier extension to *c.* 30 m from the headwall summit has been followed (*cf.* Gray 1982).

4. THE AGE OF THE FORMER GLACIERS

The former glaciers represent a phase of local glaciation that post-dates the retreat of the last main Devensian ice-sheet. The absence of evidence for relict periglacial phenomena within the mapped glacial limits is consistent with glaciation during the Loch Lomond Stadial of *c.* 12.9–11.5 cal. ka BP (equivalent to the Younger Dryas Chron of continental Europe (Walker *et al.* 1994)), the last period of cold periglacial conditions to affect Great Britain (*cf.* Ballantyne and Harris 1994).

To test this proposition, cores were taken with a Livingstone piston corer from an infilled lake basin within the former glacier limits at Cwm Gylchedd and from a similar basin outside of the former glacier limits at Ffridd-y-Fawnog (SH 860385). At the latter site, a full suite of Late-glacial sediments was removed including the classic Late-glacial tripartite sediment sequence (minerogenic clay–organic lake mud–minerogenic clay) beneath Flandrian (Holocene) lake muds and peats (e.g. Walker 1980). At the Cwm Gylchedd site, thorough and systematic sampling of the infilled basin revealed only Flandrian deposits. Detailed pollen analysis of the basal sediments (Hughes 2000) supports this interpretation of the stratigraphy, with a full Late-glacial vegetation succession present at Ffridd-y-Fawnog, whilst only an Early Flandrian succession is represented at Cwm Gylchedd.

The contrast in basin stratigraphy between the two sites is consistent with a Loch Lomond Stadial age for the glacial readvance represented at Cwm Gylchedd. In view of the similarity between the geomorphological evidence at the sites, it is likely that all four of the Aran and Arenig glaciers existed during the Loch Lomond Stadial, although both the periglacial and pollen–stratigraphic data represent negative and not conclusive evidence.

5. GLACIER RECONSTRUCTION

5.1. *Methods of reconstruction*

In order to reconstruct the former glacier surfaces, contours were generated at 10 m intervals on base maps of scale 1:10 000. Contours were plotted from the mapped ice margin and follow the general pattern as seen on modern glaciers, whereby the contour curvature closely corresponds to snout curvature in the snout area, but diminishes up-glacier to become reversed in the upper parts (*cf.* Sissons 1974, 1977). Glacier area was calculated and then former ice depth estimated at 30–80 regularly spaced points for each glacier. Glacier thickness equals glacier surface altitude (obtained from the surface contours) minus the land surface altitude. Glacier aspects were measured at each regularly spaced point from flow-direction lines drawn perpendicular to the ice surface contours.

The firn line or equilibrium line altitude (ELA) for each glacier was calculated using the method of area-weighted mean altitude, introduced by Sissons (1974). This procedure is based on two assumptions: (a) during the glacial maxima the glacier was in equilibrium; and (b) both the accumulation and ablation gradients have a linear relationship with altitude. The application of this method to modern glaciers has shown that it often overestimates the real ELA (Sutherland 1984; Rune 1996; Nesje and Dahl 2000). However, this method is thought to be suitable when applied to small cirque glaciers with even area/altitude distributions (Rune 1996). Indeed, it has been widely used to calculate the ELA of other Loch Lomond Stadial glaciers in upland Britain (e.g. Gray 1982; Ballantyne 1989; Shakesby and Matthews 1993; Wilson and Clark 1998; Anderson *et al.* 1998).

For each of the former glaciers, the potential contribution of snowblowing to glacier accumulation was calculated using the D/A ratio of Dahl *et al.* (1997), where D is the basin-drainage area and A is the glacier-surface area. The D/A ratio can be combined with estimated precipitation values to provide an estimation of total accumulation. Taking into account Sissons' (1980a) interpretation that Loch Lomond Stadial snowfalls in the Lake District were associated with southerly winds, only the area of the drainage catchment likely to contribute to snowblow input onto the glacier was considered.

The influence of avalanche contribution to the glaciers was calculated in a similar manner to that of snowblow input. The ratio between the total area susceptible to avalanche (slope $> 20^\circ$) leading directly on to the accumulation area (V) and the glacier accumulation area (A) represents the avalanche ratio (V/A) in this study.

5.2. *Glacier characteristics*

The characteristics of the glaciers are shown in Table 1. Significantly, all of the glaciers had potential snowblow catchments significantly larger than their accumulation areas. This can be mainly attributed to the local topography. The three Arenig glaciers (Llyn Arenig Fawr, Llyn Arenig Fach and Cwm Gylchedd) all lie in the lee of plateau surfaces, and the Aran glacier at Llyn Lliwbran lies in the lee of a broad rounded ridge. Conversely, avalanche ratios are low for all four glaciers, suggesting that direct avalanching of snow represented a limited contribution to glacier accumulation.

The ELAs determined for the glaciers were 503 m, 470 m, 511 m and 531 m, with an overall mean of *c.* 504 m. This compares with a mean of 600 m for north Snowdonia (Gray 1982), 540 m for the English Lake District (Sissons 1980a) and 700 m for the Macgillycuddy's Reeks in southern Ireland (Anderson *et al.* 1998). The Aran and Arenig glaciers therefore had low ELAs in comparison, although in north Snowdonia the Loch Lomond Stadial ELAs ranged from 410 to 815 m according to Gray (1982).

Table 1. Physical characteristics of the former glaciers

Glacier	Area (km ²)	Maximum depth (m)	Aspect (degree)	Snowblow ratio	Avalanche ratio	Equilibrium line altitude (m)
Llyn Lliwbran	0.181	68*	88	2.9	0.5	503
Llyn Arenig Fawr	0.92	65*	72	1.85	0.26	470
Llyn Arenig Fach	0.394	57*	56	2.62	0.42	511
Cwm Gylchedd	0.363	55	25	3.4	0.11	531

*These depths are minimum values as there are unknown depths over the lakes.

6. PALAEOCLIMATIC INFERENCES

Ablation season (May–September) temperatures at the ELA were calculated using the regression equation of Ballantyne (1989): $A = 0.915_e^{0.339t}$ ($r^2 = 0.989$, $P < 0.0001$); where A is average accumulation over the whole glacier (in metres water equivalent) and t is the mean ablation season temperature at the ELA (in °C). This relationship is based on the temperature–precipitation relationship for ten Norwegian glaciers (Liestøl, in Sissons 1980b) and reflects the fact that higher levels of mass turnover at the ELA require higher ablation, and thus higher summer temperatures, to balance the annual mass budget. A similar relationship has also been demonstrated by Ohmura *et al.* (1992) and it appears to apply globally (Nesje and Dahl 2000).

The incorporation of windblown snow into the accumulation variable (A) allows a more accurate estimation of temperature than if only winter precipitation were accounted for. Dahl *et al.* (1997) proposed that a rough estimate of total accumulation can be derived by multiplying the D/A ratio by a winter precipitation value. In order to minimize the error margins, the glacier with the smallest potential snowblow input, the Llyn Arenig Fawr glacier ($D/A = 1.85$), was used. A winter precipitation value was derived following the assumptions of Sissons (1980b), where stadial precipitation levels are equated to that of today, with winter precipitation around 80% of the annual levels. This is a rather speculative assumption but is necessary given the absence of reliable proxy data regarding precipitation values for the Loch Lomond Stadial glacial maximum in Wales.

In applying these methods, a mean ablation season temperature of 4.1°C is calculated for the Llyn Arenig Fawr glacier. Using a lapse rate of 0.6°C/100 m, this range of values equates to a mean sea-level ablation season temperature of 6.9°C. Assuming that the annual distribution of mean monthly temperatures was similar to today (Sissons 1980b), the equivalent July temperature would be around 8.4°C. However, the assumptions made here regarding lapse rates and the annual distribution of mean temperatures, as well as the many assumptions made in deriving accumulation values, result in this being only a crude estimation of July temperature. Even so, the value compares well with that calculated for north Snowdonia of 8.5–9°C by Gray (1982) and that of 9°C for central England and North Wales derived from coleopteran assemblages (Atkinson *et al.* 1987).

7. CONCLUSIONS

Detailed field survey and geomorphological mapping in the Aran and Arenig Mountains, North Wales, has revealed evidence for at least four sites of former localized glacier occupation. Collectively, the glaciers occupied an area of 1.86 km² and had a mean equilibrium line altitude of 504 m. Differences in both the lithological and pollen stratigraphy of lake sediments inside and outside of the former glacier limits, as well as periglacial–landform contrasts, are consistent with a Loch Lomond Stadial age for the former glaciers. By analogy with modern glacier–climate relationships in Norway, a mean stadial sea-level July temperature was calculated at approximately 8.4°C. Although only a crude estimation, this value compares well with other temperature reconstructions for North Wales based on similar palaeoglaciological reconstructions (Gray 1982) and coleopteran investigations (Atkinson *et al.* 1987).

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