Age and significance of former low-altitude corrie glaciers on Hoy, Orkney Islands

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Synopsis

Geomorphological mapping provides evidence for two former low-level corrie glaciers on Hoy, both defined by end moraines. Five ^{10}Be exposure ages obtained from sandstone boulders on moraine crests fall within the range 12.4 ± 1.5 ka to 10.4 ± 1.7 ka (weighted mean 11.7 ± 0.6 ka), confirming that these glaciers developed during the Loch Lomond (Younger Dryas) Stade (LLS) of 12.9–11.5 cal. ka BP, and demonstrate the feasibility of using this approach to establish the age of LLS glacier limits. The equilibrium line altitude (ELA) of one of the glaciers (99 m) is the lowest recorded for any LLS glacier, and the area-weighted mean ELA for both (141 m) is consistent with a general northward ELA decrease along the west coast of Britain. The size of moraines fronting these small ($\leq$0.75 km^2) glaciers implies that glacier termini remained at or close to their limits for a prolonged period. The apparent restriction of LLS glaciers to only two sites on Hoy probably reflects topographic favourability, and particularly the extent of snow-contributing areas.

Introduction

The Orkney archipelago (58°42'–59°25' N, 02°22'–03°24' W) lies 10–90 km north of the Scottish mainland between the Atlantic Ocean and North Sea, and for over a century has been recognized as a key area for elucidating the glacial history of northern Scotland and the adjacent North Sea Basin (Geikie 1877; Peach & Horne 1880). Most of Orkney comprises subdued undulating topography below 270 m in altitude and underlain by thinly bedded sandstones and siltstones of Middle Devonian age, but the island of Hoy in the SW part of the archipelago supports much higher ground that culminates in Ward Hill (479 m) and Cuilags (435 m) in the NW part of the island (Fig. 1). This area of high ground is underlain by more massive Upper Devonian sandstones that overlie basalt lavas and tuffs (Mykura 1976), with occasional thick beds of resistant sandstone forming conspicuous crags and caprocks at the crests of cliffs.

There is general consensus that the last ice sheet to cover Orkney moved across the archipelago from SE to NW (Helland 1879; Peach & Horne 1880; Wilson *et al.* 1935; Rae 1976). There is less agreement as to when this occurred. Several authors have favoured an Early or Mid-Devensian (MIS-4 or MIS-3) age for the last advance of ice across Orkney, implying that the archipelago escaped ice-sheet glaciation during the Late Devensian (MIS-2) (Rae 1976; Flinn 1978; Sutherland 1984, 1991; Bowen *et al.* 1986, 2002). Conversely, others have argued on stratigraphic grounds that deflection of the Moray Firth ice stream across the islands occurred during the Late Devensian (Hall & Whittington 1989; Hall & Bent 1990), a view consistent with recent offshore evidence indicating confluence of the Scottish and Scandinavian ice sheets in the northern North Sea Basin at this time (Sejrup *et al.* 1994, 2000; Hall 1996; Carr *et al.* 2006). A Late Devensian age for the last ice-sheet glaciation of Orkney is strongly supported by nine ^{10}Be exposure ages obtained for erratics and ice-moulded bedrock on the islands. These yielded exposure ages <20 ka, implying deglaciation following the Late Devensian glacial maximum rather than continuous exposure since the Mid- or Early Devensian (Phillips *et al.* 2007).

Evidence for the formation of locally nourished glaciers following ice-sheet deglaciation has been identified only on the Island of Hoy (Wilson *et al.* 1935; Godard 1965). Charlesworth (1956) depicted the limits of several Late Glacial corrie and valley glaciers in NW and central Hoy, but Rae (1976) dismissed these as unfounded; he identified only a single site (Enegars corrie in NW Hoy) where there is convincing evidence for a later ice advance, though he also suggested that glacigenic deposits in the valleys flanking Ward Hill might have been emplaced by locally nourished ice. Sutherland & Gordon (1993); Sutherland (1993) identified geomorphological evidence for two former low-level corrie glaciers on Hoy, in the form of an end moraine in Enegars corrie and 'at least three distinctive arcuate moraines' (Sutherland 1993, p. 82) on low ground below the cliffs of Dwarfie Hamars, 6 km to the SE (Fig. 1). Sutherland suggested that both ice limits may reflect renewed glaciation during the Loch Lomond (Younger

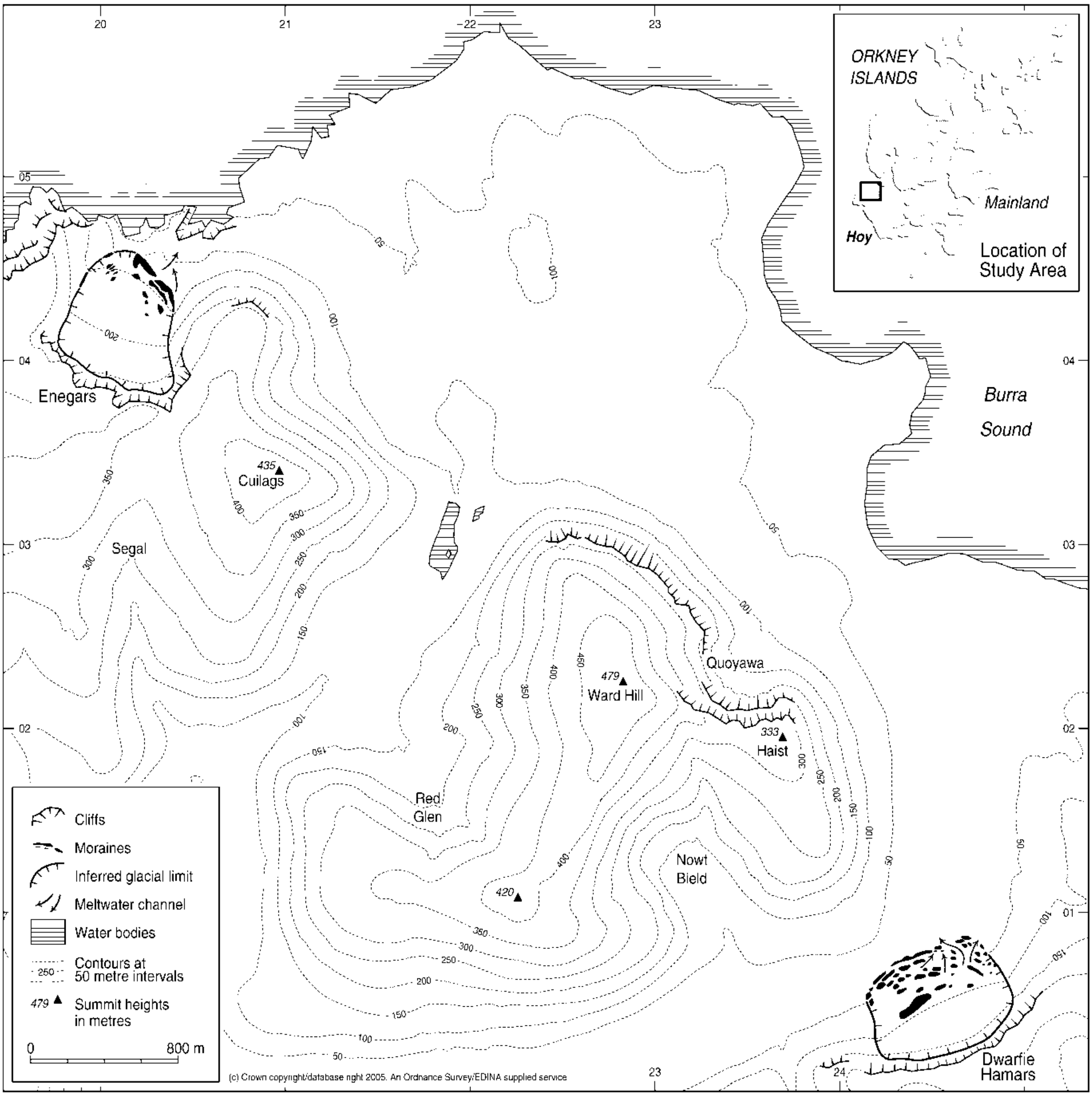

FIG. 1. Map of NW Hoy, showing the location of moraines and associated meltwater channels, the inferred extent of former glaciers, and reconstructed glacier-surface contours.

Dryas) Stade (LLS), particularly in view of contrasts in scree development inside and outside the moraine limits. An earlier age is nevertheless possible. In particular, there is evidence that various sectors of the last British–Irish ice sheet readvanced at *c.* 16.8 ka in response to renewed climatic cooling triggered by disruption of thermohaline circulation in the North Atlantic Ocean (e.g. McCabe & Clark 1998; McCabe *et al.* 1998, 2005; Everest *et al.* 2006), and it is possible that the formation of corrie glaciers on Hoy occurred at this time.

The aims of this paper are threefold: (1) to present the geomorphological evidence for the former presence of locally nourished glaciers on Hoy; (2) to establish the age of these glaciers through cosmogenic ^{10}Be surface exposure dating of boulders on moraines marking their former limits; and (3) to assess some palaeoclimatic implications of these former glaciers

Field methods

The evidence for former glacier limits on Hoy was established by examining aerial photographs covering the entire island, and traversing all high ground and adjacent corries and valleys in the NW part of the island. This reconnaissance confirmed that clear evidence for former locally nourished glaciers is restricted to the two sites in NW Hoy (Enegars and Dwarfie Hamars) identified by Sutherland (1993; Sutherland & Gordon 1993). These sites were mapped in the field on Ordnance Survey maps at 1:25 000 scale, on which were recorded drift

FIG. 2. End moraine marking the limit of local glaciation in Enegars corrie. A drift limit marking the lateral extent of the former glacier descends the far side of the corrie, and four or five small recessional moraines can be seen near the lip of the corrie on the far side of the incised stream channel.

cover, former glacier limits (end and lateral moraines, recessional moraines, the limits of drift against drift-free terrain) and meltwater channels. Aerial photographs at *c*. 1:25 000 scale were used to map detailed patterns of moraine ridges and mounds, which were then checked in the field and transferred to the final maps.

Geomorphological evidence for locally nourished glaciers

Enegars glacier

The former limit of the Enegars glacier is defined by a conspicuous end moraine, 300 m long, that extends obliquely across the floor of the low-level corrie, descending from 135 m to 90 m OD (Figs. 1 and 2). The moraine is flat-topped or domed in cross-section, and rises up to 8 m above adjacent ground on its distal side and up to 5 m on its proximal side. It curves upslope at its SE end, and is interrupted by a minor meltwater channel near its midpoint. A lower inner ridge occurs adjacent to the main moraine. Exposures in the NW end of the moraine have been described by Sutherland (1996a): the body of the moraine comprises clast-dominated to clast-supported poorly sorted angular to subangular cobble to boulder gravel, locally separated from an underlying clast-rich diamicton by laminated clays and stratified sands that probably reflect ponding of meltwater. On the NW side of the corrie the limit of the former glacier is marked by a drift limit and lateral moraine, confirming that the main end moraine was deposited by ice moving northwards out of the corrie. A group of four or five low recessional moraines are clustered near the NW limit of the former glacier.

Dwarfie Hamars glacier

The limit of a small glacier that formerly occupied low ground at the foot of the Dwarfie Hamars cliffs is marked by the abrupt outer edge of a broad moraine

FIG. 3. The moraine belt at Dwarfie Hamars. A large tabular erratic, the Dwarfie Stane, rests on the left-hand side of the moraine belt. A peat-covered area of flat ground (right) separates the moraine belt from the backing scree slopes and cliffs.

FIG. 4. The outer margin of the Dwarfie Hamars moraine belt, which rises 3–6 m above the peat-covered terrain in the foreground.

complex, 200–250 m wide, composed of thick undulating drift with occasional, more pronounced moraine ridges and hummocks up to 3 m high (Figs. 1 and 3). Occasional large angular boulders derived from the backing cliff are scattered over the moraine complex. The outer edge of this moraine belt is defined by a steep ridge, *c*. 400 m long, that rises 3–6 m above adjacent ground on its distal side (Fig. 4) and descends to 35 m OD in the NE. The eastern end of the ridge is cut by meltwater channels. Inside the moraine belt is a broad peat flat, backed by relict talus accumulations.

Other sites in NW Hoy

The clear evidence for former low-altitude corrie glaciers at Enegars and Dwarfie Hamars suggests that similar glaciers may have occupied other corries in NW Hoy at the same time, but inspection of potential sites (Quoyawa, Nowt Bield and Red Glen on Ward Hill, and Segal on Cuilags; Fig. 1) showed that although thick,

TABLE 1
Sampling locations for ^{10}Be exposure dating

Sample	Sampling site	Boulder size (length × width × height, cm)	Altitude (m OD)	OS Grid reference	Latitude (°N)	Longitude (°W)
ORK15	Enegars	70 × 60 × 25	105	HY 203045	58.9201	03.3859
ORK16	Enegars	120 × 60 × 80	129	HY 203044	58.9196	03.3855
ORK18	Enegars	90 × 70 × 60	131	HY 204044	58.9183	03.3850
ORK19	Dwarfie Hamars	250 × 165 × 40	76	HY 244005	58.8850	03.3117
ORK20	Dwarfie Hamars	320 × 170 × 105	64	HY 244006	58.8867	03.3117

peat-covered drift occupies the floors and lower slopes, there is no evidence for moraines or other landforms indicative of the formation of locally nourished glaciers. Low drift ridges on low ground NE of Cuilags may possibly reflect the former presence of a very small glacier (Sutherland 1996b), but this limited evidence appears equally consistent with deposition at the margins of the retreating ice sheet. Possible reasons for the apparent restriction of corrie glaciers to Enegars corrie and Dwarfie Hamars are considered below.

Age of the Hoy glaciers

To establish the age of the glacier advance represented by the Enegars and Dwarfie Hamars moraines, rock samples collected with hammer and chisel from the upper surfaces of large sandstone boulders on moraine crests were analysed for cosmogenic ^{10}Be accumulation to determine boulder exposure age. The boulders appear to be derived from the backing cliffs at both sites. Three samples (ORK-15, ORK-16 and ORK-18) were obtained from boulders on the Enegars end moraine and two (ORK-19 and ORK-20) from boulders on the Dwarfie Hamars moraine belt (Table 1). As all but one of the sampled boulders carry weathering pits up to 21 cm deep, sampling was confined to intact surfaces between these pits. Sample locations were determined with a GPS receiver and altitudes estimated from 1:25 000 Ordnance Survey maps. For both sampling sites, topographic screening was also calculated from 1:25 000 Ordnance Survey maps. Pure quartz was obtained from these samples by selective dissolution of other minerals with dilute HF (Kohl & Nishiizumi 1992). Beryllium-10 was separated from samples weighing 26–39 g in the presence of *c.* 250 µg ^{9}Be carrier, using conventional methods (Bierman *et al.* 2002). Details of the isotopic analyses are given in the footnotes to Table 2. Blank corrections amounted to 11–21%.

The results (Table 2) show a high degree of internal consistency. The three exposure ages for boulders on the Enegars moraine range from 11.9 ± 1.2 ka to 10.4 ± 1.7 ka (weighted mean: 11.5 ± 0.8 ka) and the two boulders on the Dwarfie Hamars moraine belt yielded overlapping exposure ages of 12.4 ± 1.5 ka and 11.6 ± 1.6 ka (weighted mean: 12.1 ± 1.1 ka). The weighted mean age for all five samples is 11.7 ± 0.6 ka. All but one of the exposure ages fall within the age range of the LLS which on the basis of GRIP and GISP2 ice core data is assigned to the interval *c.* 12.9 cal. ka BP to *c.* 11.5 cal. ka BP (Alley 2000; Lowe *et al.* 2001). The exception, ORK-15 (10.4 ± 1.7 ka), is statistically indistinguishable from this age range. As the boulder from which ORK-15 was collectd has a height of only 25 cm above the moraine surface, we tentatively attribute the comparatively 'young' age obtained for this sample to transient shielding by soil, vegetation and possibly snow, though persistent snowcover at the altitude of this sample (105 m) is unlikely since the end of the LLS. All sample ages are significantly younger than the timing of the rapid warming that marked the onset of the preceding Windermere Interstade of *c.* 14.5 to *c.* 12.9 cal. ka BP, implying that moraines cannot have been deposited by a pre-LLS readvance. Collectively the data confirm Sutherland's (1993) suggestion that the Enegars and Dwarfie Hamars moraines represent deposition by LLS glaciers. The exposure ages in Table 2 are amongst the first to be reported for LLS moraines in Great Britain, and demonstrate the feasibility of using ^{10}Be exposure dating to establish conclusively the age of locally nourished glaciers.

Glacier reconstruction and equilibrium line altitudes

Three-dimensional reconstruction of the inferred LLS glaciers was accomplished by tracing the limits of former glaciers based on the geomorphological mapping then drawing glacier surface contours at 50 m intervals (Fig. 1) following procedures introduced by Sissons (1974) and subsequently widely employed in reconstruction of LLS glaciers in Scotland. The planimetric area between adjacent glacier surface contours was measured to allow calculation of equilibrium line altitudes (ELAs).

The ELA of a glacier in a state of climatic equilibrium is the altitude at which average net ablation is exactly balanced by average net accumulation. To allow comparison with previous ELA reconstructions for LLS glaciers in Scotland, we calculated ELAs using three approaches: (1) the accumulation area ratio (AAR) method, which assumes that accumulation area occupies 60% of total glacier area (i.e. AAR=0.6); (2) the area-weighted mean altitude method introduced by Sissons (1974) and widely employed in the calculation of ELAs for LLS glaciers in Great Britain; and (3) the area-altitude balance ratio (AABR) method, which involves selection of a balance ratio (BR = ablation gradient / accumulation gradient) based on those of extant glaciers

TABLE 2
Cosmogenic ^{10}Be exposure ages

Sample	Altitude (m)	Scaling factor* (spallation)	Scaling factor* (muons)	Thickness correction†	Horizon correction‡	^{10}Be prod'n rate§ (atom/g/yr)	[^{10}Be]¦ (10^4 atom/g)	Exposure age¶ (ka)
Enegars								
ORK-15	105	1.124	1.053	0.966	0.992	5.68 ± 0.34	5.64 ± 0.84	10.4 ± 1.7 (1.6)
ORK-16	129	1.153	1.066	0.962	0.992	5.82 ± 0.35	6.47 ± 0.75	11.7 ± 1.5 (1.4)
ORK-18	131	1.155	1.067	0.973	0.992	5.82 ± 0.35	6.66 ± 0.57	11.9 ± 1.2 (1.0)
Dwarfie Hamars								
ORK-19	76	1.091	1.038	0.992	0.990	5.51 ± 0.33	6.68 ± 0.64	12.4 ± 1.5 (1.3)
ORK-20	64	1.077	1.032	0.985	0.990	5.44 ± 0.33	6.15 ± 0.78	11.6 ± 1.6 (1.5)

*Correction factor relative to 1013.25 mbar and latitude >60° (Lal 1991; Stone 2000). Effects of geomagnetic variation on scaling ≤1%; possible effects of sea level change and isostatic rebound not considered.
†Thickness correction: (Dunne *et al.* 1999) uses an exponential decrease of production rate with depth, attenuation length of 155 g/cm^2, and bulk density of 2.4 g/cm^3. Thickness data (cm): ORK-15, 4.5; ORK-16, 5.0; ORK-18, 3.5; ORK-19, 1.0; ORK-20, 2.0.
‡Horizon correction computed with angular distribution of cosmic ray flux varying as $(\sin \varphi)^{2.3}$ where φ is the horizon angle (Dunne *et al.* 1999; Balco 2006): Enegars (azimuth, horizon angle) 075–0°; 103–18°; 180–19°; 214–16°; 240–09°, 280–14°; 318–00°. Dwarfie Hamars: 043–00°; 060–06°; 078–08°; 109–18°; 167–22°; 214–16°; 233–10°; 248–00°; 262–00°; 277–08°; 289–09°; 316–08°; 323–12°; 349–00°.
§Assumed ^{10}Be production rates: spallation: 4.95 ± 0.30 atom/g SiO_2/year, muon capture: 0.11 ± 0.02 atom/g SiO_2/year, at 1013.25 mbar and latitude > 60° (Heisinger *et al.* 2002; Stone & Ballantyne 2006).
¦Measured relative to PSI/ETH Be standard S555 with a nominal value of ^{10}Be/Be = 95.5 (10^{-12}. Uncertainties propagated at ± 1σ level including all known sources of analytical error.
¶Simple exposure ages, assuming no prior exposure, no erosion, and no snow or soil cover during ^{10}Be accumulation. Uncertainties are ± 1σ (68% confidence) including ^{10}Be measurement uncertainties and an assumed uncertainty of ± 6% in the ^{10}Be production rate, to allow comparison with ages obtained with other methods. Values in parentheses are uncertainties based on measurement errors alone, for sample-to-sample comparisons.

TABLE 3
Areas and equilibrium line altitudes (ELAs) of the Hoy glaciers

	Area (km^2)	ELA1, BR = 1.67 (m)	ELA2, BR = 1.8 (m)	ELA3, BR = 2.0 (m)	ELA4, AAR = 0.6 (m)	ELA5 (Sissons) (m)
1. Dwarfie Hamars glacier	0.72	100	99	97	96	111
2. Enegars glacier	0.75	182	181	179	180	193
Area-weighted mean	1.47	142	141	139	139	153

(Osmaston 1975, 2005). The AABR method is more rigorous than the AAR method in that it incorporates glacier hypsometry, and more accurate than Sisson's method, which implicitly assumes equal accumulation and ablation gradients, and consequently overestimates regional ELAs by about 25 m (Benn & Ballantyne 2005; Ballantyne 2007). For Alaskan glaciers, BR averages *c.* 1.8 (Furbish & Andrews 1984), but Benn & Gemmell (1997) suggested that BR = *c.* 2.0 is more representative for most mid-latitude glaciers. To assess the sensitivity of calculated ELAs to assumptions regarding the choice of BR, we based our calculations on BR = 1.67 (equivalent to AAR = 0.6 for a planar glacier surface), BR = 1.8 and BR = 2.0. Balance ratio calculations were made using the spreadsheet provided by Osmaston (2005).

The results (Table 3) show that assumption of a range of BR values has limited effect on the calculated ELA: for both glaciers individually and combined the difference between BR = 1.67 and BR = 2.0 is only 3 m. BR = 1.8 (ELA2 in Table 1) is therefore considered to represent the best-estimate ELA. Similarly, ELA2 differs from ELA4 (AAR = 0.6) by ≤3 m, suggesting that the ELA calculations are internally robust. ELA5 (Sissons' method) yields rather higher values than those calculated by other methods. The relationships between different ELA estimates for the reconstructed glaciers on Hoy are similar to those calculated for LLS glaciers elsewhere in Scotland (Ballantyne 2002, 2006, 2007; Benn & Ballantyne 2005). A striking feature of these results is that the ELA of the Dwarfie Hamars glacier (ELA2 = 99 m) is by far the lowest calculated for any LLS glacier in Great Britain; that for the Enegars glacier (ELA2 = 182 m) is similar to the lowest values hitherto reported, for maritime glaciers on Mull and the Outer Hebrides (Ballantyne 2002, 2006).

Palaeoclimatic inferences

Geomorphological evidence

Given the small size of the Dwarfie Hamars glacier (0.72 km^2), the large volume of sediment contained within the 200–250 m wide moraine belt that terminates

TABLE 4
Aspect and snow-contributing areas of potential glacier sites on Hoy

Corrie or valley	Aspect	Valley-floor altitude (m)	Snow-contributing area, A_c (km^2)
Sites with evidence of former glaciers			
Enegars (Cuilags)	N	120	1.29
Dwarfie Hamars	NW	75	1.71
Sites lacking evidence of former glaciers			
Segal (Cuilags)	SSE	85	0.51
Red Glen (Ward Hill)	NW	190	0.53
Quoyawa (Ward Hill)	NE	125	0.49
Nowt Bield (Ward Hill)	SE	85	0.39

at the former glacier limit (Figs. 1 and 3) is remarkable. The width and morphological complexity of the moraine belt suggest that the glacier initially underwent very gradual and probably oscillatory retreat after reaching its maximal extent, allowing continued sediment release at the glacier margin over a prolonged period, and progressive development of the moraine belt through pushing and thrusting of sediment at the ice margin. The large volume of the moraine belt also suggests a high input of rockfall debris from the backing cliff, and/or entrainment of pre-existing sediment from the area occupied by LLS glacier ice. Only in the zone between the moraine belt and the backwall is evidence for ice-marginal deposition absent. A similar pattern is evident for the Enegars glacier (0.75 km^2), which despite its limited size deposited a single very large outer moraine, with recessional moraines confined to the outer corrie (Figs. 1 and 2), suggesting that the Enegars glacier also remained at or very close to its maximum extent for a prolonged period, then underwent uninterrupted retreat.

The above interpretation of the morphological evidence is consistent with the depositional record associated with much larger LLS glaciers elsewhere in Scotland. In many locations, the presence of numerous recessional (often hummocky) moraines upvalley from the LLS glacier limit implies that these glaciers underwent active oscillatory retreat with frequent (possibly seasonal) readvances of the retreating ice margin forming chains of recessional moraines through deformation of sediment at the ice margin (e.g. Benn 1992; Bennett & Boulton 1993; Benn & Lukas 2006). The climatic implication of this interpretation is that the LLS glaciers on Orkney, like those elsewhere in Scotland, remained close to climatic equilibrium for a prolonged period after reaching their maximum extent (Ballantyne 2002; 2006; Benn & Ballantyne 2005). Such behaviour is consistent with the temporal pattern of LLS mean July temperatures inferred from subfossil chironomid assemblages at Whitrig Bog in SE Scotland (Brooks & Birks 2000) and at sites in the Cairngorms and on Skye (S.J. Brooks, pers. comm. 2005). These reconstructions depict a rapid drop in summer temperatures early in the LLS, followed by a very gradual rise between *c.* 12.4 ka and *c.* 11.6 ka, consistent with the proposition that the Hoy glaciers remained close to their maximum extent for a prolonged period. More tentatively, the absence of recessional moraines in the upper part of the glacier basins may reflect the rapid warming that terminated the LLS after *c.* 11.6 ka.

Distribution of Loch Lomond Stadial glaciers on Hoy

The ELAs calculated for the Enegars and Dwarfie Hamars glaciers (ELA2 = 181 m and 99 m respectively) imply that glacier ice accumulated on very low ground on Hoy during the LLS; this raises the question as to why other corries or steep-sided valleys on Hoy apparently did not host glaciers at this time. Neither aspect nor corrie/valley-floor altitude provides an answer, as some unglacierized sites have favourable northerly aspects, and all have corrie/valley-floor altitudes higher than Dwarfie Hamars (Table 4). The most likely factor favouring glacier formation at Enegars and Dwarfie Hamars is topographic control on snow accumulation. Several previous studies of the altitudinal distribution of ELAs of LLS glaciers (e.g. Sissons 1979; 1980; Sissons & Sutherland 1976; Ballantyne 1989; 2002) have shown that the dominant directions of snowblow were from the west and south. Following an approach devised by Sissons & Sutherland (1976); Benn & Ballantyne (2005) developed an index of potential snow-contributing area (A_c) for LLS glaciers, which incorporates (1) snow-avalanching slopes (all slopes >25° overlooking former snow accumulation areas) and (2) snow-blowing sources, defined as terrain within a southwestern (180–270°) quadrant upslope and upwind of snow accumulation areas, including plateaus, all glacier-facing slopes and all other plateau-edge slopes with gradients <5°, irrespective of aspect. For Enegars and Dwarfie Hamars, the potential snow-contributing areas are 1.29 km^2 and 1.71 km^2 respectively, whereas those for other potential sites of glacier accumulation on Ward Hill and Cuilags are much smaller (0.39–0.53 km^2; Table 4). This contrast suggests that topographic influences on snow supply were critical in determining the location of LLS glaciers on Hoy.

Regional trends

Despite the apparently strong local topographic constraints on glacier development on Hoy during the LLS, the area-weighted mean ELA2 for the two glaciers (141 m) is consistent with a general northward decline in calculated ELA2 values for locations along the western seaboard of Scotland, from 371 m on Arran (55.6°N) to 250 m on Mull (56.4°N) and 212 m in SW Lewis (58.1°N) (Ballantyne 2002, 2006, 2007). This general trend probably reflects the northward decline in ablation-season temperatures during the Loch Lomond Stade (Ballantyne 2007).

Conclusions

Geomorphological mapping provides evidence for the formation of two former low-level corrie glaciers on the island of Hoy, Orkney, at Enegars and Dwarfie Hamars. The extent of both glaciers is delimited by end moraines.

Five rock samples obtained from the upper surfaces of sandstone boulders on moraine crests yielded ^{10}Be exposure ages of 12.4 ± 1.5 ka to 10.4 ± 1.7 ka (overall error-weighted mean 11.7 ± 0.6 ka) demonstrating that the low-altitude corrie glaciers on Hoy formed during the Loch Lomond Stade of 12.9–11.5 cal. ka BP. These exposure ages are amongst the first to be obtained on LLS moraines in Great Britain, and demonstrate the feasibility of this approach for establishing an LLS age for the limits of locally nourished glaciers.

Equilibrium line altitudes calculated for the reconstructed glaciers are 181 m (Enegars) and 99 m (Dwarfie Hamars); the latter is the lowest ELA calculated for an LLS glacier in Great Britain. The area-weighted mean ELA (141 m) is consistent with a general northward decline in ELAs along the western seaboard of Scotland.

The size of the end moraines or moraine belts on Hoy suggests that both glaciers remained at or near their maximum extents for a prolonged period during which the glaciers were at or close to climatic equilibrium. Restriction of glaciers to only two locations on Hoy probably reflects topography, and in particular the extent of upwind snow-contributing area.

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