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Surging glaciers in Scotland

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ABSTRACT
Glacier surges are cyclic oscillations of velocity and mass resulting from internal dynamic instabilities. For surge-type glaciers, cycles of advance and retreat are decoupled from climate forcing, so it is important to consider the possibility that former glaciers may have been surge-type when making climatic inferences from their dimensions and chronologies. In this paper, climatic and glacier geometric data are used to show that Scotland was likely the location of a surge cluster during the Loch Lomond Stade (~12.9–11.7 ka), with high probabilities of surging for outlets of the West Highland Icefield and the larger glaciers in the Inner Hebrides and Northern Highlands. Terrestrial and marine landforms consistent with surging occur in all of these areas, and it is proposed that surge-type glaciers existed on the Islands of Skye and Mull, in the Northern Highlands, and in a 'surging arc' along the western, southern and south-eastern margins of the West Highland Icefield. The possibility that surge-type glaciers were widespread in Scotland during the Loch Lomond Stade offers a fresh perspective on some long-standing issues, including the relationship between style of deglaciation and climate change, the climatic significance of glacial chronologies, palaeoclimatic reconstructions, and the interpretation of numerical model results.

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1. Introduction

Glacial sediments and landforms in Scotland dating from the Loch Lomond (≈Younger Dryas) Stade (~12.9 –11.7 ka) are rich sources of information on past environmental change. Reconstructed glacier equilibrium-line altitudes (ELAs) have been used in combination with palaeotemperature proxies to estimate former precipitation amounts, and the distribution of moraines and other landforms has been used to infer temporal patterns of climate change (e.g. Ballantyne, 2012; Benn et al., 1992; Benn & Ballantyne, 2005; Chandler et al., 2019; Jones et al., 2017; Lowe et al., 2019; Rea et al., 2020; Sissons, 1974; Sissons & Sutherland, 1976; Sutherland, 1984).

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Reconstructions of climatic variables from glacial evidence are based on the (often tacit) assumption that glacier advances, retreats, and stillstands were directly forced by climate. While it is recognised that glacier system response may lag climatic signals, glacier maxima are generally assumed to correspond to periods when snow accumulation and ice ablation were in balance, and the onset of glacier retreat is assumed to correspond to a switch to negative balance forced by increasing temperature or decreasing snowfall (e.g. Ballantyne, 2007a; Benn et al., 1992; Lowe et al., 2019). For the majority of the world's glaciers, these assumptions are broadly valid. For a small but important population of glaciers, however, episodes of glacier advance and retreat are decoupled from climate and are instead controlled by internal dynamic processes. These *surge-type glaciers* cycle between fast and slow flow states, known as surge- and quiescent periods, respectively (Benn, Fowler, et al., 2019; Clarke, 1987; Meier & Post, 1969). During a surge, which may be up to a few years in duration, mass is rapidly transferred down-glacier from an upper reservoir and may result in a considerable terminus advance. During the ensuing quiescent period ice flow can almost cease and glacier geometry adjusts to this new dynamic state. The upper glacier, where surface mass balance is typically positive, can undergo thickening, whereas the lower glacier, where mass balance is negative, undergoes thinning and retreat. Importantly, during quiescence retreat of the ice front is not forced by climate change, but is instead a reaction to hypsometric changes that occurred during the surge. Thus, for surge-type glaciers, neither the maximum glacier extent nor the timing of advance and retreat would necessarily have direct climatic significance. It is therefore important to know whether a glacier may have surged when undertaking palaeoclimatic analyses based on glacier geometry and the history of ice-front fluctuations.

During the Loch Lomond Stade, much of the Western Highlands, from Loch Lomond in the south to Torridon in the north, was occupied by the West Highland Icefield (WHI) (Figure 1; Bickerdike, Evans, et al., 2018; Golledge, 2010; Sissons, 1976). This took the form of a transfluent complex of ice domes and outlet glaciers similar in dimensions and relief to present-day icefields in Svalbard and Vatnajökull in Iceland. Numerous tidewater glaciers flowed into the sea-lochs (fjords) along the west coast, while outlet glaciers in the north and east terminated on land or in proglacial lakes. Smaller icecaps, icefields and valley and corrie glaciers occupied mountain massifs in the Hebrides, Northern Highlands, and eastern Grampians (Bickerdike, Evans, et al., 2018; Bickerdike, Ó Cofaigh, et al., 2018). A number of lines of evidence suggest that some of these glaciers may have surged, including anomalously low surface gradients and reconstructed equilibrium line altitudes (Ballantyne, 2002; Thorp, 1991), differences in the timing of maximum glacier extents (Ballantyne, 2012), and sediments and landforms similar to those deposited by modern surge-type glaciers (Evans & Wilson, 2006a). To date, however, there has been no systematic attempt to evaluate evidence for surging in Scotland.

In this paper, complementary lines of evidence are employed to assess the possible distribution of surge-type glaciers in Scotland during the Loch Lomond Stade. First, the distribution and characteristics of modern surge-type glaciers are reviewed, together with the physical principles that connect surging behaviour to particular climates and glacier geometries. Second, palaeoclimatic data for Scotland are used to assess whether climatic conditions in Scotland were conducive to surging. Third, geometric

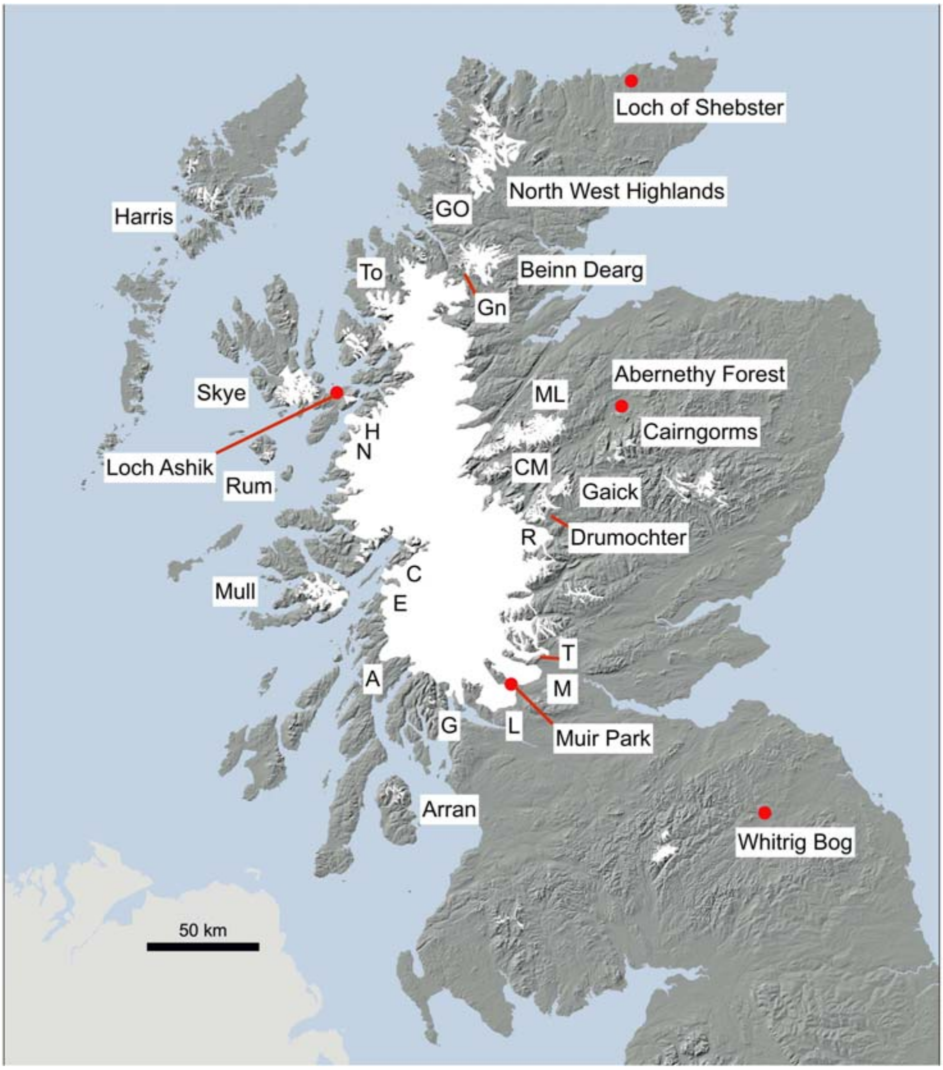

Figure 1. Loch Lomond Readvance limits in Scotland, with key locations mentioned in the text. GO: Glen Oykell, Gn: Garbhrain, To: Torridon, CM: Creag Meagaidh, R: Rannoch, T: Teith, M: Menteith, L: Loch Lomond, G: Gare Loch, A: Awe, N: Nevis, H: Hourn. The limits are approximate in Argyll (near A), Perthshire (between T and R) and in the SE Grampians (east of Gaick). Base map: Ben Chandler.

characteristics of former Scottish glaciers are compared with those of modern glaciers, to determine which sub-populations of glaciers are most likely to have been surge-type. Fourth, the characteristic landsystems formed by surge-type glaciers are reviewed, and locations in Scotland where sediment and landform evidence appears to be consistent with surging are identified. Collectively, these data provide strong support for the hypothesis that surging glaciers were widespread in parts of the Scottish Highlands during the Loch Lomond Stade. The paper concludes with a discussion of the implications for understanding relationships between glacier activity, ice dynamics and climate in Scotland.

2. Distribution and characteristics of surge-type glaciers

Surge-type glaciers are not randomly distributed but occur in well-defined geographical clusters (Sevestre & Benn, 2015, and references therein). Major clusters occur in an arcuate belt around the Arctic and sub-Arctic, including Alaska-Yukon, parts of west and east Greenland, Iceland, Svalbard and Novaya Zemlya, a zone collectively known as the *Arctic Ring* (Figure 2). A more diffuse cluster of large surge-type glaciers occurs in High Arctic Canada.

A second group of surge clusters spans the mountain ranges of central Asia, including the Karakoram, Pamirs and Tien Shan. Using ERA-I climatic reanalysis data, Sevestre and Benn (2015) showed that surge-type glaciers in the Arctic Ring and central Asia occupy a common *optimal climatic envelope* defined by air temperature and precipitation

Figure 2. Surge clusters and climate in the Arctic region. Tinting indicates areas with annual precipitation <200 mm/yr (blue) and mean July temperatures <0°C (yellow) and >10°C (red), where surge-type glaciers are rare or absent. Clusters of surge-type glaciers making up the Arctic Ring are: A-Y: Alaska-Yukon; WG: West Greenland; EG: East Greenland; I: Iceland; S: Svalbard; NZ: Novaya Zemlya. AC denotes the diffuse cluster of large surge-type glaciers in High Arctic Canada. Base map: Creative Commons; temperature data: 1968–1996 means from NOAA/ESRL.

ranges. The majority of surge-type glaciers occur within mean summer temperature limits of 0–10°C and annual precipitation limits of 200–2000 mm/yr (Figure 2). In all clusters, surge-type glaciers tend to have larger areas, greater lengths, and lower surface gradients than non-surge-type glaciers in the same region (Clarke et al., 1986; Jiskoot et al., 1998, 2000; Sevestre & Benn, 2015). Some studies (e.g. Björnsson et al., 2003; Jiskoot et al., 2000) have also shown a tendency for surge-type glaciers to occur in areas underlain by weak sedimentary strata or fractured rocks. Using the species distribution model Maxent, Sevestre and Benn (2015) showed that the location of surge clusters can be predicted with high accuracy using climatic and glacier geometric data alone, opening up the possibility of identifying past surge clusters from these variables.

The globally consistent climatic and geometric preferences of surge-type glaciers point to an underlying physical principle determining surging behaviour, regardless of glacier thermal regime and other differences. Sevestre and Benn (2015) and Benn, Fowler, et al. (2019) proposed that this principle is the relationship between glacier mass and enthalpy budgets, which determines whether stable steady states are possible. Enthalpy, or internal energy, is a function of the temperature and water content of a glacier and its bed. Enthalpy can be gained at the glacier bed as a consequence of frictional heating from sliding, from the geothermal heat flux, and from inputs of water from the surface or upglacier. Enthalpy can be lost by heat conduction toward the surface and discharge of water from the bed. Any change in enthalpy directly impacts flow speeds, because ice creep and sliding rates both increase with temperature and water storage. This means that glacier mass and enthalpy budgets must simultaneously balance if a glacier is to maintain steady flow. If not, unstable feedbacks between frictional heating and ice flow lead to instability and cyclic mass and enthalpy oscillations, or surge cycles.

Gains and losses of mass and enthalpy are both largely determined by climate and glacier geometry, explaining the observed regularities in the distribution of surge-type glaciers (Benn, Fowler, et al., 2019). The optimal climatic envelope defines concentrations of glaciers for which neither heat conduction nor runoff are efficient enough to evacuate the enthalpy produced by ice flow and geothermal heating, leading to unstable feedbacks. Within climatically controlled clusters, longer, gently sloping glaciers are more likely to be surge-type because long glaciers tend to be thicker (reducing conductive heat losses), have higher balance velocities (increasing frictional heating), and have greater total basal meltwater production, while low slopes encourage inefficient drainage. Model result show that low subglacial hydraulic conductivity also encourages surging by impeding the evacuation of water from the bed. This may explain the tendency for surge-type glaciers to occur on weak geological substrates, which typically yield fine-grained tills (cf. Minchew & Meyer, 2020).

In cold, dry climates, most glaciers are small and do not surge because they are low enthalpy producers and enthalpy is easily lost via heat conduction though thin ice. Conduction is less effective where ice is thick, so larger glaciers (e.g. in High Arctic Canada) are less likely to balance their enthalpy budgets and are more likely to surge. Glaciers in warm, humid climates (e.g. Norway, the European Alps and New Zealand) do not surge because efficient subglacial drainage systems can be maintained by abundant surface meltwater reaching the glacier bed.

The enthalpy balance theory presented by Benn, Fowler, et al. (2019) focuses on glacier dynamics under steady climate conditions, but similar ideas can be applied to understand glacier behaviour during transient climate states. An important case is that of glacier growth during a cooling cycle, in which a glacier can transition from cold-based to warm-based as glacier thickness and basal shear stresses increase. This transition can involve unstable surge-like behaviour, as exhibited by small Svalbard glaciers during the Little Ice Age (e.g. Hambrey et al., 2005; Lovell et al., 2015). Following the transition, glaciers may achieve a stable steady state, undergo periodic surges, or lapse into terminal decline (senescence), depending on the amplitude and duration of the climate cycle and other factors (Sevestre et al., 2015).

3. Climatic conditions conducive to surging in Scotland

The location of Scotland relative to the Arctic Ring (Figure 2) raises the possibility that all or part of the country may have lain within a comparable climatic envelope during the Loch Lomond Stade, when climate was considerably colder than today. Here, this possibility is evaluated using published palaeotemperature estimates and calculated annual precipitation at reconstructed glacier ELAs.

Mean July temperatures during the Loch Lomond Stade have been inferred from subfossil chironomid assemblages at five sites in Scotland: Whitrig Bog, Loch Ashik, Abernethy Forest, Muir Park and Loch of Shebster (Brooks & Birks, 2000; Brooks et al., 2012, 2016; Cochrane, 2020; Figure 1). The data indicate that mean July temperatures varied in both space and time during the Loch Lomond Stade. At Abernethy and Whitrig Bog, the coldest July temperatures occurred in the early to mid-Stade, with closely similar values of 8.3°C and 8.4°C, respectively (standardised to sea level using a mean environmental lapse rate of 0.0068°C m^{-1}; Ballantyne, 2002). At Loch Ashik and Shebster, the coldest temperatures occurred in the second half of the Stade, with sea-level equivalent values of 6.1°C and 6.4°C, respectively, while Muir Park had more constant July temperatures throughout the Stade with a minimum of 7.6°C. These variations appear to reflect a variety of regional and local influences on climate (e.g. latitude, continentality, proximity to glacier ice) as well as other ecological controls on chironomid species composition (e.g. Brooks et al., 2016). Ballantyne (2007b) used the northward decline in glacier equilibrium line altitudes in western Britain to infer a latitudinal summer temperature gradient of 0.42°C 100 km^{-1} for the Loch Lomond Stade. The lack of a clear regional pattern in the chironomid data, however, combined with uncertainties of around ±1°C in the reconstructed temperatures and generally unknown timing of glacier maxima relative to the temperature curves, mean that it is not possible to assign local values of July air temperature for the different glaciers and ice caps with any confidence. Consequently, for current purposes, a bracketing range of 6.1–8.4°C for sea-level July temperatures is adopted for the entire area of the Highlands and Islands. To convert these values into the summer (June-July-August) temperatures needed for precipitation calculations, the July temperatures are multiplied by 0.97 (Benn & Ballantyne, 2005), yielding a range of 6.0–8.1°C. In the subsequent calculations, this range is rounded to 7.0° ± 1.0°C.

Reconstructed glacier equilibrium line altitude data are compiled for 12 areas in the Hebrides, Northern Highlands, and Grampians (Figure 1). These are: Harris (Ballantyne, 2007a), Skye (Ballantyne, 1989; Ballantyne et al., 2016), Rum (Ballantyne & Wain-Hobson, 1980), Mull (Ballantyne, 2002), Arran (Ballantyne, 2007b), the North-West Highlands (NWH: Lukas & Bradwell, 2010), Beinn Dearg (Finlayson et al., 2011), Creag Meagaidh (Finlayson, 2006), the Monadhliath (Boston et al., 2015), West Drumochter (Benn & Ballantyne, 2005), the Gaick plateau (Chandler et al., 2019) and the Cairngorms (Standell, 2014). Some glaciers in these massifs may have been surge-type (see Section 6.1), which might have impacted the reconstructed ELAs. To avoid circularity, no adjustments were made at this stage of the analysis, and the possible impact of surging on reconstructed ELAs and palaeoclimate is discussed in Section 7.

In the papers cited above, glacier equilibrium line altitudes were calculated using one or more of three methods: Area-Weighted Mean Altitude (AWMA; Sissons, 1974), Accumulation Area Ratios (AAR; Porter, 1975) and Area-Altitude Balance Ratios (AABR; Furbish & Andrews, 1984). The AWMA method finds the median altitude of the glacier from hypsometric data, and implicitly assumes that the vertical gradient in mass balance is equal in the ablation and accumulation areas. In contrast, the AAR method neglects glacier hypsometry but incorporates the effect of unequal ablation and accumulation gradients by assuming that the glacier accumulation area occupies some specified fraction of the whole. The AABR method is the most rigorous, being based on both glacier hypsometry and variable ablation and accumulation gradients, and is the method adopted here. A wide-ranging compilation of modern data by Rea (2009) showed that ratios between ablation and accumulation gradients (balance ratios) vary regionally, depending on continentality and other factors. A priori, it is unclear which ratios are most appropriate for the Loch Lomond Stade, and a bracketing range of 1.67–2.00 is adopted here as a compromise between data availability and observed variability of modern balance ratios in the North Atlantic region. Data were not reported in this form in all of the original papers; some early papers reported AWMA but not AABR, and others reported AABR results but used ratios other than 1.67 and 2.00. In such cases, data gaps were filled using regression functions derived from papers that reported results from multiple methods. Because both AWMA and AABR methods are based on glacier hypsometry, correlations have very high r^2 values (~0.99) allowing conversion to AABR = 1.67 and AABR = 2.00 with a high level of confidence.

The range of chironomid-inferred temperatures and the ELA values were then used to derive bracketing mean summer temperatures at the ELA for each massif. Annual precipitation values were then calculated from the temperature estimates using the following relationship (Golledge et al., 2010):

$$P = S(14.2T^2 + 248.2T + 213.5) \tag{1}$$

where P is estimated mean annual precipitation (mm), T is summer air temperature at the equilibrium line (°C), and S is a seasonality factor. Golledge et al. (2010) suggested $S = 1.4$ and $S = 0.8$ as maximum bracketing values for summer-dominated and winter-dominated precipitation seasonality, respectively, with $S = 1$ representing neutral seasonality. For T, we use the range of chironomid-inferred summer temperatures described above, with no adjustment for glacier size. Equation 1 is based on a degree-day model for the coldest part of the Loch Lomond Stade, for modelled glacier configurations closely similar to reconstructed maximum extents. For summer-dominated seasonality it predicts similar precipitation to the global P-T curve derived by Ohmura et al. (1992), which has been used in several studies of glacier-climate relationships in Scotland (e.g. Benn & Ballantyne, 2005; Lukas & Bradwell, 2010; Rea et al., 2020). However, general circulation model simulations indicate that Scotland experienced a drier climate during the Younger Dryas than that predicted by the Ohmura curve (e.g. Björck et al., 2002; Jost et al., 2005; Renssen, 2020). Consequently, Boston et al. (2015) and Chandler et al. (2019) have argued that the Golledge function with neutral seasonality is more consistent with regional Younger Dryas precipitation scenarios. Herein, results are reported for the Golledge function with the full range of seasonality factors, thus embracing all possibilities.

Results of the analysis are shown in Figure 3. For all areas, reconstructed summer temperatures fall entirely within the optimal climatic envelope for surging. For a precipitation seasonality factor of 1, mean precipitation estimates lie within the envelope for all massifs except Harris, but the maximum estimates for Mull, Skye and, to a lesser extent, Rum and NWH extend outside it. For the winter-dominated case, precipitation values are reduced by 20%, bringing all massifs within the optimal climatic envelope. For the less likely case of summer-dominated precipitation, values are increased by 40%, shifting the mean precipitation values for the Islands and NWH above the upper limit of the envelope, and the maximum values for Beinn Dearg just above the limit.

Geographically, the West Highland Icefield lay between the Inner Hebrides (Skye, Mull, Arran) and the westernmost peripheral icecaps (Beinn Dearg, Creag Meagaidh,

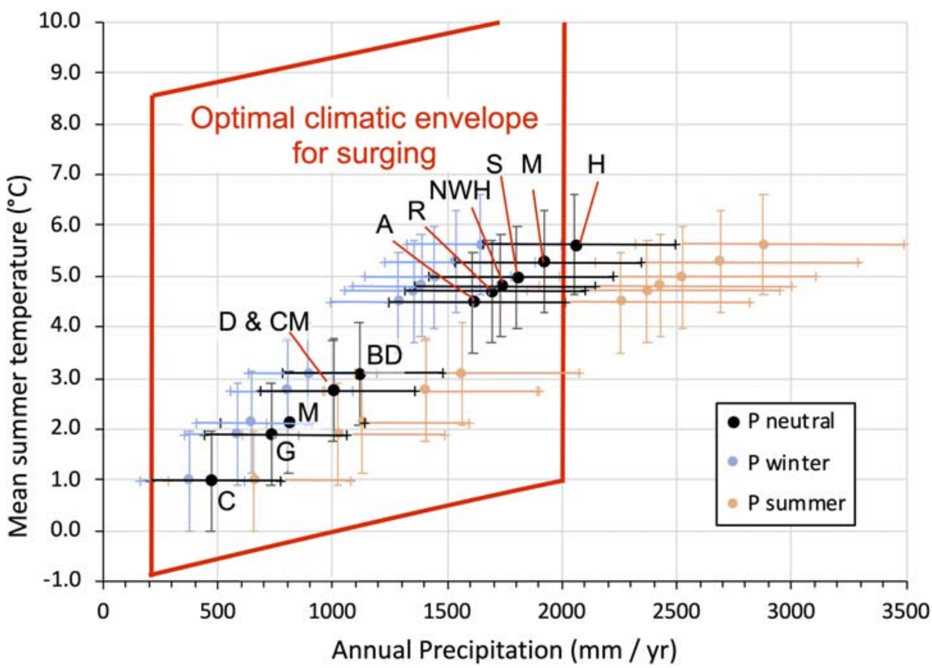

Figure 3. Reconstructed Loch Lomond Stadial summer temperature and precipitation ranges at the area-weighted mean ELA for selected massifs in Scotland, based on a sea-level mean summer temperature range of 7 ± 1°C and neutral, winter-dominated and summer-dominated precipitation seasonality. C: Cairngorms, G: Gaick, M: Monadhliath, D & CM: Drumochter and Creag Meagaidh (superimposed), BD: Beinn Dearg, A: Arran, NWH: Northwest Highlands, R: Rum, S: Skye, M: Mull, and H: Harris.

Drumochter), and it is reasonable to assume that summer temperature and precipitation at glacier ELAs were also intermediate in value (cf. Golledge et al., 2008, 2009, 2010). If valid, this indicates that for the most likely precipitation seasonality (neutral or winter-dominated) the West Highland Icefield lay entirely or almost entirely within the optimal climatic envelope for surging.

4. Glacier geometry

The palaeoclimatic analysis shows that a surge cluster could have existed in Scotland during the Loch Lomond Stade. Within all modern surge clusters, surge-type glaciers tend to have greater areas, greater lengths, and lower surface gradients than non-surge-type glaciers (Sevestre & Benn, 2015 and references therein). The model results presented by Benn, Fowler, et al. (2019) indicate that length and slope are independent controls on surging behaviour, and that the association between surging and glacier area may simply be a consequence of the correlation between glacier area and length.

In this section, the length and slope characteristics of Loch Lomond Stadial glaciers in Scotland are compared with those in the Iceland and Svalbard surge clusters, to identify which populations of glaciers could potentially have been of surge-type. The Iceland and Svalbard clusters were chosen for this exercise because they are the parts of the Arctic Ring closest to Scotland (Figure 2) and have similar ranges of glacier lengths and gradients (Figure 4; Björnsson et al., 2003; Jiskoot et al., 1998, 2000). Data for glaciers in the colder and drier environment of the Canadian High Arctic (Ellesmere Island, Axel Heiberg Island and Devon Island) were also analysed to provide additional context (Copland et al., 2003).

For the Scottish glaciers, length L was measured on published contoured reconstructions of maximum glacier extents, following the longest flowline drawn at right-angles to surface contours. Mean surface slope α was determined from the elevation difference ($Z_{max} - Z_{min}$) between the upper and lower ends of the flowline:

$$\alpha = \arctan((Z_{max} - Z_{min})/L) \tag{2}$$

For selected outlet glaciers in the southern sector of the WHI, values for L were obtained from Thorp (1984) and Z_{max} from the reconstruction of the icefield interior by Golledge (2007). In this reconstruction, the icefield surface is higher than that presented by Thorp by up to 200 m, resulting in higher mean slopes. Approximate values of L and α for other outlets of the WHI were derived from data in Bennett and Boulton (1993a), Greene (1995) and Tate (1996).

Length and slope data for glaciers in Iceland, Svalbard and the Canadian High Arctic were extracted from the Randolph Glacier Inventory 6.0 (RGI Consortium, 2017). Glaciers less than 1 km in length were excluded from the analysis. For Svalbard, the classification of surge-type glaciers in RGI 6.0 is based on a wide range of sources, and includes several glaciers with no observed surges. These were excluded from the list in the present analysis, on the grounds that criteria for inclusion were weak and inconsistent. With these adjustments, the inventory for Svalbard lists 1341 glaciers >1 km in length, 170 of which are surge-type (12.7%), and in Iceland there are 279 glaciers, 23 of which are surge-type (8.2%).

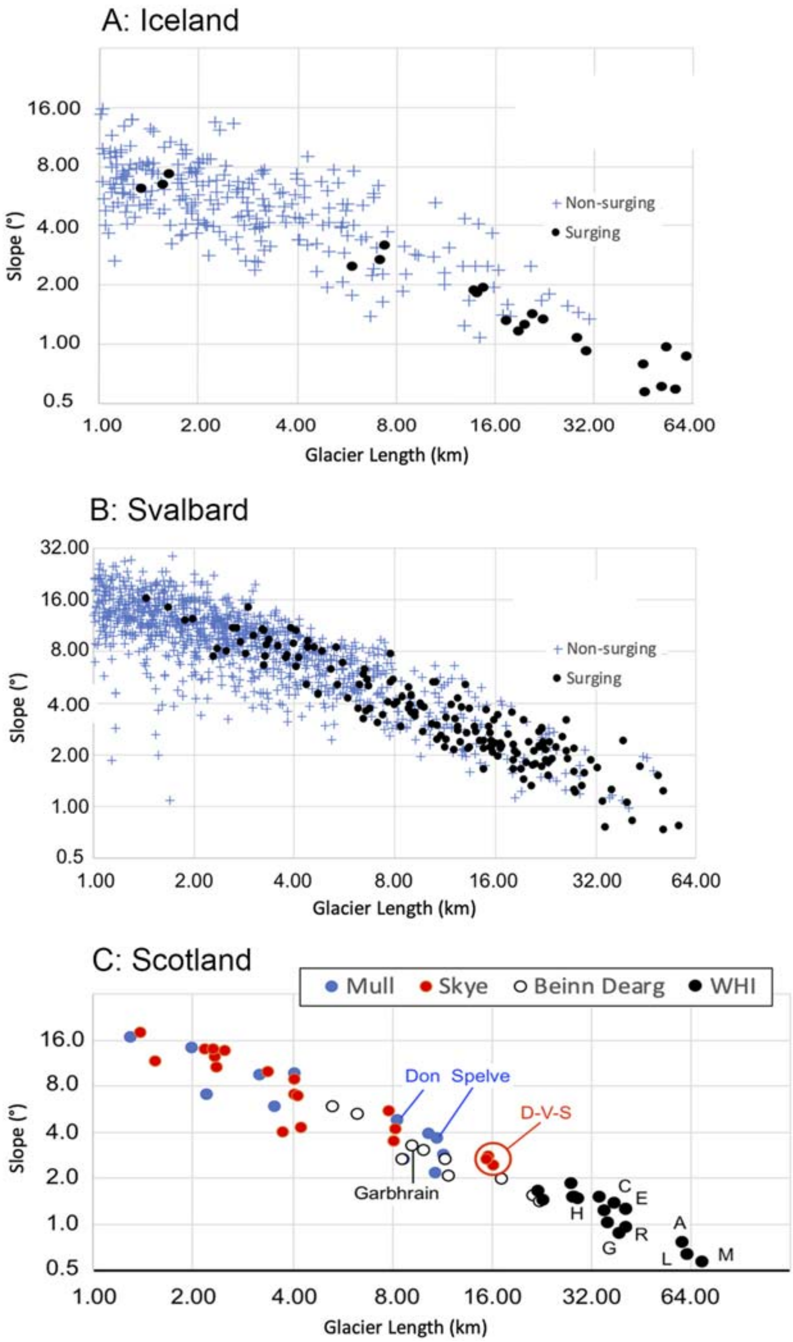

Figure 4. Length and mean slope of surge-type and non-surge-type glaciers in Iceland (A) and Svalbard (B). Data for selected glaciers in Scotland are shown in (C). D-V-S: Drynoch-Varagill-Sligachan; H: Hourn; C: Creran; E: Etive; G: Gare; R: Rannoch; A: Awe; L: Lomond; M: Menteith.

The lengths and mean slopes of the modern glaciers are shown in Figure 4, together with a selection of equivalent data for Loch Lomond Stadial glaciers in Scotland. In both Iceland and Svalbard, the frequency of surge-type glaciers increases markedly with increasing length and decreasing slope. For all glaciers less than 8.0 km in length, only 5.4% in Svalbard and 2.6% in Iceland are surge-type (Figure 5A). For lengths of 8–16 km this increases to 35% (Svalbard) and 16.7% (Iceland), and for all glaciers over 16 km in length the figures are 55% (Svalbard) and 56.5% (Iceland). In contrast, surge-type glaciers are much rarer in the Canadian High Arctic where, of a population of 3354 glaciers over 1 km in length, only 1.5% are classified as surge-type. Only 9% of glaciers 16–32 km in length are surge-type, these figures rising to 26.7% and 50% for glaciers 32–64 km and >64 km in length, respectively.

Several outlet glaciers greater than 8 km in length occurred on Skye and Mull (Figure 5B) and in the Beinn Dearg and NWH icefields (Figure 5C), indicating the possibility of surge-type glaciers in these areas on both climatic and geometric grounds. In the Grampian icecaps (e.g. Drumochter and Monadhliath; Figure 5D), a few outlet glaciers exceeded 8 km in length, but most were less than 4 km and therefore much less likely to have surged. The West Highland Icefield had numerous outlet glaciers over 16 km and several in the 32–64 km range (Figure 4C), suggesting that surge-type glaciers might have been common. The probability appears particularly high for the longest, lowest-gradient glaciers draining the southern and western portions of the icefield, such as the Lomond, Menteith, Etive, Creran and Gare Loch glaciers.

5. Surging glacier landsystems

The palaeoclimatic and geometric analyses support the proposition that surge-type glaciers might have been common in Scotland during the Loch Lomond Stade, with predicted concentrations in the Hebridean islands of Skye and Mull, the northern icefields, and the West Highland Icefield. Identification of individual former surge-type glaciers, however, must rely on evidence from sediments and landforms. Research in modern glacial environments has shown that surge-type glaciers typically produce

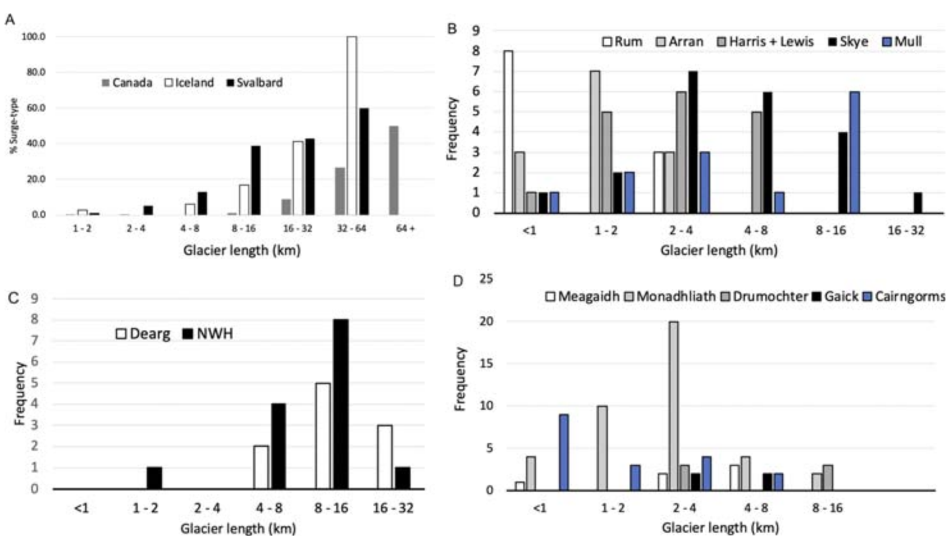

Figure 5. (A) Percentage of all glaciers that are surge-type, by length class. Equivalent length data are shown for former glaciers in the Hebrides (B), Northern Scotland (C) and the Grampian icecaps (D).

distinctive landsystems (Benediktsson et al., 2010; Evans & Rea, 1999, 2003; Ingólfsson et al., 2016; Rea & Evans, 2011; Sharp, 1985a). In particular, the combination of rapid advance of highly crevassed ice during surges and widespread ice stagnation during quiescence can create characteristic landform assemblages that contrast strongly with those formed during advance-retreat cycles of non-surge-type glaciers (cf. Evans, 2003; Evans & Rea, 2003). In terrestrial environments, landforms produced during surges include thrust-block moraines, fluted and drumlinised till, and crevasse-fill ridges, while ice stagnation and sediment reworking during quiescence typically produce chaotic hummocky moraine, kame and kettle topography, and eskers (Figure 6).

Thrust-block moraines are large masses of sediment or weak rock thrust forward and upward in front of an advancing glacier, encouraged by high subglacial water pressures and the transfer of stresses onto the glacier foreland. (Thrust-block moraines are termed 'composite ridges' or 'push moraines' by some authors, but herein the term 'push moraine' is reserved for local bulldozing of superficial sediment.) Thrust-block moraines may be single- or multi-crested, and in some cases record multiple surge events (Figure 6; Lovell, Benn, Lukas, Spagnolo, et al., 2018). Associated internal glaciotectonic structures typically include imbricated, folded slabs of sediment separated by thrust faults or zones of intense shear (e.g. Benediktsson, 2012; Croot, 1987). Glaciotectonised sediments may be cross-cut by injection dykes indicative of hydrofracturing by pressurised meltwater (Ingólfsson et al., 2016). A very distinctive type of thrust-block moraine known as a 'hill-hole pair' forms when an advancing glacier glaciotectonically excavates material from a basin and thrusts it upward and forward to create a moraine (Aber et al.,

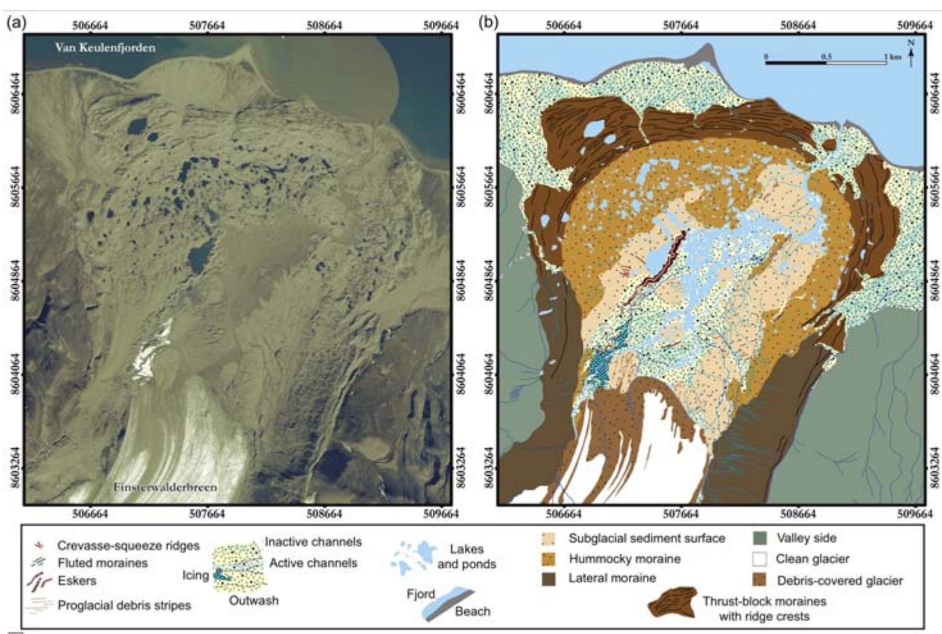

Figure 6. Aerial orthophoto (a) and geomorphological map (b) of the foreland of Finsterwalderbreen, Svalbard, showing landforms characteristic of terrestrial surge-type glaciers. From Lovell, Benn, Lukas, Spagnolo, et al. (2018).

1989). The association between thrust-block moraines and surge-type glaciers appears strong. Lovell and Boston (2017) found that of 50 Svalbard glacier forelands with thrust-block moraines ('composite moraine ridges' in their terminology), all but one had been formed by a glacier that had either been observed to surge or displayed independent evidence for having done so. Conversely, only 7% of the known surge-type glaciers in Svalbard have produced thrust-block moraines. Specific conditions are required for their formation, particularly the availability of thick, deformable sediments on glacier forelands or within fjord basins (Kristensen et al., 2009). In cases where surge-type glaciers are underlain by resistant rock, terminal moraines resulting from surge episodes may be small or insignificant (Brynjolfsson et al., 2012).

Crevasse-fill ridges represent the infilling of open fractures at the glacier bed by basal till or fluvial sediments, and are considered to be particularly diagnostic of surging glaciers (Farnsworth et al., 2016; Rea & Evans, 2011; Sharp, 1985b). 'Zig-zag eskers' are a special case of crevasse-fill ridge, in which glaciofluvial sediments preserve the planform of basal fractures that guided subglacial water flow. In modern terrestrial environments, crevasse-fill ridges are typically small, fragile landforms with poor preservation potential, although they can attain several metres in height where basal sediment is abundant (Boulton et al., 2004). Where not over-printed by other landforms, bedforms such as drumlins and fluted moraines provide evidence of streamlining of the glacier bed during fast flow.

Ice in the terminal zone of surging glaciers typically has a high debris content, due to elevation of basal debris by thrusting, sediment injection into basal crevasses and other processes. As ice melts during quiescence, debris accumulates on the surface where it is reworked and redistributed, forming belts of chaotic hummocky moraine and kame and kettle topography inside the surge limit (e.g. Ingólfsson et al., 2016; Lovell, Benn, Lukas, Ottesen, et al., 2018; Lovell, Benn, Lukas, Spagnolo, et al., 2018; Figure 6). In terrestrial environments, the forelands of surge-type glaciers may be extensively reworked by glaciofluvial processes, to the extent that all but the largest imprints of the surge are eroded or obscured. Prolonged episodes of glaciofluvial deposition in contact with stagnant, debris-rich ice can produce kettled terraces, kames, sinuous eskers and related forms (Krüger et al., 2010).

Where surging glaciers terminate in the sea, surging glacier landsystems are often exquisitely preserved because they are not reworked during quiescence to the same degree as terrestrial glacier forelands (Figure 7), although postglacial sedimentation may result in partial or complete burial. Tidewater surging glacier landsystems have similar components to their terrestrial counterparts, but with some important differences (Dowdeswell & Ottesen, 2016a; Ottesen et al., 2008, 2017; Ottesen & Dowdeswell, 2006). Subglacial bedforms (particularly flutings and mega-scale glacial lineations) are typically widespread, reflecting streamlining of marine muds and other deformable sediments during the surge phase. Mobilisation of soft sediment ahead of rapidly advancing ice can create massive multi-crested moraines, which may have characteristic indented planforms reflecting crevassed ice margins. Subaqueous thrust-block moraines commonly have large debris-flow lobes or 'mud aprons' on their distal sides, recording widespread failure of over-steepened moraine fronts (Kristensen et al., 2009; Lovell, Benn, Lukas, Ottesen, et al., 2018; Ottesen & Dowdeswell, 2006; Figure 7). Crevasse-fill ridges are common up-glacier of surge limits, forming extensive networks that mirror former patterns of strain. Eskers, in the form of sinuous, sharp-crested ridges, delineate former

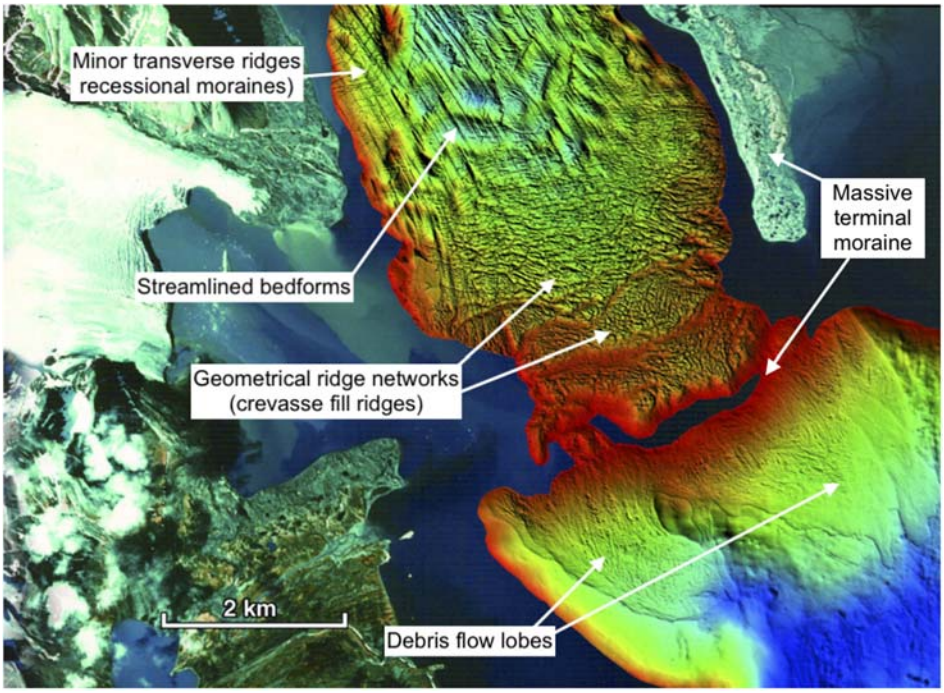

Figure 7. Submarine landforms created by the tidewater surging glacier Borebreen, Svalbard. Colours represent water depth from ~10 m (red) to ~100 m (blue). Adapted from Ottesen and Dowdeswell (2006).

positions of subglacial meltwater conduits, often located along the suture zones between ice-flow units (Benn et al., 2009; Ottesen et al., 2008). Preservation of eskers clearly requires a lack of significant basal motion during ice retreat, so is an excellent indicator of quiescent conditions (Dowdeswell & Ottesen, 2016b).

Unlike terrestrial surge-type glaciers that typically ablate by downwasting during quiescence, tidewater glaciers undergo frontal retreat interrupted by minor annual readvances (Luckman et al., 2015). Rapid frontal retreat can occur in summer by melting below the waterline and calving, and when melting is suppressed during the winter months, minor advances of the glacier terminus bulldoze sea-floor sediments, forming sequences of annual recessional moraines (Flink et al., 2015; Ottesen & Dowdeswell, 2006). The contrast in style of deglaciation between terrestrial and fjord-terminating sectors of surge-type glaciers is well illustrated by Aradóttir et al. (2019).

For the purpose of evaluating whether former Scottish glaciers surged, it is equally important to consider landform evidence that can be used to rule out surging behaviour. In terrestrial settings, the termini of non-surge-type glaciers typically undergo oscillations on a range of timescales, as the balance between ice advection and frontal melt adjusts to changing climate. During periods of overall glacier recession, such oscillations are recorded by sequences of recessional moraines, which in many cases can be directly related to variations in temperature and precipitation (e.g. Beedle et al., 2009; Bradwell, 2004; Chandler et al., 2016; Imhof et al., 2012; Winkler & Matthews, 2010). Such evidence for *active retreat* is diagnostic of glaciers that are close to equilibrium with prevailing climate, in distinct contrast with the prolonged episodes of stagnation typical of quiescent surge-type glaciers.

6. Landform evidence for glacier dynamics during the Loch Lomond Stade

Evidence for Loch Lomond Stadial glaciers has been mapped in detail in many parts of the Highlands and Islands (Bickerdike, Evans, et al., 2018). Surging behaviour has been suggested for only a handful of cases, but in this section the published evidence is re-evaluated to identify numerous possible examples of surging landsystems. In particular, locations are identified where episodes of moraine building (including glaciotectonics) were followed by widespread ice stagnation, in some cases repeatedly. The intention is not to present a definitive reinterpretation of each site, but to propose alternative ways of looking at the evidence that can be tested with additional research. First, the evidence for the peripheral glaciers and icecaps will be considered, followed by the outlet glaciers of the West Highland Icefield.

6.1. Peripheral glaciers and icecaps

During the Loch Lomond Stade the mountains of North Harris hosted several glaciers, ranging in length from ~1 km to ~7.5 km (Ballantyne, 2007a; Figure 5B). Suites of closely spaced recessional moraines occur within the limits of most glaciers, not only close to their termini but extending up into tributary valleys, corries and cols, showing that the glaciers underwent repeated minor readvances until they had almost disappeared. Ballantyne (2007a) calculated glacier ELAs for the innermost moraine positions, which imply summer temperatures ~0.5–1.0°C higher than those at the glacier maxima, consistent with a gradual and modest warming during the second half of the Loch Lomond Stade. Similar suites of moraines were deposited by ~4 km long valley glaciers in the Uig Hills of Lewis (Ballantyne, 2006). In the Outer Isles, therefore, all glaciers appear to have remained close to climatic equilibrium during retreat from their maxima, and there is no evidence for surging behaviour.

Much more varied patterns of glacier retreat are evident on the Isle of Skye. Suites of nested recessional moraines similar to those on Harris were formed by some independent glaciers and shorter outlets of the Cuillin Icefield (Ballantyne & Benn, 1994; Benn, 1993; Benn et al., 1992). For glaciers less than 3 km in length, recessional moraines are few in number and limited to within a few hundred metres of the maximum position, implying uninterrupted retreat for most of their length.

A distinctive landsystem occurs within the limits of the longest outlets of the Cuillin Icefield, consisting of fragmentary transverse moraine belts separated by areas of chaotic hummocky moraine and streamlined bedforms (Benn, 1992; Benn et al., 1992), most clearly developed in the Glen Drynoch, Glen Varagill and Loch Sligachan area (Figure 8). Six belts of moraines were interpreted by Benn et al. (1992) as successive limits of a large piedmont lobe (inset: Figure 8), although the two innermost (5 and 6) are discontinuous and may not be ice-marginal in origin. Sections through the outermost moraine in Glen Varagill expose thrust masses of basal till, indicative of glaciotectonic deformation. The areas between the moraine belts are occupied by streamlined bedforms (fluted moraines and drumlins composed of sheared till), scattered hummocks and randomly oriented ridges, eskers, and kame terraces. Some of the transverse ridges may be

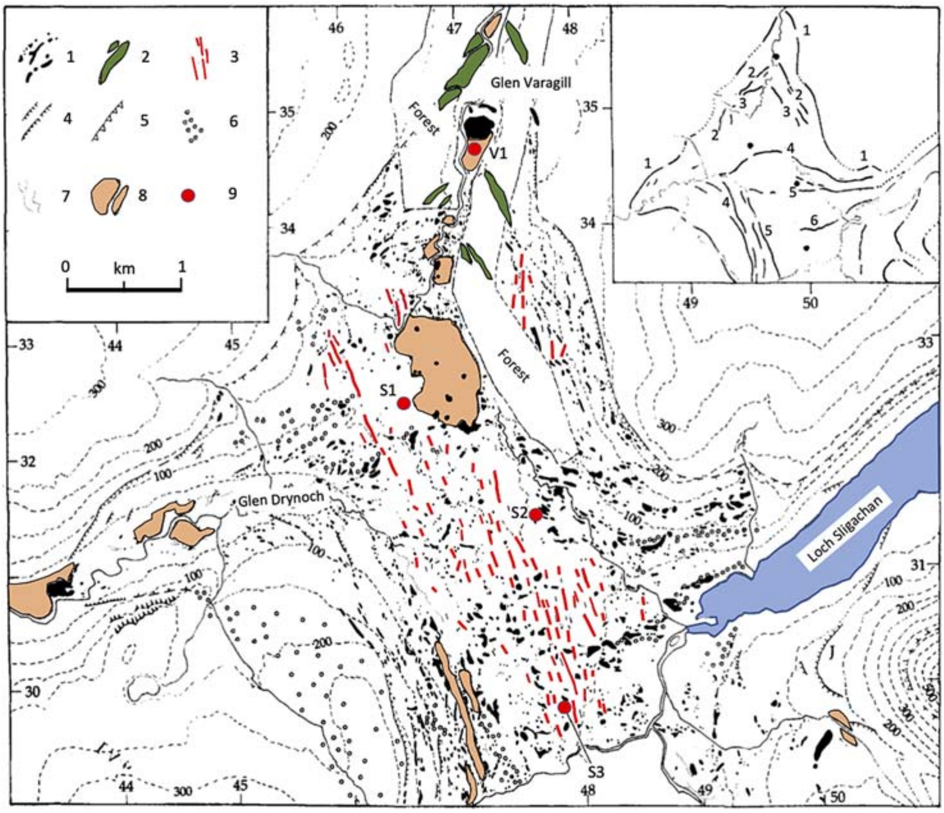

Figure 8. Landforms deposited by the Drynoch-Varagill-Sligachan lobe. 1. Moraine ridges and hummocks; 2: large moraine ridges within forestry; 3: fluted moraines and drumlins; 4: drift benches; 5: periglacial trimline; 6: glacially transported boulders; 7: eskers; 8: terraces; 9: pollen sites. Inset: numbered moraine belts. Modified from Benn et al. (1992).

crevasse fills. The anomalously low surface gradient of the Drynoch-Varagill-Sligachan lobe noted by Ballantyne (1989) is also consistent with surging over soft, deformable sediments under conditions of high subglacial water pressure.

Similar landform assemblages occur in association with the tidewater Ainort and Slapin Glaciers, particularly in Srath Mòr and on the lower slopes of Bla' bheinn (Figure 9), where massive moraine ridges are separated by areas of chaotic hummocky moraine (Benn et al., 1992). There is local evidence for glaciotectonism, including dislocated slabs of granite bedrock and folded and sheared silts. At its maximum, the Ainort Glacier extended well beyond the confines of Loch Ainort and a succession of moraines (some of which are multi-crested) mark subsequent ice margin positions in the loch (Dix & Duck, 2000). There is evidence for widespread ice stagnation after the Ainort Glacier retreated onland, in the form of chaotic hummocky moraine on the valley floor, and erratic trains and fluted moraines that indicate a lack of flow reorientation as the glacier thinned (Benn et al., 1992). These landform assemblages are consistent with repeated surges and intervening periods of ice stagnation. Thus, glaciers on Skye appear to have been a mixture of non-surge-type and surge-type, with evidence for surging restricted to glaciers greater than 8 km in length (Figure 9).

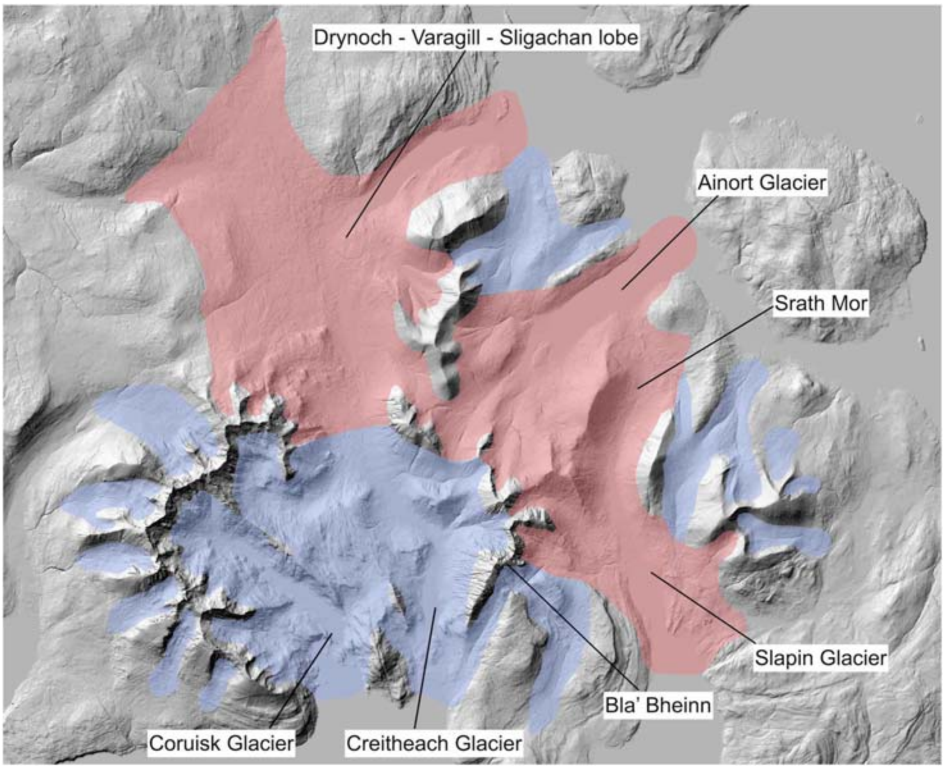

Figure 9. Loch Lomond Readvance glaciers in the Cuillin Hills, Skye, showing proposed surge-type glaciers (pink) and non-surge-type glaciers (blue). Base map: © Crown copyright and database rights 2021 Ordnance Survey (100025252).

On the Island of Mull, suites of nested recessional moraines are widespread within the limits of corrie glaciers and most of the outlets of the central icefield (Ballantyne, 2002). A striking exception is the Spelve-Don lobe that drained the SE side of the icefield (Figure 10). The limits of the lobe in Lochs Don and Spelve are marked by prominent moraines containing thrust and folded marine muds, indicating glaciotectonic sediment excavation and transport (A and B, Figure 10; Benn & Evans, 1993; Gray & Brooks, 1972). Within these limits, recessional moraines appear to be absent. Perhaps uniquely on Mull, the Spelve-Don lobe appears to have been surge-type, a conclusion consistent with its anomalously low ELA (Ballantyne, 2002). Unlike the possible surge-type glaciers on Skye, however, there appear to have been no other surges after the lobe reached its maximum limits.

In the Beinn Dearg massif and NWH, the majority of valleys contain suites of closely spaced recessional moraines, recording active retreat at least in the initial stages of deglaciation (Bradwell, 2006; Finlayson et al., 2011; Lukas, 2005; Lukas & Benn, 2006). Planforms and internal structures of recessional moraines in the NWH have been described in detail by Lukas and Benn (2006) and Benn and Lukas (2006), showing that they consist of ice-contact fans and push ridges formed during repeated stillstands and minor readvances. In a few valleys, however, there are massive moraine complexes and/or areas of ice-stagnation topography, possibly indicating surging behaviour. For example, the terminal moraine in Glen

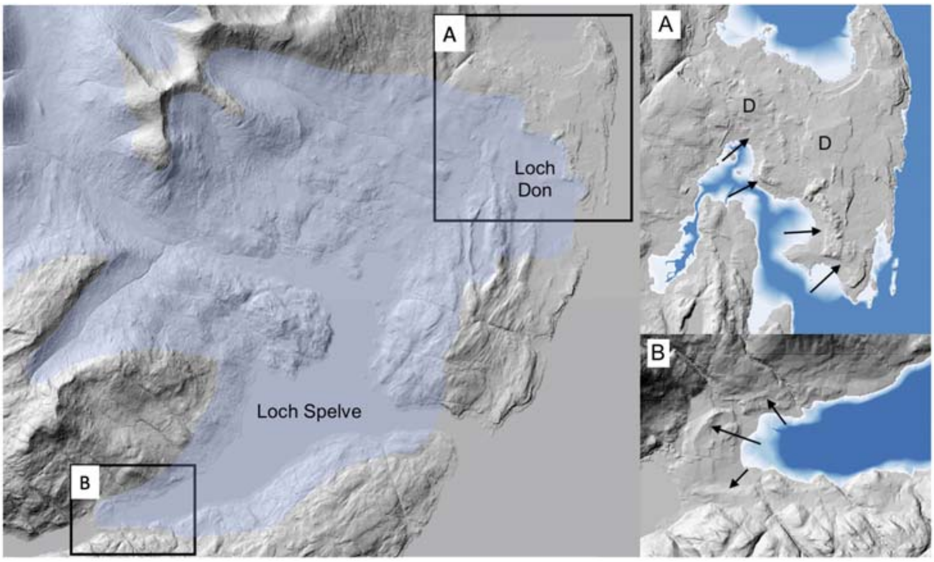

Figure 10. The Spelve-Don lobe of the Mull Icefield (pale blue in main panel), and detailed views of the Don (A) and Spelve (B) moraines. Large raised deltas (D) lie outside the Loch Lomond readvance limits at Loch Don. Base maps: © Crown copyright and database rights 2021 Ordnance Survey (100025252).

Oykell (GO: Figure 1) and the Gharbhrain moraine at the lower end of Coire Lair in the Beinn Dearg massif (A: Figure 11) are unusually large and are located immediately down-valley of lake basins; both may be examples of 'hill-hole pairs' (Finlayson et al., 2011). Geometric ridge networks occur up-valley of the Gharbhrain moraine (B, C: Figure 11), and may be either zig-zag eskers or crevasse fills. Extensive fluted bedforms in both Coire Lair and Glen Oykell record episodes of fast basal motion (Bradwell, 2006; Lawson, 1986). Other examples of possible surge-type glacier landsystems might be found in northern Scotland (e.g. in Strath Vaich, where the distribution of landforms suggests an episode of widespread glacier stagnation followed by ice readvance).

Closely spaced recessional moraines are widespread within the limits of the former outlet glaciers that drained the plateau icecaps in the Grampians, including Creag Meagaidh (Finlayson, 2006; Jones et al., 2017), the Monadhliath (Boston & Lukas, 2019), West Drumochter (Benn & Ballantyne, 2005), the Gaick plateau (Chandler et al., 2019, 2020) and the Cairngorms (Bennett & Glasser, 1991; Standell, 2014). A few outlet glaciers in this region exceed 8 km in length (Figure 5D), but all appear to have undergone prolonged active retreat and evidence for surging appears to be absent.

6.2. West Highland Icefield

The palaeoclimatic and geometric analyses suggest that surge-type outlet glaciers may have been very common in the West Highland Icefield, particularly among the longest, lowest-gradient outlets. Thorp (1986, 1991) identified five outlets of the WHI (Menteith, Lomond, Gare Loch, Creran and Etive) that had anomalously low reconstructed surface gradients and basal shear stresses. Thorp proposed that these glaciers may 'either have surged

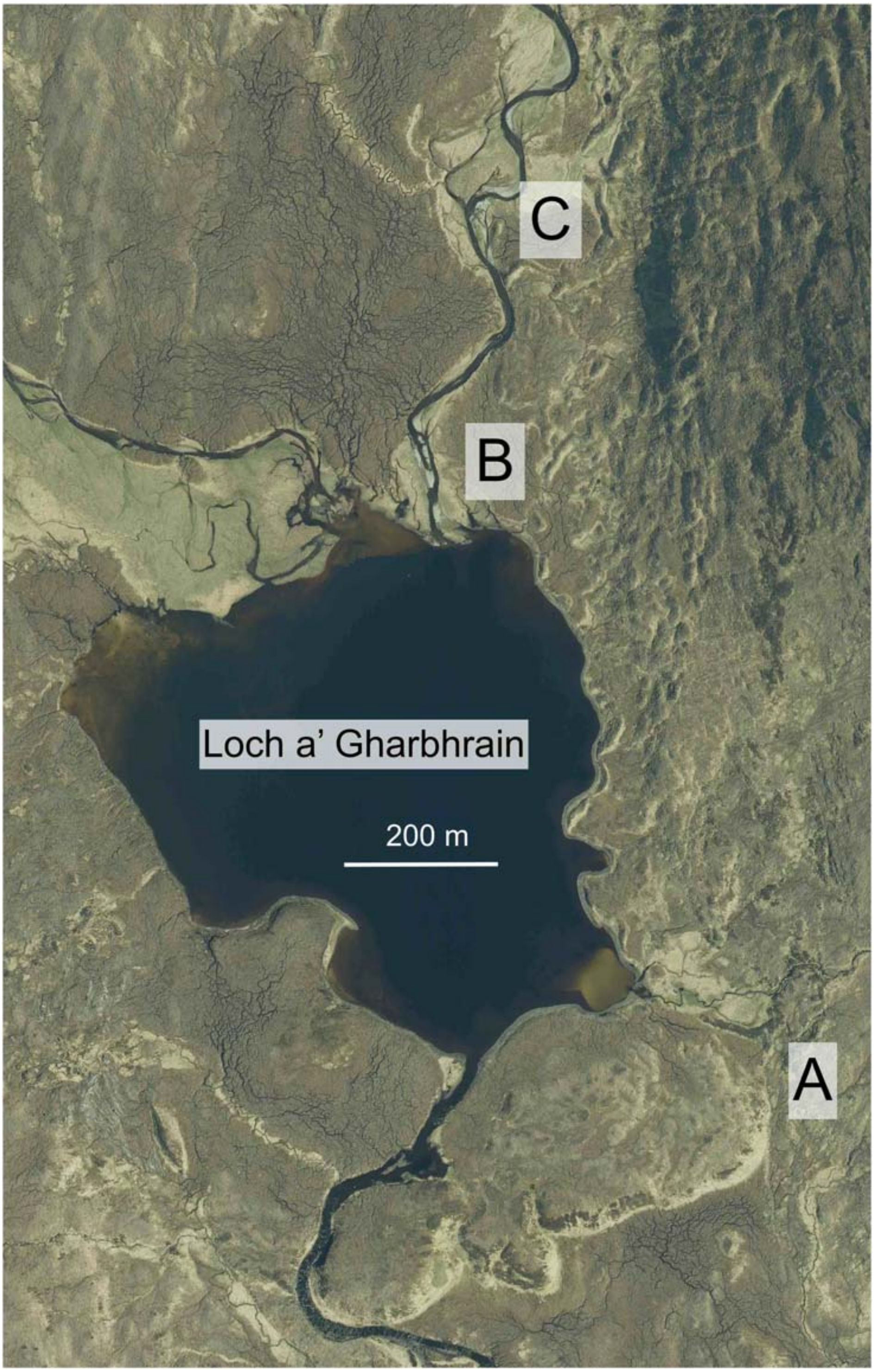

Figure 11. The Gharbhrain moraine (A) and Loch a' Gharbhrain, a possible hill-hole pair. Ridge networks at B and C may be zig-zag eskers or crevasse fills. Orthophoto: © Getmapping Plc.

(perhaps repeatedly) or flowed fast continuously' (1991, p. 87). Landforms indicative of glaciotectonics and/or widespread ice stagnation occur in association with all five of these glaciers, lending weight to the hypothesis that they surged.

The assemblages of landforms at both Loch Lomond and Menteith are closely similar to the surging glacier landsystems described by Evans and Rea (2003), and it has been argued that both lobes were prone to surging during the LLS (e.g. Bickerdike, Ó Cofaigh, et al., 2018; Evans, 2021; Evans & Wilson, 2006b). The Menteith lobe is delimited by a moraine belt made up of four segments, labelled A-D in Figure 12 (Evans, 2021; Evans & Wilson, 2006b). The northernmost segment (A) is a massive complex of sub-parallel ridges partly composed of glacitectonically transported shelly marine clay (Gray & Brooks, 1972). Evans and Wilson (2006a) argued that this ridge complex and the Lake of Menteith constitute a hill-hole pair. Segment B is rock-cored, and consists of numerous sand and gravel hummocks and transverse and longitudinal ridges, interpreted by Smith (1993) as crevasse fills. Segment C is composed of short moraine ridges, again including both flow-parallel and transverse elements. Finally, segment D consists of massive, parallel moraine ridges with intervening meltwater channels. Within the moraine loop, extensive areas of the valley floor are blanketed by Holocene deposits, but staircases of kame terraces and kettled outwash occur on the higher ground (K: Figure 12), indicating widespread ice stagnation and downwasting.

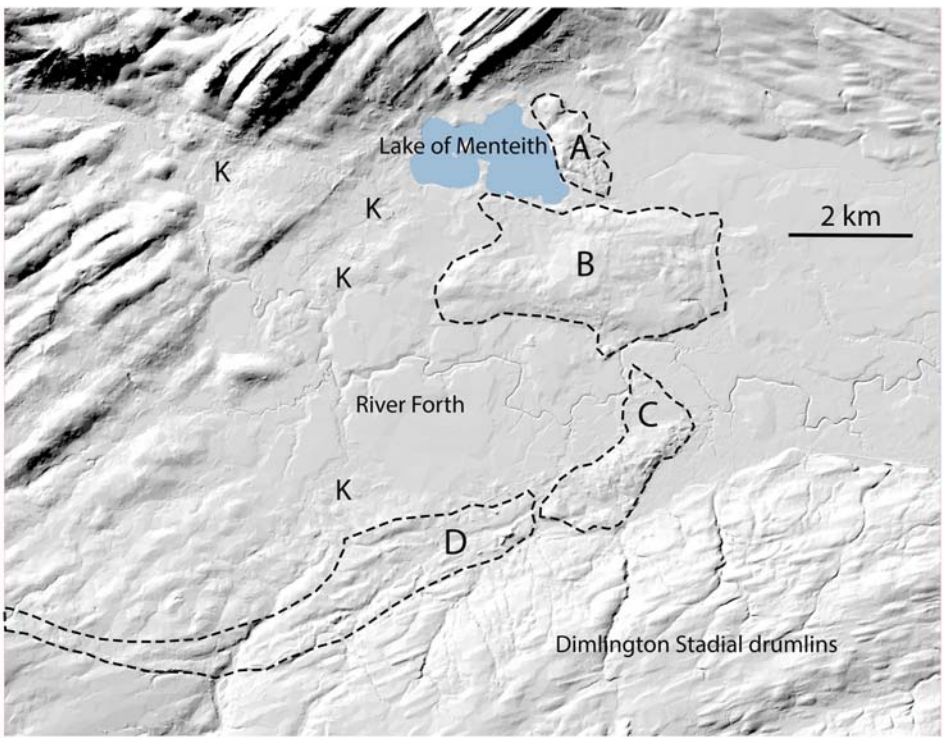

Figure 12. Landforms delimiting the Menteith lobe, showing ridge complexes A-D described in the text (based on Fig. 24.10 in Evans, 2021). K: kame and kettle topography. Base map: © Crown copyright and database rights 2021 Ordnance Survey (100025252).

The limit of the adjacent Lomond Glacier is marked by a prominent moraine belt, in places consisting of multiple parallel ridges (Figure 13; Rose, 1981; Evans et al., 2003; Rose & Smith, 2008). Within the moraine belt, hummocky moraine and kames are superimposed on a field of drumlins composed of sheared subglacial till (e.g. at Croftamie: Rose & Lloyd-Davies, 2003), suggesting fast ice flow followed by widespread stagnation. A set of sub-parallel ridges occurs within the ice limit where the glacier terminated in proglacial Lake Blane. Exposures in the outermost ridge at Gartness and Gartocharn Farm (Figure 13) record extensive proglacial glaciotectonic deformation, including thrusting, folding and shearing of sediment blocks, and hydrofracturing of sediment by pressurised water (Evans & Wilson, 2006b; Rose, 2003). At Drumbeg Quarry, ~1.2 km inside the glacier limit, evidence for proglacial and subglacial glaciotectonism was recorded in detail by Benn and Evans (1996) and Phillips et al. (2002). The evidence for two distinct episodes of proglacial tectonism (at Gartness/Gartocharn and Drumbeg) suggest that the Lomond Glacier surged at least twice when close to its maximum extent.

The moraine belt marking the terminus of the Gare Loch glacier was mapped by Anderson (1949) and Rose (1980), and descriptions of its internal structure were provided by Rose and by Gordon (1993). Exposures at Rhu Point (Figure 13) show folded and sheared clays of the Lateglacial Clyde Bed Formation, gravels and shelly till, indicating glaciotectonic transport and deformation of marine and glaciogenic sediments. Within the glacier limit on the east side of Gare Loch an area of drift hills and hummocky moraine may record ice stagnation during the initial stages of retreat.

The terminal zone of the Creran glacier has been described by McCann (1966), Peacock (1972), Gray (1973, 1975) and Peacock et al. (1989). The western limit of the glacier is marked by large multi-crested moraine ridges (Figures 14 and 15A). These are composed of till, sand, gravel, and contorted and folded Clyde Bed clays, indicating glaciotectonic transport and deformation. Gray (1975) showed that two distinct moraine belts are present, separated by an area of outwash, mounds, eskers and kettle holes, and

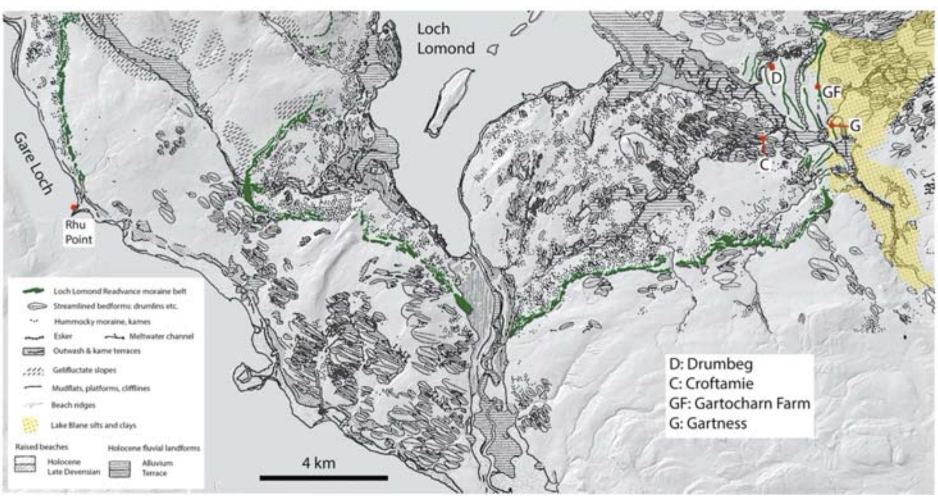

Figure 13. Landforms of the Loch Lomond piedmont lobe and the eastern terminal zone of the Gare Loch glacier, from mapping by Rose (1981).

argued that two episodes of ice advance were separated by a period of ice stagnation. Gray (1973) also described a suite of landforms in Glen Creran, some 12 km from the former glacier terminus, including an outwash terrace extending downvalley from a former ice-contact slope and dead-ice hollow, and kame and kettle topography (Figure 15B), which he interpreted as evidence for ice stagnation following a significant stillstand or read-vance. A multi-crested moraine belt farther up Glen Creran indicates reactivation of ice flow following this episode of stagnation (Figure 15B).

The landform record of the Etive glacier (Figure 14) is exceptionally well documented. A large kettled outwash terrace occurs near the Loch Lomond Readvance limit at Connell, graded to contemporary sea level at ~12 m OD (Figure 15C). The terrace rises eastwards (i.e. up-glacier) and transitions into ice-marginal kame terraces on both sides of Loch Etive, and lower, parallel sets of terraces and widespread kettle holes record stagnation and downwasting of the glacier lobe for a distance of at least 7 km from its maximum position (Gray, 1973, 1975, 1993). Stagnation of this part of the Etive Glacier is also indicated by the submarine landform record. Within the area of kame terraces described above, is an area of 'irregular hummocky terrain', on the loch floor, consisting of complex networks of longitudinal and transverse mounds and ridges (Audsley et al., 2016; Figure 16A). These are similar to ridge networks formed by tidewater surge-type glaciers in Svalbard (Figure 7), raising the possibility that they may be crevasse-fill ridges. A little to the east is a sinuous esker (Figure 16B), the preservation of which implies stagnant or slowly moving ice. The

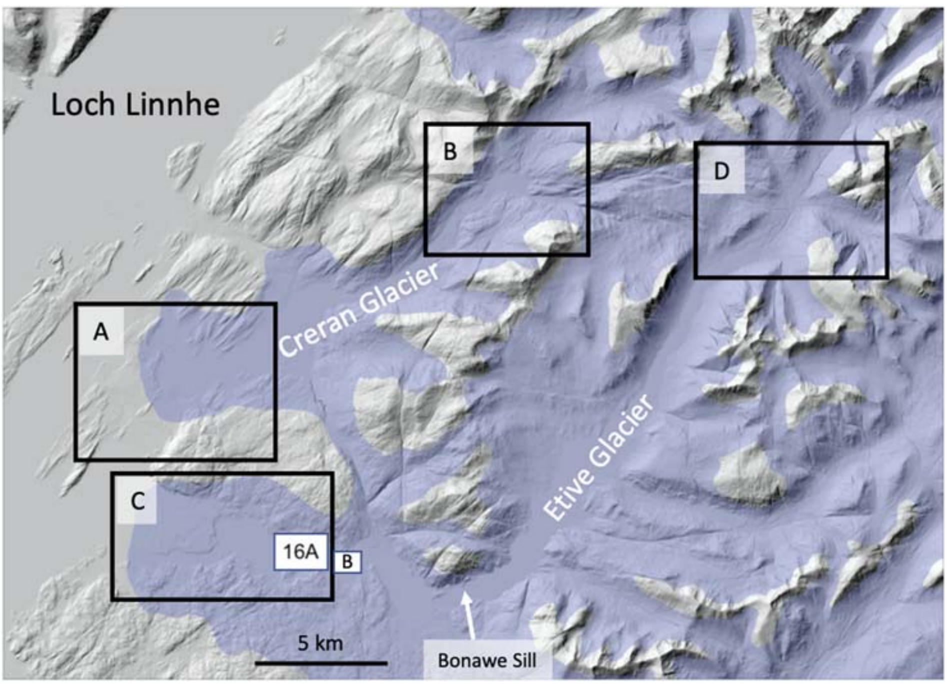

Figure 14. Limits of the Creran and Etive Glaciers, modified from Thorp (1986), showing the location of the detailed views in Figures 15 and 16. Base maps: © Crown copyright and database rights 2021 Ordnance Survey (100025252).

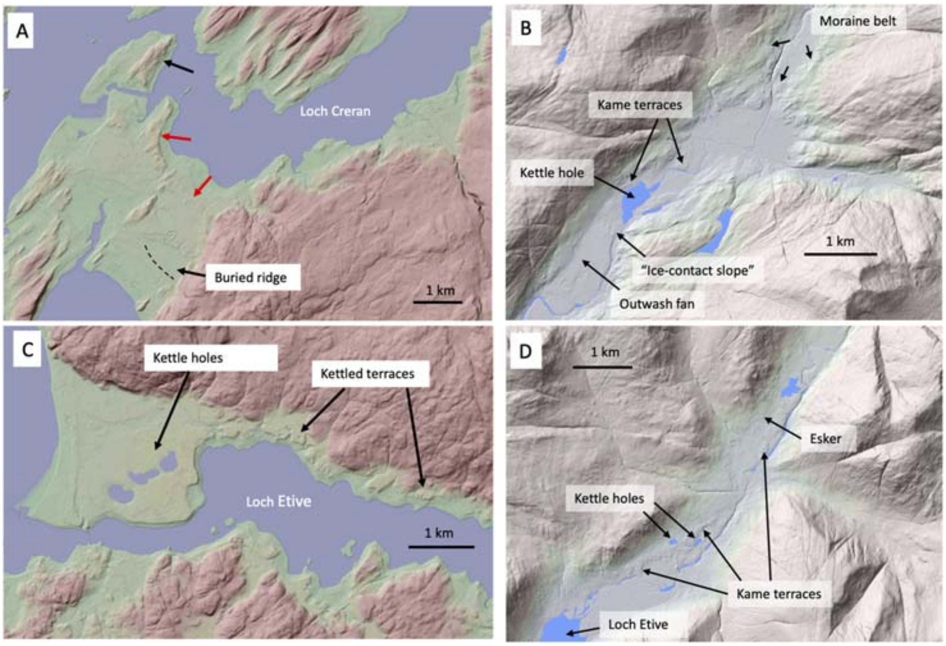

Figure 15. (A) Terminal zone of the Creran Glacier, with arrows indicating the outer (black) and inner (red) moraine ridges. (B) Glacial landforms in Glen Creran, showing evidence of ice stagnation followed by readvance. (C) Terminal zone of the Etive Glacier, showing kettled outwash and kame terraces. (D) Landforms indicating ice stagnation in Glen Etive. For locations, see Figure 13. Base maps: © Crown copyright and database rights 2021 Ordnance Survey (100025252).

terrestrial and submarine evidence therefore provide convincing evidence that the Etive glacier stagnated following its maximum.

Two massive transverse ridges near Bonawe (Figure 14; Audsley et al., 2016) may be thrust moraines, consistent with reactivation of ice flow following the stagnation of the terminal ice tongue. Groups of smaller transverse ridges occur at several locations along the loch, which bear close resemblance to annual moraines deposited during the retreat of surge-type tidewater glaciers (Ottesen & Dowdeswell 2006; Figure 7). Almost fifty longitudinal ridges have been mapped on the loch floor (Audsley et al., 2016). The majority are straight or gently curved and were not described in detail, although they may be streamlined bedforms. For several kilometres upvalley from the head of the loch, the floor of Glen Etive is occupied by irregular outwash surfaces with kettle holes, mounds and sinuous esker ridges (Figure 15D), indicating that widespread ice stagnation occurred after the Etive glacier retreated on-land.

Thus, all of the glaciers identified by Thorp (1991) as having anomalously low surface gradients and basal shear stresses left suites of landforms indicative of alternating episodes of ice advance (including proglacial glaciotectonics) and stagnation, consistent with surging and subsequent quiescence. At least two additional outlets of the southern sector of the West Highland Icefield, the Awe and Teith Glaciers, also appear to have undergone significant episodes of stagnation immediately following their maximum extents. Thorp's (1986) icefield reconstruction shows restricted ice cover at the north end of Loch Awe, but work by Gray and Sutherland (1977) and Tipping (1988, 1989)

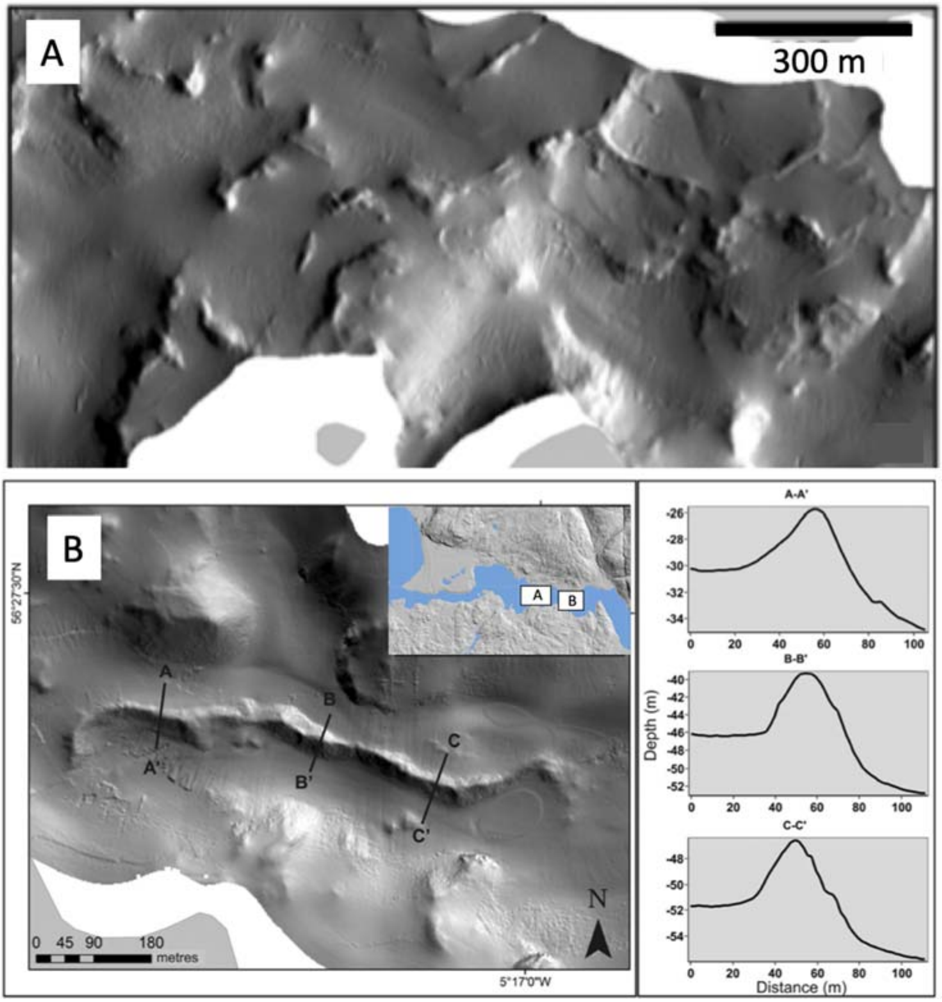

Figure 16. Submarine landforms in the outer basin of Loch Etive. (A) 'Irregular hummocky terrain' or possible crevasse-fill ridge network. (B) Sinuous esker ridge, showing three transverse profiles. Inset: location of panels (A) and (B) (i.e. overlapping the eastern edge of Figure 15C). Modified from Audsley et al. (2016).

indicates that a long, low-gradient lobe occupied the loch. The terminal zone of the glacier is marked by an area of kame terraces, kettle holes, dead-ice hollows and eskers that extends some 3 km beyond the south end of Loch Awe. Gray and Sutherland (1977) argued that stagnant ice remained at this location until drainage became established through the Pass of Brander into Loch Etive, almost 30 km to the north-north-east, consistent with pollen stratigraphic evidence that deglaciation occurred more or less synchronously along the full length of the Awe lobe (Tipping, 1988, 1989).

A terminus position of the Teith Glacier is marked by a well-dated moraine loop east of Callander, although some sedimentological evidence suggests the maximum position was ~1 km farther downvalley (Lowe & Brazier, 2020). Along part of its length, the moraine is a well-defined single- or double-crested ridge, while other parts form a 'belt of till-surfaced mounds with dead-ice and kettle hollows' up to 300 m wide (Thompson, 1972, p. 240). Within the moraine is an extensive area of kame and kettle topography, hummocky moraine, and an impressive set of eskers, indicating a zone of ice stagnation extending at least 5 km up-glacier from the glacier terminus (Lowe & Brazier, 2020). The internal structure of the Teith Glacier moraine has not been examined in detail, and it is unknown whether glaciotectonic processes played any part in its formation. However, the evidence for widespread stagnation immediately following ice advance indicates that the glacier tongue was out of equilibrium with climate, consistent with either quiescence or very rapid climatic reversal. Although the available landform evidence is much less detailed than for the glaciers considered by Thorp, it is suggested that the Awe and Teith lobes are also candidate surge-type glaciers. Major outlet glaciers also occupied Loch Fyne and Loch Long between the Awe and Gare Loch lobes (Sutherland, 1981), although the available evidence is too sparse to allow even a preliminary assessment of depositional processes at their maxima and during deglaciation.

According to Thorp (1991), the eastward-flowing Spean, Treig, Ossian, Rannoch and Lyon Glaciers and tributaries of the Linnhe Glacier had higher basal shear stresses, although surge-type glaciers with similar lengths and overall gradients occur in Svalbard and Iceland (Figure 4). Suites of recessional moraines record active retreat in the eastward-draining glens Lyon, Lochay and Dochart and around Loch Tulla (e.g. Golledge, 2006, 2007; Golledge & Phillips, 2008; Wilson, 2005), but these studies do not extend as far east as the glacier limits. Retreat of the Spean and Treig Glaciers was intimately bound up with the ice-dammed lakes that occupied Glen Roy and adjacent glens, and appears to have involved both active retreat and localised stagnation (Russell et al., 2003; Sissons, 1979a, 1979b). Active retreat may also have occurred in parts of Rannoch Moor and adjacent areas (Lowe et al., 2019; Turner et al., 2014; Wilson, 2005). Although published evidence suggests that most glaciers in this part of the West Highland Icefield may not have been surge-type, additional research is needed to firmly establish patterns and style of deglaciation.

North of the Great Glen, Bennett and Boulton (1993a, 1993b) argued that the dominant style of deglaciation was active retreat, and presented evidence for multiple still-stands and/or readvances in many glens. Independent mapping of large parts of their study area confirms that many outlet glaciers underwent active retreat (e.g. Greene, 1995; McCormack, 2011; Tate, 1996; Wilson & Evans, 2000), although differences in detail are apparent (e.g. Greene et al., 1994). There is agreement that recessional moraines are abundant in the north and east (e.g. in Torridon and in Glens Carron, Fhiodaig, Strathfarrar, Cannich and Affric), but rare or absent in the major troughs in the west (e.g. in the basins of Lochs Hourn, Nevis, Morar, Ailort, Shiel and Sunart). It is notable that in five of these western basins, the Loch Lomond Stadial glacier limits are marked by landforms consistent with surging. McIntyre et al. (2011) presented swath bathymetric data from the mouth of Loch Hourn (H in Figure 1), which show a series of lobate, multi-crested moraine belts with indented planforms (Figure 17). The lobate form indicates that the moraines represent a series of substantial ice advances rather than retreat or still-stand positions, which tend to have concave (calving bay) form on tidewater glaciers. The moraines bear a striking similarity to those marking the limits of surge-type tidewater glaciers in Svalbard (Ottesen et al., 2017; Figure 7).

Large submarine moraines at the mouths of Lochs Nevis and Ailort were interpreted by Boulton et al. (1981) as 'push' (i.e. thrust) moraines marking the limits of the Loch Lomond Readvance. An unusual seismic facies occurs on the distal side of both moraines, with strong, irregular internal reflectors dipping down-fjord. Boulton et al. (1981) interpreted these units as either proximal glaciomarine

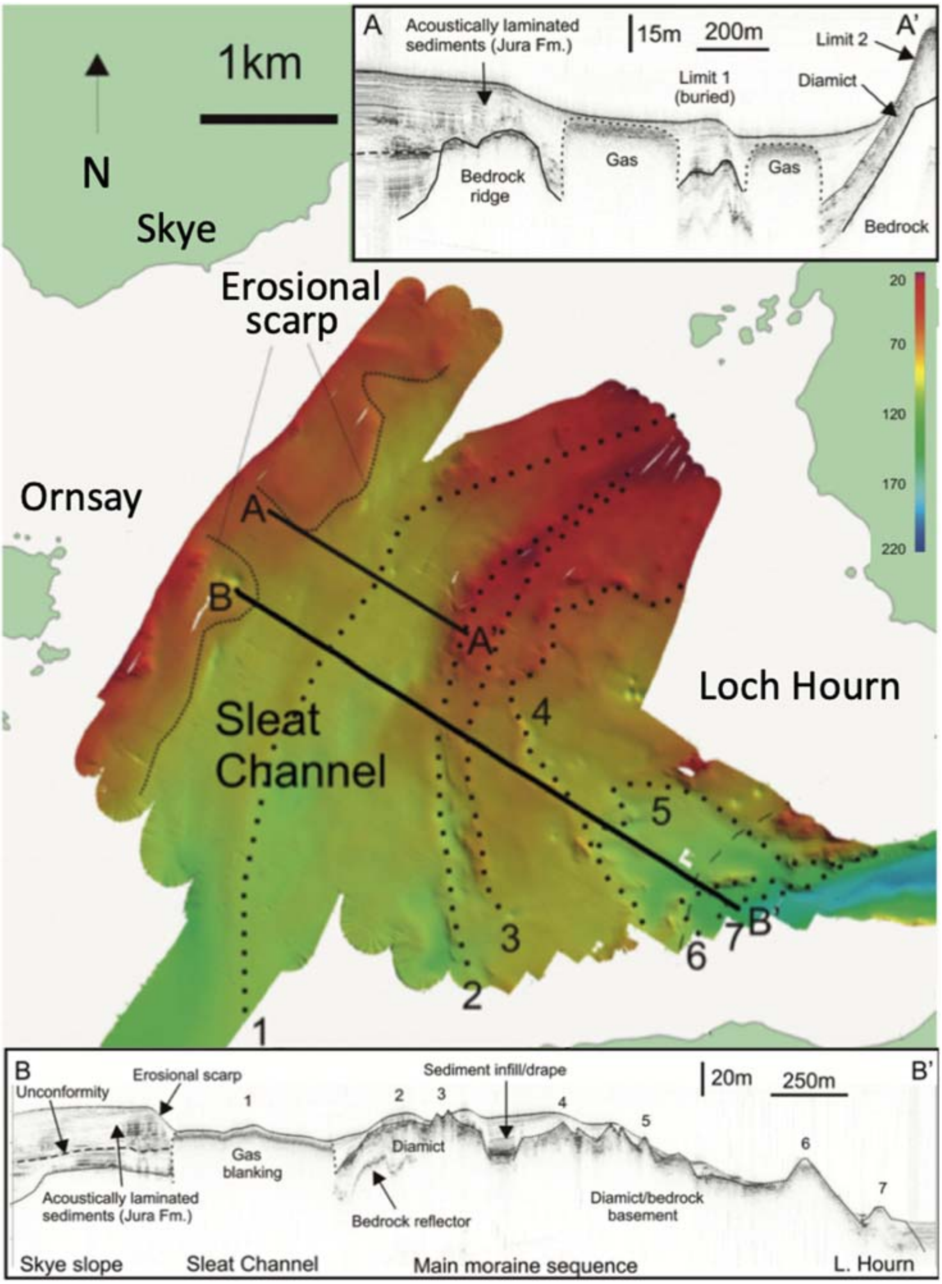

Figure 17. Bathymetry and seismic lines for the mouth of Loch Hourn, showing multiple lobate moraine crests (numbered 1–7). Modified from McIntyre et al. (2011).

outwash or postglacially reworked sediment, but they bear close similarity to mud aprons that commonly occur on the distal side of surge moraines in Svalbard fjords (Kristensen et al., 2009; Ottesen et al., 2008, 2017; Ottesen & Dowdeswell, 2006). Similar units appear to occur in association with at least one of the moraine belts in Loch Hourn (McIntyre et al., 2011; Figure 17).

Boulton et al. (1981) also described terrestrial evidence for proglacial thrusting at the western end of Loch Morar, where sections in a multi-crested terminal moraine expose folded and overturned sands, gravels and muds. At the terrestrial limit of the Shiel glacier there are only small, fragmentary moraines, but there is abundant evidence for ice stagnation during the initial stages of retreat, in the form of outwash fans with kames, eskers and kettle holes (Greene, 1995; McCann, 1966; Peacock, 1970, 1972).

The contrast between the landforms marking the eastern and western margins of the West Highland Icefield has been noted by previous authors, and a number of explanations have been proposed (Bennett, 1996; Greene, 1995; Thorp, 1984). These include geological differences, thermal regime, the influence of calving on glacier mass balance, and the relative abundance of glacier meltwater. The distribution of thrust-block moraines and ice stagnation topography supports an alternative hypothesis: that an arc of surge-type glaciers existed along the western and southern margins of the West Highland Icefield, from Loch Hourn to the Teith valley.

7. Discussion

Palaeoclimatic analysis indicates that during the Loch Lomond Stade much of Scotland lay within the optimal climatic envelope associated with surge-type glaciers, consistent with a southward shift of the Arctic Ring relative to its current position (Figures 2 and 3). Additionally, outlets of the West Highland Icefield and the larger outlet glaciers in the Inner Hebridean and mainland icecaps satisfy the geometric criteria associated with surging. Available terrestrial and marine landform records are consistent with this proposition, and there are many instances of landform assemblages recording episodes of moraine building (including glaciotectonics) followed by widespread glacier stagnation. In some cases there is evidence for repeated cycles, while in others a single advance-stagnation cycle is evident. These landform assemblages contrast distinctly with the suites of closely spaced recessional moraines widely recognised as records of active glacier retreat. Taken together, the evidence indicates that surge-type glaciers were present on Skye, Mull, in the northern Highlands, and in an arc extending along the western, southern and south-eastern sectors of the West Highland Icefield. Rather than being exceptional, surging may have been the typical dynamic state of numerous Loch Lomond Stadial glaciers in the Scottish Highlands and Islands.

The possibility that surge-type glaciers were more widespread than hitherto recognised in Scotland during the Loch Lomond Stade offers a fresh perspective on some long-standing issues, namely the relationship between style of deglaciation and climate forcing; the timing and drivers of glacier maxima and onset of retreat; the relationship between reconstructed glacier ELAs and climate; and mismatches between empirically determined glacier limits and the predictions of numerical modelling experiments. There are discussed in turn below.

7.1. Style of deglaciation and climate forcing

Prior to the early 1990s, areas of 'hummocky moraine' in Scottish glens were generally interpreted as evidence for widespread areal stagnation, which was attributed to rapid warming at the end of the Loch Lomond Stade (e.g. Sissons, 1967, 1979c). Detailed work by Bennett and Glasser (1991), Benn (1992) and Bennett and Boulton (1993a, 1993b) showed that many areas mapped as 'hummocky moraine' actually consist of closely spaced recessional moraines, providing evidence for prolonged active retreat. Phases of active retreat have been interpreted as a dynamic response to climatic changes during the latter part of the Stade, such as gradually increasing temperature or decreasing precipitation (e.g. Ballantyne, 2007a; Benn et al., 1992; Jones et al., 2017). In some cases, there is evidence that this active phase was followed by stagnation or uninterrupted retreat, which has been attributed to rapid warming at the Loch Lomond Stade-Holocene transition (e.g. Benn et al., 1992; Jones et al., 2017). According to this model of deglaciation, episodes of active retreat and stagnation were separated in time, reflecting temporal changes in climatic forcing. The possibility that ice stagnation occurred during the quiescent phase of surge cycles, however, removes this temporal constraint and implies that some glaciers could have undergone stagnation while others were experiencing active retreat. Evidence for ice readvances following episodes of stagnation (e.g. Drynoch-Varagill-Sligachan on Skye, and Creran) lends weight to the idea that periods of active retreat and ice stagnation overlapped in time.

The picture may be further complicated by the possibility that some glaciers may have switched from surge-type to non-surge-type, or vice versa, over the course of the Loch Lomond Stade. The climatic reconstructions illustrated in Figure 3 are based on chironomid-inferred temperatures for the coldest part of the Stade. It is clear that, in some cases, modest climate changes during the Stade (e.g. increases or decreases in precipitation) could have moved glaciers into or out of the optimal climatic envelope, potentially changing their dynamic state (cf. Benn, Fowler, et al., 2019). This possibility should be borne in mind when interpreting evidence for changing styles of glacial deposition.

7.2. Timing of glacial maxima and the onset of retreat

The advent of modern dating techniques has prompted research into the timing of Loch Lomond Stadial glacier maxima, and their relationship with climate and other forcings. Two contrasting views have emerged regarding the chronology of glacier expansion and retreat during the Loch Lomond Stade (Ballantyne, 2012): (1) glaciers expanded until near the end of the stade, until retreat was triggered by rapid warming; and (2) most glaciers reached their maxima by mid-stade, when retreat was initiated by more gradual climate changes. A third view, that deglaciation occurred very early in the stade (Bromley et al., 2014, 2018) is not well-founded (Lowe et al., 2019; Peacock & Rose, 2017; Small & Fabel, 2016) and is not considered here. Support for late-stade glacier maxima is provided by well-dated glacier limits at Loch Lomond (MacLeod et al., 2011) and in Glen Roy (Palmer et al., 2020), and late dates for the deglaciation of Rannoch Moor (Lowe et al., 2019; Small & Fabel, 2016). In contrast, a large set of ^{10}Be exposure ages for moraines and bedrock surfaces in the northern Highlands and

Islands indicates that glaciers reached their maxima before 12 ka BP, with the most probable dates lying in the range 12.45–12.15 ka. These dates are based on a local ^{10}Be production rate (Ballantyne & Stone, 2012); when recalibrated using the Loch Lomond local production rate (Fabel et al., 2012) the implied timing of glacier maxima is even earlier, at 12.5–12.4 ka (Ballantyne et al., 2016).

MacLeod et al. (2011), Lowe et al. (2019) and Palmer et al. (2020) invoked climatic factors to explain late-stade glacier maxima, such as a northward movement of the mean position of the North Atlantic Polar Front bringing increased snowfall. However, it is difficult to reconcile this view with evidence for mid-stade glacier maxima elsewhere, and widespread evidence for active retreat of peripheral icecaps in both maritime and continental parts of the country. Ballantyne (2012) proposed that differences in timing of glacier maxima may have been the result of contrasting dynamics, including surges, an idea that is strongly supported by the arguments developed in the present paper. Dynamic factors could include longer response times of larger glaciers, positive feedbacks between icecap growth and the area of the accumulation zone, migration of source areas and reorientation of ice flow, and contrasting behaviour of terrestrial and tidewater glaciers (e.g. Palmer et al., 2020). However, by decoupling glacier dynamics from climate, surges have potential to displace the timing of glacier maxima from climate signals, perhaps by a century or more. This point is illustrated by recent surges in Svalbard: despite several decades of negative mass balance, numerous large glaciers have undergone substantial advances in the twenty-first Century, radically altering their hypsometry and relationship with climate (e.g. Benn, Jones, et al., 2019; Lovell, Benn, Lukas, Ottesen, et al., 2018; Noël et al., 2020).

In section 6, it was argued that for some Loch Lomond Stadial glaciers the most recent surge was the most extensive (e.g. Lomond, Spelve-Don), whereas for others a series of progressively less extensive surges occurred following the maximum (e.g. Drynoch-Varagill-Sligachan, Hourn, Creran). MacLeod et al. (2011) have shown that the Loch Lomond glacier reached its maximum very late in the Stade (after 11.9 cal ka BP) and had retreated sufficiently to allow drainage of proglacial Lake Blane sometime between ca. 11.76 and 11.47 cal ka BP. This is similar in timing to the onset of rapid Holocene warming, such that post-surge ice stagnation could have occurred for both climatic and dynamic reasons. The Drynoch-Varagill-Sligachan lobe reached its maximum earlier in the Loch Lomond Stade (Benn et al., 1992), allowing subsequent repeated cycles of glacier advance and decay.

This interpretation implies that many large outlets of the WHI (of both surge-type and non-surge-type) may have reached their maxima relatively early in the Stade. One possible example is the Teith lobe, where basal ^{14}C dates from ~2 km inside the limit at Mollands suggest that retreat was underway by 12,600 years ago (Lowe, 1993; Lowe & Brazier, 2020). If, as suggested above, the Teith lobe surged, these dates imply that post-surge stagnation occurred at a time when glaciers elsewhere in the Highlands were advancing. However, Lowe and Brazier (2020) sound a cautionary note regarding the reliability of the dates, and re-evaluation of the landform and stratigraphic records in the Teith valley will be necessary to test this conjecture. Dating studies should also target sites where the landform record suggests one or more surges following the glacier maximum.

7.3. Climate reconstructions based on the assumption of steady state glacier ELAs

As noted above, reconstruction of former ELAs from glacier hypsometry rests on the assumption that, at their maxima, glaciers were in equilibrium with the prevailing climate. For surge-type glaciers this assumption breaks down because during surges glacier ablation zones can be greatly over-extended by fast flow. This is further complicated by the fact that reconstructed glacier hypsometries may be diachronous, with the most extended position of the lower glacier relating to the surge maximum and the location of trimlines on the upper glacier relating to the limit of ice build-up during quiescence. The potential impact of non-steady-state glacier dynamics on Loch Lomond Stadial glacier reconstructions can be illustrated with two examples. First, the reconstructed equilibrium line for the (possibly surge-type) Spelve-Don lobe on Mull is ~40 m lower than that of the Mull Icefield as a whole (Ballantyne, 2002), and ~80 m lower than that of the Mull Icefield minus Spelve-Don. The anomalously low ELA may reflect the influence of surging on glacier hypsometry, the effects of blown snow on patterns of accumulation, or a combination of the two (Ballantyne, 2002). Using the methods described in Section 3, an 80 m lowering of the ELA is equivalent to an increase in inferred precipitation of >10%. At present, however, it is not possible to determine whether the Spelve-Don lobe received this extra accumulation in the form of blown snow, or whether the lowered ELA was due to surge dynamics and had no climatic significance. The second example is the Skye Icefield, where the (possibly surge-type) Drynoch-Varagill-Sligachan, Ainort, Srath Mór and Slapin Glaciers had ELAs some 100–150 m lower than the southward-flowing Coruisk and Creitheach Glaciers (Figure 9). However, some apparently non-surge-type glaciers on Skye also had low ELAs, and the picture is complicated by the possible impact of snow-blow and calving losses from tidewater outlets. Disentangling the various influences on glacier ELAs is not straightforward and will require focused research. It is worth noting, however, that if the 'true' climatic ELAs of the Mull and Skye icefields were higher than the reconstructed values, the effect would be to reduce the implied palaeo-precipitation and to place both ice caps more firmly within the optimal surging envelope (Figure 3). The conclusion that the Inner Hebrides lay within the envelope thus remains robust.

7.4. Empirical glacier reconstructions and numerical model predictions

The numerical ice-sheet model results presented by Hubbard (1999) and Golledge et al. (2008, 2009) have been a rich source of insights into glacier-climate relationships during the Loch Lomond Stade. Differences between empirical reconstructions and 'best fit' model predictions have been used, for example, to investigate the role of snow-blow in redistributing mass over the Beinn Dearg icecap (Finlayson et al., 2011). Other differences have highlighted potential errors in the mapped limits, some of which have been addressed by subsequent mapping (e.g. the Monadhliath: Boston et al., 2015) whereas others (e.g. Argyll) remain to be investigated. One of the most significant differences between the 'best fit' model results and observations is the model under-prediction of the well-dated glacier limits at Gare Loch, Loch Lomond, Mentieth and Teith, in some cases by over 10 km (Golledge et al., 2008).

If, as argued above, these glacier lobes surged, this difference could reflect missing model physics. The numerical model is thermo-mechanically coupled; that is, ice temperature evolves in response to strain heating and other sources of enthalpy (Golledge et al., 2009). However, it does not include routines to represent subglacial hydrology and thus cannot exhibit the water storage – sliding feedbacks that lead to surging behaviour (Benn, Fowler, et al., 2019).

It would be straightforward to determine the magnitude of basal stress perturbation required to allow 'mismatched' model glaciers to extend to their empirically determined limits, and thus to test the plausibility of the surge hypothesis in these cases. Inclusion of realistic surge dynamics in 3-D ice sheet models, however, requires full coupling of hydrological and ice-flow model components in addition to global enthalpy conservation. This lies at the very limits of current modelling capability, and modelling surge dynamics for Loch Lomond Stadial glaciers, ice caps and icefields remains a major challenge for the future.

8. Concluding remarks

Over the last 30 years or so, a few authors have suggested that surges may have occurred in Scotland during the Loch Lomond Stade. These suggestions have tended to be tentative, with the implication that surges were rare and localised phenomena, exceptions from the general rule (e.g. Bickerdike, Ó Cofaigh, et al., 2018). The combined climatic, glaciological and geomorphological perspectives presented in this paper make a strong case for the opposite view, that surging glaciers were not exceptional but common in many parts of the Scottish Highlands and Islands. Rigorous testing of this proposition will require targeted fieldwork on land and in sea- and freshwater lochs, as part of a systematic re-evaluation of the dynamic significance of glacial landforms of Loch Lomond Stadial age. Indeed, the possibility of widespread glacier surging provides renewed motivation for studies of glacier dynamics, chronologies, and glacier-climate relationships, and should be an essential component of the research paradigm for palaeo-glaciological investigations in Scotland.

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