Ice-sheet deglaciation and Loch Lomond Readvance in the eastern Cairngorms: implications of a Lateglacial sediment record from Glen Builg

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ABSTRACT: We present new lithostratigraphic, pollen-stratigraphic and tephrochronological data obtained from a sediment sequence in a small lake basin in Glen Builg, eastern Cairngorms, with mapping of the surrounding glacial geomorphological features. The collective evidence indicates that basin organic sediment accumulation started during the Windermere Interstadial at ~14.3 ka. The new results reaffirm the conclusions of Clapperton *et al.* (1975), that any occupation of the eastern Cairngorms by Loch Lomond ('Younger Dryas') Stadial glacier ice was spatially restricted. The record also suggests that harsh climatic conditions prevailed throughout the Windermere Interstadial, probably due to the relatively high altitude of the site (~460 m) and its proximity to major Cairngorm peaks. Our new, more comprehensive study provides a robust chronology, and reveals several palaeoenvironmental signals congruent with other recently reported Scottish Highlands records. Key similarities with regional records are: (i) a short climatic reversal corresponding to GI-1d in the Greenland stratotype sequence; (ii) a two-phased Loch Lomond Stadial, with a transition around the Vedde Ash, dating to ~12.1 ka; and (iii) a delayed response to Early Holocene climatic warming of ~250 years, before soils were sufficiently stabilised to permit shrub vegetation establishment.
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KEYWORDS: geomorphology; Lateglacial; pollen; tephrochronology; Younger Dryas

Introduction

Clapperton *et al.* (1975) reported limited pollen data and a single radiocarbon date from a small lake basin site in Glen Builg in the eastern Cairngorms. This lake sediment record was one of few such records reported for this part of the Scottish Highlands that spanned the interval of the Last Glacial–Interglacial Transition (LGIT; ca. 16 to 10 ka), but despite the skeletal nature of the record, it has proved pivotal for constraining the extent and timing of the last glaciers to occupy the region. Since this publication, major advances have been made in the reconstruction of the final phases of the glacial history of the Scottish Highlands at the end of the last glacial stage, as well as in the range and refinement of the proxy and chronological methods now adopted for the detailed analysis of associated stratigraphic sequences (Walker and Lowe, 2019). Given the site's recognised critical location in constraining the timing of regional deglaciation, a more detailed investigation of its glacial and palaeoenvironmental significance was considered necessary, with the new data reported here.

Glacial and palaeoenvironmental background

During the latter stages of the Last Glacial period known locally as the Dimlington Stade (31–14.7 ka), the Scottish sector of the British and Irish Ice Sheet (BIIS) sustained several independent ice centres in mainland Scotland, peripheral to the dominant western Highlands ice centre (Ballantyne and Small, 2019). One of these auxiliary ice centres was located in the Cairngorm range, northeast Scotland (Fig. 1), generating ice that coalesced with ice flowing northeast from Strathspey and east along the Dee valley toward the North Sea Basin, where it ultimately met the Fennoscandian Ice Sheet during the Last Glacial Maximum (Hughes *et al.*, 2016; Merritt *et al.*, 2017; Clark *et al.*, 2018).

During the later stages of the Dimlington Stade it is thought that the ice cover in northeast Scotland reached a local maximum at ~24.0 ka, before thinning and retreating significantly over the following 9 ka (Merritt *et al.*, 2017). Within northeast Scotland, ice flow was largely topographically constrained even when ice overtopped the regional mountain ranges; this is particularly evidenced in the Cairngorms where the Don and Dee valleys constrained ice flow to the east (Hughes *et al.*, 2016; Sugden *et al.*, 2018). The recession of the Scottish sector of the BIIS was spatially asynchronous (Fig. 1), with a general east-to-west retreat pattern around the margins of the Cairngorms and eastern Grampians, but with notable local readvances around the northeast coast and within Strathspey (Brazier *et al.*, 1998; Hall *et al.*, 2016; Merritt *et al.*, 2017). The timing of this contraction has been widely studied, suggesting that by ~17.0 ka much of coastal eastern Scotland was ice-free (Ballantyne and Small, 2019 and references therein). Indeed, some valleys in the Cairngorms may have deglaciated as early as 16.9 ± 1.1 ka based on cosmogenic nuclide dates obtained from rock

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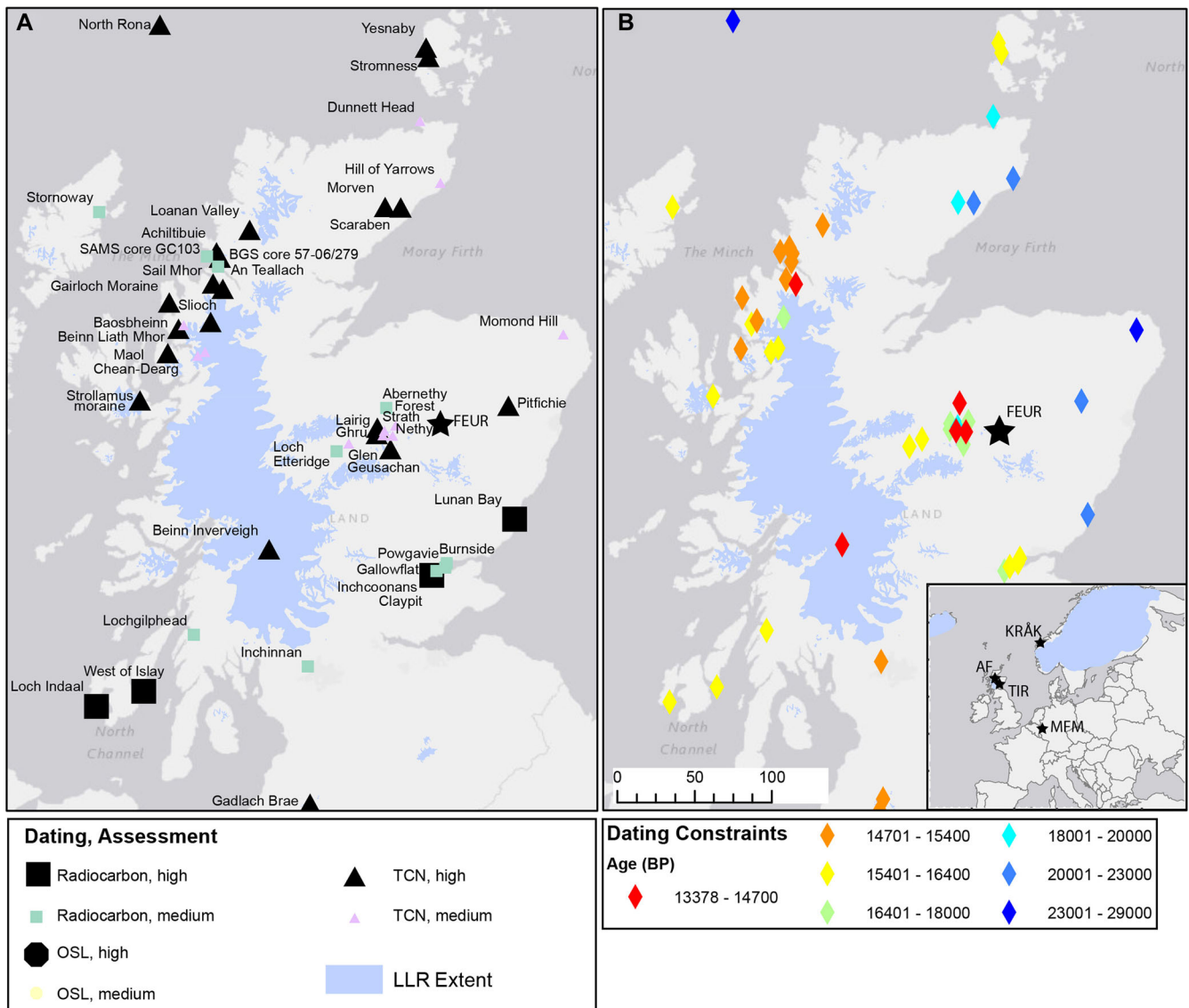Email: Alice.Carter-Champion.16@ucl.ac.uk

Figure 1. Key chronological evidence for retreat of the last BIIS. In both panels, blue shading indicates Loch Lomond Readvance extent as presented in Bickerdike *et al.* (2018). A) Quality controlled terrestrial cosmogenic nuclide (TCN), radiocarbon and optically stimulated luminescence (OSL) dates from the BRITICE V2 project, as presented in Small *et al.* (2017). The smaller symbols denote chronological information with an amber (medium quality) assignment by Small *et al.* (2017). B) Estimates of deglaciation are presented using a colour scale for all chronological information available of high–medium quality from Small *et al.* (2017). Where radiocarbon dates are available, the age should be inferred as an indirect minimum limiting age compared with direct OSL and TCN age estimates. The broad pattern seen in this panel is that of a progressively westward retreat from the Scottish lowlands onto higher ground. Inset is an overall context of Europe with relevant sites discussed in the text, with blue shading denoting the Younger Dryas ice extents from Hughes *et al.* (2016), AF = Abernethy Forest, TIR = Tirinie, MFM = Meerfelder Maar, KRÅK = Kråkenes, FEUR = Lochan Feurach. [Color figure can be viewed at wileyonlinelibrary.com]

surfaces on the high ground of the Cairngorms (1156 m OD) (Phillips *et al.*, 2006). However, the limited chronological data currently available for deglaciation within northeast Scotland (Fig. 1) suggest a complex regional retreat pattern with potential asynchroneity in parts of Strathspey and the Dee Valley (Kirkbride and Gordon, 2010; Hall *et al.*, 2016; Sugden *et al.*, 2018).

During the Windermere Interstadial (WI), a significant period of warming between 14.7 and 12.9 ka, the BIIS is thought to have vacated all of Scotland, although vestigial small ice caps may have survived in the western Highlands (Ballantyne and Small, 2019). The WI, at least in low-lying areas, was a period of landscape stabilisation in Scotland, recorded by the accumulation of organic sediments in lake basins, testifying to widespread plant colonisation and soil development (Walker and Lowe, 2019). This episode was followed by a climatic reversal, locally termed the Loch Lomond Stadial (LLS: 12.9–11.7 ka) which equates approximately to the Younger Dryas in

Scandinavia (Mangerud, 2021) and Greenland Stadial 1 (GS-1) in the Greenland stratotype sequence (Rasmussen *et al.*, 2014). This cold period was associated with the Loch Lomond Readvance (LLR), a renewed phase of glacier growth with a major icefield located in the western Highlands, and peripheral glacial advance elsewhere in Scotland (Bickerdike *et al.*, 2018; Chandler *et al.*, 2018, 2019; Walker and Lowe, 2019). Here we provide new evidence that re-examines landscape responses during the LGIT in the eastern Cairngorms.

Reconstructions of LLR ice extent in the Cairngorms suggest the ice was confined predominantly to valleys and corries in the western Cairngorms, with a west–east precipitation gradient considered the likely cause of much more restricted ice cover in the eastern sector (e.g. Sissons and Grant 1972; Sissons 1974; Bennett and Glasser, 1991). However, this has not always been the consensus: a more extensive glaciation of the Cairngorms during the LLS was proposed by Sugden (1970) but this was contested by Sissons (1972), who favoured much
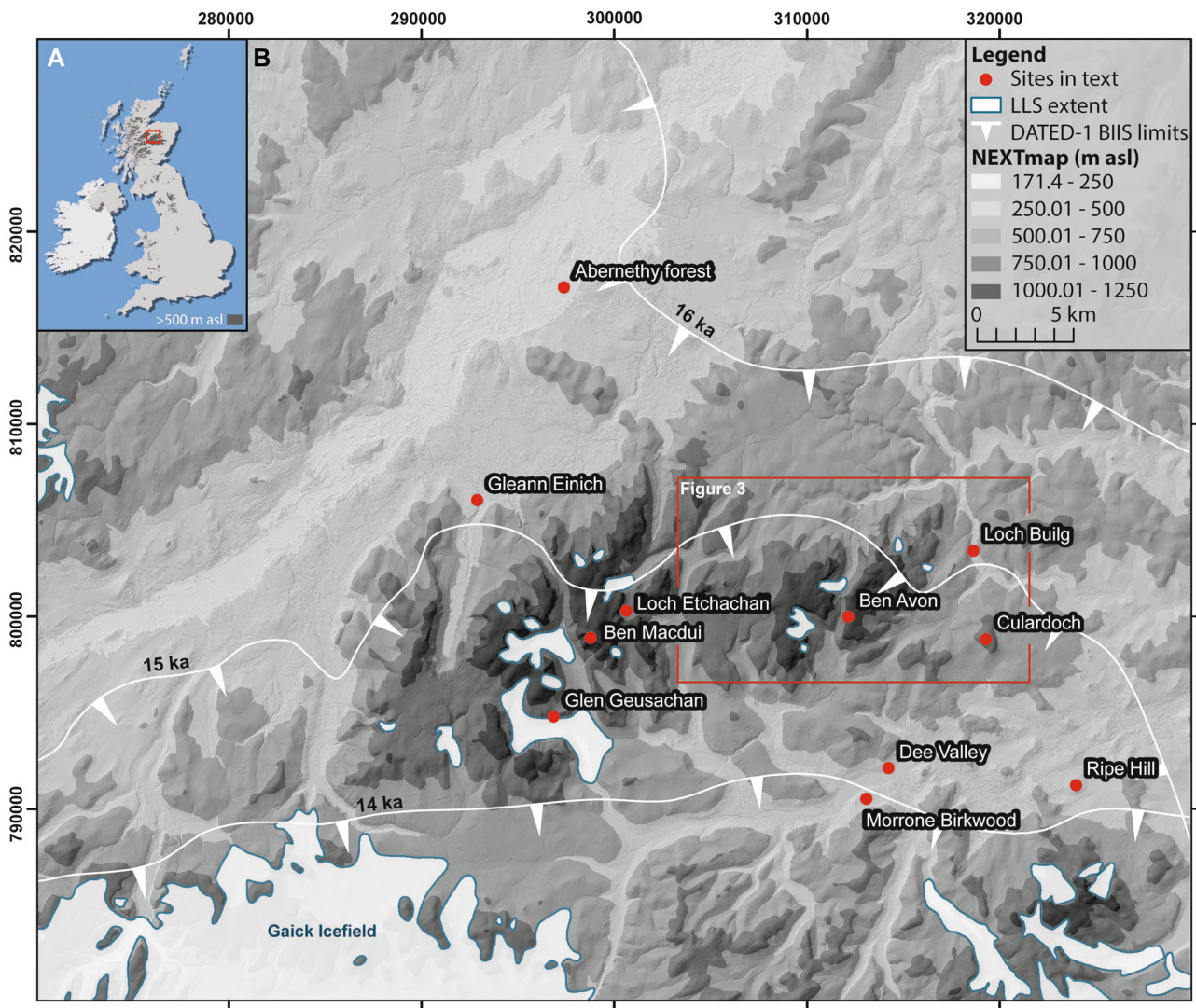
Figure 2. A) Context of the area studied within the Scottish Highlands. B) Context for the Builg site within the wider region of the Cairngorms, with the spatial extent of the Loch Lomond Readvance indicated (Bickerdike et al. 2018). Red circles mark sites mentioned in the main text, and the red rectangle denotes the area selected for geomorphological mapping in Fig. 3. NEXTmap DEM was accessed through the NERC Earth Observation Data Centre and is at 5 m resolution. [Color figure can be viewed at wileyonlinelibrary.com]

more limited glacial ice cover. It was the stratigraphic evidence preserved in the site in Glen Builg in the eastern Cairngorms (Figs. 3C and 7; Clapperton et al., 1975) that supported the limited ice cover proposal of Sissons (1972), since the basin contains sediments that extend back to the WI, indicating that much of the area must have remained ice-free throughout the LLS (Clapperton et al., 1975).

The published sediment record named 'Loch Builg' was, however, recovered from a separate much smaller basin located immediately south of Loch Builg which is mostly infilled with lacustrine and peat deposits but also retains a small area of open water, named Lochan Feurach (Figs. 2B, 3A, 3B, Suppl. Fig. 1 – BNG 318951, 802743). Although this site occupies a crucial location with respect to the local glacial landforms and history, the published stratigraphic and chronological evidence reported by Clapperton et al. (1975) is limited by modern standards. First, pollen data were presented for only seven stratigraphic horizons, but these were not reported in full and are widely spaced throughout the proposed WI and Early Holocene intervals, while no pollen data were presented for the clay-rich sedimentary unit assigned to the LLS (Clapperton et al., 1975). Second, a single uncalibrated radiocarbon date of 11 770 ± 87 ^{14}C a BP was used to anchor the record within the LGIT. The radiocarbon measurement was based on a bulk-sediment sample that spans a wide stratigraphic interval, an approach that is usually avoided in more recent studies due to potential contamination through sediment reworking or assimilation of inert carbon from carbonaceous sources (e.g. Lowe and Walker, 2000; Lowe et al., 2019). Third, the basal lithostratigraphic sequence is complex, with evidence for a separate organic unit predating that from which the radiocarbon date was obtained, the significance of which is difficult to assess. Fourth, the landform assemblage that surrounds the basin has been interpreted as either possible ice-marginal moraines (Sissons, 1967; Sissons and Grant, 1972) or as glaciofluvial deposits, including kames and kame terraces (Clapperton et al., 1975).

In view of these limitations, a reinvestigation of the Lochan Feurach basin aimed to meet the following main objectives: (i) to map the glacial features in the vicinity of the basin in greater detail; (ii) to systematically survey the basin to identify an optimal location for stratigraphic investigation; (iii) to generate more highly resolved records of the litho- and pollen-stratigraphic variations throughout the LGIT interval; and (iv) to examine the sequence for possible cryptotephra layers, in view of the important role that tephrostratigraphy now plays in the correlation and dating of LGIT sediment sequences in Scotland (Timms et al., 2019).
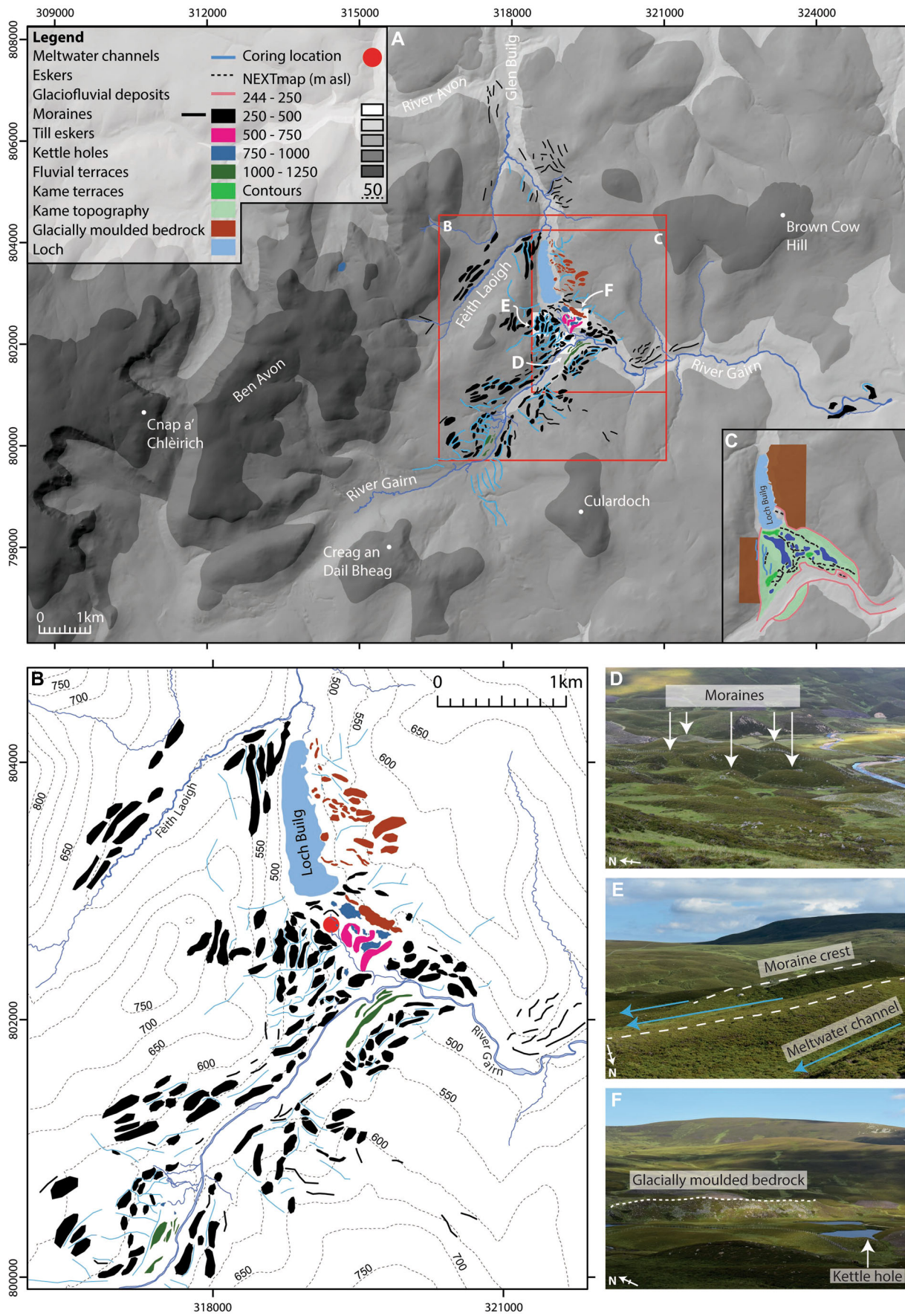
Figure 3. Detailed mapping conducted as part of this investigation. A) Area selected for detailed geomorphological investigation with NEXTmap data overlain by remotely sensed landforms confirmed from field investigations. Corries outside of the region of study identified based on existing reconstructions from Standell (2014) and Clark *et al.* (2018). B) overview of glaciological features within the study area, particularly surrounding the coring location (marked red). C) Inset of previously published geomorphology from Clapperton *et al.* (1975). D) Example of the numerous moraines draped over the valley floor to the south of Loch Builg. E) Example of parallel moraines and meltwater channels within the valley. F) Glacially moulded bedrock perched above kettle holes at the Builg–Gairn confluence. [Color figure can be viewed at wileyonlinelibrary.com]

Field and laboratory methods

Glacial geomorphological mapping of landforms immediately adjacent to Loch Builg, with a focus on the area encompassing Lochan Feurach, was conducted using a combination of field-based mapping and remotely sensed satellite imagery (Fig. 2). The latter comprised NEXTMap digital elevation model (DEM) data with a 5 m resolution used in conjunction with the ESRI ArcGIS 'world imagery' service. To eliminate bias in landform identification, multiple hillshades were examined with varying azimuth and altitude positions of the illumination source (cf. Chandler *et al.* 2018).

A systematic auger survey, using a 2.5 cm diameter Dutch gouge, was undertaken to establish the bathymetry of the infilled basins south of Loch Builg and the nature of the sedimentary deposits contained within them. Initial evidence indicated that no Lateglacial deposits are preserved in the southern part of the Feurach basin complex (Suppl. Fig. 1), so six additional transects were surveyed in the northern part of the basin covering a total area of 0.054 km^2. All sampling points for this bathymetric survey were located using a handheld GPS and total station (Topcon OS Series), the latter calibrated to two OS spot heights (496 m and 512 m).

Five basal sediment sequences were recovered using a 1 m long Russian coring device (internal diameter 50 mm) with a further four basal cores retrieved using a 50 cm long Russian corer, all collected from the same locality. For this study, only the sequence from Borehole 1 was analysed, with sediment characteristics described, and units assigned based on grain size, sorting and structure, with colours assigned using the Munsell Soil Colour System. Details of the laboratory procedures employed in the analyses of the core – magnetic susceptibility, loss-on-ignition, X-ray fluorescence, pollen and tephrostratigraphy – are given in Supplementatry Information I.

Geomorphological mapping and interpretation

The detailed mapping based on field observations, satellite and NEXTMap imagery (Figs. 2, 3A, 3B, 3C) indicates that many of the landforms in the vicinity of Loch Builg form distinct linear ridges, usually running parallel or slightly obliquely to local valley sides with their axes trending toward the valley floor, while a small number are curvilinear in form, usually concave up-valley. These landforms are between 100 and 250 m in length, up to 10 m in relief, and are generally concentrated to the west and southwest of Lochan Feurach, but also further to the southwest up-valley in the Gairn valley. These ridges are separated by a network of distinct channels (Fig. 3D, 3E) whose long axes are usually parallel to the crest of the ridges, but some cut through the ridges, normal to the ridge axes. Exposures of bedrock to the east and southeast of Loch Builg have been glacially moulded, with crest-lines also parallel to the local valley sides. Depressions within all of these landforms are either infilled with sediments or small lochans have formed that are concentrated on the valley floor to the southeast of Loch Builg. The larger depressions lie within or are perched upon three large accumulations (10–15 m high; 150–300 m in length) of glacigenic deposits. These have sinuous crests with an overall axis that runs from southwest to northeast. Fragments of terraces up to 600 m in length are found on the southern flank of the Gairn valley.

The suite of landforms that occupy the Gairn valley and the lower ground to the south of Loch Builg clearly reflect glacial deposition or glacial moulding of bedrock. The area of ridges and channels are interpreted as recessional moraine features deposited at the margins of an actively retreating ice margin (Lukas and Benn, 2006; Chandler *et al.*, 2016). The overall plan pattern of the moraine ridges suggests sequential retreat of an ice margin that was also thinning as meltwater channels formed at the glacier margins (Chandler *et al.*, 2016). It is, however, possible that these landforms are erosional remnants generated by a combination of ice-marginal and proglacial glaciofluvial incision into glacigenic sediment (Chandler *et al.*, 2021) and it is these forms that delimit the former margins of the ice during retreat.

Additionally, some sinuous ridges located toward the centre of the valley are more difficult to explain based on their valley position and long-axis orientation; they are provisionally interpreted as till eskers (Christoffersen *et al.*, 2006; Larsen *et al.*, 2006; Evans *et al.*, 2010, 2016). To test these proposals, additional information on their sedimentary nature is needed. Within this area the identification of numerous kettle holes is suggestive of stagnant ice as part of the glacier became detached from the actively retreating ice margin. Clapperton *et al.* (1975) interpreted the hummocky terrain immediately south of Loch Builg as comprising kames, kame terraces and eskers (Fig. 3D, 3E). We believe that the alignment of the linear ridges and meltwater channels is more suggestive of ice-marginal control, as ice retreated and down-wasted episodically.

At this specific locality, the lineation of the moraine and bedrock ridges suggests that ice originally flowed northeastward through the Gairn valley and bifurcated just south of Loch Builg, with one branch continuing south-eastward into the lower Gairn valley and the other flowing north into Glen Builg (Standell 2014). As ice retreated from Loch Builg, separation of the ice into two lobes is likely to have occurred, with one lobe retreating southwestward up the tributary valley of Fèith Laoigh (Fig. 3), while the other continued to retreat southward from Loch Builg and then in a southwesterly direction into the Gairn valley, as indicated by the pattern of recessional moraines. The higher elevation of the area south of Loch Builg may have meant that ice thinning caused a threshold to be reached where stagnant ice became detached from the active ice in the Gairn valley and created a series of kettle holes.

The subsurface coring transects revealed that the deepest surveyed part of the Lochan Feurach basin lies close to the lochan (Suppl. Fig. 1), where infilled sediments reach 12.3 m below local ground surface, with a base recorded at 465.05 m OD. It is possible that the basin may be deeper than this beneath the lochan, but this part of the basin was inaccessible during this investigation. The basin is surrounded by elevated hummocks with several meltwater channels feeding into it from the west. The edges of the Lochan Feurach basin are significantly steeper in the east than in the west but with a much lower total relief, cut by several palaeo-inflow channels.

Stratigraphic results and interpretation

Lithostratigraphy

The lithostratigraphic findings for the sequence in Borehole 1 are summarised in Fig. 4. Principal component analysis (PCA) of the *z*-scored µXRF data using Xcelerate (Bro and Smilde 2014) indicates that the first axis explains 53.1% of variance in the dataset, while axis two explains 14% (Suppl. Fig. 2). Elements associated with inorganic material (Fe, K, Rb, Zn) and organic material (Mo Incoherent, Ca) are both grouped along the primary and secondary axes, respectively, several of which were selected to display the down-core variations in the sequence. Ti and Fe best represent changes in detrital input to the basin based on the affinity they showed with the PCA and with large variations in the magnetic susceptibility (MS) data while Ti is frequently used as a proxy for detrital inwash (Balascio *et al.*, 2011). At the base of the sequence (FEUR-L1) is a 4 cm thick unit of massive coarse
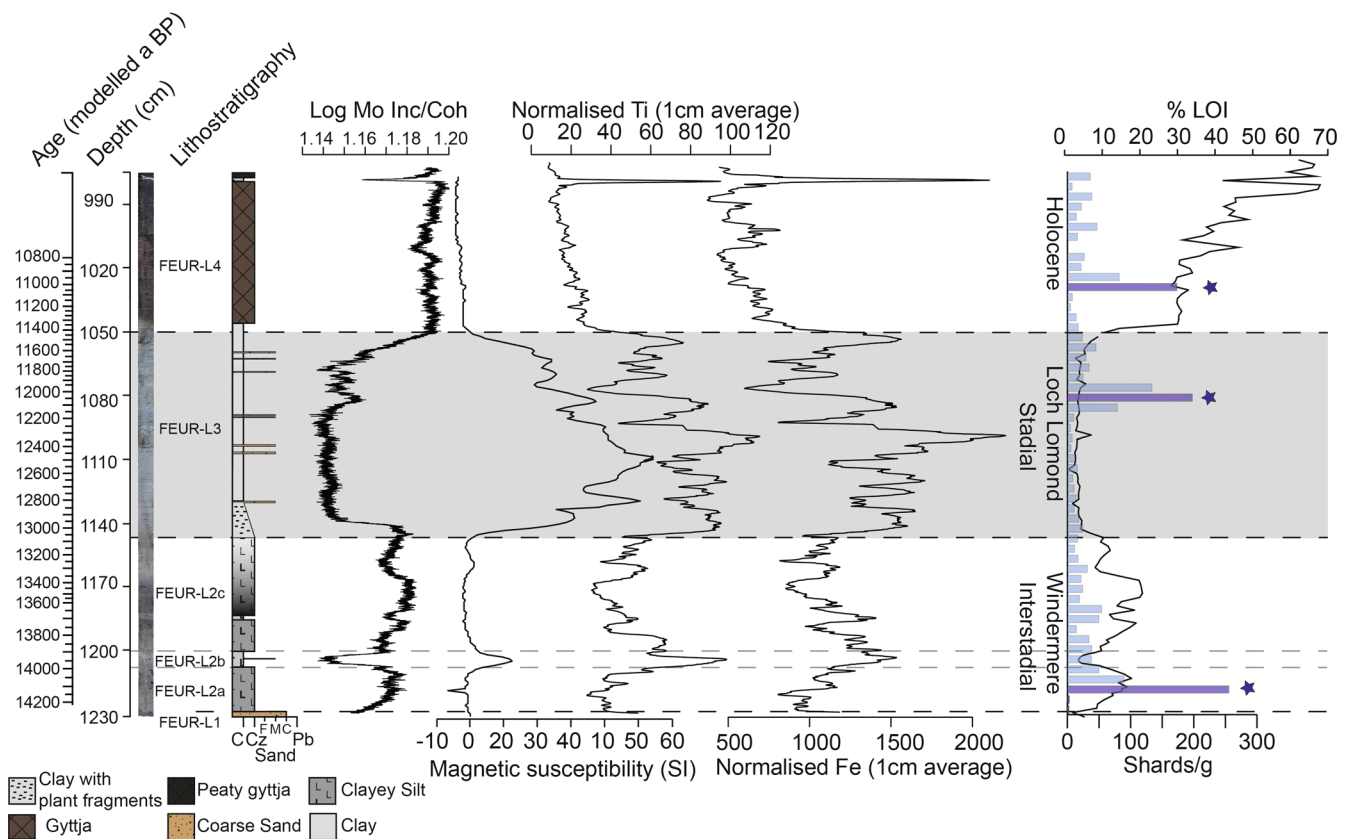
Figure 4. Summary of sedimentology of Lochan Feurach, against depth, with four sedimentary units labelled and key climatostratigraphic units detailed with the tephra shard profile. Lithostratigraphic units are marked by dashed lines and labelled on sediment log. Log Mo Inc/Coh profile is at 200 µm resolution, while Ti and Fe are normalised to cps and are 1 cm moving averages of the 200 µm data. Blue stars on the tephra graph denote the purple intervals selected for geochemical analyses, while the blue bars denote the 5 cm range-finder profile. [Color figure can be viewed at wileyonlinelibrary.com]

sand (1232–1228 cm; Fig. 4). FEUR-L2 comprises dark grey silts and clays with variable loss-on-ignition (LOI) values of 10–20%, while two bands of clay ~4 cm thick were noted at 1204–1200 cm and 1183–1179 cm (Fig. 4). The first band of clay has been assigned as a subunit (FEUR-L2b) based on the magnitude of the excursions seen in the increased MS, LOI (~5%) and µXRF (increased Ti) data. FEUR-L2c contains some further variability within the %LOI and µXRF data, but not in the MS data. FEUR-L2c becomes stiffer and qualitatively transitions diffusely into the overlying unit: in the quantitative data (MS, % LOI, µXRF) this boundary is sharp. FEUR-L3 comprises a light grey silty clay with no regular structure from 1148 to 1050 cm and within the unit there are eight fine sand beds <3 cm thick. The MS and normalised Fe and Ti values are variable and reveal several oscillations within the unit while LOI values remain <5% throughout. Towards the top of the unit there are visible flecks of plant fragments within the silty clay and there is a clear lithological transition into the subsequent lake mud at 1050 cm.

FEUR-L4 extends from 1050 to 975 cm and comprises micaceous lake mud, with higher %LOI, Log Mo Inc/Coh ratios and much lower MS, Fe and Ti values (Fig. 4). There is a fine clay band <1 cm thick at 980 cm, before the sediment darkens in colour and becomes more humified. This unit likely continues before transitioning into the peat that covers the surface of the basin at present, but the upper material was not retrieved as part of this investigation.

Pollen stratigraphy

Variations in relative percentages of terrestrial and aquatic pollen taxa, fern spores and the cells (or cocci) of the green algae *Pediastrum* are all calculated as percentages of total land

pollen (TLP; Fig. 5). Broadly, the data are in accord with the lithostratigraphic and pollen-stratigraphic succession that is typical for Lateglacial–Early Holocene sequences in Scotland (Walker and Lowe, 1990, 2019), with the assignment of the Feurach sequence to this period supported by the tephrochronological results that are presented in the next section.

Overall trends in the data suggest a broad threefold division of the spectra into WI, LLS and Early Holocene stratigraphic units on the criteria outlined below. A more intricate subdivision of the data into local pollen assemblage zones is not attempted as it is considered likely to generate equivocal results for the following reasons. First, some of the pollen totals are numerically low (supplementary data), significantly lower than the 500 TLP recommended by Berglund and Ralska-Jasiewiczowa (1986), though it is claimed that totals as low as 100 TLP can generate statistically significant data in certain cases (Djamali and Cilleros, 2020). Second, the microfossil identifications are mostly made to genus or family level only, with no complementary macrofossil data to help determine the species represented in the pollen records. This can have a major bearing on any ecological inferences drawn from the data. For example, it cannot be certain whether the pollen records of *Betula* and *Salix* represent dwarf or shrub/tree species. Third, recycling of pollen has been found to be a significant problem in deposits of Lateglacial age, as illuminated by the analysis of the state of preservation of fossil pollen grains in several Lateglacial sequences (e.g. Lowe and Walker, 1986; Walker and Lowe, 1990). The percentages of corroded or otherwise degraded pollen grains are especially evident during episodes of significant climatic deterioration, for example during the transition from the WI to the LLS. A systematic analysis of the number and types of degraded
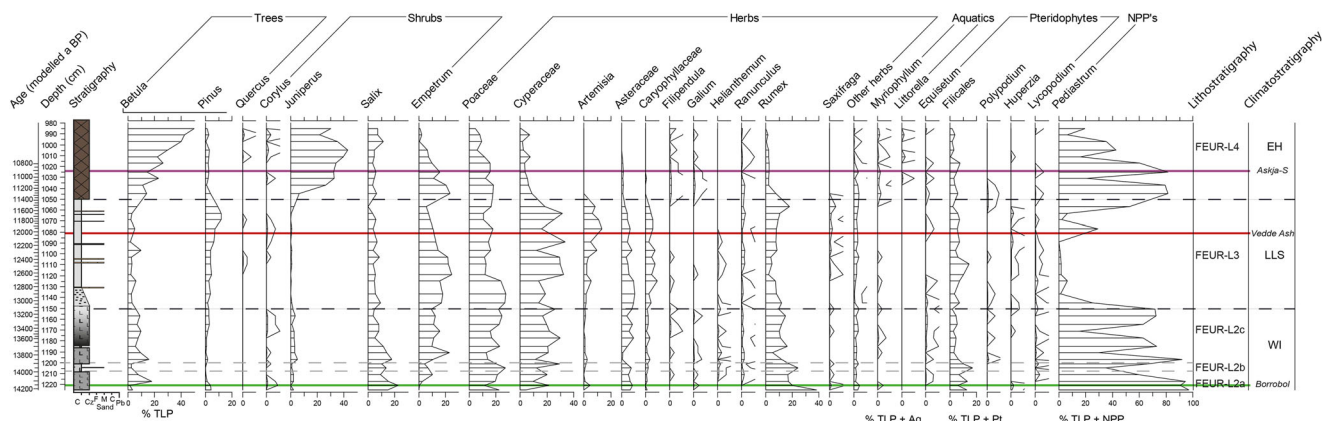
Figure 5. Relative pollen percentage diagram (some minor taxa excluded) for the basal sediment sequence in Lochan Feurach, broadly zoned into Windermere Interstadial (WI), Loch Lomond Stadial (LLS) and Early Holocene (EH) assemblages, with the positions of the peak concentrations of Borrobol, Vedde and Askja-S tephra shard counts indicated. Along the left-hand side, the stratigraphy from Fig. 4 is presented for context. [Color figure can be viewed at wileyonlinelibrary.com]

microfossils was not attempted here, however, as it can be very time-consuming, while the classification process can be subjective. Finally, although some clear temporal trends can be discerned in the data, these are complicated by several short-term fluctuations (Fig. 5), most of which appear irregular and which would require analysis at a higher stratigraphic resolution to establish their significance. Taken together, these caveats constrain the degree to which the data can be interrogated; nevertheless, the broad trends discernible in the data are consistent with other pollen-stratigraphic records from the Scottish Highlands that straddle the LGIT, and the focus here is more on the chronostratigraphic interpretation of the results than on their palaeoecological significance.

The pollen spectra within the interval 1225 to 1140 cm, which span the weakly organic unit FEUR-L2 (Figs. 4, 5), are typical for WI records obtained from sites located within the Scottish Highlands and Hebridean islands, in that they record very low amounts of tree (*Betula*) and shrub (*Juniperus, Empetrum*) pollen but are dominated by taxa of open grassland communities, with *Rumex*, Poaceae, Cyperaceae and Asteraceae prominent (cf. Pennington *et al.*, 1972; Birks and Williams, 1983; Lowe and Walker, 1986; Walker and Lowe, 1990; Birks, 1994).

Values for *Betula* and *Juniperus* pollen are particularly low in the Feurach sequence in comparison with other Highland records, while *Empetrum* values are extremely low at the base of the profile, but gradually increase throughout the WI interval. This suggests that the relatively high values for *Betula* (up to 19% TLP) and *Salix* (up to 22% TLP) near the base of the profile are likely to reflect the local growth of the dwarf species *B. nana* and *S. herbacea*, as components of a pioneer stage in vegetation succession that preceded the encroachment of *Empetrum* heath into the vicinity. The pollen spectra in this part of the diagram therefore suggest that the catchment around the Feurach basin remained dominated by an open steppic or tundra vegetation throughout the WI, similar to modern assemblages recorded, for example, in arctic Norway and Svalbard (Nevalainen *et al.*, 2012).

A notable feature within the WI part of the record is the curve for percentage values of *Pediastrum* cocci, which record high values near the base of the profile but decline to minimal values in the upper part of the unit. There is increasing evidence to suggest that *Pediastrum* could be a very important palaeoenvironmental indicator in Lateglacial lake records, apparently being most sensitive to changes in lake water pH, dissolved organic content, nutrient influx and possibly water temperature, which can all co-vary with changes in lake level

(e.g. Jankovská and Komárek, 2000; Sarmaja-Korjonen *et al.*, 2006; Weckström *et al.*, 2010). The high values at the base of the profile could indicate a period of high productivity in the lake, suggesting reasonably mild local climatic and perhaps eutrophic lake waters. The subsequent decline in *Pediastrum* values could possibly indicate gradually deteriorating climatic conditions and more oligotrophic lake waters. Prompting this suggestion is the significant oscillation in *Pediastrum* values evident between ca. 1215 and 1190 cm depth (FEUR-L2b), which coincides with parallel declines in *Betula*, *Salix* and *Empetrum* values. These features also coincide with prominent oscillations recorded in LOI, MS, normalised Ti and Log Mo values (Fig. 4), the relevance of which is assessed in the section 'Palaeoenvironmental implications', below.

The lower boundary of the LLS unit (FEUR-L3) is marked by the start of a steady increase in values for *Artemisia* and Caryophyllaceae pollen percentages and sustained reduced percentages in *Rumex*, Poaceae, *Salix* and *Betula*. Perhaps appearing anomalous in this context is the rise in *Empetrum* pollen percentages in the early part of the LLS: although not quantified, it was clearly evident during pollen analysis that the majority of these grains were badly corroded, and hence are likely to have been recycled from local soils as climatic conditions became more severe. The data suggest a shift towards more disturbed ground and a sparser vegetation cover, a change which appears to have intensified after deposition of the Vedde Ash ('Tephrostratigraphy', below), when *Artemisia* percentages markedly increase in concert with small but sustained increases in *Saxifraga* and spores of *Huperzia selago*. Also prominent in this later part of the LLS is a peak in *Pinus* pollen which is thought to be the result of far-travelled wind-blown pollen (cf. Birks *et al.*, 2005), the representation of which is likely to be artificially enhanced in relative percentage terms by a low local pollen influx (e.g. Tipping, 1985 Hoek, 2001; Birks *et al.*, 2005; Paus *et al.*, 2011).

The lower boundary of the Early Holocene is clearly marked by strong declines in several herbaceous taxa, notably *Artemisia*, Caryophyllaceae and Asteraceae, while other herbaceous taxa become more strongly represented, including *Filipendula, Galium* and *Rumex*. The boundary is also marked by a resurgence of *Pediastrum*, which appears to have been absent from the lochan during most of the LLS, while pollen of the aquatic taxa *Myriophyllum* and *Littorella* are well represented in the profile for the first time. The most characteristic features in this part of the diagram are the sequential sharp rises to high values of *Empetrum, Juniperus*

and *Betula* pollen, the hallmark succession for the Early Holocene in Scottish pollen diagrams (Walker and Lowe, 2019). The fact that these three taxa become so quickly established after the LLS, reaching percentage levels far higher than were attained at any time during the WI, suggests that conditions were much less benign in and around the Feurach basin during the WI than were quickly established during the Early Holocene.

Tephrostratigraphy

Tephra shards in low concentrations (<20 shards/g) were detected in all of the contiguous 5 cm samples extracted from core BH1 with the exceptions of three samples where concentrations of 255, 197 and 173 shards g^{-1} were obtained from depths of 1222–1217 (FEUR-L2a), 1085–1080 (FEUR-L3) and 1025–1020 (FEUR-L4) cm, respectively. Resampling of these three intervals at 1 cm depth resolution refined peak shard concentrations of 524, 550 and 365 shards g^{-1} at depths of 1221–1220, 1082–1081 and 1024–1023 cm depth, respectively. Glass shards were extracted from each of these levels to be processed for chemical analysis, with successful measurements obtained from 7, 19 and 14 shards from the upper, middle and lower samples, respectively (Fig. 6; Supplementary data).

Of the three peaks identified, the lowest in the sediment sequence (FEUR-T1221) occurs close to the base of the unit (FEUR-L2a) assigned to the WI on pollen-stratigraphic evidence (Figs. 4, 5, 6) and has a subalkaline rhyolitic chemical signature indicating an Icelandic origin (Lind *et al.*, 2016). Three tephra layers identified in LGIT sequences from Scotland have this 'Borrobol-type' chemical signature, one of which (CRUM1-597) has been identified at only one site thus far, at Crudale Meadow, Orkney, and lies close to the WI-LLS transition (Timms *et al.*, 2018) and hence is unlikely to be a correlative of the FEUR-T1221 record. The more likely correlatives are either the Borrobol Tephra or the Penifiler Tephra, both of which are consistently found close to the base of WI records in a number of sites in Scotland, both dating to between ~14.1 and 13.9 cal ka BP (Timms *et al.*, 2019). Since their chemical signatures are so similar, it can be difficult to

determine which is represented when only one of the layers is preserved in a sequence, as is the case here, while the possibility that there may have been a third 'Borrobol-type' tephra dispersed at around this time complicates things further (Larsson and Wastegård, 2022). However, several records from sites in Scotland show evidence for a short-lived climatic oscillation near the base of the WI which is assumed to equate with the GI-1d oscillation in the Greenland stratotype sequence, which dates to around the same time (Rasmussen *et al.*, 2014), and this provides a means of further refinement: the Borrobol Tephra (*sensu* Timms *et al.*, 2019) immediately predates this oscillation, while the Penifiler Tephra coincides with its termination (see Matthews *et al.*, 2011; Brooks *et al.*, 2016; Abrook *et al.*, 2020). The prominent oscillation immediately below 1200 cm depth in the Feurach stratigraphical record, clearly signalled by the Log Mo Inc/Coh, MS, Ti and LOI data (Fig. 4), is a new record from Scotland that most likely represents this event, and since the FEUR-T1221 tephra layer predates this, it is most likely a correlative of the Borrobol Tephra. It should be noted, however, that two of the chemical measurements from this horizon yielded Katla-type outlier values, which could indicate reworking from an earlier tephra with this chemistry or some downward relocation of the Vedde Ash (considered next) during coring operations, but the data are too sparse to resolve this issue.

The chemical data for FEUR-T1082 are also rhyolitic in composition but with a Katla distribution that plots precisely within the data-spread typical for the Vedde Ash, especially in terms of CaO–FeO ratios (Fig. 6). The Vedde Ash is one of the most distinctive ash layers preserved in Scottish Lateglacial sequences, as it typically presents the highest shard concentrations when compared with other Lateglacial cryptotephra layers and is consistently found well within the boundaries of the minerogenic sediments assigned to the LLS (Bronk Ramsey *et al.*, 2015; Timms *et al.*, 2019), as is the case for Lochan Feurach. FEUR-T1082 can therefore be confidently assigned to the Vedde Ash.

The uppermost of the three tephra peaks, FEUR-T1023, is composed of rhyolitic glass shards with high CaO (1.5–1.6 wt%) and low K_2O (~2.5 ± 3 wt%) values, a chemical signature that closely matches the Askja-S eruptive reported in Early Holocene
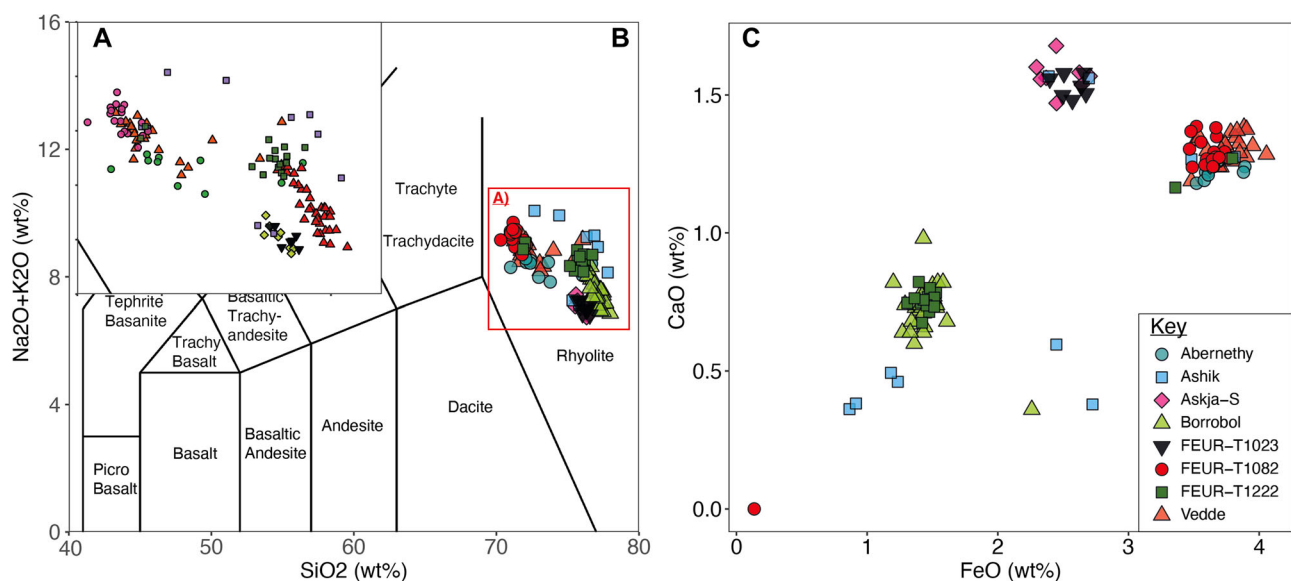

Figure 6. Results of the electron probe micro-analysis geochemical analyses on shards extracted from the peak shard concentrations at 1222–1217 cm, 1081–1082 cm and 1023–1024 cm depth, compared with published data from the nearby Abernethy Forest and Loch Etteridge sites (Matthews *et al.*, 2011; Timms *et al.*, 2019). A) Inset denotes a zoomed in version of a total alkali vs silica plot by Bas *et al.* (1986) which is shown in B). C) A bi-plot of FeO vs CaO for the same data. [Color figure can be viewed at wileyonlinelibrary.com]

records ranging from Norway (Pilcher *et al.*, 2005) to Soppensee in Switzerland (Lane *et al.*, 2011) but with a mainly northwest European distribution (Ott *et al.*, 2016; Jones *et al.*, 2017). It has also been identified in several sites in Scotland where it is consistently found within the Early Holocene *Juniperus* phase in pollen-stratigraphic sequences (Kelly *et al.*, 2017; Lowe *et al.*, 2019; Weston *et al.*, 2021), as is also the case in the Feurach sequence.

Age model

The three tephra isochrons detected in the Feurach sequence are all consistent with previously published records from Scotland, in terms of their chemical affinities and their stratigraphic positions with respect to the tripartite litho- and pollen-stratigraphic succession that is consistent with LGIT sediment sequences in Scotland (Walker and Lowe, 2019). The current best-estimate age for the Borrobol Tephra is 14.10 ± 0.09 cal ka BP (Bronk Ramsey *et al.*, 2015; Timms *et al.*, 2019), for the Vedde Ash is 12.02 ± 0.09 cal ka BP (Bronk Ramsey *et al.*, 2015) and for the Askja-S tephra is 10.82 ± 0.10 cal ka BP (Kearney *et al.*, 2018). The radiocarbon date reported for the sequence by Clapperton *et al.* (1975) of $11\ 770 \pm 87$ ^{14}C a BP calibrates (using IntCal20) to between 13.8 and 13.47 cal ka BP at 2σ statistical range, and since it was obtained from a horizon that lies between those of the Borrobol Tephra and Vedde Ash reported here (Fig. 7), it is compatible with the tephrochronological data.

Collectively, therefore, the new chronological data provide a coherent timeframe for the Lochan Feurach record, except for the basal inorganic sediments which could not be dated by the methods adopted in this study. In order to constrain the minimum age of the onset of organic sediment accumulation in the basin, therefore, cosmogenic nuclide dates for the ages of Late Devensian moraine ridges in the nearby Cairngorm valleys of Strath Nethy and Gleann Einich (Hall *et al.*, 2016) were used as a limiting age for the onset of sedimentation by utilising an 'After' function. This constrains sedimentation to only occurring after the estimate of deglaciation produced by the cosmogenic nuclide dates (Bronk Ramsey, 2008). These dates were utilised alongside the radiocarbon and tephrochronological age estimates reported above to generate a Bayesian age–depth model for the Lochan Feurach sequence (Fig. 8). Underpinning the results is a *P_Sequence* depositional model constructed in OxCal V.4.4.2 (Bronk Ramsey, 2008, 2009) with dates calibrated using the IntCal20 calibration curve (Reimer *et al.*, 2020). The k_parameter (Bronk Ramsey, 2008) was permitted to vary over two orders of magnitude from a starting value of one and a general outlier detection model was used for all age estimates used within the model. The radiocarbon date reported by Clapperton *et al.* (1975) was based on a bulk-sediment sample that spanned a depth
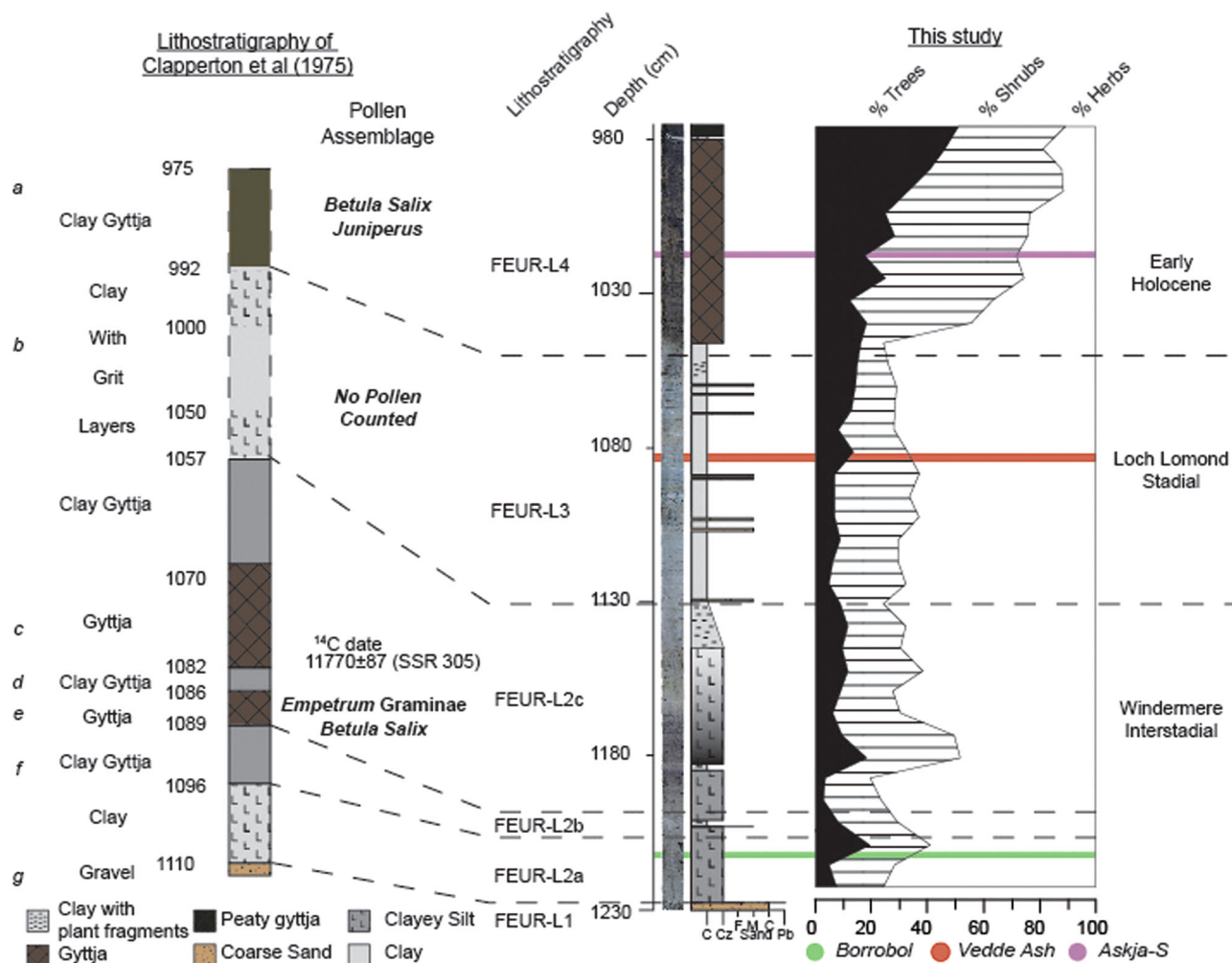

Figure 7. Correlation of the lithostratigraphic sequence reported by Clapperton *et al.* (1975) and the sequence reported in the current study, showing the position of the radiocarbon date reported in the earlier study with respect to the lithostratigraphic and tephrostratigraphic sequence reported in the present study. [Color figure can be viewed at wileyonlinelibrary.com]
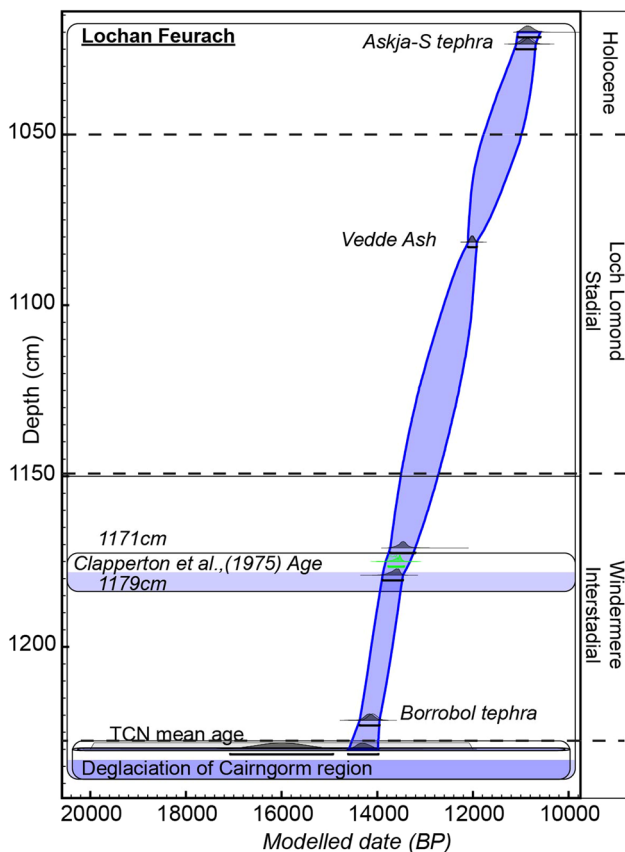
Figure 8. Output of the age–depth model produced in Oxcal using a broad constraint for the timing of deglaciation derived from existing cosmogenic age estimates for the region and the published age estimates for the LGIT tephra signatures recorded in this sequence. The model also incorporates the single radiocarbon date reported by Clapperton et al. (1975), allowing for the broad stratigraphic interval from which the dated sample was obtained (see text). This model was constructed using the Intcal20 calibration curve for the radiocarbon date in addition to the calendar ages of the tephra layers (Reimer et al., 2020), with broad climato-stratigraphic units outlined on the right of the figure. [Color figure can be viewed at wileyonlinelibrary.com]

interval of 6 cm. Its stratigraphic position was transferred to our new core sequence before being integrated into the model. The spread in depth intervals was accounted for using the approach outlined in Lowe et al. (2019) and Lincoln et al. (2020) and assumes that the date obtained is an equal amalgamation of the whole stratigraphic interval. Although the resulting age model is based on a limited number of tie-points, the raw data are based on three independent dating methods that have yielded coherent results, while internal model agreement measures are strong. The results are therefore used to provide a timescale for the timing of key palaeoenvironmental changes reflected in the Lochan Feurach LGIT sediment succession, which are considered next.

Palaeoenvironmental implications

The earliest sediments recorded at Lochan Feurach (FEUR-L1; Fig. 4) consist of coarse sands which likely reflect the flushing of coarse sediment into the basin from unstable newly abandoned glacial deposits. The age model suggests that the end of this phase of sand deposition and the onset of increasingly organic deposition dates to 14.27 ± 0.15 cal ka BP, but this is a minimum age given that (a) the basal deposits have not been dated directly, and (b) the uncertainty ranges of

the cosmogenic dates incorporated into the age model are of the order of several hundred years (Hall et al., 2016). Nevertheless, taking the available evidence and the associated uncertainties into consideration, the implication is that the basin likely became ice-free and experienced organic sedimentation ~400 years after the onset of the GI-1e warming dated in the Greenland stratotype sequence to ~14.7 cal ka BP (Rasmussen et al., 2014). This timing is in line with evidence obtained from a growing number of LGIT lake basin sequences in Scotland which indicate a similar age for the onset of organic sedimentation (e.g. Turney et al., 1997; Lowe et al., 2008; Matthews et al., 2011; Candy et al., 2016; Timms et al., 2019; Abrook et al., 2020). However, other inorganic sediment inputs (slumping, inwash from unvegetated slopes, buried ice melt-out) may have dominated in the earliest WI and cannot be discounted.

The accumulation of finer-grade sediments and the onset of the influx of pollen and spores recorded in FEUR-L2 suggest that environmental conditions ameliorated in the Feurach catchment during the WI, but a series of significant fluctuations in the µXRF data suggest that local slopes continued to be relatively unstable (cf. Standell, 2014). Furthermore, the low relative representation of pollen of *Betula*, *Juniperus* and *Empetrum*, coupled with relatively high percentages of *Salix* and *Rumex* (Fig. 5), suggests a local vegetation cover dominated by prostrate and dwarf shrub taxa, while the predominance of minerogenic sediments in this unit suggests that unstable and exposed landscapes prevailed throughout the WI (cf. Wijk 1986). LOI values also remain intermediate (mostly <20%) throughout this interval, which suggests that soils were weakly developed around the basin margins with the organic component of the sediment infill probably mostly sourced from autogenic lacustrine sources, notably from the green algae *Pediastrum*, which appears to have flourished in the basin throughout the WI.

A notable oscillation in the lithological and biostratigraphic data between c. 1210 and 1200 cm depth (FEUR-L2b), the onset of which occurs immediately above the horizon in which the Borrobol Tephra was identified, is considered a local expression of the GI-1d event detected in the Greenland stratotype sequence (Rasmussen et al., 2014). Three short-lived cooling episodes have been identified in the Greenland record within the WI/GI-1 interval: from oldest to youngest, GI-1d (~14 ka), GI-1c2 (~13.65 ka) and GI-1b (~13.2 ka), but the most prominent climatic oscillation in records from the Scottish Highlands is dated to 14.0 ka and is considered an equivalent to GI-1d (Brooks et al., 2016). There are some minor inflections in the Ti and Log Mo Inc/Coh data within FEUR-L2c that could reflect climatic perturbations equivalent to GI-1c2 and GI-1b, but these are not as obvious as the oscillation within FEUR-L2b which is equated with GI-1d. In these respects, therefore, the Feurach record is in accord with the general pattern that is emerging for WI records located within the Scottish Highlands, but the vegetational response to climatic amelioration during the WI is subdued in the Feurach record, probably reflecting the relatively high altitude of its catchment within Glen Builg.

A change to a more severe climatic regime at the start of FEUR-L3 is indicated by a sharp reduction in *Pediastrum* values and by equally strong inflections in the data for Log Mo Inc/Coh, MS and Ti, as well as more gradual changes in key pollen taxa (reductions in *Betula*, *Juniperus*, *Salix* and *Rumex*; increases in *Artemisia*, Caryophyllaceae and Cyperaceae). The onset of this transition in this sequence is dated to 12.96 ± 0.19 cal ka BP close to the date for the onset of GS-1 identified in the Greenland stratotype sequence. As noted earlier ('Pollen stratigraphy', above), an increase in the number

of badly corroded pollen grains was observed in this part of the sequence, especially with respect to *Empetrum* grains, which is attributed to the inwashing of disturbed soils into the basin. The erratic values for Ti and, to a lesser extent, for MS measurements, suggest pulsed inputs of sediment from the catchment slopes, as do the occasional thin layers of sand detected throughout the FEUR-L3 unit. The collective evidence suggests the influence of permafrost-related processes in the lake's catchment at that time.

Recent studies of LLS records in Scotland have reported significant changes that coincide with, or date close to, the horizon in which peak Vedde Ash glass shards are detected (Brooks *et al.*, 2012, 2016; Abrook *et al.*, 2020; Palmer *et al.*, 2020). This bipartition of the LLS is also evident in the Lochan Feurach sedimentological record (Fig. 4), highlighted by contrasting absolute values and the magnitude of a series of abrupt fluctuations in the MS and Ti records both above and below the Vedde Ash. A further important distinction is that pollen percentages of *Artemisia* and *Pinus* values are noticeably higher above the Vedde Ash than below it – increased percentages of *Artemisia* are frequently cited as indicating a change to a drier or more unstable climatic regime (Birks, 1994; Brauer *et al.*, 1999; Mangerud *et al.*, 2016). In the absence of independent quantified palaeoclimatic information, the cause for this mid-Stadial shift is difficult to gauge, but we hypothesise that the initial phase was cold and wet, perhaps with spring-melts following periods experiencing particularly heavy winter snow loads being responsible for the pulsed delivery of sediment into the basin, while the later phase remained cold but drier by comparison. Additional records with quantified palaeoclimatic data are required to gain a fuller understanding of these apparent regional disparities in Scotland during the LLS.

The LLS–Holocene (FEUR-L3/FEUR-L4) boundary is sharply defined in the Feurach sequence by the μXRF, LOI and pollen-stratigraphic data, but the MS and Log Mo Inc/Coh data show more gradual transitions (Figs. 4 and 5). The collective evidence, however, suggests the most marked palaeoenvironmental change to be registered at ~1050 cm depth in the sequence, which dates to around 11.40 ± 0.18 cal ka BP (Fig. 5). By the time of the lithological change at this level, there are marked and sustained increases in *Pediastrum* and *Empetrum* with *Betula* and *Juniperus*, the percentages of which increased quickly after this time. The rapid expansion of the latter suggests that more benign conditions were established in the Early Holocene than were attained at any time during the WI, at least in this part of the Cairngorm Mountains. While warming temperatures may have been initiated a little earlier, it is not until 11.40 ± 0.18 cal ka BP that sustained stabilisation of the landscape enabled sufficient soil development to permit the colonisation of local slopes by *Juniperus* scrub and *Betula* woodland, an indication that is in common with Early Holocene records from most other parts of Scotland (Walker and Lowe, 2019). The persistence of high *Juniperus* percentages until well after the Askja-S tephra was deposited at around 10.82 ± 0.10 cal ka BP and the very gradual increase in birch pollen percentages suggests that a more open juniper–birch association persisted in this upland locality for a longer period than is typically depicted in records obtained from lower altitude and more southern sites in Scotland (Tipping, 1997; Ramsay and Dickson, 1997; Huntley 1994; Edwards *et al.*, 2019).

The wider context

This reinvestigation of a sediment sequence preserved in Lochan Feurach corroborates the main conclusion drawn by Clapperton *et al.* (1975); that the basin started to fill with sediment during the WI. This demonstrates that glacier occupation of this sector of the Cairngorm Mountains during the LLS must have been restricted in extent, supporting Sissons' (1979) proposals for the Cairngorms area in general. Our new results are based on a more detailed examination of the local geomorphological features adjacent to Loch Builg and a more highly resolved pollen-stratigraphic sequence for the Feurach sequence than that reported by Clapperton *et al.* (1975); we also generated data using analytical methods unavailable at the time, notably high-precision μXRF measurements and the detection of cryptotephra layers. The tephra results, when combined with a single radiocarbon date obtained by Clapperton *et al.* (1975), provide a refined age model for the sequence and enables the timing of palaeoenvironmental changes reflected in the proxy evidence to be estimated, which are summarised below.

The oldest organic sediments in the basin are dated to 14.27 ± 0.15 cal ka BP, which post-dates the marked warming reflected in the Greenland stratotype record at the start of the GI-1e (Rasmussen *et al.*, 2014) by ~400 years. It is not known whether this result indicates that ice-sheet withdrawal from this location occurred close to this date of ~14.3 cal ka BP, or whether buried ice occupied the basin after the ice-sheet margin retreated from the area. Alternatively, we note the large uncertainties on the model and its reliance on the correlation with the Borrobol Tephra at ~14.14 cal ka BP. However, a number of basins in localities dispersed throughout the Scottish Highlands and the Inner Hebrides also contain sediment sequences extending into the WI which seem to have started to accumulate sediment at a similar time (Timms *et al.*, 2019; Walker and Lowe, 2019; Lowe *et al.*, 2021). This might suggest the imposition of a common controlling factor over a wide area, perhaps some potent regional climatic shift, or the widespread sudden collapse of what remained of the retreating Late Devensian ice sheet (Bradwell *et al.*, 2008, 2021), or a combination of the two. These are speculations, however, in need of wider and more forensic investigation.

Similar to a number of LGIT records from Scotland is the short climatic reverence signal detected near the base of the Feurach sequence which accords in timing with the GI-1d interval in the Greenland stratotype sequence (Fig. 9). Two younger reversals in the Greenland record (GI-1c2 and GI-1b) tend to be poorly resolved in Scottish pollen records, as in the case of the Feurach pollen record. In this instance this may reflect the fact that climatic conditions were already challenging in the Feurach catchment, as the pollen evidence suggests the preponderance of poorly developed soils and a vegetation cover dominated by dwarf shrub and grassland taxa throughout the WI interval, although the actual climatic conditions cannot be quantified using the available data. The nearest sites for which quantified palaeoclimatic data for the WI are available are Abernethy Forest, which lies on the northern margin of the Cairngorm National Park at an altitude of 210 m (Matthews *et al.*, 2011), and Tirinie near Blair Atholl, some 80 km southwest of the Feurach site (altitude 323 m; Abrook *et al.*, 2020). Chironomid-inferred mean July temperatures for the WI from both sites average ~11 to 12°C, and employing the modern environmental lapse rate of 0.67°C per 100 m suggests that the mean July temperature at Feurach may have been 1.5 to 2°C cooler. However, this is but one facet of the climatic regime that prevailed at the time, and aspects that are not known, for example, the contemporaneous seasonal temperature range or duration of winter minima typical of the time, may have been more critical. An additional key factor may have been the exposure of Lochan Feurach to cold winds funnelled down the upper Gairn valley from the Beinn Bhuird massif located to the west of the site, the highest summits of which are at 1197 m in altitude.
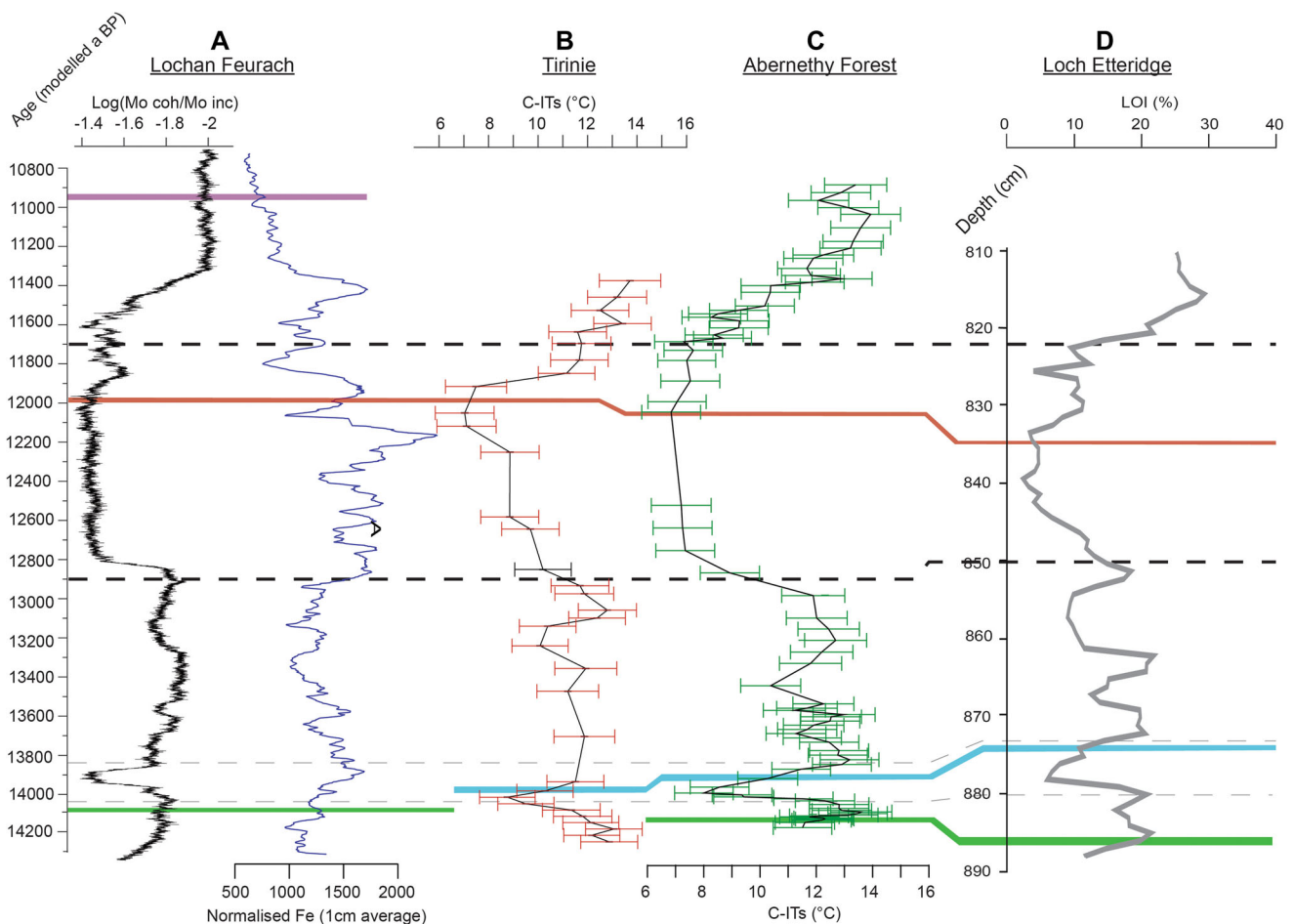
Figure 9. The LGIT record from the Loch Builg valley placed in the context of other, nearby published sites recording the LGIT. A) Lochan Feurach with Log Mo Inc/Coh and Fe as proxies for organic content and inwash. B) Tirinie chironomid-inferred temperatures (C-ITs) from Abrook *et al.* (2020). C) Abernethy Forest C-ITs from Brooks *et al.* (2012). C) No chironomid data were available for Loch Etteridge but the % loss-on-ignition (LOI) is presented as this responds sensitively to environmental changes at this time. Sites are stratigraphically linked based on the positions of the Vedde Ash and the Borrobol Tephra, as well as through large changes in the palaeoenvironmental record or sedimentology inferred as reflecting a climatostratigraphic change. The blue line denotes where the Penifiler Tephra has been identified in Tirinie, Abernethy Forest and Loch Etteridge. [Color figure can be viewed at wileyonlinelibrary.com]

A further intriguing feature that is emerging from recently reported Scottish records that span the LGIT is the evidence for some penecontemporaneous bipartition of the LLS (see 'Palaeoenvironmental implications', above). That LLS pollen records from Scotland are characterised by distinctive trends or contrasts in the pollen assemblage data, most marked by a significant increase in *Artemisia* percentages in the later Stadial, has long been recognised and was generally attributed to a change towards drier climatic conditions and/or more disturbed ground surfaces (e.g. Walker, 1975; Lowe and Walker 1977, 1986; Birks and Matthewes, 1978; Caseldine, 1980; Macpherson, 1980; Walker and Lowe, 1990). This palynological trend is also evident in the part of the Feurach record assigned to the LLS (Fig. 5). So far as these older records were concerned, there was no reliable means of establishing the relative timing of these significant shifts in the pollen assemblage data; that has changed with the increased adoption of the tracing of cryptotephra isochrons in the investigation of LGIT sediment sequences (Timms *et al.*, 2019; Walker and Lowe, 2019). The results indicate that the main change during the LLS is consistently aligned at or before the horizon at which peak Vedde Ash shards are recorded (Brooks *et al.*, 2016; Palmer *et al.*, 2020). This suggests the influence of a regional forcing factor dating to around or before 12.1 cal ka BP, based on the timings of change at Lochan Feurach.

Evidence is mounting for a significant shift in climatic conditions affecting northern Europe that dates to around 12.15 cal ka BP, which Bakke *et al.*, (2009) attribute to the northward migration of the Atlantic Oceanic Polar Front from its southernmost migration position off the Iberian coast during the early Stadial (Baldini *et al.*, 2015). This northward shift is hypothesised to have allowed westerly winds to resume their dominant track across northwest Europe, leading to the break-up of sea ice in the northeast Atlantic. The response to this proposed climatic regime shift appears to have been locally diachronous, impacting on central Germany ~140 years before western Norway (Lane *et al.*, 2013), due possibly to gradual northward movement of the Atlantic Oceanic Polar Front, or to local factors that initially hampered any environmental response. It is possible that the stratigraphic evidence from Scotland for a significant change at around 12.1 cal ka BP is linked to this wider climatic regime change, but the pattern of environmental response within the Scottish Highlands appears to have been complex. For example, while glaciers in the northwest Highlands and Hebridean islands maintained a sustained decline after 12.1 cal ka BP, one that appears to have commenced three or four centuries earlier (Ballantyne, 2012), larger ice masses in the southwest Highlands continued to expand, some not reaching their maxima until 11.8 cal ka BP or later (MacLeod *et al.*, 2011; Palmer *et al.*, 2020). Chironomid-inferred palaeotemperature records for the LLS are also divergent, with some suggesting a shift from cold to warmer conditions after 12.1 cal ka BP while others suggest the opposite trend, thought to result from snow melt influencing lake temperatures (Brooks *et al.*, 2016; Abrook

et al., 2020; Francis et al., 2021). In the case of the Feurach record, there is no evidence for any significant warming in the later Stadial, post-12.1 cal ka BP. While it has been hypothesised that these different trends may reflect local factors, such as proximity to large ice masses (Palmer et al., 2020; Lowe et al., 2021), too few well-resolved and quantified palaeoclimatic records for the LLS are presently available to test this proposal robustly. Nevertheless, the narrative for this period clearly needs to heed these divergent lines of evidence as signs that the pattern of environmental change in Scotland during the LLS was possibly more complex and dynamic than previously assumed.

Finally, the Feurach proxy record provides new insight into the LLS/Early Holocene transition. Several proxy indices suggest significant change in mineral sediment recruitment into the basin after ~12.1 cal ka BP (Log Mo Inc/Coh, magnetic susceptibility and normalised Ti data), whereas the LOI and pollen data do not register a marked change in organic accumulation and local vegetation cover until 11.4 ± 0.18 cal ka BP ('Palaeoenvironmental implications', above; Figs. 4, 5 and 9). While this is within the uncertainties of the formal boundary for the onset of Holocene warming (Walker et al., 2009), it is also consistent with the slightly delayed deglaciation of the Scottish Highlands (Lowe et al., 2019; Palmer et al., 2020). At present our chronology at Lochan Feurach is insufficiently precise to determine whether there was either a delay in the onset of warming in the Cairngorm Mountains or a delay in local environmental adjustments to the warming. The latter seems the more likely, since the robust varve chronology developed for the ice-dammed lakes that occupied Glen Roy and Glen Spean during the LLS indicates that the glacier margins started to retreat ~11.8 cal ka BP, a process that accelerated at ~11.65 cal ka BP (Palmer et al., 2020), while the retreating glaciers did not vacate the main source area on the Rannoch Plateau until ~11.5 cal ka BP (Lowe et al., 2019). This suggests that following initial warming, it took three centuries or more for the landscape in parts of the Scottish Highlands, including Glen Builg, to adjust to the initial warming, a transitional period that also appears to have had parallels in the deglaciation history of parts of west and south Norway (Høgaas et al., 2022).

Conclusions

1. The Lochan Feurach basin contains a sediment sequence that extends back into the WI, supporting the view that glacier occupation of the Cairngorms during the LLS was spatially restricted.
2. Sediment accumulation in the basin did not commence until 14.27 ± 0.15 cal ka BP, in line with other records obtained from widely dispersed lake basins in the Scottish Highlands and Inner Hebrides. This emerging pattern suggests the imposition of an important regional control over the onset of sedimentation during the WI.
3. A climatic revertence near the base of the sequence accords in timing with the GI-1d interval in the Greenland stratotype sequence. There is little evidence of the equivalents of two other later revertence episodes reflected in the Greenland record, probably because the climatic conditions in the Feurach catchment were harsh during the WI, hampering soil development and vegetation succession.
4. A distinctive change in the LLS pollen record coincides approximately with the deposition of the Vedde Ash, also in line with some other records from Scotland. This appears to be connected to a significant mid-Stadial change that affected the northeast Atlantic and northwest Europe, although the nature of the response in Scotland is complex.

5. Following the onset of the Holocene epoch, it is possible that it took around ~250 years or more for the landscape to adjust, this being the interval before more mature soils and a juniper–birch scrub vegetation could become established.

Supporting information

Additional supporting information can be found in the online version of this article.

Supp. Figure 1. A) Detailed results of the bathymetry of the northern and southern Lochan Feurach basins from augur investigations in 2017 and 2018. Bathymetry map produced in QuikGrid V3, and locations of boreholes recorded using GPS data. Shorelines were also mapped in the field using GPS and total station data. B) Photo of the coring site within the broader context of high-relief glacial features. Loch Builg is located to the left of the photo.

Supp. Figure 2. Comparison of the regressions between different sedimentological components recorded from the Lochan Feurach sequence. Left-hand column contains whole-sequence regressions (linear and polynomial) between % loss on ignition (LOI), Log Mo Inc/Coh and Log Fe/Ti, showing a strong relationship between the µXRF data and macroscale sedimentological quantifications. Middle column represents different lithostratigraphic units and the changing relationships between %LOI and Log Mo Inc/Coh, showing the best performance of Log Mo Inc/Coh as a proxy for organic content when the organic content is intermediate and not too variable. Right-hand column shows how the different lithostratigraphic units vary on depth in relation to the regressions detailed in the middle column.

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