

Environmental variability in response to abrupt climatic change during the Last Glacial–Interglacial Transition (16–8 cal ka BP): evidence from Mainland, Orkney

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Abstract: The Last Glacial–Interglacial Transition (LGIT) is a period of climatic complexity where millennial-scale climatic reorganization led to changes in ecosystems. Alongside millennial-scale changes, centennial-scale climatic events have been observed within records from Greenland and continental Europe. The effects of these abrupt events on landscapes and environments are difficult to discern at present. This, in part, relates to low temporal resolutions attained by many studies and the sensitivity of palaeoenvironmental proxies to abrupt change. We present a high-resolution palynological and charcoal study of Quoyloo Meadow, Orkney and use the Principal Curve statistical method to assist in revealing biostratigraphic change. The LGIT vegetation succession on Orkney is presented as open grassland and *Empetrum* heath during the Windermere Interstadial and early Holocene, and open grassland with *Artemisia* during the Loch Lomond Stadial. However, a further three phases of ecological change, characterized by expansions of open ground flora, are dated to 14.05–13.63, 10.94–10.8 and 10.2 cal ka BP. The timing of these changes is constrained by cryptotephra of known age. The paper concludes by comparing Quoyloo Meadow with Crudale Meadow, Orkney, and suggests that both Windermere Interstadial records are incomplete and that fire is an important landscape control during the early Holocene.

Supplementary material: All raw data associated with this publication: raw pollen counts, charcoal data, Principal Curve and Rate of Change outputs and the age-model output are available at <https://doi.org/10.6084/m9.figshare.c.4725269>

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The Last Glacial–Interglacial Transition (LGIT; 16–8 cal ka BP; [Rasmussen *et al.* 2014](#)) is a complex period of palaeoclimatological and palaeoecological variability. The abundance of research focused on the LGIT, which in part is a product of the high stratigraphic and temporal resolution afforded by many records, has generated an improved understanding of dynamic climatic and environmental shifts (e.g. [Lowe *et al.* 2008](#); [Brooks *et al.* 2012, 2016](#); [Brooks & Langdon 2014](#); [Whittington *et al.* 2015](#); [Walker & Lowe 2019](#)). In Britain, the LGIT is associated with cold climates of the Dimlington Stadial (DS; [Rose 1985](#)), succeeded by relative climatic warmth during the Windermere Interstadial (WI; [Pennington 1977](#)), a return to cold conditions during the Loch Lomond Stadial (LLS; [Gray & Lowe 1977](#)) and a warming climate during the Holocene. Palynological data from northern Britain and Scotland (e.g. [Pennington *et al.* 1972](#); [Lowe & Walker 1986](#); [Walker & Lowe 1990](#)) largely track these climatostratigraphic phases with woody vegetation development during warm phases and Arctic/alpine open herbaceous vegetation during cold periods.

During the LGIT, abrupt centennial-scale climatic perturbations are observed in Greenland (GI-1d; GI-1b; 11.4 ka BP events; [Rasmussen *et al.* 2006, 2014](#)) and in palaeoclimatic records from NW Europe ([Brooks & Birks 2000](#); [Marshall](#)

et al. 2002; [Brooks *et al.* 2012, 2016](#); [Whittington *et al.* 2015](#); [Candy *et al.* 2016](#)). However, evidence for palynological change at centennial scales during the LGIT is difficult to discern. This may relate to the temporal resolution of the palynological study, lack of palynological sensitivity or the lack of a numerical method that explains considerable variation within the data. Ordination techniques, with the first axis typically used to define variability, may only explain <40% of the total variation within the data due to the existence of multiple environmental and ecological gradients ([Simpson & Birks 2012](#)). However, Principal Curves (PrC; [Hastie & Stuetzle 1989](#); [De’ath 1999](#); [Simpson & Birks 2012](#)) may distinguish changes in palynological data and are defined as a smooth one-dimensional curve passing through an *m*-dimensional dataspace. PrCs capture more variance within a dataset than standard ordination techniques and have recently been used to demonstrate phases of change in palaeoecological records ([Simpson & Birks 2012](#); [Bennion *et al.* 2015](#); [Shumilovskikh *et al.* 2017](#)).

In this study, we address issues of vegetation response to centennial-scale climatic variability and present the lithostratigraphy, palynostratigraphy, charcoal and PrC analysis from a sedimentary sequence spanning the LGIT from Quoyloo Meadow, Orkney. In particular we use a PrC to

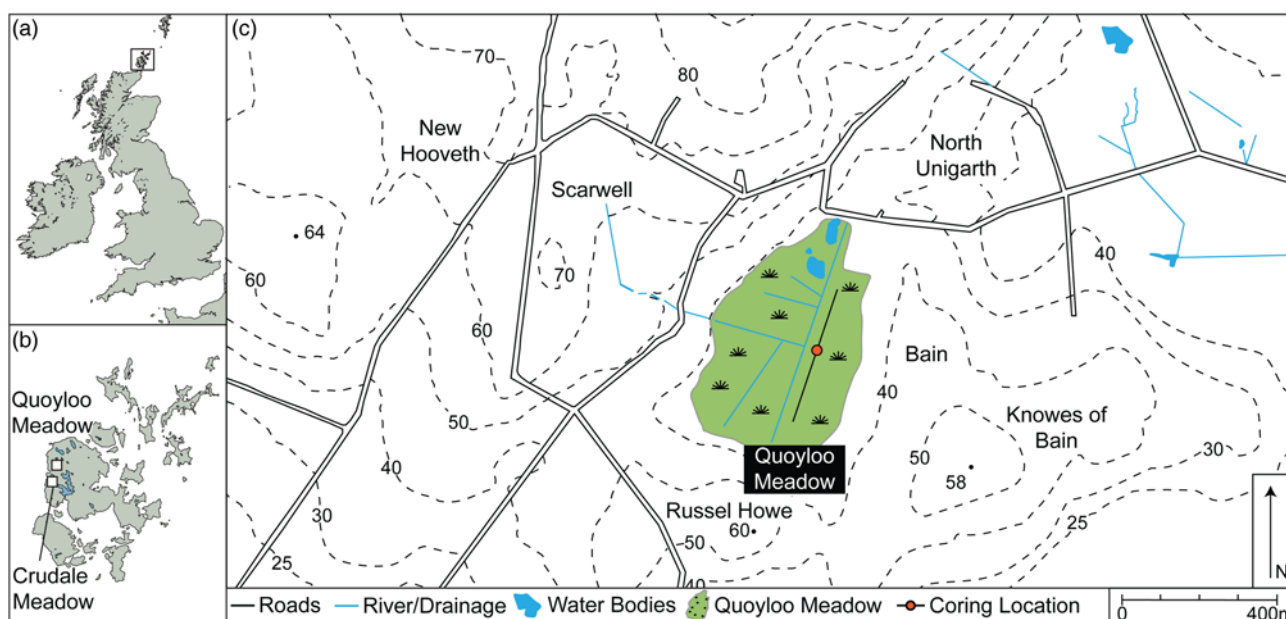


Fig. 1. Location of Quoyloo Meadow. (a) Position of Orkney with respect to the British Isles; (b) the location of Quoyloo Meadow and Crudale Meadow within Mainland, Orkney; and (c) topographic map of Quoyloo Meadow and coring location.

assist in defining periods of vegetation change during the LGIT and compare the data generated within this study to vegetation and isotopic reconstructions from Crudale Meadow, a site within 6 km of Quoyloo Meadow (Fig. 1). The comparison of these two datasets allows for an understanding of the number and impact of different climatic events within Mainland, Orkney during the LGIT.

Site context

Consisting of *c.* 70 islands, the Orkney Isles are located *c.* 10 km from the north coast of Scotland and 80 km SW of Shetland (Fig. 1). Quoyloo Meadow (59.066417, -3.309333; HY250206) is a shallow basin situated in the west of Mainland, Orkney, *c.* 22 km NW of Kirkwall. The site occupies a topographic low within Upper and Lower Stromness Flagstones, a geological group composed of mudstone, limestone, siltstone and sandstone formations (Mykura *et al.* 1976). At its maximum extent the basin is 0.6 × 0.3 km, occupies an area of 0.1 km², and lies at an altitude of 30 m a.s.l. (Fig. 1). The hydrological catchment of the site is estimated to be 1.6 km². At present an active valley mire occupies the site, with one inflow focused from the hills to the west and one outflow at the northern edge of the basin (Fig. 1). However, during the late Pleistocene and early Holocene, the site was characterized by a shallow, open-water body with evidence of lacustrine sedimentation (Bunting 1994; Timms *et al.* 2017).

The earliest high-resolution pollen-stratigraphic investigation at Quoyloo Meadow was undertaken by Bunting (1994), who reported a 260 cm core sequence with the lowest 120 cm attributable to the LGIT. From the basal sediments no pollen was recovered, hinting at either taphonomic issues or a lack of vegetation surrounding the site during the earliest WI. Following catchment stabilization, the vegetation was dominated by low-lying dwarf shrub heathland (*Empetrum nigrum*) and an open grassland (Poaceae, Cyperaceae). The LLS assemblage was characterized by herbaceous taxa,

notably *Artemisia* and *Rumex*. During the Holocene the vegetation was defined by grassland communities prior to the establishment of a *Betula* and *Corylus* woodland. Recently, the site was reinvestigated as part of a tephrostratigraphic assessment of the archipelago (Timms *et al.* 2017, 2018). Timms *et al.* (2017) recovered a similar sequence to Bunting (1994), albeit with a shorter sediment stratigraphy (242 cm). Twelve tephra horizons were identified throughout the sequence (see Timms *et al.* 2017), with a number of these tephra used to construct a robust age-model for the site.

Methodology

Fieldwork and lithostratigraphy

Sediments were extracted from the deepest area of the Quoyloo Meadow basin following depth sounding along a NNE-trending transect (Timms *et al.* 2017). Individual sediment cores were extracted using a Russian corer (50 × 5 cm). The core sequence is 242 cm in length, as presented by Timms *et al.* (2017).

All cores were described using the Troels-Smith (1955) sediment classification scheme. Sediments were assessed for organic content using the Loss on Ignition (LOI) method, with combustion at 550°C for two hours. Units containing calcium carbonate were assessed for carbonate percentages using a Bascomb calcimeter (Gale & Hoare 1991). Estimates were obtained through measuring the amount of carbon dioxide eluted from the sediments following the addition of hydrochloric acid (Gale & Hoare 1991). Magnetic susceptibility estimates were obtained using a Bartington Instruments MS2C core-scanning sensor. All bulk sedimentological analyses, where possible, were performed at contiguous 1 cm resolution.

Palynology

Duplicate cores to those reported by Timms *et al.* (2017) were used in the palaeoecological assessment, which have been tied to the original sequence based on key marker

horizons and visual stratigraphy. The composite Quoyloo Meadow sediment profile was analysed for pollen between 242 to 131 cm using standard procedures outlined in [Faegri & Iversen \(1989\)](#), [Moore *et al.* \(1991\)](#) and [Munsterman & Kerstholt \(1996\)](#). This included the addition of *Lycopodium* for pollen concentration estimates, the use of density separation techniques using sodium polytungstate (SPT; at a specific gravity of 2.0 g cm⁻³) and acetolysis. All palynomorph materials were mounted using glycerine jelly. The record was analysed at a contiguous 1 cm resolution, although between 205 and 195 cm the resolution was decreased to 2 cm. Between 242 and 223 cm the sediment record contained no palynomorphs. Pollen identification was undertaken using an Olympus CX41 binocular microscope at 400× magnification, with critical identifications at 1000× magnification. A minimum sum of 300 Total Land Pollen (TLP) was aimed for; however, this was not always feasible between 222.5 and 195.5 cm due to low pollen concentrations. Between these depths TLP sums ranged from 100–300 TLP. Pollen percentage calculations were performed in reference to TLP with aquatic pollen, pteridophyte spores and *Pediastrum* (a Non-Pollen Palynomorph; NPP) expressed as a function of TLP + aquatics, TLP + pteridophytes and TLP + NPP, respectively. The latter follows [van Geel *et al.* \(1980\)](#). Pollen type nomenclature follows [Moore *et al.* \(1991\)](#) and [Stace \(2010\)](#). All pollen diagram production was undertaken in 'C2' V. 1.7.7 ([Juggins 2016](#)) with zones placed visually, assisted by CONISS ([Grimm 1987](#)), using changes in principal taxa alongside *Pediastrum*.

Principal Curve analyses

Principal Curves (PrC) were modelled using both Correspondence Analysis (CA) and Principal Components Analysis (PCA) axis one scores following the method of [Simpson & Birks \(2012\)](#). All pollen, spores and *Pediastrum* whose abundances were greater than 5% were selected for analysis. The final curve was modelled using CA axis one as the starting curve in the PrC owing to greater variance being explained in the palynological data. The data are presented as stratigraphic plots in the form of PrC outputs and Rate of Change (RoC) analyses. All numerical analyses were performed using the computer programming software 'R' and the 'Rioja', 'Vegan' and 'Analogue' packages ([Juggins 2017](#); [Oksanen *et al.* 2019](#); [Simpson & Oksanen 2019](#)).

Charcoal analysis

Micro- and macro-charcoal analyses were undertaken matching the resolution of the pollen record. However, only macro-charcoal is presented due to the comparability between the two records. Individual cubic centimetres of sediment were analysed following [Carcaillet *et al.* \(2007\)](#). All macro-charcoal estimates are presented as fragments >125 µm. Charcoal size differentiation was not performed due to the lack of sediments retained at 250 µm. Charcoal was counted in a segmented petri dish using a low power binocular microscope.

Chronology

The age model based on tephrostratigraphic information presented in [Timms *et al.* \(2017\)](#) has been updated to include

the current best age estimates for the tephra horizons identified at Quoyloo Meadow. These updated age estimates and their stratigraphic position within the Quoyloo Meadow sequence were used to construct an age model using a p_sequence depositional model and the IntCal13 calibration curve ([Reimer *et al.* 2013](#)) within OxCal V. 4.3 ([Bronk Ramsey 2008, 2009](#)). No boundaries were added to the model over areas of lithostratigraphic change and the k_parameter was kept variable.

Results

The composite stratigraphy from Quoyloo Meadow is presented in [Figure 2](#) and [Table 1](#).

Sedimentology and stratigraphy

The basal units from the sequence, QML-1a and QML-1b, are characterized by silty clay sediments with a gradual increase in organic content. QML-1a is characterized by LOI percentages of <4%; whereas QML-1b exhibits LOI percentages of <10%. The final unit within the lower profile, QML-1c, is characterized by silts and clays with greater LOI values of up to 17%.

Throughout QML-2 silt and clay sedimentation dominates. However, a shift to a dark grey colour is noted from the underlying units, perhaps reflecting reduced organic content, as shown by LOI values (<5%). QML-2b exhibits a light brown/orange staining which likely relates to the dissolution of basaltic glass shards from a known tephra ([Pollard *et al.* 2003](#); [Timms *et al.* 2017](#)).

Within QML-3 and QML-5 a shift from minerogenic sediments to those dominated by high percentages of calcium carbonate reflects marl sedimentation. High CaCO₃ percentages (>85%) are interrupted within QML-4 as CaCO₃ percentages fall to 73%. This is coupled with an increase in magnetic susceptibility and the deposition of a visible volcanic ash layer ([Timms *et al.* 2017](#)). Overlaying this unit, QML-5 returns to high percentages of CaCO₃, between 84–90%, and steadily rising LOI values.

Palynology

The pollen, spore and NPP percentage and concentration diagram has been divided into 11 local pollen assemblage zones (QMP-*n*) based on 83 samples ([Fig. 3](#) and [Table 2](#)).

Zone QMP-1. QM1 depth: 223–217 cm

QMP-1 is dominated by herbaceous taxa with Poaceae values oscillating throughout. *Rumex* percentages rise to between 18 and 20%. Additional herbaceous taxa include Cyperaceae, *Artemisia*, Compositae: Lactuceae, and Saxifragaceae all with percentages <10%. The main shrub contributor is *Salix*. The algae *Pediastrum* exhibit percentages of >26% throughout the zone. TLP concentrations are low throughout QMP-1 although total concentrations, including all aquatic, pteridophyte and algal indicators peak with 19 100 palynomorphs cm⁻³ at 217.5 cm.

Zone QMP-2. QM1 depth: 217–210 cm

QMP-2 demonstrates an increase in arboreal pollen types, with *Betula* increasing from 21 to 33% with a brief decline at

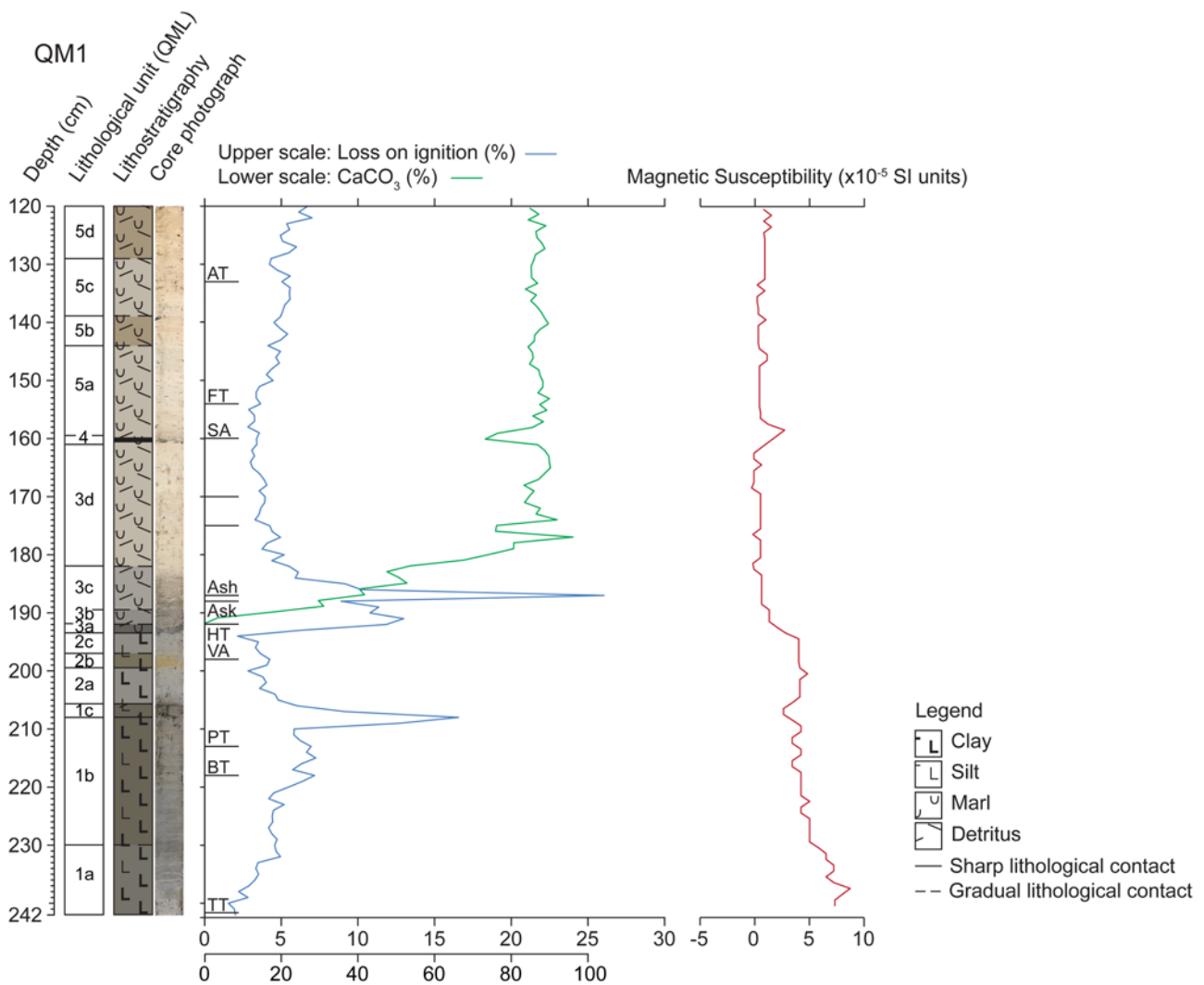


Fig. 2. Stratigraphy of the QM1 sequence from Quoyloo Meadow. Loss on Ignition, calcimetry and magnetic susceptibility are shown alongside the tephra within Timms *et al.* (2017). Abbreviations for tephra from bottom to top: TT, Tanera Tephra; BT, Borrobol Tephra; PT, Penifiler Tephra; VA, Vedde Ash; HT, Hässeldalen Tephra; Ask, Askja-S Tephra; Ash, Ashik Tephra; SA, Saksunarvatn Ash; FT, Fosen Tephra; and AT, An Druim Tephra. Modified from Timms *et al.* (2017).

211.5 cm. *Pinus* oscillates between 7 and 18% throughout. Values of *Rumex* decline from the first zone, although at 211.5 cm percentages increase. Additional taxa include: *Empetrum*, *Salix*, *Artemisia*, Caryophyllaceae and Compositae: Lactuceae. At 211.5 cm percentages of *Pediastrum* increase to 17%. Concentrations are low throughout and are comparable to the previous zone, although a decrease in concentration is noted at 211.5 cm.

Zone QMP-3. QM1 depth: 210–202 cm

Empetrum percentages rise at the onset of QMP-3 then decrease from 34 to 14%. *Betula* percentages follow a downward trend, whilst *Pinus* and Cyperaceae values rise throughout. Additional taxa include *Artemisia*, Caryophyllaceae and Saxifragaceae alongside spores of *Selaginella*. Throughout the zone, percentages of the algae *Pediastrum* are high. TLP concentrations peak at 207.5 cm at 24 100 grains cm^{-3} then decrease. Total concentrations rise to 125 100 palynomorphs cm^{-3} at 205.5 cm.

Table 1. Main lithological units from the Quoyloo Meadow sequence

Unit	Depth (cm)	Sediment classification	Comparable unit (Bunting 1994)
QML-5a; 5b	120–159	Marl	QM-S2 (130–207 cm)
QML-4	159–160	Tephra	
QML-3c; 3d	161–189	Marl	
QML-3a; 3b	189–194	Detrital marl	
QML-2	194–206.5	Silty clay	QM-S1b (207–225 cm)
QML-1c	206.5–208	Silty clay with organics	QM-S1a (225–260 cm)
QML-1a; 1b	208–242	Silty clay	

Adapted from Timms *et al.* (2017). Comparable units from Bunting (1994).

Zone QMP-4. QM1 depth: 202–192 cm

Pinus is the principal pollen taxon in QMP-4; peaking at 42% towards the middle of the zone. The second major taxon, *Artemisia*, demonstrates an oscillatory trend, whereby successive percentages of 29, 9 and 20% are observed. Poaceae and Cyperaceae percentages fluctuate between 15 and 20%, respectively. Additional taxa closely resemble those of the upper levels of QMP-3, with Caryophyllaceae, *Rumex* and Saxifragaceae present. Concentrations are as low as QMP-1, with a TLP average of 4100 grains cm^{-3} .

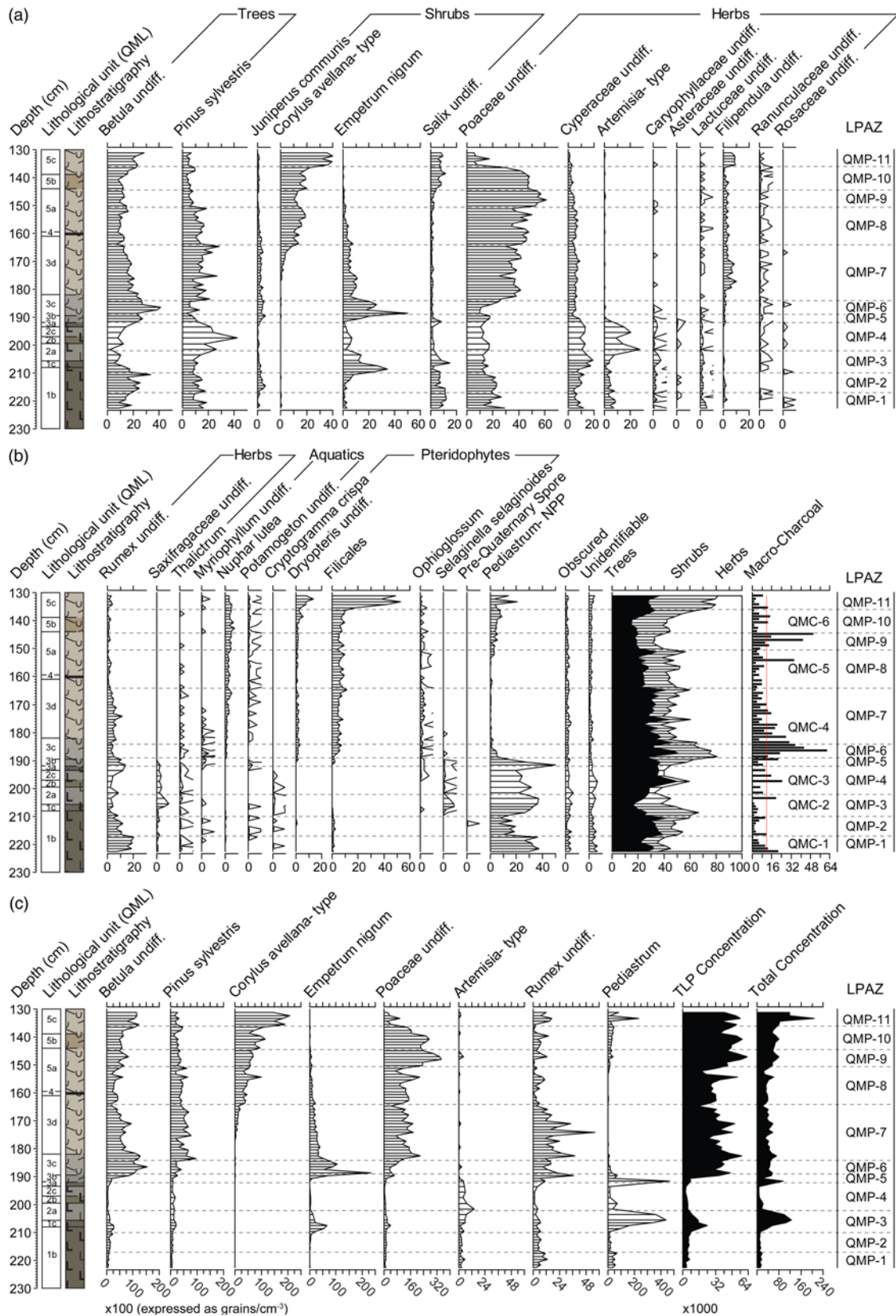


Fig. 3. Selected pollen, spore and algae profiles from Quoyloo Meadow: (a, b) pollen, spore and algal percentage data; (b) macro-charcoal presented as raw counts; and (c) selected pollen concentration data with values shown as $\times 100$ grains cm^{-3} unless stated. LPAZ, local pollen assemblage zone; TLP, Total Land Pollen.

Zone QMP-5. QM1 depth: 192–189 cm

Zone QMP-5 is dominated by *Pediastrum*. The algae peak at the onset of the zone, at 50%, and fall to 15% at the zone

terminus. *Betula* percentages are moderate throughout with a high of 27%. From low percentages, *Empetrum* increases to 21% at 189.5 cm. *Poaceae* percentages increase to 18%.

Table 2. Quoyloo Meadow pollen zone information (including the algae *Pediastrum*)

LPAZ	Depth (cm)	Key indicators
QMP-11	131–136	Filicales, <i>Corylus</i> , <i>Betula</i>
QMP-10	136–144.5	Poaceae, <i>Corylus</i> , <i>Betula</i>
QMP-9	144.5–150.5	Poaceae
QMP-8	150.5–164	Poaceae, <i>Corylus</i> , <i>Pinus</i>
QMP-7	164–184	Poaceae, <i>Pinus</i> , <i>Betula</i>
QMP-6	184–189	<i>Empetrum</i> , <i>Betula</i> , Poaceae
QMP-5	189–192	<i>Pediastrum</i> , <i>Betula</i> , <i>Empetrum</i> , Poaceae
QMP-4	192–202	<i>Pinus</i> , <i>Artemisia</i> , <i>Pediastrum</i>
QMP-3	202–210	<i>Empetrum</i> , <i>Pediastrum</i> , Cyperaceae
QMP-2	210–217	<i>Betula</i> , Poaceae, <i>Pediastrum</i>
QMP-1	217–223	<i>Pediastrum</i> , Poaceae, <i>Rumex</i>

Shown are the local pollen assemblage zone (LPAZ) number, the depth at which they occur in the sequence and the key indicators within each zone.

Rumex percentages are highest towards the base of the zone. TLP concentrations are higher than QMP-4 and increase to 35 100 grains cm⁻³ at 189.5 cm.

Zone QMP-6. QM1 depth: 189–184 cm

QMP-6 is characterized by high values of shrub pollen. *Empetrum* rises sharply to a sequence high of 50% at 188.5 cm and then falls to 18%. The arboreal component is dominated by *Betula*, which peaks to a sequence high of 41% at 186.5 cm. Herbaceous taxa exhibit percentages less than 7%. TLP concentrations are high at 186.5 cm between 30 000 and 40 000 grains cm⁻³. Concentrations of *Empetrum* (23 500 grains cm⁻³) and *Betula* (15 400 grains cm⁻³) are high.

Zone QMP-7. QM1 depth: 184–164 cm

QMP-7 is characterized by elevated percentages of Poaceae. *Betula* percentages decrease from 25% at 183.5 cm to 12% at 165.7 cm. *Pinus* peaks at different stages throughout the zone, with peaks associated with reductions in *Filipendula* and *Empetrum* and increases in *Rumex*. Greater percentages of *Pinus*, *Rumex* and Poaceae are associated with increases in concentrations of these taxa and with decreases in concentrations of *Empetrum*.

Zone QMP-8. QM1 depth: 164–150.5 cm

QMP-8 is again dominated by Poaceae with percentages oscillating between 34 and 50%. *Corylus* achieves percentages above 10% and reaches a zone maximum of 19%. Additional taxa include Cyperaceae, *Filipendula* and *Rumex*. Throughout the zone TLP concentrations are variable, with maximum and minimum values of 53 600 grains cm⁻³ and 18 200 grains cm⁻³. A peak in Poaceae to 21 800 grains cm⁻³ is observed at 154.3 cm.

Zone QMP-9. QM1 depth: 150.5–144.5 cm

The dominant taxon in QMP-9 is Poaceae, with percentages up to 61%. *Filipendula* is continually recorded, with percentages between 2 and 4%. *Pinus* and *Corylus* percentages are generally lower than the previous zone. Pollen concentrations are largely greater than the previous zone, with a TLP peak of 63 100 grains cm⁻³ mid-zone, reflecting greater concentrations of *Betula* and *Rumex*.

Zone QMP-10. QM1 depth: 144.5–136 cm

Poaceae is dominant, although percentages decrease to 29% at the top of the zone. *Betula* and *Pinus* are represented by fluctuating percentages and *Corylus* reaches higher values from the middle of the zone. *Salix* percentages also rise, peaking at 12% at the top of the zone. Filicales fluctuates between 6 and 10% throughout. TLP concentrations are high, with a maximum of 58 300 grains cm⁻³, and *Corylus* and *Betula* concentrations increase throughout.

Zone QMP-11. QM1 depth: 136–131 cm

The final zone in the sequence is dominated by *Corylus*, which nearly doubles in percentage from 22 to 40% at the top of QMP-11. *Betula* percentages fluctuate between 19 and 29% throughout. Large increases are observed in percentages of Filicales spores. TLP concentrations are similar to QMP-10.

Principal Curve analyses

The CA-based PrC explains 81% of the variation within the palynological dataset. Changes in the PrC are directional with the PrC gradient defined as having *Corylus* shrub/woodland and open herbaceous vegetation as the two end-members. Variability in the PrC is confined to a single high-magnitude oscillation between 206 cm and 193 cm (QML-2; Fig. 4). However, further episodes of variability can be defined as inflections in the gradient of the PrC and a plateau in the general shift towards lower values (Fig. 4). These periods of change in the PrC are minor compared to the oscillation

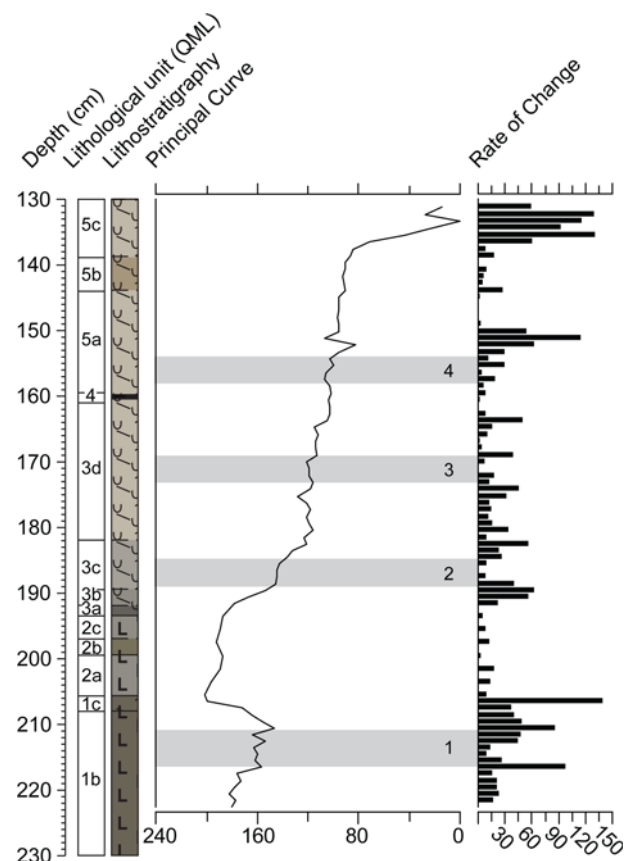


Fig. 4. Principal Curve and Rate of Change analysis. Grey bars highlight phases of short-term compositional change, after Simpson & Birks (2012). See Figure 2 for key to lithostratigraphy.

Table 3. Summary of the tephra data and unmodelled input ranges used to create an age model at Quoyloo Meadow

Name	Depth (cm)	Unmodelled range (cal ka BP)	Modelled range (cal ka BP)	$\mu \pm \sigma$ (this study)	Reference (original)
Boundary	120		9.78–7.74	9024 \pm 651	
An Druim Tephra	133	9.81–9.49	9.80–9.53	9666 \pm 66	Timms (2016)
Høvdarhagi	133	9.97–9.48	(Combined)	(Combined)	Wastegård <i>et al.</i> (2018)
Fosen Tephra	155	10.40–10.0	10.27–10.04	10 164 \pm 57	Lind & Wastegård (2011)
Saksunarvatn Ash	160	10.28–10.14	10.28–10.15	10 215 \pm 51	Lohne <i>et al.</i> (2014)
Askja-S Tephra	188	10.92–10.73	10.95–10.73	10 843 \pm 78	Kearney <i>et al.</i> (2018)
Hässeldalen Tephra	193	11.44–11.19	11.45–11.18	11 317 \pm 80	Wastegård <i>et al.</i> (2018)
Vedde Ash	198	12.11–11.94	12.11–11.93	12 021 \pm 57	Bronk Ramsey <i>et al.</i> (2015)
Penifiler Tephra	213	14.07–13.81	14.08–13.82	13 951 \pm 67	Bronk Ramsey <i>et al.</i> (2015)
Borrobol Tephra	218	14.19–14.00	14.18–13.99	14 086 \pm 48	Bronk Ramsey <i>et al.</i> (2015)
Boundary	242		17.06–14.08	15 246 \pm 864	

Shown are the modelled outputs (95.4% confidence interval) and $\mu \pm 1\sigma$ error.

within QML-2 and their significance is difficult to reconcile. None the less, increased variability is noted between 216.5 and 210.5 cm, 188.5 and 185.5 cm, 173.1 and 168.9 cm, and 158.4 and 154.3 cm (labelled 1, 2, 3, 4 on Fig. 4). Within these episodes, variability is noted within the Rate of Change analysis (RoC; Fig. 4), suggesting greater compositional turnover in the palynological dataset. Episodes that are confined to single data points are not considered here.

Charcoal

The charcoal record exhibits a continuous background signal with specific phases of increased abundance (Fig. 3). Charcoal values range from 1 to 62 fragments cm^{-3} . Discrete peaks in charcoal coincide with episodes of variability in the vegetation and PrC record, with all charcoal peaks above the calculated average deemed important (Fig. 3).

Chronology

In total 12 tephra layers, given by the QM1 prefix and depth, were identified in the Quoyloo Meadow stratigraphy (Timms *et al.* 2017, 2019). Of these, nine tephra and their best age estimates were used to construct a Bayesian age model (Table 3 and Fig. 5). Two tephra (QM1 218 and QM1 213), which exhibit a Borrobol-type chemical signature, have not previously been integrated into a tephrochronological model at Quoyloo Meadow due to uncertainties with their stratigraphic placing (see Timms *et al.* 2017). However, in light of their close association across multiple sequences in the British Isles (Timms *et al.* 2019), and new biostratigraphic information presented here, the age model has been re-run to include these tephra. These two ash layers have been correlated to the Borrobol and Penifiler tephra, respectively. The output produced good model agreement across the sequence and has therefore been used to provide age estimates to support environmental interpretations. The model suggests that sediments began to accumulate in the basin from 15.25 ± 0.86 cal ka BP (Fig. 5).

Interpretation

Stratigraphy

Within this study, QML-1 can be attributed to the terminal Dimlington Stadial (DS) and Windermere Interstadial (WI)

based on two main lines of evidence. First, increasing LOI values throughout QML-1 suggests an increase in organic content. This increase likely reflects greater vegetation development in the Quoyloo Meadow catchment and/or increased lacustrine productivity as a result of climatic amelioration at the onset of the WI (e.g. Pennington 1986; Bunting 1994; Whittington *et al.* 2015). However, catchment

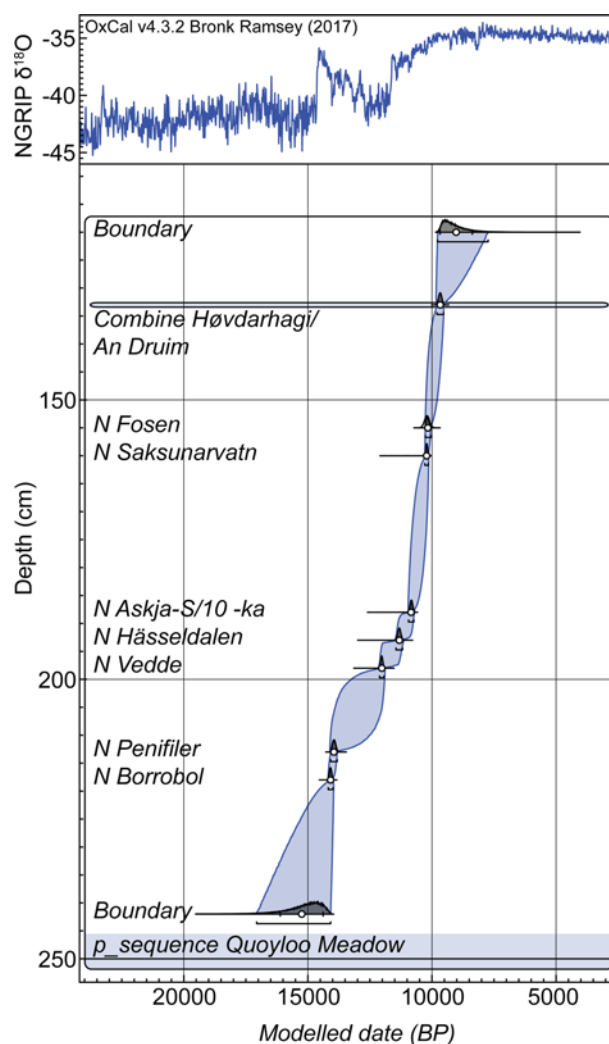


Fig. 5. Age–depth, p_sequence depositional model for Quoyloo Meadow, with age uncertainties plotted at 95.4% confidence intervals and $\mu \pm \sigma$. For software, see Bronk Ramsey 2017.

stabilization was not achieved, inferred from the continued deposition of clastic sediments, which were likely derived from either loosely bound glacial materials or the weathering of local geological outcrops in an unstable environment. It is also postulated that the lack of carbonate formation throughout QML-1, which is observed within QML-3 to QML-5, results from continued clastic sedimentation nullifying carbonate accumulation. Second, the identification of two tephra horizons, which can be correlated to the Borrobol and Penifiler tephtras. These tephtras have frequently been identified towards the base of Scottish WI stratigraphies indicating tephtra deposition soon after the retreat of the Devensian ice-sheet (e.g. Turney *et al.* 1997; Pyne-O'Donnell 2007; Matthews *et al.* 2011; Timms *et al.* 2019). The apparent late stratigraphic position of these tephtra, with respect to the depth of sediment between the base of the sequence and the Borrobol Tephtra, suggests that the basal sediments were either rapidly accumulating or that the basin was exposed prior to the onset of the WI. At present it is difficult to establish which scenario is more likely, and the two scenarios may not be mutually exclusive. However, the tentative finding of the Tanera Tephtra at the base of the sequence (Timms *et al.* 2019) suggests that at least part of QML-1a was deposited during the DS and QML-1b during the WI.

QML-2 is attributed to the Loch Lomond Stadial (LLS) on the basis of continued clastic sedimentation, a drop in LOI values and the identification of the Vedde Ash, a tephtra widely documented from this time interval (e.g. Lane *et al.* 2012; Timms *et al.* 2017, 2019). The decrease in LOI suggests a reduction of organic input into the lake under deteriorating climatic and environmental conditions. These conditions are confirmed through a change in pollen assemblage, from those dominated by shrubs to those dominated by herbaceous vegetation.

The upper sedimentological units, QML-3 to QML-5, can be attributed to the early Holocene based on the precipitation of calcium carbonate and the identification of early Holocene tephtra (Timms *et al.* 2017). In temperate mid-latitude lacustrine settings, CaCO₃ precipitation is often a product of the increased abundance of macrophytes and greater in-lake productivity as a response to climatic amelioration (e.g. Marshall *et al.* 2002; Palmer *et al.* 2015; Whittington *et al.* 2015). The increase in photosynthetic activity removes CO₂ from lake waters, which acts to increase pH and causes supersaturation of lake waters with respect to calcium and bicarbonate (Kelts & Hsü 1978). The result of this process is the precipitation of CaCO₃. The cessation of clastic sedimentation likely demonstrates catchment stabilization within warm climatic conditions of the early Holocene. The sedimentological profile from Quoyloo Meadow is therefore comparable to that of Bunting (1994), who similarly identified associations with the Late-glacial and Holocene periods.

The Quoyloo Meadow palaeoenvironmental record

DS to early WI: 15.25 ± 0.86–13.89 ± 0.21 cal ka BP

The Tanera Tephtra suggests sediment deposition during the DS and the late stratigraphic position of the Borrobol and Penifiler tephtras, within the WI, would indicate an expanded early WI stratigraphy compared to the remainder

of the WI record. The lack of pollen between 15.25 ± 0.86 and 14.33 ± 0.35 cal ka BP (242–223 cm) could be driven by: (1) unfavourable conditions for pollen production; (2) taphonomic issues preventing pollen preservation; or (3) the lack of vegetation within the catchment. If it is accepted, through increasing organic content, that QML-1b can be attributed to the WI (see 'Stratigraphy'), climatic conditions would have been favourable for plant flowering, given that cooler climatic conditions within the high Arctic were not a barrier to plant flowering at this time (Birks 2015). Taphonomic issues can be discounted based on observations of chironomid head capsules within the sediments, which are less structurally resistant than pollen grains, and abundant *Lycopodium* within the same samples. This suggests that neither field taphonomy or laboratory process prevented pollen preservation. Therefore, it is more likely that the absence of pollen indicates that there was limited or no catchment vegetation surrounding Quoyloo Meadow during the terminal DS and earliest WI, which prohibited landscape stabilization. Bunting (1994) came to a similar conclusion at Quoyloo Meadow, suggesting that the erosivity and clastic sedimentation were related to the strong wind action on Orkney in an unvegetated landscape. Alternatively, continued clastic sedimentation could result from greater seasonality and cold winter temperatures at this time, increasing the effect of periglacial activity. This explanation cannot be quantified at this stage, however, due to the lack of a suitable proxy.

Open tundra grassland communities developed in the catchment after 14.30 ± 0.33 cal ka BP (222.5 cm; QMP-1), dominated by Poaceae, *Rumex*, *Salix*, Cyperaceae, *Artemisia* and Compositae: Lactuceae with some occurrences of Caryophyllaceae and Saxifragaceae (Figs 3 and 6). This grassland community reflects the colonization of substrates by pioneering taxa. Low pollen concentrations suggest the vegetation coverage was sparse, which provides further evidence of incomplete catchment stabilization and continued clastic sedimentation with a lack of carbonate accumulation. Constant sedimentological loading likely led to increased nutrient supply to the lake and algal blooming, as inferred from high *Pediastrum* abundances (Weckström *et al.* 2010).

As with other records attributed to the WI, *Pinus* is likely reflective of long-distance transport (e.g. Birks *et al.* 2005; Paus 2010; Whittington *et al.* 2015). Low *Pinus* concentrations suggest the lack of *Pinus* growing on Orkney despite the elevated percentages recorded at Quoyloo (19%). Elevated percentages of far-travelled taxa have been shown by Birks *et al.* (2005) to result from low local pollen production, as we propose was the case during the early WI. The same scenario may be true for *Betula* (Birks *et al.* 2005). However, the relative contribution of *B. nana* to the pollen spectrum cannot be determined without macrofossil evidence (Birks & Birks 2000). Considering a lack of evidence for tree birch establishment in northern Scotland during the WI (Birks & Birks 2014; Whittington *et al.* 2015), combined with the lack of vegetative development in the Quoyloo Meadow catchment, increases in *Betula* and reductions in *Rumex* from 14.30 ± 0.33 cal ka BP likely represent greater colonization of *B. nana*.

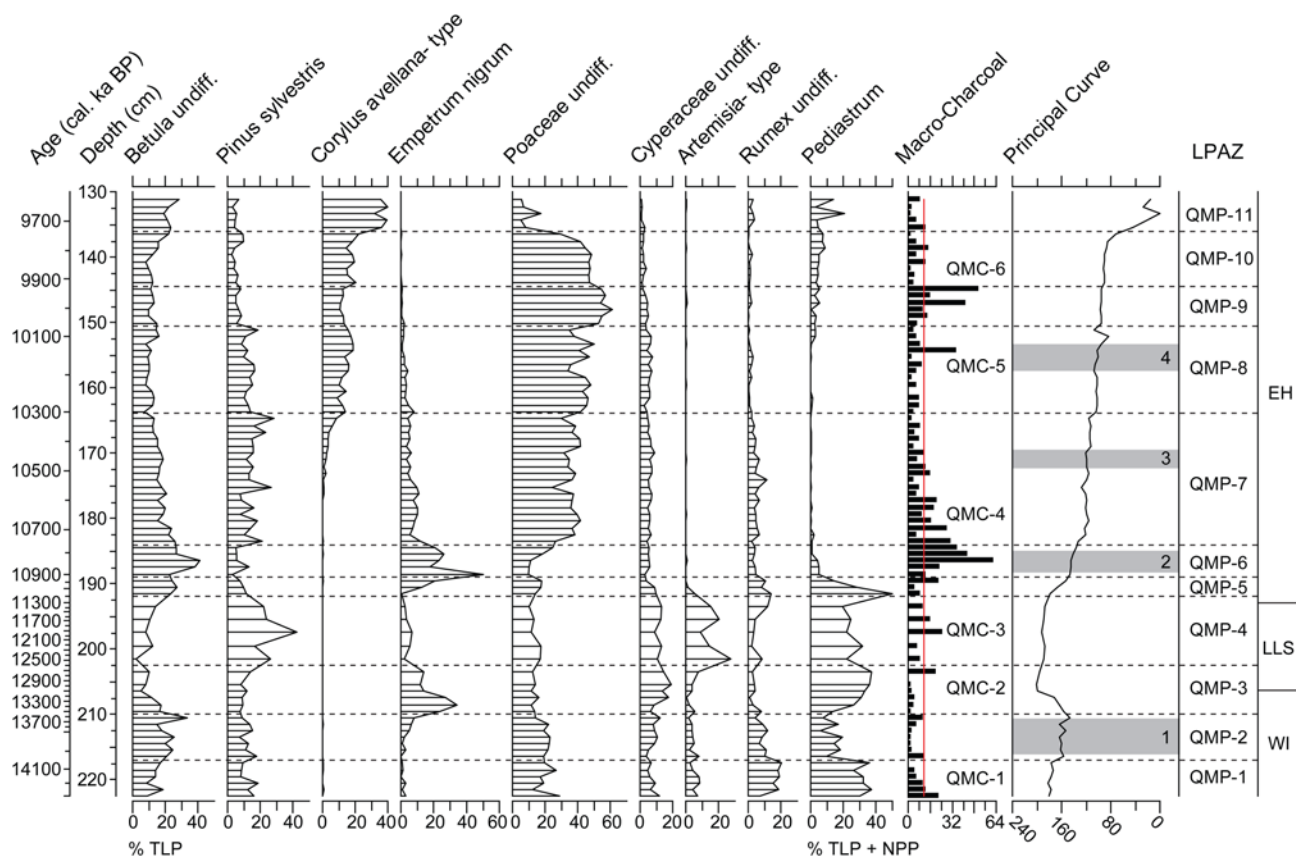


Fig. 6. Summary pollen and algal percentage diagram displaying the principal taxa alongside macro-charcoal and the Principal Curve. All data presented against age. WI, Windermere Interstadial; LLS, Loch Lomond Stadial; EH, Early Holocene; LPAZ, local pollen assemblage zone; NPP, Non-Pollen Palynomorph; TLP, Total Land Pollen.

Mid to late WI: 13.89 ± 0.21 – 13.12 ± 0.57 cal ka BP

During the mid-late WI, reductions in *Betula* pollen are noted with increases in *Empetrum nigrum* (Figs 3 and 6). This change is mirrored by concomitant increases in organic content (Fig. 2). Increased *E. nigrum* pollen likely reflects colonization and proliferation of heathland at Quoyloo Meadow, reflective of relatively moist climatic conditions (Bell & Tallis 1973). The spread of heathland may also reflect the development of increasingly mature, well-drained, albeit base poor soils (Birks 1970). Continued presence of Poaceae, Cyperaceae, *Betula* and *Salix* suggests a well-developed heathland mosaic, with areas of open vegetation and dwarf-shrub heath in the catchment of Quoyloo Meadow.

The occurrence of *Empetrum* during the mid-WI coincides with widespread heathland expansion throughout Scotland at this time (e.g. Pennington *et al.* 1972; Lowe & Walker 1986; Walker *et al.* 1994). This mid-WI heathland expansion provides further evidence of an expanded basal stratigraphy and the stratigraphically ‘late’ positions of the Borrobol and Penifler Tephra as Scottish sites often show heathland expansion towards the base of Late-glacial stratigraphies (e.g. Walker & Lowe 1990; Candy *et al.* 2016). This finding implies that the remainder of the WI sediment record is relatively compressed as 6.5 cm of sediment covers *c.* 800 years between the deposition of the Penifler Tephra and the modelled onset of the LLS. Palynological evidence across the Scottish Islands and Highlands during the late WI reveals a double peak or extended phase of *Empetrum* dominance

with high abundances of *Betula* and *Juniperus* (e.g. Lowe & Walker 1977; Walker & Lowe 1990; Mayle *et al.* 1997; Whittington *et al.* 2015). Given the small low-relief catchment surrounding Quoyloo Meadow, once vegetation had stabilized the landscape it may have starved the basin of sediment, resulting in low sedimentation rates and a short stratigraphic resolution. Alternatively, a depositional hiatus occurred following the mid-WI, which may have been caused by fluctuating lake levels; however, this is not suggested here as there are no indicators of lake level change or abrupt shifts in pollen data. Therefore, the late WI record appears to be compressed at Quoyloo Meadow.

LLS: 13.12 ± 0.57 – 11.46 ± 0.22 cal ka BP

Whilst clastic sedimentation continues throughout the LLS, a shift in vegetation assemblage and organic content occurs at 13.12 ± 0.57 cal ka BP (206.5–193 cm; Figs 2 and 6). The reduction in LOI throughout QML-2 likely indicates reduced organic input into the lake body. This is supported by the marked change in vegetation during this phase (QMP-3). However, an initial phase of both high organic content and abundant *Pediastrum* likely result from landscape erosion and the input of Interstadial soils (Weckström *et al.* 2010) following increased periglacial activity under severely cold climates.

Occurring alongside changes in *Pediastrum*, woody vegetation (*Empetrum* and *Betula*) declined, with increasing populations of *Salix*, Saxifragaceae, Cyperaceae, Caryophyllaceae and *Selaginella selaginoides* (Fig. 3).

These changes suggest the loss of heathland and expansion of an open herbaceous assemblage at the onset of the LLS. The presence of taxa that can survive on disturbed and unstable soils (Caryophyllaceae and *Salix*), and the appearance of *S. selaginoides*, reflect a cold climate vegetation assemblage (Heusser & Igarashi 1994). The increase in *Salix* points to the incidence of late snow lie or exposed landscapes (Wijk 1986; Birks & Birks 2014). The lingering presence of *Empetrum* perhaps supports the idea of late snow lie with moisture and protection derived from continued snow presence. However, *Empetrum* will not tolerate continuous long-lying spring snow (Elvebakk & Spjelkavik 1995). During this phase, charcoal values increased, suggesting an increased fuel source on the landscape following a breakdown of the vegetation community (Fig. 6).

After 12.73 ± 0.56 cal ka BP (203.5 cm; QMP-4) *Artemisia* expanded within the landscape, alongside Poaceae, Cyperaceae, Caryophyllaceae, *Rumex* and Saxifragaceae (Fig. 3). The addition of *Artemisia* and *Rumex* suggests the establishment of a tundra community following the onset of the LLS, as *Artemisia* is inferred to reflect dry and cold conditions with the establishment of dry, well-drained soils (Birks & Birks 2014; Whittington *et al.* 2015).

Within the LLS a vegetational change, bracketed by this Arctic tundra community, is noted between 12.21 ± 0.34 and 11.95 ± 0.17 cal ka BP (199.5–197.5 cm). Here, reductions in both the xerophytic *Artemisia* and *Rumex*, with increased *Pinus* and minor increases in *Empetrum* (Figs 3 and 6), suggest an opening of the landscape and contraction of Arctic/alpine vegetation (e.g. Birks & Birks 2014). Similar to the early WI, high *Pinus* percentages are interpreted to reflect long-distance transport. No evidence suggests that *Pinus* was a landscape component during the LLS in Britain and its presence in Scandinavia has been called into question (e.g. Birks *et al.* 2005). Under a cold stadial climatic regime where wind shear may have been stronger than under warm climatic conditions (e.g. Brauer *et al.* 2008), the increase in a far-travelled component may reveal greater apparent dominance over low pollen producing local herbaceous plants (Birks & Birks 2000). Low concentrations of pollen during the LLS support this explanation. However, low pollen count sums in samples covering the LLS mean that theories of short-term vegetation change currently are tentative.

Early Holocene: 11.46 ± 0.22 – 9.02 ± 0.65 cal ka BP

CaCO₃ precipitation indicates climatic amelioration during the early Holocene, which is also clearly recorded in the vegetation (QMP-5). Increased *Pediastrum* and low land pollen concentrations suggest high levels of catchment soil erosion under low vegetation densities. Subsequent expansions of *Rumex* and *Salix* indicate the re-colonization of the Quoyloo catchment by pioneering taxa following the loss of the Arctic tundra assemblage from the LLS (Lowe & Walker 1986; Birks & Birks 2014). The expansion of *Salix* in this instance may point to areas of exposed ground in the catchment, as opposed to late snow lie, which may be less prevalent within interglacial climatic conditions, due to the open nature of the environment. Between 10.94 ± 0.17 and 10.75 ± 0.13 cal ka BP (189–184 cm; QMP-6), *Empetrum*

and *Betula* expansion reflects accelerated soil development, alongside major increases in pollen concentrations, suggesting the establishment of an extensive dwarf-shrub heathland. Greater LOI values indicate high organic input at this time, which is a product of an extensively vegetated catchment. Initially during the early Holocene, some *Betula* is interpreted to be *B. nana*. Local tree birch may have been present; however, due to the expansion of shade-intolerant *Empetrum* (Bell & Tallis 1973), widespread tree birch colonization was unlikely.

Between 10.75 ± 0.13 and 9.73 ± 0.11 cal ka BP (184–136 cm), Quoyloo Meadow experienced a different vegetation dynamic to most of Scotland due to the lack of woodland development (e.g. Walker *et al.* 1994; Kelly *et al.* 2017). At this time reduced populations of dwarf-shrub heathland taxa, compared to earlier in the Holocene, favoured an expansion of Poaceae alongside *Filipendula* and the pteridophytes *Dryopteris* and Filicales (Figs 3 and 6). The dominance of Poaceae indicates the establishment of a grassland community. The establishment of *Filipendula* suggests relatively wet climatic conditions (Whittington *et al.* 2015), whilst the pteridophytes suggest the establishment of moist and well-drained soils. These are taken to reflect a phase of landscape stability in the Quoyloo Meadow catchment. Throughout this grassland phase localized areas of dwarf-shrub heathland and *Corylus* scrub existed in the catchment.

After 9.73 ± 0.11 cal ka BP (136 cm; QMP-11) *Corylus* expanded, which, alongside greater incidences of *Betula* and reduced Poaceae, suggests the beginnings of woodland development (Fig. 6). The lack of birch woodland prior to this phase likely stems from migratory lags to an island location (Birks 1989) or the out-competing of birch by grass in an environment with strong wind-shear (Bunting 1996). Continued presence of *Filipendula*, *Salix*, Filicales and *Dryopteris* in conjunction with woodland development (Fig. 3) suggests areas of moist well-developed soils continued into tree clearings or into wetland edges (Bunting 1996). This flora is similar to the present-day Orkney dales-type community (Chapman & Crawford 1981).

Abrupt palynological change

The PrC at Quoyloo Meadow allows for an understanding of abrupt change in the palynological record. This relates to considerable variance being explained by the technique (81%). The clearest trend in the PrC is the shift associated with the LLS. This change reflects increased abundances of *Artemisia*, *Pinus*, Caryophyllaceae and *Selaginella selaginoides*, with reductions in *Betula* and *Empetrum*. Whilst this millennial-scale change is clearly shown in the zonation approach, as the PrC identifies this shift to open herbaceous communities between 13.12 ± 0.57 – 11.46 ± 0.22 cal ka BP (206–194 cm; QMP-3/4), we propose that the technique can be utilized to identify centennial-scale changes within the record. Due to the short nature of centennial-scale variability, these changes are beyond the scope of standard pollen zonation techniques. Therefore, centennial-scale changes occur across specific samples within pollen zones.

During the WI, PrC variability is evident between 14.05 and 13.63 cal ka BP (216.5 and 210.5 cm), a phase bracketed

by the Borrobol and Penifiler tephra. During this period, within QMP-2, minor reversions towards higher PrC values are observed (Figs 4 and 6). Occurring for specific samples within QMP-2, small increases in Poaceae, Cyperaceae, *Rumex* and *Artemisia*, with decreases in *Betula*, suggest greater occurrence of open ground vegetation. Increases in these taxa are interpreted to reflect a brief phase of vegetation change. Coeval with these changes, small increases in *Pediastrum* reflect an increase in algal blooming within the lake. However, the significance of this phase is difficult to ascertain as only small changes in pollen and/or PrC are noted, which may be a product of noise within the dataset, or more likely stems from open vegetation at Quoyloo Meadow during the early WI and the lack of clear changes between indicators of instability and stability. None the less, subtle PrC shifts at this time are likely a result of greater landscape disturbance, with increased *Pediastrum* reflecting increased sedimentological loading of the lacustrine environment.

All further phases of palynological variability, as defined by the PrC, occur in the early Holocene (Figs 4 and 6). However, like the WI these phases are subtle and cannot be delimited from palynological data alone. From the PrC, potential phases of palynological change occur between 10.94 and 10.8 (189–186 cm), at *c.* 10.5 (173–169 cm) and *c.* 10.2 cal ka BP (158–154 cm). Between 10.94 and 10.8 cal ka BP a plateau in the shift towards lower values within the PrC is noted (Fig. 6). The PrC appears to be driven by increases in *Pinus* with variability in the *Empetrum* and *Betula* curves. At this time *Pediastrum* values stabilize. Although the changes in the *Empetrum* curve are confined to single samples, simultaneous change across multiple pollen spectra, also observed in concentration data, suggest a period of vegetation change (Figs 3 and 6). Whilst sedimentation rates may be variable at this time, they are unlikely to be wholly responsible for the changes in palynological indices as both *Empetrum* (falling) and *Betula* (rising) display opposing signals. Equally, as samples represent between *c.* 25–60 years, vegetation changes are possible. Variability in *Empetrum* and *Betula* perhaps indicate a change in hydrological regime at this time, as the former requires moist and well-drained soils (Bell & Tallis 1973) with the latter, which includes *B. nana*, possibly outcompeting *Empetrum* as a pioneering taxon (Birks & Birks 2014). The increase in charcoal (QMC-4) may further suggest that following heathland establishment, a climatic regime shift caused a change in the heathland mosaic and a coeval increase in fire within the landscape.

Potential vegetation change at 10.5 cal ka BP is again shown by PrC variability. However, closer scrutiny of the palynological data reveals that variability is largely driven by variations in Poaceae. Ecologically, this phase does not reveal increases in cold or xeric taxa and, as pollen concentrations do not change, this variation is likely due to noise within the dataset.

Between 10.2 and 10.14 cal ka BP further variability is noted in the PrC together with increased charcoal abundance (QMC-5). Throughout this phase, expansions in Poaceae and *Rumex* drive changes in the PrC alongside reduced *Empetrum* and variable *Betula*. The reduction of *Empetrum* and variations in *Betula* suggest a retraction of dwarf shrub heath and an expansion of open grassland communities.

Higher concentrations of Poaceae, alongside low concentrations of *Empetrum*, would support this view (Fig. 3). Although a stable grassland community exists prior to this change in vegetation, small increases in the occurrence of *Rumex* may indicate a phase of greater landscape instability, which appears to correlate with increased burning within the catchment. Therefore, at this time, a shift in vegetation and greater fire prevalence occurs at Quoyloo Meadow.

Discussion

Palaeoenvironmental and climatic comparisons: Crudale Meadow

As it has been demonstrated that phases of the Quoyloo Meadow record are compressed, with low sedimentation rates, comparisons with additional highly resolved sequences are necessary to examine the full suite of palaeoenvironmental changes on Orkney during the LGIT. Crudale Meadow affords this opportunity as not only are the sediments analysed for pollen at high resolution, the site also contains oxygen isotopic data to establish palaeoclimatic change (Fig. 7; Whittington *et al.* 2015). However, the chronology from Whittington *et al.* (2015) is not sufficiently precise to make direct comparisons with Quoyloo Meadow. Therefore, the two sequences are compared using the palynological data and supported by changes within the PrCs (Fig. 8). The PrC for Crudale Meadow was run using the same criteria outlined for Quoyloo Meadow.

The base of the record at Crudale Meadow contains high Poaceae and elevated *Betula* percentages, suggesting an open grassland with sporadic *Betula*, likely *B. nana* (Whittington *et al.* 2015). The transition into a heathland- (*Empetrum*-) dominated environment occurs within CRU-1 and CRU-2. Conversely, the open herbaceous vegetation of QMP-1 and part of QMP-2 is not dominated by *Empetrum*. Therefore QMP-1 and part of QMP-2 are not represented within the Whittington *et al.* (2015) record. Further, CRU-1 and CRU-2 are reported by Whittington *et al.* (2015) as occurring in calcareous sediment. However, a reinvestigation of Crudale Meadow by Timms *et al.* (2018) suggests these calcareous sediments are underlain by clastic sediments, not represented in the Whittington *et al.* (2015) study. These clastic sediments suggest initial phases of sedimentation in a sparsely vegetated landscape. The absence of clastic sediments within Whittington *et al.* (2015), coupled with the difference in pollen assemblages between the two sites, suggests that the record from Quoyloo Meadow pre-dates the Crudale Meadow record. Therefore, it is reasonable to suggest that CRU-1 aligns with a later phase of the early WI.

Crudale Meadow does not appear to record the earliest phase of the WI but may provide superior stratigraphic resolution in other periods – specifically, in the late WI where Quoyloo Meadow appears to be stratigraphically compressed. In this period Crudale Meadow displays variability in the *Empetrum* curve, which is absent from Quoyloo Meadow (Fig. 8). Considering the proximity of the two sites (*c.* 6 km), similar variability in *Empetrum* might be expected. After the reduction in heathland taxa at the base of CRU-3, percentages of *Empetrum* increase, interpreted to reflect a renewed phase of heathland expansion towards the latter phases of the WI (Whittington *et al.* 2015). Therefore, if it is

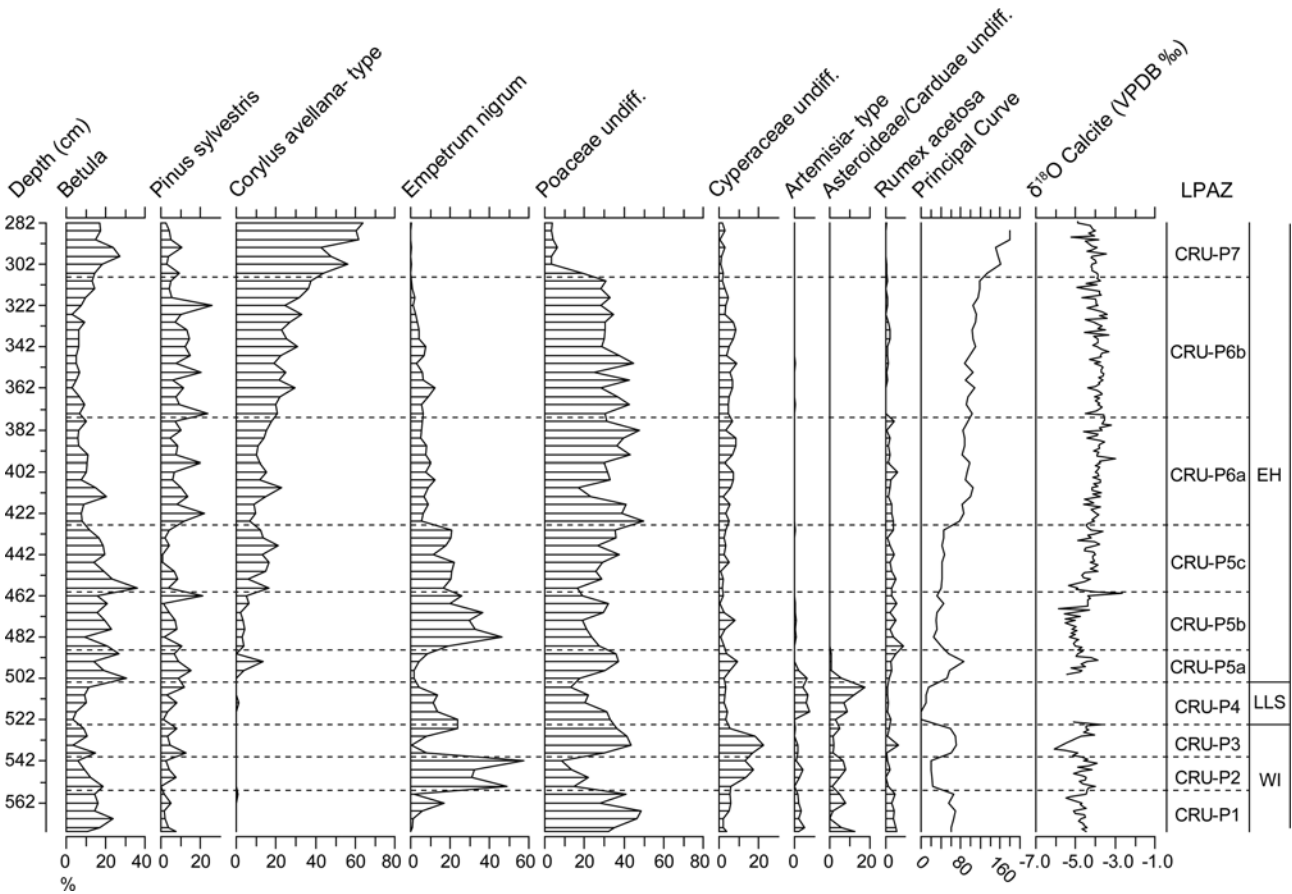


Fig. 7. Selected pollen percentage data from Crudale Meadow (Whittington *et al.* 2015). Shown alongside the pollen data is the Principal Curve and the $\delta^{18}\text{O}$ record from the sequence (Whittington *et al.* 2015). LPAZ, local pollen assemblage zone.

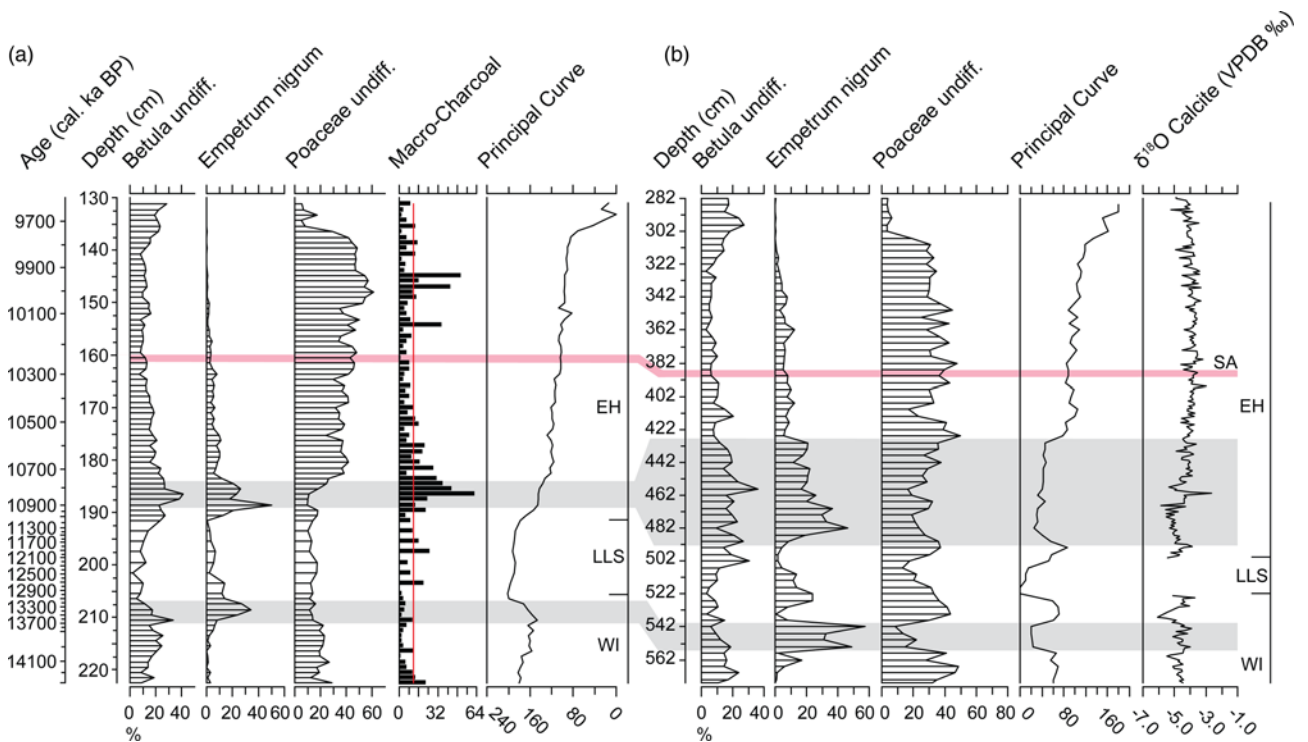


Fig. 8. Comparisons between (a) the Quoyloo Meadow palynological, Principal Curve and charcoal records and (b) the Crudale Meadow palynological, Principal Curve and climate records. Grey bars approximate equivalency between the two sequences with the Saksunarvatn Ash (SA; pink bar) used to tie the records. WI, Windermere Interstadial; LLS, Loch Lomond Stadial; EH, early Holocene.

assumed that *Empetrum* variability is regional at this time, the Crudale Meadow record, as reported in Whittington *et al.* (2015), affords greater stratigraphic resolution in comparison to Quoyloo Meadow.

From these differences we suggest two key observations. First, as both Quoyloo Meadow and Crudale Meadow record climatic and/or palynological variability at an early phase of the WI, a climatic deterioration occurred at this time on west Mainland, Orkney. Second, the depletion in oxygen isotopes and loss of *Empetrum* during the latter phases of the WI from Crudale Meadow (CRU-3) reflect a further climatic deterioration. The compression and lack of resolution in the Quoyloo Meadow record may explain why this deterioration is not recorded at both sites.

Pollen records from both sites show an expansion of Arctic/alpine taxa and high compositional turnover during the LLS (Fig. 8). Greater abundances of, and an absence of variability in, *Artemisia* at Crudale Meadow suggests either a lack of sensitivity to mid-Stadial perturbations or variability in the abundance/distribution of *Artemisia* between site catchments. However, without palaeoclimatic data from either site during the LLS this cannot be quantified.

During the early Holocene, there is strong agreement between the Quoyloo Meadow and Crudale Meadow sequences with key taxa and both PrCs following a trend towards greater environmental stability (Fig. 8). Both records show the transition from the LLS into the early Holocene and the expansion of *Empetrum* heathland, suggesting that the records can be tied with similarities in assumed regional pollen signals (Fig. 8). During this phase the PrCs indicate palynological variability during the Holocene. Whilst this is manifest as a plateau in the PrC at Quoyloo Meadow (QMP-6; see *Abrupt palynological change*), the expansion of heathland and subsequent shift in the PrC occurs alongside depletion in the oxygen isotopic curve at Crudale Meadow, defined as the Pre-Boreal Oscillation (PBO; CRU-5b; Whittington *et al.* 2015). However, the shift in the PrC at Crudale Meadow is shown to extend beyond the period of climatic variability as inferred by the isotopic excursion. At an approximate mid-point in the plateau within the PrC, increased charcoal abundance suggests an increase in fire at Quoyloo Meadow (Fig. 6; QMC-4). If this is extrapolated to the Crudale Meadow dataset, via the alignment of the *Empetrum* curve and the PrC, fire may be an important component in understanding continued PrC variability in the latter stage of, and immediately following, the climatic oscillation at Crudale Meadow. However, it is acknowledged that this assumes that the charcoal signal is regional and to formally test this hypothesis charcoal analysis needs to be undertaken at Crudale Meadow. None the less, the tying of these two records over this phase of the early Holocene suggests that in west Mainland, Orkney, a climatic event, as indicated by oxygen isotopic depletion at Crudale Meadow, led to a contraction of heathland (Whittington *et al.* 2015) which continued to be modulated by fire. It may be that positive feedbacks between heathland and fire explain this continued charcoal abundance. Using available chronological information this event occurred between 10.94–10.8 cal ka BP.

No further attempts to correlate the two PrC datasets have been made, although both records show heightened

percentages of Poaceae, suggesting that west Mainland, Orkney was dominated by open grassland. This confirms the views of Bunting (1994) and Whittington *et al.* (2015) that a treeless landscape persisted until at least after the deposition of the Saksunarvatn Ash ($10\,210 \pm 70$ cal ka BP; Lohne *et al.* 2014).

Palaeoenvironmental and climatic comparisons: Britain and Europe

The timing of millennial-scale transitions at Quoyloo Meadow, including the onset of sedimentation at 15.25 ± 0.86 cal ka BP and the bio/lithostratigraphic changes that occurred during the LLS and early Holocene at 13.12 ± 0.57 cal ka BP and 11.46 ± 0.22 cal ka BP respectively, within age uncertainties, are comparable to similar millennial-scale transitions across Britain and Europe (e.g. Matthews *et al.* 2011; Brooks *et al.* 2012; Muschitiello & Wohlfarth 2015) as well as the Greenland ice-core records (e.g. Rasmussen *et al.* 2006, 2014). The onset of sedimentation across many Scottish sequences is notoriously hard to constrain chronologically as basins were formed following the retreat of late Devensian ice and little datable material is present within basal sediments (Walker & Lowe 2019). However, as Orkney has been shown to have been ice free between 17 and 15 ka BP (Phillips *et al.* 2008; Hughes *et al.* 2016), the modelled ages from the base of the Quoyloo Meadow record are plausible. Whilst it is likely that Crudale Meadow affords a similar scenario, the lack of an independent chronology precludes this assessment.

The suite of tephra during the WI and early Holocene at Quoyloo Meadow affords greater precision in constraining periods of centennial-scale variability. Equally, as the Quoyloo Meadow and Crudale Meadow records exhibit similar features (see caveats: *Palaeoenvironmental and climatic comparisons: Crudale Meadow*) centennial-scale variability can be shown across Mainland, Orkney. A short-lived palaeoecological shift is identified between 14.05 and 13.63 cal ka BP at Quoyloo Meadow. The timing of this event is comparable to an abrupt climatic event identified in Europe (e.g. Brooks *et al.* 2012; van Asch *et al.* 2012) and within Greenland dated to 14.08–13.94 years b2k (GI-1d; Björck *et al.* 1998; Walker *et al.* 1999; Rasmussen *et al.* 2014). In Scotland an early WI climatic deterioration, comparable to the GI-1d climatic event, occurs between 14.09–13.65 cal ka BP, which has frequently been found bracketed by the Borrobol and Penifiler tephtras (e.g. Matthews *et al.* 2011; Timms *et al.* 2019). Whilst quantified climatic proxies are not presented from Quoyloo Meadow or Crudale Meadow, the shift to more open vegetation can be interpreted as a response to this climatic deterioration which has been defined by a 3.5–5°C decline in summer temperature elsewhere (e.g. Brooks & Birks 2000; Brooks *et al.* 2012, 2016). To better understand environmental changes on Orkney at this time, quantified climatic data, for example chironomid-inferred summer temperatures, are required to establish the magnitude of climatic change on Orkney.

The centennial-scale climatic and palynological changes identified during the early Holocene within Mainland, Orkney, require further explanation as they have frequently either not been identified or have not been constrained

chronologically. In part this relates to the lack of high-resolution sampling during this phase and multiple plateaux in the radiocarbon curve during the early Holocene (Björck *et al.* 1996; Lowe *et al.* 1999). The shift in vegetation and changes within the PrCs from Orkney between 10.94 and 10.8 cal ka BP do not appear to contain any formal climatic correlative in Greenland (Rasmussen *et al.* 2014). However, climatic shifts of *c.* 1–1.5°C from Hawes Water (Lang *et al.* 2010) and Palaeolake Flixton (Blockley *et al.* 2018), both in northern England, whose chronological uncertainties overlap with those of the present study, suggest a phase of climatic variability during this time. Within continental Europe, early Holocene climatic variability is shown by short phases of vegetation change relating to the PBO (11.4–11.25 cal ka BP; Björck *et al.* 1997). This event frequently exhibits reductions in *Betula*, *Pinus* and *Filipendula* with increases in open grassland taxa (Björck *et al.* 1996, 1997). However, more recently, multiple phases of cool climatic conditions have been identified across northern Europe between 11.4–10.8 cal ka BP (e.g. Andresen *et al.* 2007; Fišoc *et al.* 2018), suggesting that multiple cool phases characterized this period of the early Holocene. It is therefore probable that changes in heathland, PrCs and fire across Orkney at *c.* 10.9 cal ka BP relate to pre-Boreal climatic variability observed in Britain and Europe.

The change in the pollen assemblage, PrC and charcoal that occurs at 10.2 cal ka BP at Quoyloo Meadow has been poorly recorded in palynological studies. To the best of our knowledge, this is the first instance of environmental variability at 10.2 cal ka BP in Scotland. However, at 10.3 cal ka BP evidence exists for climatic variability and glacial re-advances across the North Atlantic region (e.g. Bond *et al.* 1997; Björck *et al.* 2001; Dahl *et al.* 2002; Jessen *et al.* 2008). Evidence from continental Europe suggests that over the same period vegetation became more open. Palynological data from Norway suggest that the landscape was characterized by open vegetation (Paus 2010), whilst evidence from Poland suggests *Pinus* forests were temporarily replaced by *Betula* (Fišoc *et al.* 2018). These palynological changes suggest a period of climatic variability in Europe. Thus, the vegetation changes recorded at Quoyloo Meadow at 10.2 cal ka BP may be linked to climatic change in the North Atlantic region, although the expression of these changes needs to be further investigated.

Principal Curves in ecological data

Within this paper, we have demonstrated the use of Principal Curves to assist in capturing significant variance within palaeoecological records (e.g. Simpson & Birks 2012; Bennion *et al.* 2015). Through applying this technique to the Quoyloo Meadow and Crudale Meadow datasets, our aim was to help delineate abrupt ecological change during the LGIT and to assist in the comparison of the two datasets (Fig. 8). However, whilst the approach has been successful, caution is required when comparing across datasets. Namely, where stratigraphic differences occur between two records, for example during the late WI at Quoyloo Meadow and Crudale Meadow, or where differences in taxon representation occur. At Crudale Meadow, as *Empetrum* appears alongside *Artemisia*, Poaceae and Asteraceae during the WI,

as well as during the LLS (despite not being a typical pollen type of Arctic/alpine environments), it has the effect of driving the PrC towards values that are observed during phases of catchment instability. However, it has been shown that heathland establishment at Quoyloo Meadow is reflective of relatively stable conditions. Whilst it is encouraging that the PrC can capture complex data features, the output needs to be scrutinized to understand what drives the PrC, especially when the technique is used for comparison between sequences. None the less, we recommend the use of PrCs in palaeoecological research.

Conclusions

A reanalysis of Quoyloo Meadow allows for an understanding of vegetation history at both the millennial and centennial scales. The PrC in this respect is vital to help identify subtle phases of palaeoecological change which may not be obvious from visual assessments or pollen zonation. The data generated within this study and a comparison with the nearby site of Crudale Meadow (Whittington *et al.* 2015) have resulted in a number of conclusions.

- A clear biostratigraphic structure of the LGIT exists at Quoyloo Meadow, corroborating observations within Bunting (1994), with open herbaceous vegetation and heathland during the Windermere Interstadial, an Arctic/alpine disturbed ground assemblage during the Loch Lomond Stadial and a dwarf shrub heath, open grassland and woodland during the early Holocene.
- The PrC generated from the Quoyloo Meadow data delineates the Loch Lomond Stadial, and potentially a further three phases of variability in the vegetation record. These phases are driven by expansion and contraction in herbaceous or shrub vegetation. Variability is shown to broadly correlate with the GI-1d event, a climatic deterioration between 10.94 and 10.8 cal ka BP also observed in northern England and climatic variability at 10.2 cal ka BP inferred from the North Atlantic region.
- In the absence of suitable material for radiocarbon dating, the use of cryptotephra to develop an age model has been invaluable for establishing the timing of events recorded at Quoyloo Meadow, and further shows the versatility of this approach in traditionally ‘hard to date’ sequences (Timms *et al.* 2019).
- Through comparing data generated within this study with the Crudale Meadow record presented in Whittington *et al.* (2015), the sediment records from both sites are not completely resolved. The earliest Windermere Interstadial does not appear to be present from Crudale Meadow, whilst the late Windermere Interstadial is compressed at Quoyloo Meadow.
- During the early Holocene, both records appear to show variability in response to one or more phases of the Pre-Boreal Oscillation. This event is manifested by a climatic deterioration, a change in vegetation and an increase in fire. The increase in fire appears to have an impact on vegetation beyond the duration of the climatic event.

- The data presented here suggest that a complete profile from Orkney can only be obtained through comparing multiple records and multiple proxies.

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