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Snapshots in time: precise correlations of peat-based proxy climate records in Scotland using mid-Holocene tephras

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Abstract: Mid-Holocene tephra layers have been located and geochemically analysed from seven ombrotrophic bogs in Scotland. The tephras found in these Scottish peats occur as stratigraphically discrete horizons, not visible to the naked eye, and originate from volcanic activity in Iceland. Identifying and geochemically typing the tephra layers can enable precise correlations between sites on regional scales, depending on the spatial extent of the airfall events. Dispersal of both the Glen Garry and Hekla-4 tephras is excellent over Scotland, enabling snapshot views of the past at the time of these tephra depositions. Palaeoecological analyses have also been undertaken on these bogs, providing detailed reconstructions of past changes in bog vegetation and surface wetness, a proxy for past climates. Correlations between the ombrotrophic bogs at the time of the Glen Garry tephra revealed significant differences between the proxy climate records in the north and the south of Scotland, suggesting asynchronous changes between northern Scotland and the rest of Great Britain.

Key words: Tephra, Scotland, bog, mire, surface wetness, proxy climate record, Glen Garry, Hekla-4, mid-Holocene.

Introduction

Investigations of peat stratigraphy have been used to elucidate Holocene climatic changes for over 100 years, from the broadly defined climatic zones identified by Blytt (1876) and Sernander (1908) to more recent work in the last two decades which has concentrated on producing replicable results within sites (e.g., Barber, 1981; Barber *et al.*, 1998; Charman *et al.*, 1999; Chiverrell, 2001; Langdon *et al.*, 2003) and between sites (Barber *et al.*, 2000), as well as attempting to quantify the observed changes (e.g., Woodland *et al.*, 1998; Hendon *et al.*, 2001). The precise comparison of results between sites has, however, remained problematic, mainly due to the reliance on radiocarbon dating to provide chronological control of peat sequences (Pilcher, 1991; Kilian *et al.*, 1995; Speranza *et al.*, 2000) and the temptation to 'suck in and smear' results (Baillie, 1991). Peat-based proxy climate records have been derived in order to compare both local and regional climatic fluctuations with climate reconstructions from other proxies, but it is only through time parallel markers, such as tephra isochrons, that precise correlations can be made between such records.

The main assumptions behind tephrochronological dating of peat are: (1) that the ash is deposited instantaneously (in geological terms); (2) that the ash from each eruption possesses a unique geochemical signature (Hunt and Hill, 1993); and (3) that the shards are not mobile within the peat profile. It is generally accepted that ash layers were deposited instantaneously although spatial variations in fallout can occur, and this often results in each tephra layer displaying a patchy areal distribution (Dugmore *et al.*, 1995). Studies have shown that peak influxes of tephra are frequently restricted to less than 1 cm of peat stratigraphy (Dugmore and Newton, 1992; Hall *et al.*, 1994), suggesting that the likely vertical diffusion of an individual tephra within the peat profile would be on the millimetre rather than centimetre scale (Dugmore *et al.*, 1996).

Almost all the tephras which have been identified in Holocene deposits from NW Europe originate from Iceland. Detailed work on the geochemical characterization of individual layers has led to the sources of many being identified (e.g., Dugmore *et al.*, 1992; Larsen *et al.*, 1999; 2001). Through the dating of individual tephra layers, either by radiocarbon dating prehistoric layers or by using documentary evidence for historical layers, regional tephrochronologies have been developed from tephrostratigraphical records (e.g., Dugmore *et al.*, 1995; Pilcher *et al.*, 1996). These tephrochronologies can be used to provide a chronological framework for sequences which are rich in tephra layers, although care must be taken when interpreting the accuracy of such a chronology due to the variability of the precision in dating the prehistoric tephras and the potential for misattribution through poor analysis or geochemical equifinality. Some prehistoric tephras have been dated only by single radiocarbon dates performed on peats immediately above the tephra layer or by

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stratigraphic interpolation (e.g., Dugmore *et al*., 1995). Although many single dates derived from peats for a specific tephra make that tephra a frequently dated tephra isochron, the many single dates derived do not refine the precision of the date of the eruption. The dating of some tephra layers, however, has been refined through wiggle-matching dating of rapidly accumulating peats in which the distal tephra did not represent a hiatus (e.g., Pilcher *et al*., 1995). Although the development of tephrochronology has advanced rapidly over the last decade, and the usefulness of individual tephra isochrons for correlative purposes within palaeoenvironmental studies has been emphasized (Hall and Pilcher, 2002), very few studies have utilized this application. Tephras have, however, been used for the purposes of correlation in Lateglacial contexts (e.g., Lowe *et al*., 1999), although they have yet to be used for the correlation of Holocene peatland palaeoclimate reconstructions.

This paper presents detailed palaeoclimate reconstructions from seven ombrotrophic peat sites in Scotland around the times of both the Glen Garry and Hekla-4 tephra airfalls. The Glen Garry tephra was originally dated to 2100 ^{14}C BP by Dugmore *et al.* (1995) but more recently has been AMS ^{14}C dated (AA 40454) to 2139 ± 61 ^{14}C BP (cal. 2325–1952 BP) from Walton Moss and is the subject of further research (Barber and Langdon, unpublished results). Hekla-4 has been wiggle-match dated to 2310 ± 20 BC by Hall *et al.* (1994). The peat-based palaeoclimate records have been constructed using three proxies: plant macrofossils, testate amoebae and humification analysis. These records can be correlated precisely between sites due to the presence of the tephra isochrons, and thus the synchroneity of the reconstructed climatic changes can be tested.

Sites and field methodologies

Changes in Holocene palaeoclimates in Scotland have been reconstructed from seven sites (Figure 1): six ombrotrophic raised bogs (Longbridge Moss, Langlands Moss, Temple Hill Moss, Shirgarton Moss, Mallachie Moss and Craigmaud Moss) and one ombrotrophic blanket bog (Ben Gorm Moss: Langdon and Barber, 2001). The geographical range of site locations reflects the present-day climatological gradients within Scotland and should thus reflect the regional variability of past climatic changes as well as site sensitivity. The individual site characteristics are detailed in Table 1.

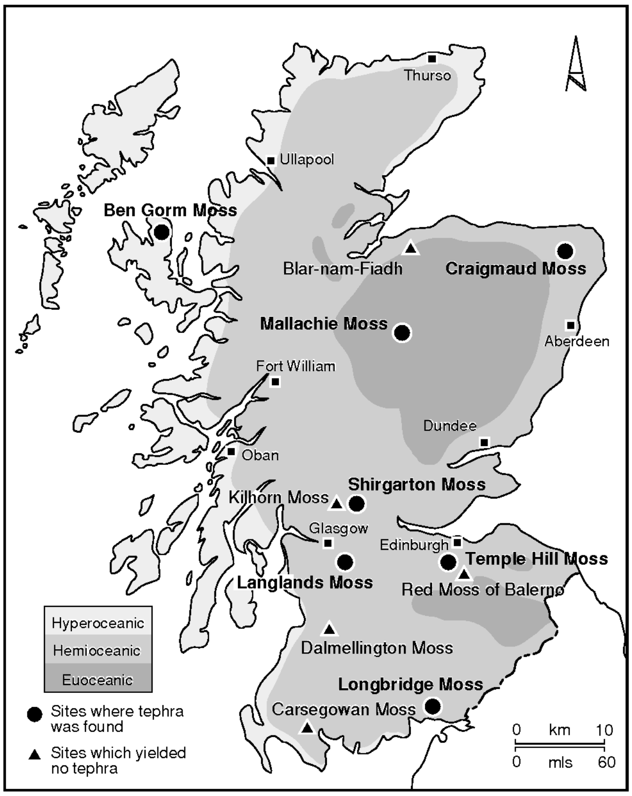

Figure 1 Map of Scotland to show the location of sites where tephras were recovered (circles). The other sites (triangles) yielded little or no tephra. Climate subregions are adapted from Birse (1971).

Detailed stratigraphic field investigations were undertaken at each site prior to a master core being taken for laboratory analysis (cf. Barber *et al*., 1998). A Russian corer (9 cm diameter) was used to obtain samples from each site, with the exception of Ben Gorm Moss, on which monolith tins (50 × 10 × 10 cm) were used for sampling a freshly cut vertical peat face. The raised bogs were sampled to a depth of 5 m in an attempt to locate both the Glen Garry and Hekla-4 tephras. Ben Gorm Moss was sampled to a depth of 140 cm with an iron pan present at 137 cm (Langdon and Barber, 2001).

Tephra analysis

The Holocene tephras found in Scotland form stratigraphically discrete horizons in the peat, not visible to the naked eye (cryptotephras *sensu* Lowe and Hunt, 2001), and hence need to be first located and recognized as tephra before the glass shards can be extracted and characterized geochemically. Peat samples were initially subdivided into 5 × 1 × 1 cm segments along the length of the core, and ashed at 600°C following the procedure of Pilcher and Hall (1992). The residue was analysed using a compound microscope at × 400 magnification for glass shards, and once a tephra horizon had been identified parallel 1 × 1 × 1 cm peat samples were taken in order to refine the peak concentrations of tephra (Table 2), all of which were restricted to no more than 1 cm in depth. Shard counts were undertaken using a compound microscope at × 400 magnification on each sample in order to obtain an estimate of tephra concentration (Table 2). Once a tephra horizon had been located, further peat samples were taken from the depths of maximum tephra concentration in order to isolate the glass shards in preparation for geochemical analysis. These samples were subjected to an acid digestion (Persson, 1971; Dugmore *et al*., 1992) and once the shards had been isolated from the peat matrix they were analysed using the electron probe microanalysis (EPMA) facility at Edinburgh University. A standard wavelength dispersive analytical technique was employed with a voltage of 20 kV, beam current of 15nA and a beam diameter of 1–2 μm. An andradite standard was checked approximately every 12 analyses to ensure precision. A single analysis on a tephra shard consisted of counts on nine major elements using two spectrometers, with a single count lasting 10 seconds. Every analysis performed was recorded sequentially, and due to its mobilization potential sodium was checked at the start and finish of each analysis (see Hunt and Hill, 1993; 2001). Any mobility during the overall analysis can thus be assessed. Corrections were made for counter dead time, atomic number effects, fluorescence and absorption using a ZAF correction program based on Sweatman and Long (1969).

Major element geochemical abundances were obtained for 14 tephra layers from the seven sites. By comparing the data with other published studies (e.g., Dugmore *et al*., 1995) and Tephrabase (http://www.geo.ed.ac.uk/tephra/tbasehom.html) the Glen Garry tephra was identified at six sites (Appendix A) whereas Hekla-4 is present at four sites (Appendix B). Other tephras were also identified (Langdon, 1999), two of which were from Ben Gorm Moss (BGMT-1 and BGMT-3) and have been discussed elsewhere (Langdon and Barber, 2001).

Geochemical characterization of two of the tephras (Glen Garry

Table 1 Sites investigated, based on a southwest to northeast gradient. The annual effective precipitation was calculated by subtracting the potential evaporation (calculated from gridded data of Barrow *et al*., 1993) from the annual precipitation for each site

Site	National grid reference	Intact area (hectares)	Altitude (O.D.)	Mean annual temperature	Annual effective precipitation	Comments
Longbridge Moss	NY 3053 5694	125	15 m	8.8°C	369.2 mm	Original extensive Lochar mosses have been afforested with conifer plantations, although Longbridge Moss remains intact with good raised peat stratigraphy.
Langlands Moss	NS 2634 6513	25	214 m	7.3°C	971.4 mm	One half of the bog was forested which has now been cleared. Some shallow drainage ditches on the surface, and modified flora consisting of high levels of Ericaceae.
Temple Hill Moss	NT 3113 6613	43	294 m	5.0°C	881.1 mm	Bog with a relatively well-humified stratigraphy but no signs of drainage ditches. Contains typical raised-bog floral assemblages with abundant *Sphagnum*.
Shirgarton Moss	NS 2645 6963	58	18 m	8.6°C	933.3 mm	Site appears intact with only small drains on the surface and abundant *Sphagnum* coverage.
Mallachie Moss	NH 2963 8170	*c*. 80	225 m	6.8°C	514.0 mm	Large area of raised peat with cuttings around the edge, although the centre of the bog appears undisturbed, with swathes of *Sphagnum magellanicum*.
Craigmaud Moss	NJ 3885 8588	17	106 m	7.6°C	309.2 mm	Although only a small site, Craigmaud appears intact. The peat is well humified, although some plant macrofossil remains could be seen in the field.
Ben Gorm Moss	NG 1432 8658	*c*. 10	454 m	4.7°C	2142.6 mm	Water shedding uncut blanket bog with some peat hagging.

from Shirgarton Moss and Hekla-4 from Ben Gorm Moss) could be considered ambiguous and requires further discussion. Only a few shards were identified from both these layers, and many became damaged by the electron beam before completion of analysis, resulting in low totals (some of which are displayed in Appendix B(iv)). Only two geochemical analyses with totals approaching 95% have been obtained from Shirgarton Moss. Analysis no. 125 has a geochemistry very similar to that of the Glen Garry tephra, noticeable by the CaO:MgO and FeO: TiO_2 ratios. However, analysis no. 124 has similar ratios of CaO:MgO and FeO:TiO_2, but an anomalously high K_2O value. This high potassium value is not replicated in any of the Glen Garry tephra data found in Tephrabase. The low Na_2O value for analysis no. 124 is replicated by some data from Glen Garry tephra, although it cannot necessarily be explained by the migration of sodium during the analysis of silicic glass. The sodium content is measured at the start and end of each analysis, and actually decreased during analysis no. 124 by only 17% (from 1137 to 949 counts per 10 seconds), as opposed to more common decreases of over 50% (e.g., typical value for Glen Garry Na_2O being *c*. 1500 counts at the start and only *c*. 600 counts after 10 seconds). The alkali content of analysis 124 therefore should be treated with caution, and cannot be fully explained if the shard is from the Glen Garry tephra. However, the shard analysed as no. 125 displays all the characteristics of Glen Garry tephra, and the depth at which the tephra occurs is also stratigraphically acceptable, based on ^{14}C dates of 1960 ± 40 BP from 120–128 cm and 2630 ± 45 BP from 196–204 cm, suggesting that Glen Garry would be a reasonable candidate match and is therefore tentatively accepted as such.

Most of the shards from the stratigraphically lower tephra at Ben Gorm Moss have the characteristics of Hekla-4, but two (analyses 85 and 86) are more similar to the Lairg A layer (see Dugmore *et al*., 1995). The accumulation rate produced by the radiocarbon dates from the sequence suggest that the tephra is of Hekla-4 age, but because the tephra is so near to the base of the profile, and there are no dates stratigraphically below it, this is not conclusive. The tephra does, however, possess the characteristics of a Hekla tephra, and is tentatively accepted as being of Hekla-4 age although other Hekla tephras exist in this period, only a few hundred years apart from Hekla-4 (for a full discussion, see Langdon and Barber, 2001).

Geochemical and spatial variability of tephra distribution

The geochemical variability of silica within a defined tephra isochron allows inferences to be made about tephra dispersal. During some silicic Icelandic eruptions the silica content of the ash frequently decreases over time (Thorarinsson, 1967). This is particularly evident in the case of the Hekla central volcano which evolves a zoned magma chamber given sufficient repose. These changes can be detected in the distal fallout material, allowing reconstructions of the path of the ash cloud to be established.

As silica content changes throughout a major Icelandic eruption, the less evolved (i.e., dacitic to andesitic) phase of an eruption tends to occur towards the end of the eruptive phase. Larsen and Thorarinsson (1977) suggest that the silica content for Hekla-4 ranges between *c*. 74% initially to 57% towards the end of the eruption. Thus, when dacitic to andesitic shards are recovered from a tephra deposit, there is evidence that material from

Table 2 Summary of the tephra isochrons identified from each site

Site	Total depth of peat (cm)	Depth of tephra horizon (cm)	Peak concentration (shards/gram)	Tephra isochron
Longbridge Moss	684	282–283	1460	Hekla-4
Langlands Moss	>800	30–31	45	AD 860 layer
(Langdon and Barber, 2002)		85–86	175	Glen Garry
Temple Hill Moss	541	114–115	2030	Glen Garry
(Langdon *et al*., 2003)		444–445	265	Lairg A
Shirgarton Moss	471	134–135	2150	Glen Garry
Mallachie Moss	796	120–121 261–262	700 7075	Glen Garry Hekla-4
Craigmaud Moss	>275	104–105 139–140	3175 36500	Glen Garry Hekla-4
Ben Gorm Moss	137	30–31	80	BGMT-1
(Langdon and Barber, 2001)		66–67	405	Glen Garry
		82–83 134–135	225 90	BGMT-3 Hekla-4

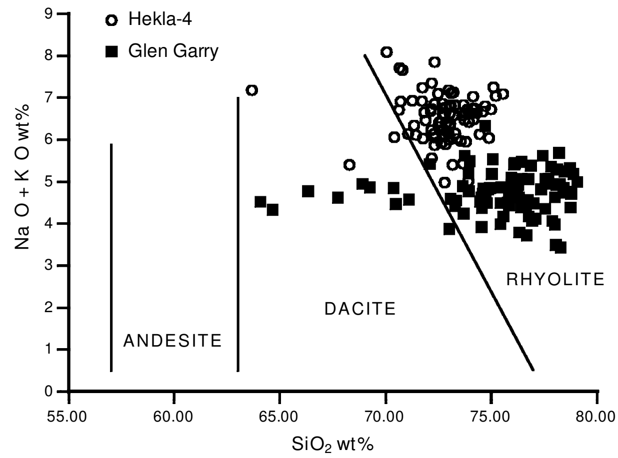

Figure 2 Bi-plot of silica:total alkali ratios for Hekla-4 and Glen Garry tephras from the seven sites in Scotland. Geochemical fields follow Le Maitre (1989).

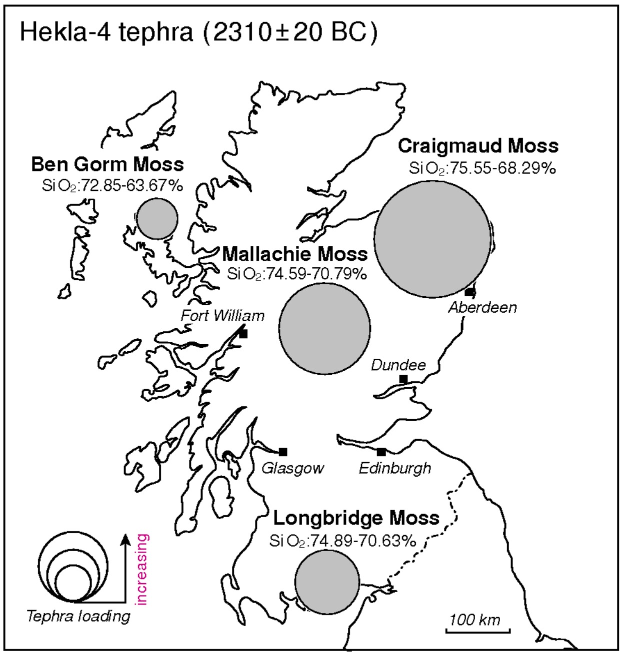

Figure 3 Tephra loading of the Hekla-4 isochron from four sites over Scotland. The diameter of the circles relates to relative not absolute variations in concentration. The relative silica proportions from all the tephra shards analysed for each site are shown.

the later stages of the eruption reached the area where the ash was deposited, whereas when only rhyolitic shards are recovered, deposition (and therefore probably dispersal) may only have occurred from the initial stages of the eruption. A plot of the Hekla-4 and Glen Garry SiO_2:Na_2O+K_2O ratio from each site is shown in Figure 2, indicating the relative amount of rhyolitic to dacitic proportions of ash that can be traced across Scotland.

An indication of tephra loading for sites where Hekla-4 and Glen Garry tephras have been found is plotted in Figures 3 and 4. The dispersal pattern shown by Hekla-4 tephra in Figure 3 suggests high concentrations in northeast Scotland, which are of an order of magnitude greater than in more southerly locations over the sites studied. The west coast site at Ben Gorm Moss, however, appears to have only low concentrations of tephra, suggesting that it may have been on the periphery of the fallout cloud, or it could be the result of variations in precipitation or bog surface topography.

A key feature shown in Figure 3 is a gap in the fallout pattern around central Scotland. Hekla-4 tephra was not recovered from the three sites in this region (Shirgarton Moss, Langlands Moss and Temple Hill Moss) despite extensive searches. No literature exists on Hekla-4 having been found in this region. Negative evidence, such as this, is by no means ideal, but here it is suggested as more than a coincidence. Hekla-4 tephra has been located in southernmost Scotland (Longbridge Moss), as well as in northern England (Pilcher and Hall, 1996) and in Ireland (Pilcher and Hall, 1992; Hall *et al*., 1994; Pilcher *et al*., 1995; 1996; Hall and Pilcher, 2002). The most likely explanation for this would be that, although the ash cloud probably passed over the whole of Scotland, northern England and Ireland, deposition only occurred in northern Scotland, the Borders, northern England and Ireland. Suggestions that deposition occurred mainly by wet fallout would apply to this model, with central Scotland having thus received little or no precipitation when the ash cloud passed over. This would result in the patchy fallout patterns, the dispersal of individual eruptions being limited due to the mechanisms of atmospheric transport as noted by Dugmore *et al.* (1995). Some dry deposition may have occurred, the result of which would be low concentrations of glass shards found at sites in central Scotland. Wet and dry deposition mechanisms have also been tested in relation to Chernobyl fallout and local weather conditions. It has been found that, of the radionuclides which finally reached

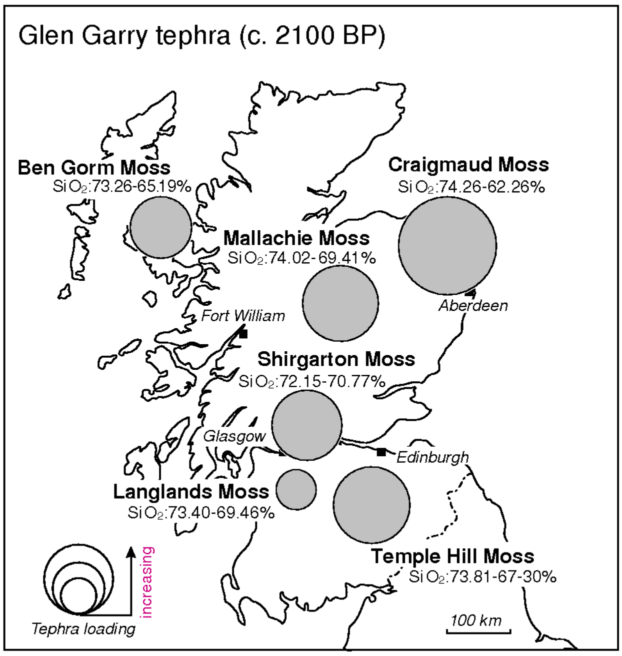

Figure 4 Tephra loading of the Glen Garry isochron from six sites over Scotland. The diameter of the circles relates to relative not absolute variations in concentration. The relative silica proportions from all the tephra shards analysed for each site are shown.

the ground, only about 1% was deposited in dry form, and the other 99% was deposited as the result of a single period of rain (Mattsson and Vesanen, 1988). It is suggested that tephra deposition follows the same model.

Further evidence for a patchy fallout pattern comes from sites which did not contain any tephra horizons. No tephra was found in a 5 m profile investigated from Blar-nam-Fiadh Moss (NGR: NH 834 537), which is only *c.* 40 km from Mallachie Moss, which has comparatively high tephra loading. The lack of tephra at Blar-nam-Fiadh may be due to the effect of a rain shadow, produced by the Black Isle, situated to the northwest of the site. Additionally, no clearly defined tephra layers were identified in a core from the Red Moss of Balerno (NGR: NT 162 635), while less than 8 km away relatively high concentrations of tephra were recovered from Temple Hill Moss, reflecting local variability in fallout.

Certain characteristics pertaining to the dispersal patterns can be seen within this patchy distribution. Northern Skye has a low tephra loading, suggesting that this area may have been on the periphery of the ash cloud or there was less precipitation as the ash cloud passed over the site. The ash cloud appears to have been carried over Scotland and northern England, towards Ireland, driven by an anticyclone, as suggested by Larsen and Thorarinsson (1977). The latter phase of the eruption may be detected from the range of dacitic and andesitic shards which have been analysed. A few shards of the tephra analysed from Craigmaud exhibit a slight dacitic nature, and one shard has been found at Ben Gorm of only 63.67% silica, indicating that the latter phase of the eruption still reached northwest Scotland. Dacitic and some

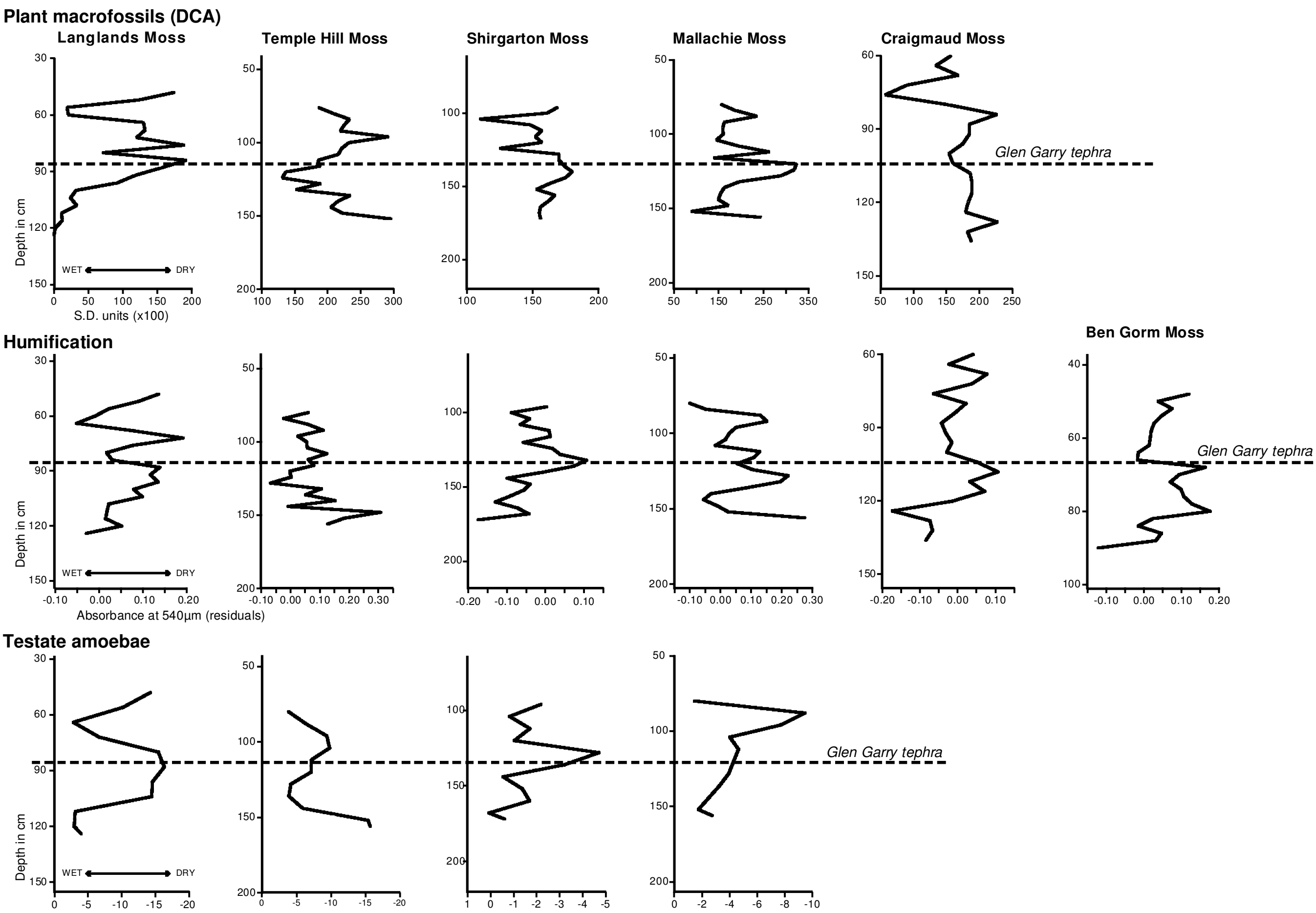

Figure 5 Graphs showing the variations in plant macrofossil DCA records, humification and reconstructed water-table depths from testate amoebae analyses from six sites where the Glen Garry tephra has been located.

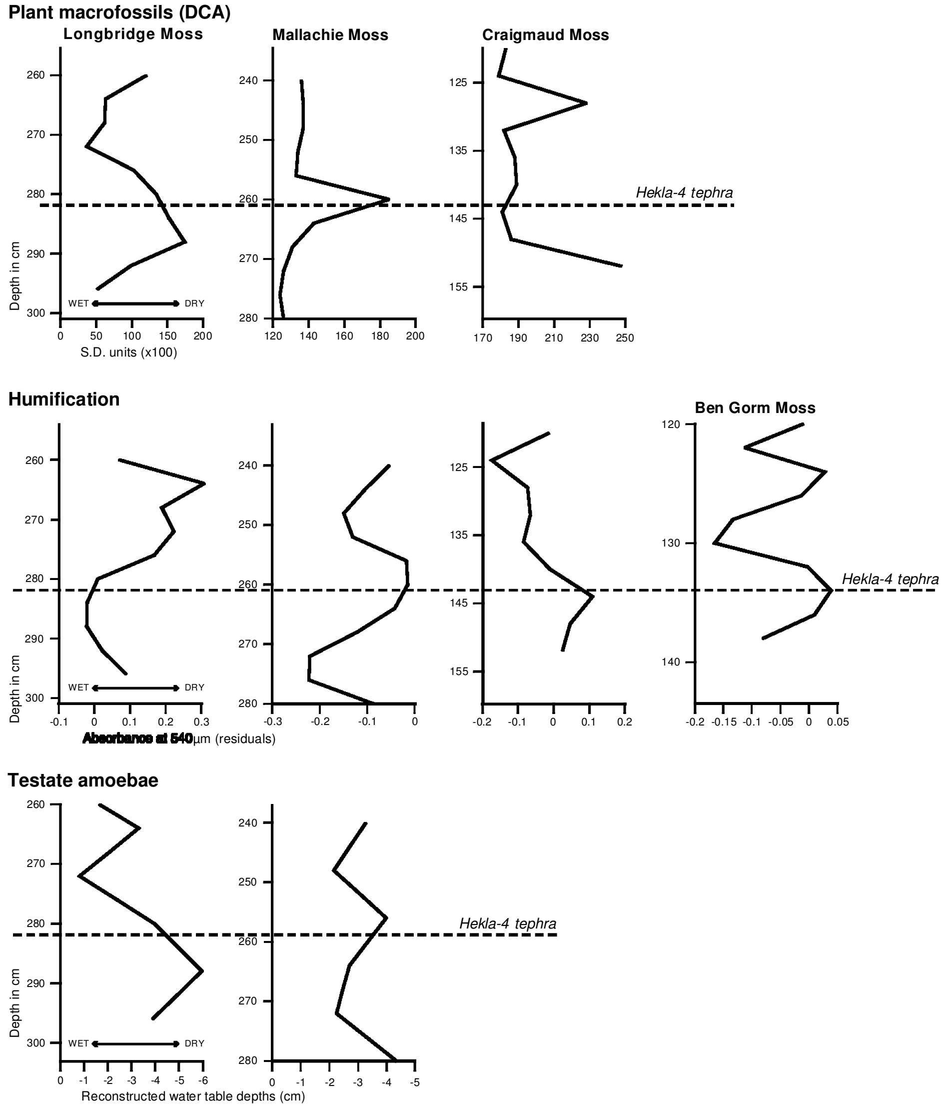

Figure 6 Graphs showing the variations in plant macrofossil DCA records, humification and reconstructed water-table depths from testate amoebae analyses from four sites where the Hekla-4 tephra has been located.

andesitic shards have been recovered from northern Scotland (Dugmore *et al.*, 1995) and therefore confirm that the later phase of the eruption can be detected in these areas.

The distribution of Glen Garry tephra is illustrated in Figure 4. These data suggest that most of Scotland was covered by the initial phase of the eruption. Glen Garry tephra has also been located on the Western Isles (Dugmore *et al.*, 1995) as well as in northern England (Pilcher and Hall, 1996), but has not yet been reported in Ireland. The initial phase of the eruption, indicated by the highest amounts of silicic glass, has been deposited around northeast Scotland (Craigmaud Moss). This region also has the highest tephra loading, occurring in the north and northeast, with the lowest amounts in west central Scotland.

Palaeoclimate reconstructions

The six raised bogs (Longbridge Moss, Langlands Moss, Temple Hill Moss, Shirgarton Moss Mallachie Moss and Craigmaud Moss), were sampled at 4 cm intervals for plant macrofossil and colorimetric humification analysis and at 8 cm for testate amoebae analysis in order to reconstruct changes in past bog surface wetness, a proxy for past climatic change. Ben Gorm Moss was sampled at 2 cm intervals for humification, testate amoebae and plant macrofossil analysis, but the plant macrofossils and testate amoebae were poorly preserved and no useful data were gained. The testate amoebae concentrations were also very low from Craigmaud Moss, and were not used for climate reconstruction.

Plant macrofossils were prepared and quantified following the methods outlined in Barber *et al.* (1994) and Mauquoy and Barber (1999) and testate amoebae samples were prepared following Charman *et al.* (2000). The procedure for colorimetric humification analysis followed Blackford and Chambers (1993).

The three proxy indicators were used together in order to provide a composite palaeoclimate record (Charman *et al.*, 1999; Chiverrell, 2001). The plant macrofossil data were modelled using detrended correspondence analysis (DCA) (Barber *et al.*, 1994; Charman *et al.*, 1999; Mauquoy and Barber, 1999; Hughes *et al.*, 2000; Chiverrell, 2001). A mean water-table depth transfer function (Woodland *et al.*, 1998) was applied to the testate amoebae data (Charman and Hendon, 2000; Hendon *et al.*, 2001) and the humification data were detrended linearly (Chambers *et al.*, 1997).

Tephra isochrons – precise correlations of palaeoclimate data

As dispersal of the Glen Garry tephra over Scotland is good, a detailed reconstruction of climate can be made from the palaeo-

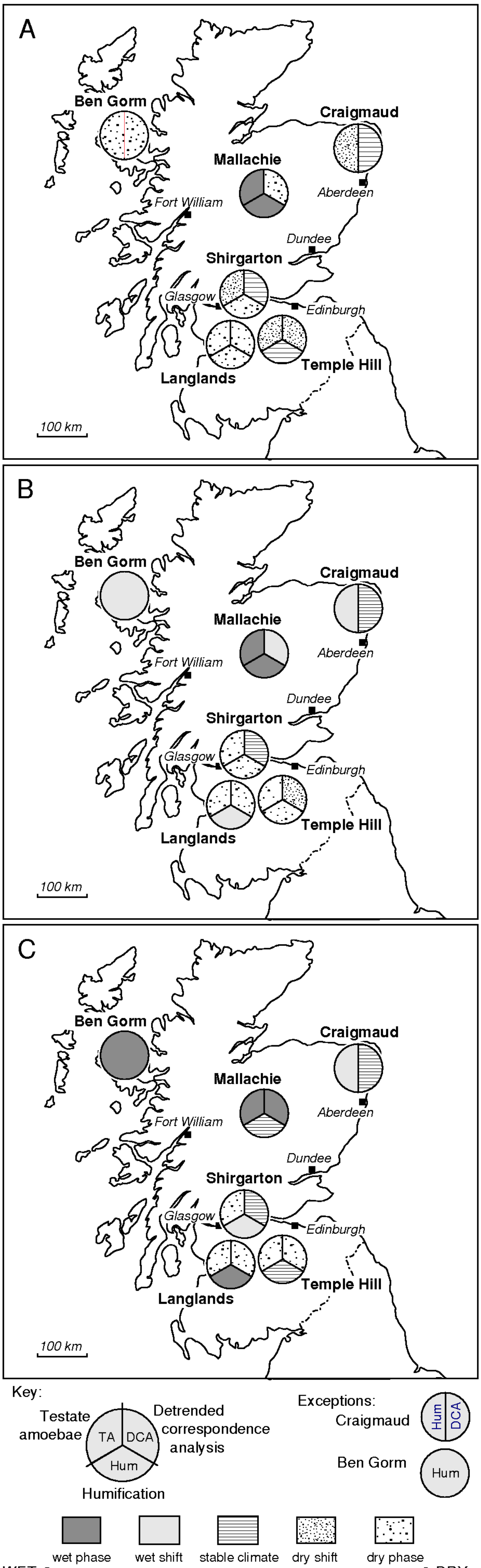

Figure 7 The pie charts represent the spatial variability between sites for each of the proxy reconstructions at the Glen Garry tephra isochron. The reconstructions are represented as a wetness gradient, from the wettest (a wet phase) through to a dry phase at the opposite end of the scale. The climatic changes are shown from the samples immediately before (A), at (B) and after (C) the tephra isochron, enabling the direction of change over the isochron to be determined.

ecological evidence at the time of this tephra (Figure 5 and Table 3) and can also be represented spatially (Figure 7). The cores were sampled every 4 cm (8 cm for testate amoebae), with each sample representing an average of *c.* 10–12 years and the 4 cm interval representing, on average, 40–50 years. Depending on whether the isochron at an individual site is located near a sample or not, the records displayed in Figure 7(a–c) may fall temporally close together or a few decades apart. The reconstructions therefore produce low-frequency but high-resolution data, which filter out the annual variability and detect decadal to centennial shifts in climate.

The palaeoecological evidence from central/southern Scotland (Langlands Moss, Temple Hill Moss and Shirgarton Moss) suggests a relatively dry climate before the Glen Garry isochron, remaining dry at and after the isochron. There are two exceptions to this pattern; the humification record at Langlands Moss which documents a wet shift at the isochron, and the humification record at Shirgarton which exhibits a wet shift just after the isochron. Although the reconstructed water-table level from the testate amoebae reconstruction is comparatively high (–4.7 cm) at Shirgarton Moss, this is relatively dry compared to the rest of the stratigraphy, and is due to a peak in *Difflugia pulex*, which has no modern analogue and is poorly modelled by the transfer function (D. Hendon, personal communication). Previous research has suggested that *Difflugia pulex* is often associated with more xerophilous taxa (Hendon, 1998). The suggested lowering of the water table at Shirgarton Moss also corresponds with an increase in humification, and is thus considered comparatively dry. The testate amoebae and DCA records at Temple Hill Moss suggest a dry shift before the isochron, resulting in a dry phase after the isochron. In contrast, the humification curve from Ben Gorm Moss indicates a wet shift through the isochron, being dry just before, to wet in the sample after the isochron. The same pattern of change occurs in the DCA data from Mallachie Moss, with the other proxy records suggesting a wet phase throughout. The reconstruction from Craigmaud Moss shows an ambiguous DCA record, being dominated by unidentified organic matter (UOM) around this time, although the humification data does suggest a clear wet shift around the isochron. It therefore appears that different climatic patterns were affecting northern and central/southern Scotland at the time of deposition of the Glen Garry tephra.

A similar pattern of climatic change can be observed for the Hekla-4 isochron (Figures 6 and 8; Table 4) although only four sites are represented. There is a change in the palaeoecological data at Longbridge Moss from the sample before the isochron suggesting a dry phase (testate amoebae water-table reconstruction and DCA) followed by a wet shift at and after the isochron, although the humification record implies a wet phase throughout the samples. This pattern is mirrored by the humification record at Craigmaud Moss. In the Cairngorms, palaeoecological evidence from Mallachie Moss suggests a wet climate immediately before the isochron, which then becomes comparatively drier through and immediately after the isochron. The humification record from Ben Gorm Moss suggests a relatively dry climate before and during the isochron, followed by a wet shift immediately after Hekla-4 deposition. In general, the palaeoecological evidence from the bogs around the deposition Hekla-4 suggests a pattern of climatic change showing wet climates at or soon after the ashfall event.

Table 3 A summary of the palaeoecological and palaeoclimatic interpretations at the time of the Glen Garry ashfall over six sites in Scotland

Site	Plant macrofossils	DCA	Testate amoebae	Water-table depth (cm)	Humification	Climate reconstruction
Langlands Moss	Large amounts of UOM, Ericaceae and *Eriophorum vaginatum*. Declining *Sphagnum* to zero. Charcoal after deposition.	Dry throughout, although wet phase (rise in *S.imbricatum*) *c*. 200 years later.	Dominated by *Hyalosphenia subflava* before, throughout and after tephra deposition.	Tending around –16 cm.	Dry before, but start of slight decrease in values (possible wet shift) after deposition.	Plant macros and testate amoebae suggest a low mire water-table depth, inferring a dry climate.
Temple Hill Moss	*c*. 40% monocots and declining Sphagna (*S.s. Acutifolia*).	Tending towards lower water tables and drier climate.	Declining levels of *Amphitrema flavum* and increasing *H. subflava*.	–7 cm lowering to –9 cm.	Values are relatively high.	All three proxies suggest relatively low water tables and infer a dry climate.
Shirgarton Moss	Dominated by *S. imbricatum* (>80%).	Difficult to interpret as dominated by one taxon.	Dominated by *Difflugia pulex* – which could be indicative of lowered bog water table.	–3 cm tending to –5 cm.	Dry – high values, but lowering *c*. 200 years after deposition.	Ambiguous plant macros, but humification and testates suggest drier phase.
Mallachie Moss	High levels of UOM followed by *S. cuspidatum*. High levels of charcoal, indicating some mire burning.	Wet phase through Glen Garry.	No sample at 120 cm, suggestion of no testates due to burning. Fauna dominated by *A. flavum*, *Cyclopyxis arcelloides* type.	–4 cm, indicative of high mire water tables.	Relative drop in values indicative of climatic deterioration.	After possible burning event suggestion of wetter climate.
Craigmaud Moss	Dominated by UOM, with a small amount of *Sphagnum* preserved.	Slight indication of higher bog surface wetness.	No samples.	No samples.	Relative decline associated with deposition.	Suggestion of a wetter climate, mainly from humification data.
Ben Gorm Moss	No samples.	No samples.	No samples.	No samples.	Relative decline in values.	Wet shift.

Table 4 A summary of the palaeoecological and palaeoclimatic interpretations at the time of the Hekla-4 ashfall over four sites in Scotland

Site	Plant macrofossils	DCA	Testate amoebae	Water-table depth (cm)	Humification	Climate reconstruction
Longbridge Moss	Decline in Ericaceae, High levels of *Aulacomnium palustre* succeeded by *Dicranum scoparium*. Very little *Sphagnum*.	Start of wet shift, leading to wet phase.	*Difflugia pristis*, *Difflugia pulex*, *Amphitrema flavum* all present, rise in *A. flavum* after deposition and first signs of *Arcella discoides* and *Centropyxis aculeata* type.	–4 cm tending to –1 cm after tephra deposition.	Wet phase.	All proxies suggest start of wet shift when H4 is deposited followed by a wet phase after deposition (*c*. 200 years).
Mallachie Moss	Dominated by *S.s. Acutifolia*, with increase in Ericaceae (30%) just after deposition.	Wet/stable climate, drier soon after deposition.	Dominated by *A. flavum* (>70%), slight increase in *Assulina muscorum* after deposition.	Between –3 cm to –4 cm.	End of wet phase, becoming drier.	End of a wet phase, becoming drier. Another wet phase after deposition (*c*. 200 years).
Craigmaud Moss	Dominated by UOM and monocots (undiff).	Stable reconstruction.	No samples.	No samples.	Wet phase.	Difficult to interpret, but possibly wetter.
Ben Gorm Moss	No samples.	No samples.	No samples.	No samples.	Dry phase.	Dry phase, with wet shift *c*. 200 years later.

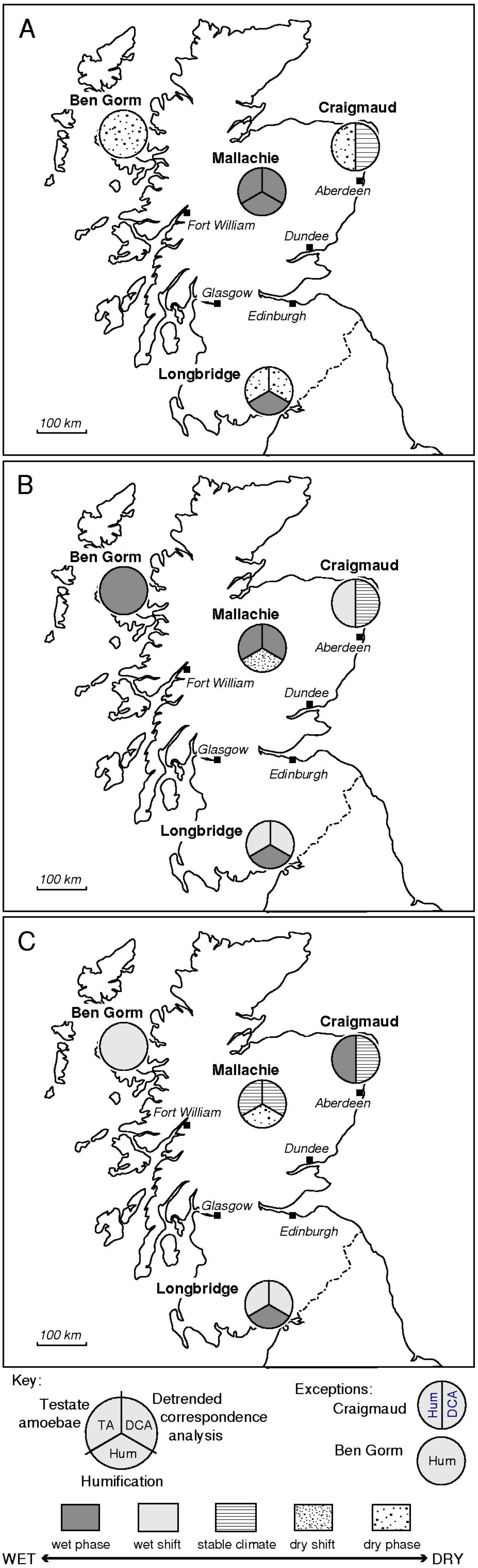

Figure 8 As Figure 7, for Hekla-4.

These palaeoecological reconstructions are important because they present a regional picture, showing that the patterns of climatic change were different in distinct parts of Scotland. By using radiocarbon dating alone, these changes would probably have been 'smeared' into the same event (*sensu* Baillie, 1991). Although the geographical spread of these data are good, more sites need to be analysed before the trends observed at the time of these isochrons can be validated on a regional scale. The Hekla-4 tephra has been shown to be particularly widespread in northern Scotland (Dugmore *et al.*, 1995), northern England (Pilcher and Hall, 1996) and Ireland (Pilcher and Hall, 1992; Pilcher *et al.*, 1996), although to date very few environmental records (with the exceptions of Blackford *et al.*, 1992, and Hall *et al.*, 1994), particularly climatic proxies, have been correlated utilizing the isochron. An increase in bog wetness was noted by Dwyer and Mitchell (1997) and Caseldine *et al.* (1998) across a tephra isochron at cal. 2300 BC, although the tephra was never geochemically typed, and Dwyer and Mitchell report two separate isochrons around 4000 BP. The increase in wetness at this time does, however, correlate with the evidence presented here relating to the Hekla-4 isochron in Scotland. If the climatic changes recorded by bogs are more a function of coherent temperature regimes, then it is possible that sites with similar thermal regimes will react synchronously to climatic changes, whereas when the bogs record climatic shifts that are out of phase the sites may be reacting to a non-coherent rainfall regime (cf. Barber *et al.*, 1999).

Conclusion

Before invoking a broad, dramatic climatic shift, it is always desirable to have sources of evidence from many regions (Adams *et al.*, 1999). In this case, seven sites have been analysed for palaeoclimatic changes throughout Scotland, each one differing in geographical and climatological characteristics. The establishment of synchronous climatic changes at different sites thus implies that a regional climate signal is being recorded. Defining synchroneity on a radiocarbon timescale remains problematic and hence the value of tephras in assessing regional palaeoclimatic changes cannot be underestimated.

Acknowledgements

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Appendix A: Glen Garry tephras from six ombrotrophic bogs in Scotland

Analysis No (1)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
(i) Langlands Moss										
287	73.40	0.57	12.61	3.93	0.29	0.53	2.23	2.65	1.99	98.20
288	72.38	0.63	12.43	3.90	0.26	0.53	2.20	2.62	1.95	96.90
84	71.35	0.64	12.66	4.29	0.13	0.58	2.78	2.23	1.77	96.43
86	69.46	0.85	12.87	5.27	0.13	0.75	3.08	2.83	1.77	97.01
Mean	71.65	0.67	12.64	4.35	0.20	0.60	2.57	2.58	1.87	97.14
SD	1.68	0.12	0.18	0.64	0.08	0.10	0.43	0.25	0.12	0.75
(ii) Temple Hill Moss										
260	73.81	0.43	12.68	3.92	0.14	0.37	2.28	2.82	1.95	98.40
107	73.62	0.58	12.56	3.80	0.17	0.42	2.40	1.40	2.04	96.99
108	73.44	0.58	12.54	3.80	0.18	0.44	2.24	1.49	2.01	96.72
265	73.41	0.52	12.53	3.91	0.09	0.39	2.46	2.04	1.95	97.30
269	73.31	0.53	12.60	3.71	0.10	0.42	2.32	2.08	1.99	97.06
261	73.04	0.46	12.44	3.66	0.14	0.37	2.25	2.37	1.99	96.72
115	72.88	0.51	12.57	3.79	0.18	0.45	2.10	2.68	2.15	97.31
106	72.68	0.56	12.69	3.64	0.16	0.51	2.23	2.17	1.96	96.60
268	72.41	0.48	12.31	3.42	0.07	0.37	2.27	2.23	1.95	95.51
109	72.34	0.62	12.72	4.42	0.18	0.61	2.47	1.86	1.87	97.09
263	71.76	0.75	12.88	4.37	0.15	0.51	2.57	3.25	1.85	98.09
112	71.46	0.63	12.69	4.24	0.21	0.56	2.60	2.20	1.98	96.57
262	71.36	0.45	12.18	3.81	0.11	0.40	2.33	2.57	1.93	95.14
104	71.02	0.67	12.84	5.00	0.15	0.69	2.84	3.49	1.70	98.40
Mean	72.26	0.57	12.59	4.03	0.14	0.48	2.42	2.38	1.94	96.81
SD	1.63	0.10	0.18	0.46	0.04	0.12	0.24	0.60	0.10	1.15
(iii) Shirgarton Moss										
125	72.15	0.51	12.26	3.67	0.09	0.40	2.12	3.45	2.03	96.68
124	70.77	0.56	11.97	3.76	0.08	0.46	2.40	2.75	3.59	96.34
(iv) Mallachie Moss										
246	74.02	0.52	12.65	3.83	0.10	0.42	2.29	2.85	1.87	98.55
18	74.00	0.56	12.83	3.72	0.09	0.47	2.13	2.48	1.91	98.19
21	73.73	0.51	12.73	3.83	0.12	0.43	2.26	2.75	2.11	98.47
14	73.73	0.47	12.59	3.60	0.07	0.43	2.15	2.77	1.97	97.78
242	73.60	0.50	12.66	3.65	0.12	0.44	2.36	3.02	1.93	98.28
19	73.50	0.56	12.57	3.74	0.12	0.46	2.13	2.72	2.59	98.39
233	73.45	0.43	12.35	3.52	0.10	0.39	2.18	2.95	1.98	97.35
237	73.16	0.58	12.82	3.95	0.09	0.44	2.46	3.04	1.92	98.46
244	73.05	0.59	12.67	3.86	0.14	0.41	2.28	3.11	1.97	98.08
10	72.59	0.43	12.62	3.84	0.10	0.41	2.31	2.51	1.98	96.79
247	72.50	0.54	12.56	3.79	0.09	0.46	2.45	3.47	1.92	97.78
238	72.40	0.54	12.50	4.01	0.12	0.48	2.33	3.14	1.93	97.45
243	72.13	0.49	12.70	3.90	0.12	0.49	2.16	3.04	2.04	97.07
11	72.04	0.60	12.92	4.49	0.11	0.56	2.69	2.70	1.94	98.05
24	71.97	0.54	12.42	3.95	0.11	0.38	2.16	2.72	1.98	96.23
249	71.89	0.66	12.95	5.02	0.14	0.72	3.04	3.52	1.93	99.87
17	71.37	0.64	12.99	4.55	0.10	0.60	2.65	2.98	1.89	97.77
239	70.63	0.81	13.09	5.29	0.17	0.77	2.96	2.94	1.69	98.35
5	70.14	0.74	12.61	4.65	0.10	0.67	2.78	3.19	2.02	96.90
248	69.99	0.74	12.99	5.05	0.20	0.72	3.10	3.81	1.82	98.42
20	69.95	0.71	12.77	4.32	0.09	0.60	2.76	2.50	1.75	95.45
240	69.67	0.84	13.02	5.19	0.18	0.82	3.11	2.85	1.71	97.39
9	69.41	0.66	12.66	5.07	0.15	0.64	2.74	2.05	1.83	95.21
Mean	71.88	0.56	12.58	4.02	0.11	0.49	2.38	2.90	2.07	96.99
SD	1.45	0.14	0.36	0.67	0.03	0.15	0.39	0.38	0.59	1.65
(v) Craigmaud Moss										
117	74.26	0.56	12.59	3.70	0.14	0.41	2.11	2.96	2.04	98.77
125	74.11	0.60	12.72	3.59	0.10	0.44	2.31	3.18	2.01	99.06
122	73.98	0.48	12.59	3.73	0.11	0.42	2.23	3.26	2.07	98.87
255	73.77	0.54	12.48	3.88	0.13	0.40	2.24	2.90	2.35	98.69
256	73.56	0.54	12.40	3.80	0.07	0.45	2.30	3.68	2.02	98.82
137	73.46	0.51	12.41	3.76	0.11	0.45	2.28	3.26	2.03	98.27
134	73.16	0.51	12.47	3.67	0.06	0.39	2.09	3.17	1.91	97.43
144	72.55	0.49	12.37	3.61	0.08	0.40	2.18	2.48	1.60	95.76
119	72.32	0.50	12.33	3.90	0.11	0.41	2.25	2.47	1.99	96.28
131	72.02	0.70	12.38	3.98	0.10	0.45	2.40	2.98	1.95	96.96
130	71.96	0.68	13.00	4.25	0.14	0.58	2.53	2.96	1.79	97.89
61	71.77	0.60	13.01	4.18	0.12	0.48	2.62	3.01	1.92	97.71
60	71.66	0.61	13.07	4.37	0.13	0.50	2.51	2.85	1.88	97.58
121	70.95	0.76	12.64	5.01	0.19	0.64	2.79	3.06	1.80	97.84
140	70.87	0.77	12.89	4.63	0.12	0.65	2.83	3.05	1.77	97.58
57	70.67	0.67	13.05	4.66	0.10	0.62	2.99	2.89	1.84	97.49
141	70.66	0.79	12.91	4.89	0.19	0.64	2.97	2.79	1.81	97.65
56	70.63	0.80	13.22	4.17	0.12	0.64	2.87	2.23	1.70	96.38
120	70.15	0.73	12.97	4.97	0.10	0.69	2.93	3.09	1.69	97.32
257	66.40	1.06	13.38	6.28	0.21	1.19	4.12	3.33	1.54	97.51
127	64.06	1.24	13.29	7.11	0.24	1.58	4.66	3.42	1.36	96.96
136	62.72	1.32	13.32	7.56	0.16	1.69	4.68	3.01	1.33	95.79
126	62.26	1.40	13.41	8.02	0.20	1.90	5.35	3.39	1.14	97.07
Mean	70.98	0.70	12.81	4.53	0.13	0.66	2.78	3.03	1.85	97.47
SD	3.49	0.29	0.39	1.38	0.05	0.45	0.95	0.37	0.33	1.08
(vi) Ben Gorm Moss										
161	73.26	0.46	12.48	3.7	0.14	0.44	2.32	3.49	1.88	98.17
162	72.94	0.54	12.23	4.09	0.09	0.45	2.37	3.68	1.95	98.34
16	72.13	0.64	12.6	4.27	0.08	0.46	2.66	2.62	1.77	97.23
17	72.06	0.55	12.27	3.32	0.11	0.44	2.61	2.11	1.69	95.16
11	71.92	0.49	12.23	3.59	0.12	0.47	2.4	2.94	2.02	96.18
18	71.87	0.45	12.29	3.79	0.06	0.40	2.5	3.27	2.15	96.78
163	71.06	0.48	11.82	3.63	0.05	0.42	2.17	3.58	1.96	95.17
2	69.92	0.71	13.14	5.08	0.15	0.82	2.97	3.17	1.73	97.69
4	69.63	0.76	12.98	4.70	0.10	0.67	2.88	2.74	1.69	96.15
3	68.67	0.72	12.52	5.12	0.08	0.68	2.84	3.6	1.83	96.06
10	67.39	0.85	13.00	5.80	0.10	1.35	4.33	2.96	1.52	97.30
159	66.12	1.00	11.96	7.10	0.16	2.55	6.00	3.53	1.43	99.85
Mean	70.11	0.65	12.47	4.55	0.10	0.75	3.01	3.08	1.79	96.50
SD	2.54	0.19	0.38	1.08	0.04	0.57	1.02	0.45	0.20	1.61

Total iron is expressed as FeO.

Appendix B: Hekla-4 tephras from four ombrotrophic bogs in Scotland

Analysis No (2)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
(i) Longbridge Moss										
140	74.89	0.11	13.15	2.03	0.02	0.03	1.40	3.26	2.79	97.68
141	73.91	0.13	12.80	1.81	0.03	0.05	1.41	2.28	2.74	95.16
101	73.73	0.08	12.88	1.83	0.02	0.02	1.42	3.87	2.61	96.46
144	73.65	0.09	12.80	1.97	0.08	0.05	1.26	2.96	2.48	95.34
119	73.22	0.17	12.74	2.12	0.11	0.06	1.51	3.98	2.61	96.52
113	73.02	0.07	12.75	1.88	0.07	0.02	1.25	4.08	2.75	95.89
103	72.98	0.08	12.70	1.95	0.06	0.03	1.47	4.33	2.86	96.46
100	72.69	0.06	12.73	1.82	0.13	0.04	1.35	4.17	2.70	95.69
111	72.48	0.14	12.66	1.83	0.10	0.04	1.30	4.20	2.91	95.66
121	72.18	0.10	11.97	1.95	0.05	0.05	1.35	4.38	2.98	95.01
118	71.72	0.12	12.92	1.97	0.07	0.06	1.36	4.08	2.85	95.15
Mean	72.69	0.11	12.68	1.92	0.06	0.04	1.37	3.72	2.74	95.33
SD	1.08	0.04	0.26	0.10	0.03	0.01	0.08	0.76	0.14	1.17
(ii) Mallachie Moss										
229	74.59	0.07	13.10	1.95	0.07	0.07	1.40	3.85	2.83	97.93
228	74.24	0.13	12.80	2.06	0.07	0.02	1.27	3.97	2.77	97.33
49	74.16	0.12	13.41	2.01	0.08	0.04	1.31	3.63	2.86	97.62
44	74.12	0.11	13.34	1.99	0.12	0.06	1.26	3.89	2.85	97.74
45	73.94	0.13	13.16	1.98	0.11	0.05	1.36	3.61	2.82	97.16
223	73.87	0.07	12.91	1.97	0.06	0.04	1.27	4.12	2.61	96.92
222	73.64	0.09	12.90	2.02	0.10	0.03	1.33	3.89	2.70	96.70
187	73.29	0.10	12.79	1.97	0.08	0.07	1.44	3.47	2.69	95.90
219	73.28	0.07	12.75	1.91	0.04	0.05	1.38	4.00	2.83	96.31
54	73.05	0.14	13.44	2.04	0.08	0.06	1.32	3.48	2.91	96.52
210	73.03	0.14	12.87	1.98	0.12	0.03	1.31	4.01	2.62	96.11
53	73.02	0.10	13.16	1.83	0.06	0.04	1.19	3.48	2.84	95.72
47	73.00	0.11	12.92	1.84	0.16	0.04	1.34	3.21	2.80	95.42
224	72.97	0.08	12.86	1.90	0.10	0.01	1.40	3.44	2.72	95.48
218	72.90	0.15	12.90	1.87	0.07	0.05	1.35	3.54	2.66	95.49
32	72.79	0.06	13.15	2.02	0.08	0.05	1.39	3.27	2.81	95.62
46	72.68	0.08	12.88	2.03	0.10	0.04	1.29	3.14	2.95	95.19
42	72.13	0.12	13.15	1.84	0.08	0.02	1.33	3.51	3.18	95.36
Mean	72.94	0.10	12.94	1.95	0.10	0.04	1.32	3.58	2.86	95.83
SD	0.91	0.03	0.25	0.12	0.03	0.02	0.07	0.31	0.38	1.10
(iii) Craigmaud Moss										
77	75.55	0.15	13.40	2.02	0.20	0.04	1.42	4.15	2.95	99.88
80	75.21	0.12	13.36	2.07	0.16	0.06	1.38	3.98	3.07	99.41
78	75.10	0.18	13.41	2.05	0.14	0.05	1.34	3.61	3.65	99.53
183	74.99	0.07	13.19	1.98	0.09	0.01	1.33	3.89	2.84	98.39
153	74.71	0.08	13.08	1.93	0.11	0.01	1.35	4.06	2.75	98.08
70	74.45	0.11	13.58	1.98	0.13	0.10	1.37	3.42	2.72	97.86
168	74.30	0.11	12.65	2.04	0.08	0.03	1.38	3.71	2.93	97.23
171	74.17	0.11	12.90	1.97	0.06	0.03	1.35	3.84	2.92	97.35
182	74.14	0.18	12.99	1.89	0.10	0.03	1.38	4.03	3.01	97.75
181	74.01	0.09	12.96	1.98	0.13	0.01	1.32	3.97	2.67	97.14
73	73.80	0.15	13.18	2.15	0.13	0.04	1.23	3.39	2.57	96.64
151	73.76	0.12	13.18	1.97	0.05	0.04	1.30	3.55	3.09	97.06
75	73.68	0.13	13.35	2.23	0.06	0.04	1.17	4.00	2.84	97.50
67	73.56	0.10	13.20	2.01	0.13	0.06	1.25	2.99	2.99	96.29
149	73.36	0.10	12.93	1.92	0.08	0.00	1.33	3.29	2.74	95.75
166	73.21	0.08	12.82	2.05	0.07	0.02	1.19	3.80	3.34	96.58
173	73.10	0.10	12.64	1.88	0.09	0.02	1.30	4.41	2.71	96.25
175	73.08	0.15	12.71	1.76	0.03	0.03	1.21	3.68	3.13	95.78
177	72.86	0.11	12.70	1.80	0.10	0.04	1.27	3.70	2.70	95.28
65	72.78	0.19	13.31	2.04	0.13	0.05	1.41	3.68	2.93	96.52
159	72.70	0.10	13.03	2.06	0.08	0.04	1.37	4.01	2.61	96.00
179	72.69	0.08	12.54	1.91	0.07	0.04	1.13	3.88	2.88	95.22
150	72.55	0.13	13.77	2.79	0.11	0.06	1.79	3.83	2.60	97.63
163	72.32	0.11	12.40	2.06	0.10	0.07	1.27	3.00	4.86	96.19
160	72.31	0.07	12.62	1.89	0.06	0.05	1.25	4.11	2.75	95.11
72	71.89	0.13	13.02	2.10	0.15	0.06	1.36	3.62	2.85	95.18
66	71.06	0.24	14.10	3.36	0.18	0.06	2.03	3.63	2.52	97.18
178	70.71	0.22	13.61	3.39	0.17	0.03	2.04	4.23	2.69	97.09
164	70.41	0.22	13.77	3.78	0.14	0.05	2.24	3.62	2.45	96.68
Mean	73.03	0.14	13.08	2.19	0.11	0.04	1.42	3.67	2.87	96.54
SD	1.46	0.05	0.44	0.56	0.05	0.02	0.31	0.39	0.43	1.43
(iv) Ben Gorm Moss										
78	72.85	0.08	12.79	1.88	0.12	0.04	1.32	3.88	2.90	95.86
89	72.16	0.08	12.46	1.98	0.14	0.02	1.23	3.52	2.72	94.31
91	71.83	0.05	12.70	1.83	0.12	0.07	1.25	3.95	2.71	94.51
76	71.43	0.07	12.32	1.64	0.08	0.03	1.31	3.62	2.50	93.00
86	70.66	0.16	11.73	2.81	0.11	0.05	0.43	3.48	4.24	93.67
85	70.05	0.21	11.87	2.68	0.10	0.08	0.42	3.94	4.16	93.51
92	63.67	1.63	14.29	6.65	0.22	1.55	3.83	4.58	2.61	99.03
Mean	70.38	0.33	12.59	2.78	0.13	0.26	1.40	3.85	3.12	94.84
SD	3.10	0.58	0.85	1.76	0.04	0.57	1.15	0.38	0.75	2.06

Total iron is expressed as FeO.

References

Adams, J., Maslin, M. and **Thomas, E.** 1999: Sudden climate transitions during the Quaternary. *Progress in Physical Geography* 23, 1–36.
Baillie, M.G.L. 1991: Suck in and smear: two related chronological problems for the 90s. *Journal of Theoretical Archaeology* 2, 12–16.
Barber, K.E. 1981: *Peat stratigraphy and climatic change: a palaeoecological test of the theory of cyclic peat bog regeneration.* Rotterdam: Balkema.
Barber, K.E., Battarbee, R.W., Brooks, S.J., Eglinton, G., Haworth, E.Y., Oldfield, F., Stevenson, A.C., Thompson, R., Appleby, P., Austin, W.N. , Cameron, N., Ficken, K.J., Golding, P., Harkness, D.D., Holmes, J., Hutchinson, R., Lishman, J. P., Maddy, D., Pinder, L.C.V., Rose, N.L. and **Stoneman, R.E.** 1999: Proxy records of climate change in the UK over the last two millennia: documented change and sedimentary records from lakes and bogs. *Journal of the Geological Society* 156, 369–80.
Barber, K.E., Chambers, F.M., Maddy, D., Stoneman, R.E. and **Brew, J.S.** 1994: A sensitive high-resolution record of late-Holocene climatic change from a raised bog in northern England. *The Holocene* 4, 198–205.
Barber, K.E., Dumayne-Peaty, L., Hughes, P.D.M., Mauquoy, D. and **Scaife, R.G.** 1998: Replicability and variability of the recent macrofossil and proxy-climate record from raised bogs: field stratigraphy and macrofossil data from Bolton Fell Moss and Walton Moss, Cumbria, England. *Journal of Quaternary Science* 13, 515–28.
Barber, K.E., Maddy, D., Rose, N., Stevenson, A.C., Stoneman, R.E. and **Thompson, R.** 2000: Replicated proxy-climate signals over the last 2,000 years from two distant peat bogs: new evidence for regional palaeoclimate teleconnections. *Quaternary Science Reviews* 19, 481–87.
Barrow, E., Hulme, M. and **Jiang, T.** 1993: *A 1961–90 baseline and future climate change scenarios for Great Britain and Europe. Part I: 1961–90 Great Britain baseline climatology.* University of East Anglia, Norwich: Climatic Research Unit.
Birse, E.L. 1971: *Assessment of climatic conditions in Scotland. 3. Bioclimatic sub-regions.* Aberdeen: Macaulay Institute for Soil Research.
Blackford, J.J. and **Chambers, F.M.** 1993: Determining the degree of peat decomposition for peat based palaeoclimatic studies. *International Peat Journal* 5, 7–24.
Blackford, J.J., Edwards, K.J., Dugmore, A.J., Cook, G.T. and **Buckland, P.C.** 1992: Icelandic volcanic ash and the mid-Holocene Scots pine (*Pinus sylvestris*) pollen decline in northern Scotland. *The Holocene* 2, 260–65.
Blytt, A. 1876: *Essay on the immigration of the Norwegian flora during alternating rainy and dry periods.* Christiana: Cannermeye.
Caseldine, C., Hatton, J., Huber, U., Chiverrell, R. and **Woolley, N.** 1998: Assessing the impact of volcanic activity on mid-Holocene climate in Ireland: the need for replicate data. *The Holocene* 8, 105–11.
Chambers, F.M., Barber, K.E., Maddy, D. and **Brew, J.** 1997: A 5500-year proxy-climate and vegetation record from blanket mire at Talla Moss, Borders, Scotland. *The Holocene* 7, 391–99.
Charman, D.J. and **Hendon, D.** 2000: Long-term changes in soil water tables over the past 4500 years: relationships with climate and North Atlantic atmospheric circulation and sea surface temperature. *Climatic Change* 47, 45–59.
Charman, D.J., Hendon, D. and **Packman, S.** 1999: Multiproxy surface wetness records from replicate cores on an ombrotrophic mire: implications for Holocene palaeoclimate records. *Journal of Quaternary Science* 14, 451–63.
Charman, D.J., Woodland, W.A. and **Hendon, D.** 2000: *The identification of testate amoebae (Protozoa: Rhizopoda) from British oligotrophic peatlands.* Quaternary Research Association Technical Guide Number 9.
Chiverrell, R.C. 2001: A proxy record of late Holocene climate change from May Moss, northeast England. *Journal of Quaternary Science* 16, 9–29.
Dugmore, A.J. and **Newton, A.J.** 1992: Thin tephra layers in peat revealed by X-radiography. *Journal of Archaeological Science* 19, 163–70.
Dugmore, A.J., Larsen, G. and **Newton, A.J.** 1995: Seven tephra isochrones in Scotland. *The Holocene* 5, 257–66.
Dugmore, A.J., Newton, A.J., Edwards, K.E., Larsen, G., Blackford, J.J. and **Cook, G.T.** 1996: Long-distance marker horizons from small-scale eruptions: British tephra deposits from the AD 1510 eruption of Hekla, Iceland. *Journal of Quaternary Science* 11, 511–16.
Dugmore, A.J., Newton, A.J., Sugden, D.E. and **Larsen, G.** 1992: Geochemical stability of fine-grained silicic Holocene tephra in Iceland and Scotland. *Journal of Quaternary Science* 7, 173–83.
Dwyer, R.B. and **Mitchell, F.J.G.** 1997: Investigation of the environmental impact of remote volcanic activity on north Mayo, Ireland, during the mid-Holocene. *The Holocene* 7, 113–18.
Hall, V.A. and **Pilcher, J.R.** 2002: Late-Quaternary Icelandic tephras in Ireland and Great Britain: detection, characterization and usefulness. *The Holocene* 12, 223–30.
Hall, V.A., Pilcher, J.R. and **McCormac, F.G.** 1994: Icelandic volcanic ash and the mid-Holocene Scots pine (*Pinus sylvestris*) decline in the north of Ireland: no correlation. *The Holocene* 4, 79–83.
Hendon, D. 1998: Robustness and precision of Holocene palaeoclimatic records from peatlands, using testate amoebae analysis. PhD thesis, University of Plymouth.
Hendon, D., Charman, D.J. and **Kent, M.** 2001: Palaeohydrological records derived from testate amoebae analysis from peatlands in northern England: within-site variability, between-site comparability and palaeoclimatic implications. *The Holocene* 11, 127–48.
Hughes, P.D.M., Mauquoy, D., Barber, K.E. and **Langdon, P.G.** 2000: Mire development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England. *The Holocene* 10, 465–79.
Hunt, J.B. and **Hill, P.G.** 1993: Tephra geochemistry: a discussion of some persistent analytical problems. *The Holocene* 3, 271–78.
—— 2001: Tephrological implications of beam size – sample-size effects in electron microprobe analysis of glass shards. *Journal of Quaternary Science* 16, 105–17.
Kilian, M.R., van der Plicht, J. and **van Geel, B.** 1995: Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climate change. *Quaternary Science Reviews* 14, 959–66.
Langdon, P.G. 1999: Reconstructing Holocene climate change in Scotland utilizing peat stratigraphy and tephrochronology. PhD thesis, University of Southampton.
Langdon, P.G. and **Barber, K.E.** 2001: New Holocene tephras and a proxy climate record from a blanket mire in northern Skye, Scotland. *Journal of Quaternary Science* 16, 753–59.
—— 2002: The 'AD 860' tephra in Scotland: new data from Langlands Moss, East Kilbride, Strathclyde. *Quaternary Newsletter* 97, 11–18.
Langdon, P.G., Barber, K.E. and **Hughes, P.D.M.** 2003: A 7500 year peat-based palaeoclimatic reconstruction and evidence for an 1100 year cyclicity of surface wetness from Temple Hill Moss, Pentland Hills, Southeast Scotland. *Quaternary Science Reviews* 22, 259–74.
Larsen, G. and **Thorarinsson, S.** 1977: H4 and other acidic Hekla tephra layers. *Jökull* 27, 28–46.
Larsen, G., Dugmore, A.J. and **Newton, A.J.** 1999: Geochemistry of historical age silicic tephras in Iceland. *The Holocene* 9, 463–71.
Larsen, G., Newton, A.J., Dugmore, A.J. and **Vilmundardóttir, E.G.** 2001: Geochemistry, dispersal, volumes and chronology of Holocene silicic tephra layers from the Katla volcanic system, Iceland. *Journal of Quaternary Science* 16, 119–32.
Le Maitre, R.W. editor, 1989: *A classification of igneous rocks and glossary of terms.* Oxford: Basil Blackwell.
Lowe, D.J. and **Hunt, J.B.** 2001: A summary of terminology used in tephra-related studies. In Raynal, J.-P. and Juvigne, E.T., editors, *Tephra: chronology, archaeology*, Les Dossiers de l'Archéo-Logis 1, 17–22.
Lowe, J.J., Birks, H.H., Brooks, S.J., Coope, G.R., Harkness, D.D., Mayle, F.E., Sheldrick, C., Turney, C.S.M. and **Walker, M.J.C.** 1999: The chronology of palaeoenvironmental changes during the Last Glacial-Holocene transition: towards an event stratigraphy for the British Isles. *Journal of the Geological Society* 156, 397–410.
Mattsson, S. and **Vesanen, R.** 1988: Patterns of Chernobyl fallout in relation to local weather conditions. *Environment International* 14, 177–80.
Mauquoy, D. and **Barber, K.E.** 1999: A replicated 3000 year proxy-record from Coom Rigg Moss and Felecia Moss, the Border Mires, northern England. *Journal of Quaternary Science* 14, 263–75.
Persson, C. 1971: Tephrochronological investigations of peat deposits in Scandinavia and on the Faroe Islands. *Sveriges Geologiska Undersokning* 65, 3–34.
Pilcher, J.R. 1991: Radiocarbon dating for the Quaternary scientist. *Quaternary Proceedings* 1, 27–33.

Pilcher, J.R. and **Hall, V.A.** 1992: Towards a tephrochronology for the Holocene of the north of Ireland. *The Holocene* 2, 255–59.
—— 1996: A tephrochronology for the Holocene of the north of England. *The Holocene* 6, 100–105.
Pilcher, J.R., Hall, V.A. and **McCormac, F.G.** 1995: Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats. *The Holocene* 5, 103–10.
—— 1996: An outline tephrochronology for the Holocene of the north of Ireland. *Journal of Quaternary Science* 11, 485–94.
Sernander, R. 1908: On the evidence of postglacial changes of climate furnished by the peat-mosses of northern Europe. *Geologiska Föreningens I Stockholm Förhhandlingar* 30, 465–78.
Speranza, A., van der Plicht, J. and **van Geel, B.** 2000: Improving the time control of the Subboreal/Subatlantic transition in a Czech peat sequence by ^{14}C wiggle-matching. *Quaternary Science Reviews* 19, 1589–604.
Sweatman, T.R. and **Long, J.V.P.** 1969: Quantitative electron probe microanalysis of rock forming minerals. *Journal of Petrology* 10, 332–79.
Thorarinsson, S. 1967: The tephra-fall from Hekla on March 29th, 1947. In Einarsson, Th., Kjartansson, G. and Thorarinsson, S., editors, *The eruption of Hekla 1947–1948*, Reykjavik: Socientatis Islandica II(3), 1–68.
Woodland, W.A., Charman, D.J. and **Sims, P.C.** 1998: Quantitative estimates of water tables and soil moisture in Holocene peatlands from testate amoebae. *The Holocene* 8, 261–73.