A Holocene tephra record from the Lofoten Islands, Arctic Norway

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A tephrochronology has been established for a peat bog in the Lofoten Islands that provides a dating framework for future lake and bog studies of climate variation in this climatically sensitive area. Twenty-three tephra layers were identified, all apparently of Icelandic origin. These included the historically dated tephras of AD 1875 (Askja), AD 1362 (Öraefajökull), AD 1158 (Hekla), AD 1104 (Hekla) and the Landnam tephra identified at AD 875 in the GRIP ice core. Other layers, previously radiocarbon dated in Ireland and elsewhere, include the Hekla eruptions of *c.* 2310 BC and *c.* 5990 BC. The basal clays below the peat contain tephra of both the Askja eruption of *c.* 9500 BC (10 000 radiocarbon years BP) and the well-known Vedde Ash of *c.* 12 000 BP (10 030 ± 80 BC in GRIP ice core).

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Tephrochronology has been used in many parts of the world to provide time scales for past environmental studies. Much of this work has depended on massive layers visible in the field. Good examples are the Mazama ash in the USA (Bacon 1983; Hallett *et al.* 1997) and the Kakaroa ash in New Zealand (Froggatt & Lowe 1990). The use of tephra present in microscopic amounts (called cryptotephra by Lowe & Hunt 2001) has been most actively pursued in NW Europe based on tephras from Iceland (e.g. Dugmore *et al.* 1995; Pilcher *et al.* 1996; van den Bogaard & Schmincke 2002). The geochemistry of the tephras from the Icelandic volcanic systems has been extensively researched (e.g. Thorarinsson 1981a, b; Larsen *et al.* 1999; Haflidason *et al.* 2000). Many of the eruptions that occurred in about the last millennium are historically dated, with many earlier eruptions radiocarbon-dated (Haflidason *et al.* 2000). The Icelandic volcanic systems are ideal for tephrochronology as they are geochemically diverse, often making possible the separation both of volcanoes and their individual eruptions.

Icelandic tephras have been found in Scotland (Dugmore 1989; Dugmore *et al.* 1995), in England (Pilcher & Hall 1996), in Ireland (Pilcher *et al.* 1995, 1996; Hall & Pilcher 2002), in Germany (e.g. van den Bogaard & Schmincke 2002), in Sweden (Oldfield *et al.* 1997; Boygle 1998; Wastegård *et al.* 2003; Bergman *et al.* 2004), in Norway (Persson 1971; Holmes 1998), and in the Faroe Islands (Persson 1971; Wastegård *et al.* 2001). In Ireland, the rapidly accumulating, *Sphagnum*-rich, lowland raised bogs have provided ideal material for high precision radiocarbon-dating of a number of the Holocene tephra layers that are of value as chronological markers (Pilcher *et al.* 1995; Plunkett *et al.* 2004). We can now apply this dating to the more slowly accumulating peats and lake sediments of the Lofoten Islands.

In the summer of 2000, a team from the University of Massachusetts and the Queen's University of Belfast undertook a pilot study of deep-water lakes in the Lofoten Islands in Arctic Norway. The Lofoten Islands are towards the northernmost end of the Norwegian Current, itself a northern extension of the North Atlantic Drift, and should thus be sensitive to changes in the ocean circulation of the North Atlantic. Many deep-water lakes were identified and several of these were cored. Initial study of the sediment properties suggests that these cores would be suitable for climate studies; however, dating of these lake sediments provides a challenge. Many have a low organic content and while AMS radiocarbon-dating of terrestrial macrofossils such as birch seeds can be reliable, dating of unidentified organics is problematic. This is particularly true of deep lakes that are close to sea level, as many would have passed through a marine stage during the Holocene. As the marine radiocarbon correction for the Holocene is poorly understood in the area and the proportions of marine versus terrestrial carbon not known, these sediments are unsuitable for bulk-carbon radiocarbon-dating. Because of these difficulties, we turned to tephra to provide an outline chronology. For the purposes of establishing a detailed tephrochronology for the region, we chose to study a peat section rather than a lake sediment. There are a number of advantages in this approach. Peat is faster to process and uses fewer toxic (and expensive) chemicals. Using a peat section rather than a core let us use large samples for tephra separation, thus maximizing the tephra

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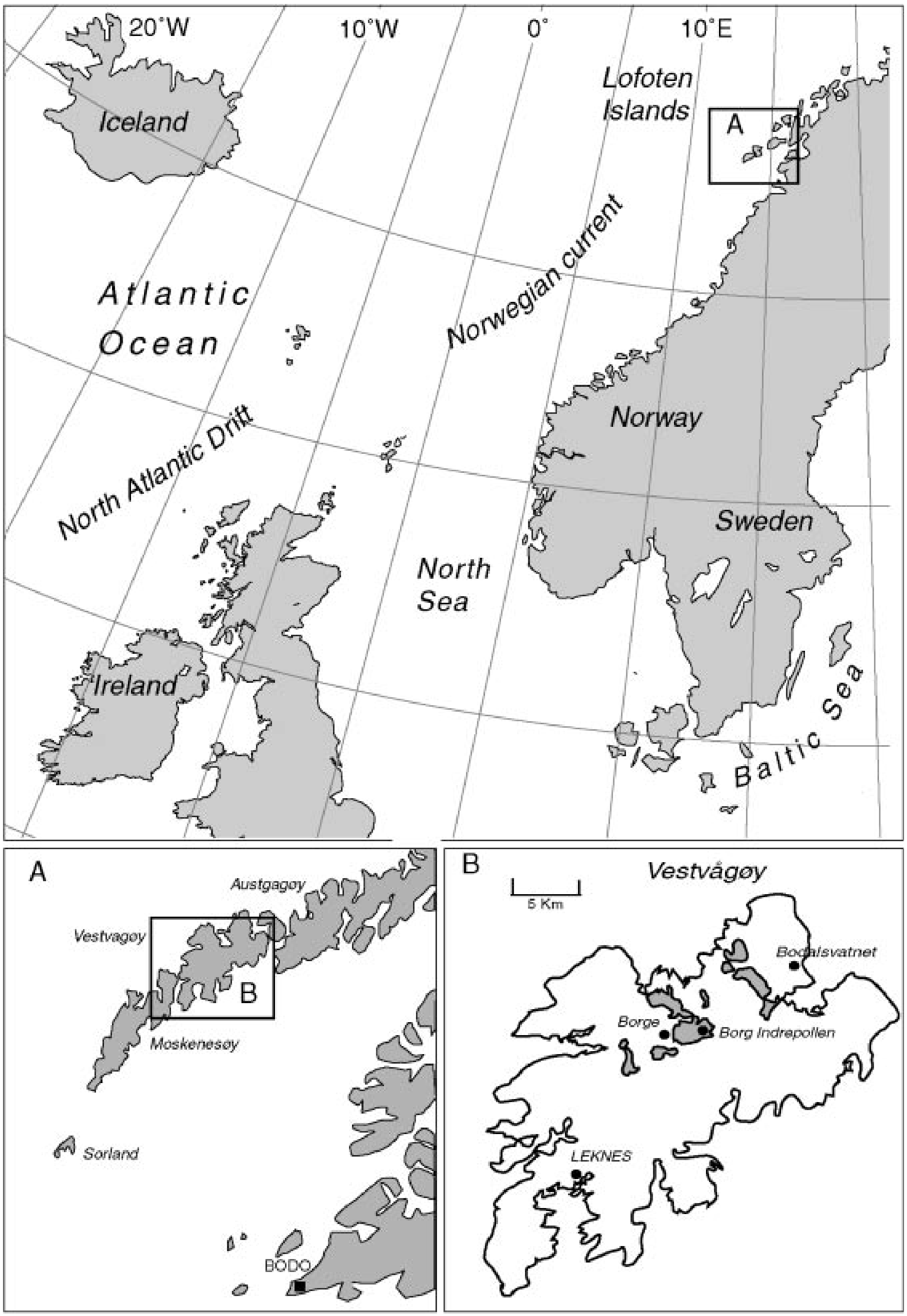

Fig. 1. Location map of Borge bog, Lofoten Islands, Arctic Norway.

harvest. We also processed a few samples from the pilot study of lake cores to demonstrate that satisfactory preparation techniques existed for such material.

The sites

A number of peat bogs were sampled, but the one selected for detailed study was at Borge (68°14.8′N, 13°44.5′E, 18 m a.s.l.; Fig. 1) close to the Viking Museum of Lofotr on the island of Vestvågøy. This bog had previously been the site of a pollen study by Johansen & Vorren (1986), who had also made a number of radiocarbon determinations on the peat profile. From this work, it appeared that the peat started to form in the early Holocene. In addition to the peat bogs, we cored a number of lakes, and from these selected two cores for some preliminary tephra study. These were Bødalsvatnett (68°19′07″.39 N, 13°56′26″.66 E, 42 m a.s.l.), which occupies a glacial U-shaped valley, and Borg Indrepollen (68°14′58″N, 13°49′44″E), a large lake/estuary system.

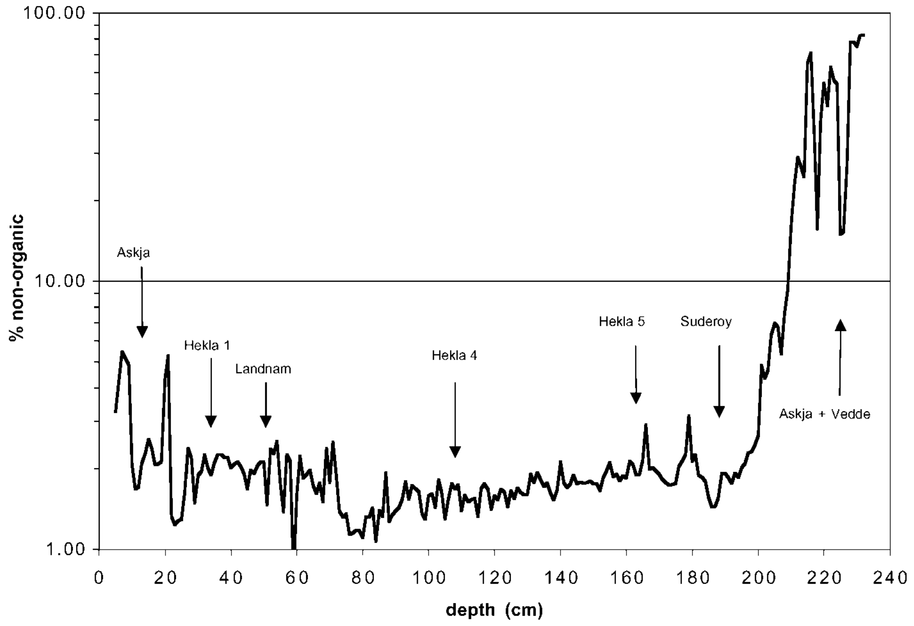

Fig. 2. Percent minerogenic (non-organic) content, based on burning at 550°C for 4 h in the samples prepared for tephra examination. The major, microscopically identified, tephra layers are marked for comparison with Fig. 3.

Methods

The bog was dug to the basal clays and monoliths of peat were removed. These were sliced and bagged in 1-cm subsamples and transported back to the laboratory. The 1-cm slices were further subsampled for a survey of tephra content. This was carried out using the rapid burning technique described by Pilcher & Hall (1992). As part of this process, the water and mineral contents of the peats were recorded. The burnt residues were mounted on microscope slides and systematically searched for tephra particles. Where tephra concentrations were recorded, further subsamples were taken from the slices and prepared by the wet oxidation method (Dugmore *et al.* 1992 as described in Pilcher *et al.* 1996). Where samples prepared in this way contained too much minerogenic matter to permit easy analysis of the tephra, the tephra was further concentrated using heavy liquid separation (Turney 1998). Heavy liquid separation was used on all the samples below 204 cm depth, both for the burnt and the wet oxidation samples, as the sampling extended well into the clays below the peat.

Major element chemical analysis of the tephra layers was carried out using wavelength dispersive analysis on a Jeol 733 Superprobe electron microprobe. Where the tephra from a particular layer was sparse, we utilized the technique of recording the position of tephra particles in the polarized light microscope and then translated these co-ordinates to the stage co-ordinates of the electron microprobe. As usual when analysing volcanic glasses (Hunt & Hill 1993), precautions were taken to minimize the effect of migration of sodium under the electron beam. The accelerating voltage was 15 kV, the beam current was 10 nA and the beam was de-focused to a diameter of about 8 μm. Sodium was analysed first with a short count time of 10 s. Count times for other elements varied from 15 to 40 s. The ZAF correction (for atomic number, absorption and fluorescence effects) was used and the results are presented un-normalized. The instrument was standardized using elements and simple compounds. Probe accuracy was checked by analysing a sample of Lipari obsidian before and during each analysis session. In most cases analyses with totals below 95% were rejected; however, some Holocene tephras routinely produce low totals and for these a lower cut-off was permitted.

Results

No tephra layers were visible in the peat section. The mineral content of the peats is shown in Fig. 2. Some of the main identified tephra layers are labelled, but as can be seen these make no significant contribution to the total mineral content of the peat. Throughout most of the Holocene the mineral content remains relatively consistent at close to 2%. There are two peaks of mineral in the recent samples (at 7 and 21 cm depths) that are clearly visible in the microscope slides. We interpret these as the effect of increased soil erosion following agricultural activity (within the last *c.* 500 yr), perhaps very close to the sampling site. The gradual climb in mineral content, and its increased variability, from about 70 cm depth up to about 31 cm, covers the period of Viking occupation of the nearby settlement at Borge from about AD 500 to AD 950. The peak of mineral content at 20–21 cm comes just after the AD 1362 Öraefajökull tephra (in sample 31–32 cm). The

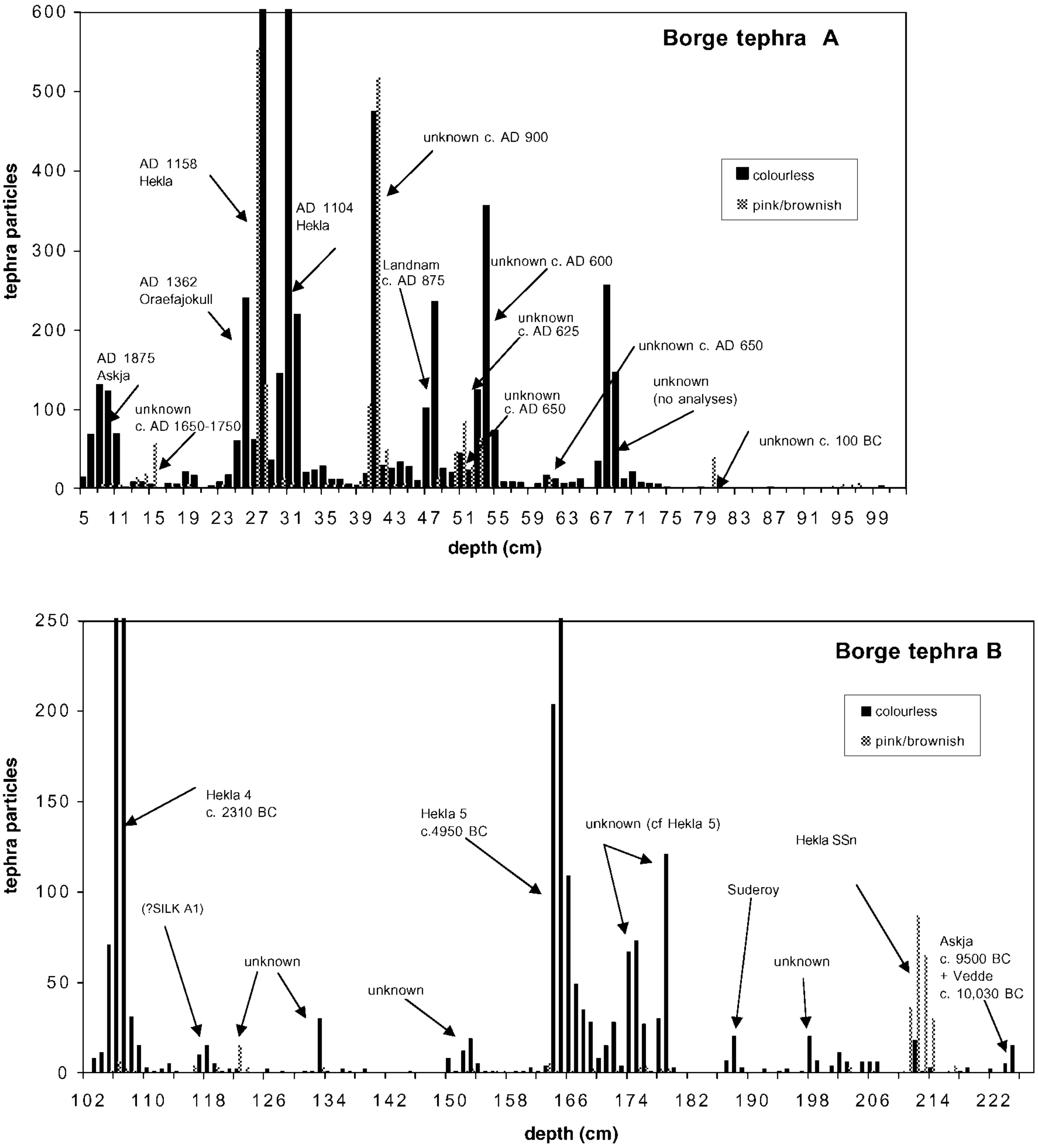

Fig. 3. A, B. Microscopic counts of tephra from each 1-cm subsample. The tephra was counted in three categories: colourless, pale brownish and pinkish and brown. Some tephra populations graded uniformly from colourless to brownish, thus the categories were somewhat arbitrary.

mineral in the basal samples reflects the fact that we sampled well below the true peat. It is likely that this material is cryoturbated and may not contain an undistorted stratigraphic record.

The Borge tephra stratigraphy

Figures 3A and B present the tephrostratigraphic record for the Borge samples based on microscope counts. Layers were selected from this record for geochemical analysis where the abundance and the size of tephra particles were adequate for microprobe analysis. Layers were selected where there seemed to be a clear peak of tephra, even where the absolute amounts were relatively small. Tephra layers identified on the basis of their geochemistry are indicated on the graph. We suggest ages for the tephras where a specific attribution is warranted, and an approximate age for other tephras, based on interpolation between dated layers. Analytical results are given in the Appendix.

Tephra layers

The depths given in the descriptions below are for the peat slice analysed. In some cases the tephra layer spanned more than this 1 cm slice, as shown in Fig. 3. Analyses are given in the Appendix.

9–10 cm, Askja, AD 1875. – This layer appears somewhat dispersed (Fig. 3A). The upper samples that contained this tephra were a very unconsolidated *Sphagnum* peat. The Askja tephra has been found at several sites in Sweden (e.g. Oldfield *et al.* 1997; Boygle 2004). The main eruption occurred on 29th March 1875 and the eruption volume is variously estimated at between 1.77 and 2.25 km^3 magma (Brandsdóttir 1992) (see www.norvol.hi.is and follow links to Askja for a detailed description of the volcanic system and this particular eruption). The eruption spread tephra over much of NE Iceland, damaging agriculture and forcing a migration to the USA and Canada from the region. The Appendix gives the analyses from the Borge sample with the mean and standard deviation of analyses from Sweden (Oldfield *et al.* 1997). This finding opens the possibility of using this marker to date and compare recent climate change between northern Norway and southern Sweden.

15–16 cm, 4 unknown tephras, c. AD 1650–1750. – The analysis showed a mixture of four populations, the identities of which are, as yet, unknown. Two analyses (group 1) appear similar to the Lough Portain B tephra that was found together with the Hekla AD 1510 tephra in Scotland (Dugmore *et al.* 1995). No analyses from this sample match the Hekla 1510 tephra nor those in this time range listed by Haflidason *et al.* (2000).

26–27 cm, Öraefajökull, AD 1362. – In terms of the amount of tephra produced, this was the largest eruption in Iceland in historic times with an estimated production of 10 km^3 of tephra (Thorarinsson 1958). The tephra has been found at a number of sites in Ireland (Pilcher & Hall 1992; Pilcher *et al.* 1996) and Sweden (but not so far in Scotland). At Borge, the Öraefajökull tephra (group 2) is mixed with tephra of another eruption of unknown origin with a higher FeO (total)% composition (group 1). The Öraefajökull tephra predominates in this sample and has also been found in the GRIP ice core from Greenland (Palais *et al.* 1991).

27–28 cm and 28–29 cm, Hekla, AD 1158. – This second eruption of Hekla in historic times started in January 1158 (Thorarinsson 1967). While not as big as the AD 1104 eruption of Hekla (see below) or that of Öraefajökull in AD 1362, its tephra was widely spread, being found at one site in Ireland and in the Lofoten Islands. The tephra has a pale brownish colour and tends to be vesicular. It is an abundant tephra in the Lofoten samples and should form a valuable addition to the widespread AD 1104 tephra.

31–32 cm, Hekla, AD 1104. – This was the largest eruption of Hekla in historic times, producing some 2.5 km^3 of tephra (Thorarinsson 1967). The local distribution of tephra shows the ash plume extended due north from Hekla. The tephra has been found at a number of sites throughout Ireland extending to the extreme southwest of the island. It has also been found in the Faroe Islands (Wastegård *et al.* 2001). It has not so far been found in the Greenland ice. The Hekla 1 tephra (group 2) was less abundant than the shards of the AD 1158 tephra (group 4) in this sample. Two shards of unknown origin (groups 1 and 3) were also present.

41–42 cm, BIP-24, c. AD 900. – This abundant tephra has also been found in the lake sediments of Borg Indrepollen close to the Borge peat bog site. The sample analysed from Borge contained four geochemical populations, the most abundant of which (group 3) is the BIP-24a tephra. None of the four populations resembles the basaltic Landnam tephra described by Larsen *et al.* (1999), nor any of the populations from Ireland of this approximate date. The widespread tephra known at present as the '860 tephra (B)' was not seen at Borge.

48–49 cm, Landnam tephra, c. AD 875. – The sample at 48–49 cm depth contains tephra of three geochemical populations. The largest group (group 2) appears to be the same as the rhyolitic component of the Landnam tephra from Ásólfsstadir in southwest Iceland as given by Wastegård *et al.* (2003) and also as found in the GRIP ice core (Grönvold *et al.* 1995), where it is dated to *c.* AD 875. The other two components comprise a group of three analyses (group 1) that appear to be the same as that known as the OWB-105 tephra in Ireland (Pilcher *et al.* 1996), but would require better replication for confirmation. The date of the OWB-105 tephra had previously been estimated by extrapolation to approximately AD 700. Group 3, of four analyses, has no attribution at present.

51–52 cm, unknown tephra, c. AD 650. – The sample at 51–52 cm contains tephra of two populations. Group 1 shards were colourless with FeO (total) of about 2% and group 2 brownish with an FeO of *c.* 7%. So far, no attributions have been found for these tephras (they are unlike the Tjørnuvík tephras from the Faroe Islands which are dated to the AD 800s; Wastegård *et al.* 2003).

53–54 cm, unknown tephra, c. AD 625. – This sample also shows a mixed chemical population, the main group having *c.* 2.0% FeO (total). Even within this group there is considerable variation.

54–55 cm, unknown tephra, c. AD 600. – This sample has a mixed population of at least four chemical types.

There is a strong likelihood that there is some movement of tephra in the closely spaced layers at

51–52 cm and 54–55 cm. At least one of the tephra populations appears to be present in all three samples, suggesting movement of tephra up to 3 cm vertically in the profile. At present, these poorly resolved layers do not provide good chronological markers. Study of this time period in the Greenland ice cores, or in annually laminated lake sediments, may help to resolve these layers into a usable chronological sequence.

61–62 cm, unknown tephra, c. AD 400—500. – A single population with tightly constrained analyses with FeO (total) of *c.* 2% (group 1). A few shards with FeO (total) of 5–7% (group 2) are also present. No tephras of this age range have been found in Ireland and none has been reported elsewhere of this date range and this composition. This layer was poorly represented in the slides prepared for light microscopy, but was well represented in the microprobe slides. This tephra has the potential to form a valuable chronological marker as it occurs at a time when there are few other Icelandic tephras.

68–69 cm, unknown tephra. – This tephra, prominent in Fig. 3A, was present as very small, flat, mostly tabular shards. No analyses have been possible so far.

80–81 cm, unknown tephra, c. 100–500 BC. – A pale brown tephra with a rather variable composition. FeO (total) varies from 2.5 to 4.5%. The date estimated from the deposition rate graph is similar to that of the Glen Garry tephra found in Scotland (Dugmore *et al.* 1995) and England (Pilcher & Hall 1996); however, the chemical composition is distinctly different (Fig. 4).

107–108 cm, Hekla 4, c. 2310 BC. – This abundant tephra shows some stratigraphic spread from 103–110 cm depth, with the peak concentration in the 107–108 cm slice. The single, sharply defined, chemical population identifies this as Hekla 4. The eruption produced tephra whose stratigraphy in Iceland grades from white at the base to black at the top during the course of the eruption. This is reflected in FeO (total) values ranging from about 1.9 to 6%. Part of this range is also seen in the Faroes, Scotland and Sweden. In Ireland, only the extreme Plinian phase is represented with FeO (total) values close to 1.9%. A similar situation was found in Lofoten.

In both Shetland and in Sweden a slightly younger Hekla tephra has been found. This was called the Kebister tephra in Shetland (Dugmore *et al.* 1995) but is now widely known as Hekla H-S (Boygle 2004). Its chemistry is close to that of Hekla 4, but the values of MgO and CaO show the Borge layer to be Hekla 4 (Fig. 5). The best estimate of the date of Hekla H-S is 1792–2122 cal. yr BC (Dugmore *et al.* 1995). Another widespread tephra in the mid-Holocene is Hekla 3 with a date of 1087–1006 cal. yr BC (van den Bogaard & Schmincke 2002). This has been found in Ireland (Plunkett 1999), in Sweden (Boygle 2004) and in Germany (van den Bogaard *et al.* 1994). So far, Hekla 3 tephra has not been isolated in the Lofotens.

118–119 cm, (? possibly SILK A1), c. 3850 BC. – This was a sparse layer of colourless to pale pink tephra. Five shards were analysed (mostly with two analyses per shard), all of different compositions. One shard (two analyses) was similar to the Katla tephra known as SILK A1 with a date of *c.* 3850 BC (Wastegård 2002).

122–123 cm, unknown tephra, sparse layer. – No analyses so far.

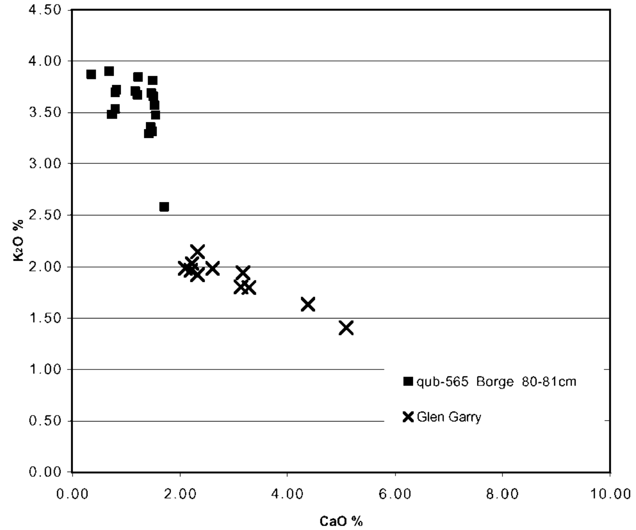

Fig. 4. Selected major element chemistry of the 80–81 cm tephra from Borge compared with Glen Garry tephra (Dugmore *et al.* 1995).

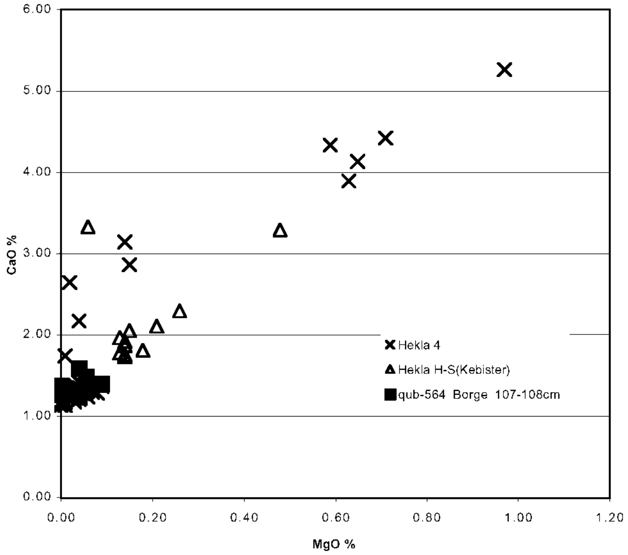

Fig. 5. Selected major element chemistry of the 107–108 cm tephra from Borge compared with the Hekla 4 and Kebister tephras (Dugmore *et al.* 1995).

133–134 cm, unknown tephra, c. 4420 BC. – In the light microscope, this tephra was variable in colour and mostly thin-walled and vesicular. The analyses are unsatisfactory, as the totals are below the normally acceptable 95%. However, shards with totals between 90 and 95% showed no sign of burning under the electron beam, so these totals may be realistic and represent a high water content or some degradation of the glass. Taking just those analyses with totals over 94%, this small data set has some similarities to the Hoy tephra from Scotland (Fig. 6). However, the Na_2O and K_2O are too low and the TiO_2 is too high. At present, this tephra is of unknown origin. The Hoy tephra was originally radiocarbon-dated to 5560 ± 90 BP (4227–4605 cal. yr BC) in Scotland (Dugmore *et al.* 1995).

153–154 cm, unknown tephra, c. 4700 BC. – This tephra has a composition similar to the Hekla 1 and Hekla 3 tephras and may thus be an unrecorded Hekla eruption. Interpolation between the dated Hekla 4 and Hekla 5 tephras suggests a date of *c.* 4700 BC.

165–166 cm and 175–176 cm, cf. Hekla 5. – These two layers, which appear stratigraphically distinct (and according to the extrapolated chronology are probably nearly 500 years apart in time), have an almost identical major element chemistry. In the literature there are several candidates. A pair of tephras were identified from Lairg in Scotland (Dugmore *et al.* 1995) and two similar tephras were found in several sites in Ireland (Pilcher *et al.* 1996). Since that time the so-called Lairg B in Ireland has been attributed to the Torfajökull system and is now known as the 'Torfajökull 4700 BC tephra', and dated using high precision ^{14}C wiggle matching to 4778–4614 cal. yr BC (Pilcher *et al.* 1996). This tephra has not been found at Borge. The Lairg A tephra was identified in Scotland and in Ireland, where it is dated to 5048–4859 cal. yr BC (Pilcher *et al.* 1996). It seems likely that this is the same as the Hekla 5 tephra known in Iceland, but this is still under dispute. As Fig. 7 shows, both the 165 and 175 cm layers are unlike the Hoy or Torfajökull tephras and identical to the Lairg (Hekla 5?) tephra. The Borge site suggests that there could be, in fact, two distinct tephras, which is problematic for dating as the finding of a single tephra will produce a choice of dates. It is already well known that the Lairg A tephra is sufficiently similar to Hekla 4 tephra to preclude separating them on major element composition (Dugmore *et al.* 1995). This new finding further complicates the use of these tephras. At present, the possibility remains that the two layers are caused by some depositional anomaly. A search at other Lofoten peats should resolve this issue. Meanwhile, we could use either 165 or 175 cm as the 4900 BC date. We have used the 165 cm sample as the 'true' Hekla 5 marker in construction of the deposition rate graph (Fig. 10B).

179–180 cm, unknown tephra. – A colourless tephra of several different major element populations was identified here. The most abundant population (group 1) is again similar to the Hekla 5 tephras, reinforcing the possibility that some depositional anomaly or contamination is responsible.

188–189 cm, Suderoy tephra, c. 6050 BC. – This tephra has a chemistry similar to the Vedde tephra. Wastegård (2002) describes a tephra originating from the Katla system that is chemically very similar to the Vedde tephra, with a date of *c.* 6050 BC on the Faroe Islands. This has the potential to provide a useful early Holocene marker in the Lofoten lakes.

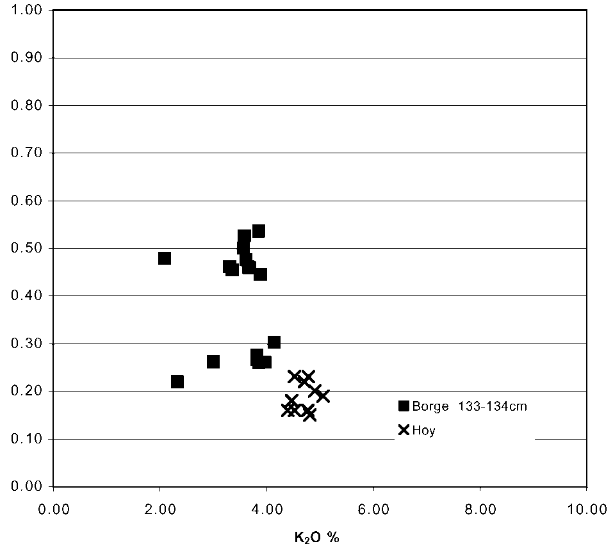

Fig. 6. Selected major element chemistry of the 133–134 cm tephra from Borge compared with the Hoy tephra.

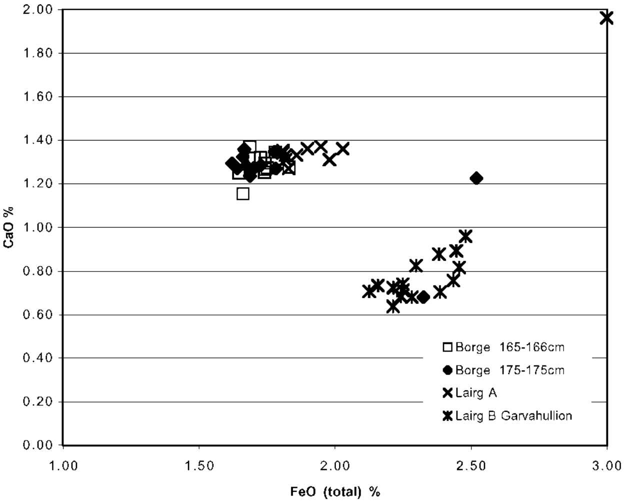

Fig. 7. Selected major element chemistry of the 165–166 cm and 175–176 cm tephra layers from Borge compared with Lairg A, Lairg B and Hoy tephras from various sites.

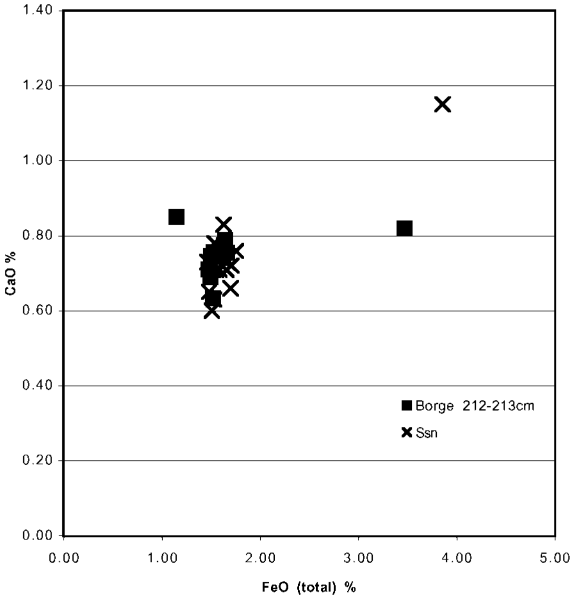

Fig. 8. Selected major element chemistry of the 212–213 cm tephra from Borge compared with the SSn tephra (Boygle 1998).

198–199 cm, unknown tephra. – A sparse layer of which only a single shard was analysed. No attribution so far.

212–213 cm, SSn tephra, c. 7500 BC. – The main group of 9 analyses (group 3) from this sample appears to belong to the same population as the SSn tephra of Haflidason *et al.* (2000) (Fig. 8). This was reported from Svinavatn, N. Iceland (Boygle 1998) and is thought to derive from the Snaefellsjökull volcano. Haflidason gives a date estimate of 7000–9000 BP, which is too imprecise to use in our deposition rate graph. Interpolation from Fig. 8 suggests a date of *c.* 7500 BC, which would fall within the calibrated range of Haflidason's radiocarbon age.

225–226 cm, Askja and Vedde. – This layer is well into the sandy clays below the peat, as can be seen from the mineral content curve in Fig. 2. The tephra, which was separated from the other mineral component by heavy liquid, is of two chemical populations (Fig. 9). These match the chemical composition of two known tephras – the Askja tephra of *c.* 9500 BC (Sigvaldason 2002; Davies *et al.* 2003) (group 1) and the well-known Vedde Ash (group 3). The Vedde has been dated at many sites, both terrestrial and marine. The current best estimate of its calibrated age is probably *c.* 10 030 BC from the GRIP ice core (Grönvold *et al.* 1995). The presence of these tephras is interesting in that it implies an early start for deposition in this valley and that the Islands were already de-glaciated some 12 000 years ago. It also offers great promise for the finding of these valuable marker tephras in Lofoten lake sediments. The Vedde, in particular, has been found in numerous marine cores in the north Atlantic, in the North Sea, and in terrestrial sediments in Norway, Iceland, Scotland, Sweden and Russia (summarized by Davies *et al.* 2002 and Wastegård *et al.* 2000) and is a major chronological marker in lateglacial studies (Turney *et al.* 1997, 2004). That the two tephras are found together may be attributed to either a very slow deposition or, more plausibly, to some disturbance or cryoturbation of the sandy clays.

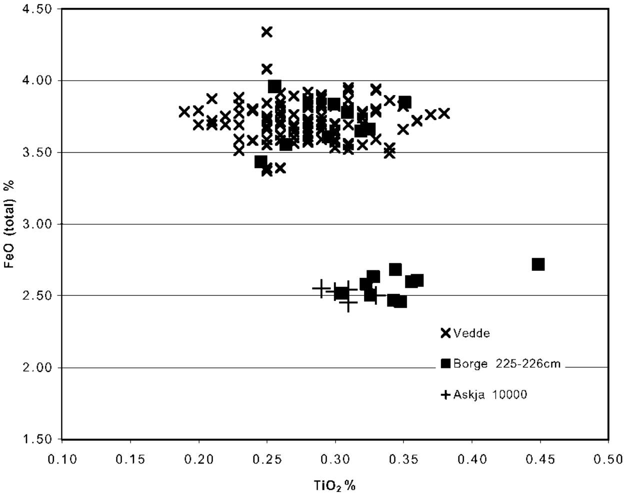

Fig. 9. Selected major element chemistry of the 225–226 cm tephra from Borge compared with Vedde Ash (many sites from Tephrabase) and the Askja tephra (Wastegård *et al.* 2000).

The chronology

Figure 10 shows the age/depth curves for the Borge bog. The upper figure expands the scale for the period with historical dates, the lower gives the whole scale. Superimposed on the tephrochronology in Fig. 10 is a radiocarbon chronology based on Johansen & Vorren (1996). The dates from this study were taken from the pollen diagram and calibrated using INTCAL 98. The exact location of Vorren's sampling is not known and it is likely that the stratigraphical sequence is slightly different from our sampling site. In spite of this, the upper part of the profile is similar. The tephrochronologies in Fig. 10 have been used to interpolate the dates of unidentified tephras. As the dating of the early Holocene tephras is improved, particularly where they can be identified in GRIP and NGRIP ice cores, the chronology of the earlier part of the sequence will become more precise.

Preliminary study of tephras from lake sediments

Only three short series of lake sediment samples have been studied so far, mainly to investigate the

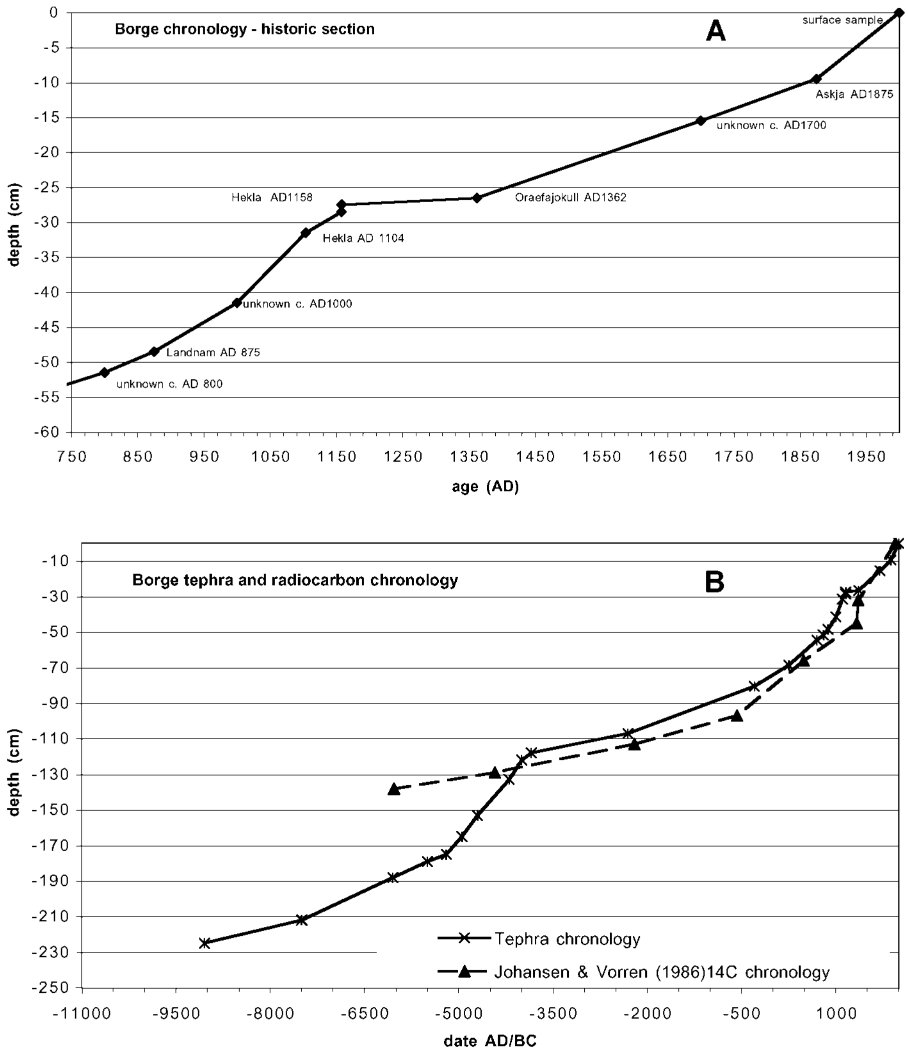

Fig. 10. Time–depth relationship for Borge bog. The solid line is based on tephra layers. Unknown tephras have been placed by interpolation between dated tephras. The dashed line is from the pollen study of Johansen & Vorren (1986). A. Expanded scale for portion dated by historic tephras. B. The full chronology. We have chosen the 165 cm depth tephra layer to represent Hekla 5. As we have shown above, tephra of Hekla 5 geochemistry was found at 165, 175 and 179 cm depths.

sedimentation rate and sediment type in the lakes. Typically, the samples had an organic content of 30–50%, with a high proportion of diatoms. In addition, only very small sample sizes were available for tephra study. This required a rather different approach from our usual procedure. As there was not enough material for two preparations, all samples were prepared as if for microprobe analysis. The organics were removed by acid oxidation (as above) followed by 4 h heating in dilute potassium hydroxide to dissolve diatoms, followed by heavy liquid separation. The clean residue was mounted in epoxy resin which could be examined under the light microscope, and if tephras were found could then be polished for microprobe analysis.

Bodalsvatnett

Bodalsvatnett (68°19′07″.39N, 13°56′26″.66E, 42 m a.s.l.; Fig. 1) occupies a glacial U-shaped valley facing west. Several cores were taken to assess the potential of the lake for further study. We retrieved one 137-cm-long sequence using a percussion corer within 12 m of water depth. The lower part of the core up to 81-cm depth is made of detrital minerogenic material fining upward and depleted of diatoms. The hemipelagic lacustrine facies starts above 81 cm to the top. The sediment is fine-grained, rich in diatoms, with traces of sulphur framboids. In thin sections, some signs of gentle bioturbation (such as faecal pellets) are visible. Some coarser sand-sized terrigenous beds, about 2 cm in thickness, interrupt the gentle sedimentation facies. Both the sand-rich beds and the bioturbation may have disturbed the sequence, but the perturbation should be minimal.

Two short series of samples were selected from the core, based on date estimates using the sediment/water interface and a single radiocarbon date. The date obtained on a piece of wood is 4325 ± 40 BP. The upper sample at 13.4-cm depth contained the Öraefajökull

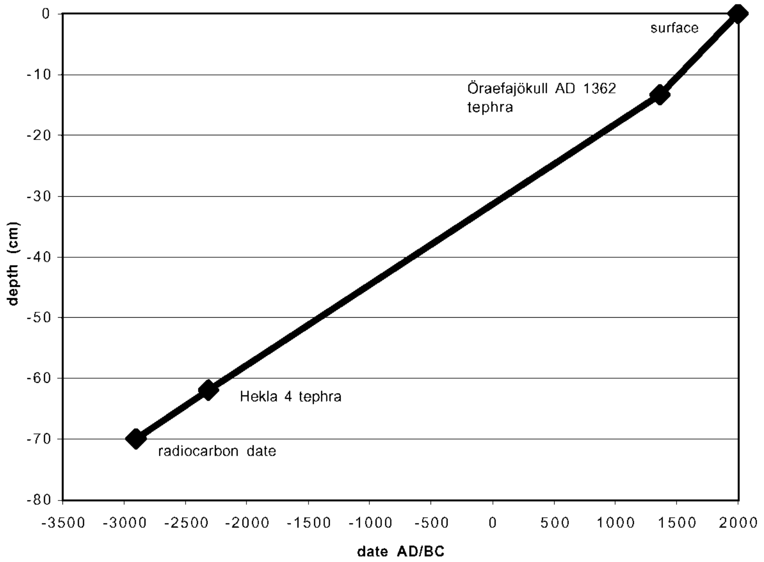

Fig. 11. Preliminary time–depth relationship for Bodalsvatnett lake core based on one radiocarbon measurement (calibrated) and the Öraefajökull AD 1362 and Hekla 4 tephra.

AD 1362 tephra while the sample at 65 cm contained the Hekla 4 tephra. In the latter case, the tephra could, in theory, belong to Hekla 5 but the radiocarbon measurement at 75-cm depth shows that the attribution to Hekla 4 is correct (Fig. 11). This limited investigation demonstrated the potential of tephras for dating such cores and with the 23 Holocene tephras already characterized, the scope for core dating is considerable.

Borg Indrepollen

Borg Indrepollen (68°14′58″N, 13°49′44″E) is a large lake/estuary system, with multiple sedimentary basins, which is gradually emerging from the sea. The site is of particular cultural interest as it formed the former safe harbour for Viking ships belonging to the local chieftain. Much archaeological research has been carried out around the lake, and a detailed sedimentary record from Indrepollen will provide a continuous palaeoenvironmental record of changes in this watershed during the time of Viking settlement. Viking-age boathouses on the shores of this system suggest that there has been a regression of 1–2 m over the last 1000–1500 years. Limnological measurements show saline or brackish water and anoxic conditions in the deepest parts of the basin as well as a strong thermal stratification below 10 m. Three cores of up to 107 cm in length were recovered from Indrepollen. As expected, these sediments are laminated in some sections, and preliminary thin-section analysis (Francus *et al.* 2002) points to sections where laminae can be resolved for several hundred years. Mean thickness is 0.56 mm in the upper 15 cm.

A limited tephra study showed the presence of the AD 860 tephra and also probably Tjornuvik B, which is of a similar age (Fig. 12). There is the possibility of obtaining a very precise historical chronology for this lake using additional tephras if these can be recovered.

Future work at these and other deeper-water lakes in the Lofoten islands will require more sophisticated coring equipment. Tephras will be used to provide a chronological framework for the study of a range of climate proxies preserved in the sediments.

How precise is a tephrochronology?

There is uncertainty (in some cases) in the dating of the tephra at its Icelandic type location. The dating

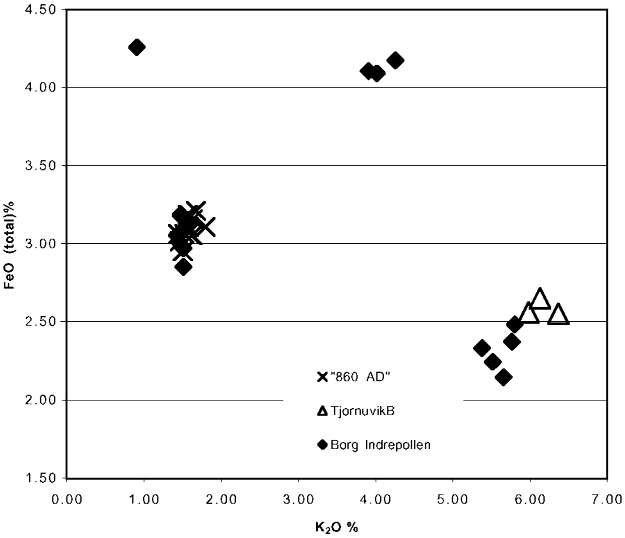

Fig. 12. Selected major element chemistry of the mixed tephra population in the Borg Indrepollen lake core indicating an age of *c.* AD 800–900.

of the historic tephras is reliable often to the month of eruption, certainly to the year. Tephras that have been identified in ice cores will probably be accurate to within ±1 year in the last two millennia, and eventually as close as ±10 years in the last 10 000 years. Radiocarbon-dated tephras vary in precision and the radiocarbon dates must be calibrated. Where high precision dating has been carried out on rapidly accumulating peats, the precision can be about ±40 at 2 sigma, e.g. the dating of the Microlite tephra which was carried out independently in Germany (730–664 cal. yr BC) by van den Bogaard & Schmincke (2002) and in Ireland (755–680 cal. yr BC) by Plunkett *et al.* (2004). Where the dating is based on a single conventional radiocarbon date, and where this is based on slow-deposition peat (on Iceland for example), the realistic precision can be worse than ±200 years.

Added to the dating uncertainty is the stratigraphic uncertainty. This is best illustrated using one of the historic tephras from Borge. Although we know the date of the Hekla 1104 eruption exactly, its tephra is concentrated in 2 cm of peat. From the deposition rate graph, 2 cm of peat at this age represents about 30 years. The peat or an event described from the peat cannot thus be resolved to better than 30 years. In the case of the Hekla 4 tephra, the stratigraphic spread is 3 cm and the deposition rate is 80 years/cm giving a stratigraphic age span of 240 years! This, of course, is not a problem unique to tephra, but to all forms of dating that depend on stratigraphic control (including radiocarbon dating, where it is usually ignored). The dating ideal is a combination of historic tephras with annually laminated sediments.

Conclusions

The combination of the range of geochemically distinct Holocene tephras demonstrated in the Borge peat section and the success of the pilot study of lake sediments shows that tephra has great potential for building chronologies in this area. Even allowing for the limitations discussed above, tephra is still the best dating tool where radiocarbon dating is problematic. The series of tephras reported here is one of the most detailed outside Iceland, and will be of value well beyond the Lofoten Islands. Tephra markers provide an ideal way of correlating between sequences of different origin – the Greenland ice, marine sediments, terrestrial lakes and peat. This will allow the study of regional climatic events over a wide area and by a multi-proxy approach. One particular application will be the use of tephras to help establish the magnitude of the marine radiocarbon offset.

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Appendix. Microprobe determined major element chemistry of tephras from Borge Bog, Lofoten Islands. Results are presented as oxides by stoichiometry and are not normalized. Totals below 95% are given in italics.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
9–10 cm, qub-383, Askja 1875								
75.45	0.17	12.17	2.33	0.44	1.09	3.09	2.80	97.55
72.01	0.31	14.38	3.59	0.28	2.14	4.76	2.54	100.01
Group 1								
72.36	0.72	12.56	3.28	0.68	2.31	3.62	2.32	97.84
73.10	0.76	12.53	3.14	0.63	2.22	3.70	2.36	98.44
74.01	0.79	12.60	3.50	0.67	2.43	3.36	2.30	99.65
73.86	0.80	12.77	3.43	0.70	2.28	3.62	2.46	99.93
72.97	0.80	12.68	3.35	0.65	2.44	3.80	2.27	98.97
73.48	0.81	12.47	2.93	0.56	2.07	3.78	2.55	98.63
74.75	0.81	12.71	3.10	0.58	2.22	3.87	2.42	100.46
72.40	0.82	12.58	3.36	0.69	2.42	3.99	2.34	98.59
72.79	0.84	12.90	3.66	0.73	2.72	3.72	2.24	99.59
72.67	0.84	12.70	3.54	0.75	2.71	3.75	2.27	99.22
71.40	0.86	12.51	3.35	0.68	2.46	3.72	2.28	97.25
72.11	0.86	12.72	3.84	0.81	2.74	3.70	2.29	99.06
72.78	0.88	12.74	3.41	0.64	2.62	3.77	2.45	100.29
69.94	0.90	13.22	4.26	0.89	3.15	3.48	2.14	97.97
71.92	0.97	12.93	3.84	0.79	2.84	3.77	2.39	99.44
Mean and SD of group 1 ($n = 15$)								
72.70 ± 1.15	0.83 ± 0.06	12.71 ± 0.20	3.46 ± 0.33	0.70 ± 0.09	2.51 ± 0.29	3.71 ± 0.15	2.34 ± 0.10	99.02 ± 0.92
Mean and SD of Askja tephra from Oldfield *et al.* (1997) ($n = 17$)								
72.28 ± 1.20	0.88 ± 0.05	12.86 ± 0.59	3.54 ± 0.21	0.73 ± 0.03	2.48 ± 0.22	3.79 ± 0.16	2.37 ± 0.09	98.92 ± 0.89
15–16 cm, qub-384, 4 unknown tephras, *c.* AD 1500–1600								
Group 1 (unknown cf. Lough Portain B, Dugmore *et al.* 1995)								
70.94	*0.19*	*12.36*	*1.78*	*0.09*	*0.81*	*4.32*	*3.15*	*93.64*
75.26	0.16	13.10	1.86	0.14	0.99	4.67	3.33	99.51
Group 2 (unknown)								
65.29	1.24	14.19	5.54	1.14	3.03	3.90	0.98	95.30
Group 3 (unknown)								
67.34	0.47	14.63	5.57	0.46	3.17	4.36	2.33	98.32
68.52	0.48	14.80	5.82	0.47	3.16	4.53	2.40	100.18
63.13	*1.18*	*13.68*	*5.31*	*1.10*	*2.96*	*4.37*	*2.48*	*94.22*
66.70	1.22	14.29	5.35	1.20	3.10	4.64	2.61	99.10
64.29	0.86	13.61	5.83	0.81	2.69	4.44	2.67	95.21
64.88	0.89	13.65	5.97	0.81	2.84	4.44	2.72	96.21
66.94	1.10	14.14	5.48	1.18	3.13	5.59	2.84	100.38
66.52	0.91	14.04	6.85	0.92	3.24	4.85	2.85	100.18
Mean and SD group 3								
66.04 ± 1.76	0.89 ± 0.29	14.11 ± 0.45	5.77 ± 0.50	0.87 ± 0.29	3.04 ± 0.19	4.65 ± 0.41	2.61 ± 0.19	97.97 ± 2.44
Group 4 (unknown)								
66.22	0.73	14.06	4.38	0.56	1.85	4.33	2.92	95.05
67.40	0.73	13.66	4.35	0.58	2.11	4.76	2.96	96.53
68.64	0.78	13.85	4.67	0.58	1.99	4.79	3.23	98.52
70.10	0.68	13.65	4.31	0.47	1.81	4.53	3.25	98.80
Mean and SD group 4								
68.09 ± 1.66	0.73 ± 0.04	13.80 ± 0.20	4.43 ± 0.16	0.55 ± 0.05	1.94 ± 0.14	4.61 ± 0.22	3.09 ± 0.18	97.23 ± 1.77
26–27 cm, qub-385, colourless, Öraefajökull + unknown								
Group 1 unknown (similar to Hekla 1158)								
64.55	*0.46*	*14.48*	*5.09*	*0.44*	*3.13*	*4.49*	*2.13*	*94.75*
64.93	0.52	16.45	4.55	0.36	2.08	4.76	3.83	97.47
65.26	0.55	16.21	4.70	0.40	2.00	5.08	3.74	97.94
67.24	0.46	16.07	4.68	0.41	2.04	5.42	3.72	100.03
Mean and SD group 1								
65.49 ± 1.20	0.50 ± 0.05	15.80 ± 0.90	4.75 ± 0.23	0.40 ± 0.03	2.31 ± 0.55	4.94 ± 0.40	3.35 ± 0.82	97.55 ± 2.17
Group 2 Öraefajökull AD 1362								
71.41	0.27	13.27	3.19	0.03	1.00	5.06	3.33	97.57
71.54	0.25	13.13	3.30	0.00	0.99	5.04	3.36	97.61
71.73	0.30	13.29	3.22	0.00	1.21	5.16	3.40	98.31
72.09	0.28	13.35	3.15	0.00	1.05	4.95	3.38	98.25

Appendix. Continued.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
73.00	0.24	13.40	3.27	0.00	0.97	5.21	3.45	99.53
73.15	0.18	13.57	3.31	0.00	1.08	5.27	3.41	99.96
73.20	0.25	13.44	3.16	0.00	0.90	5.49	3.37	99.79
73.42	0.21	13.33	3.05	0.04	1.02	5.60	3.34	100.01
73.43	0.27	13.52	3.31	0.04	1.03	5.21	3.39	100.19
73.57	0.27	13.50	3.31	0.00	1.08	5.47	3.16	100.36
Mean and SD group 2								
72.65±0.86	0.25±0.03	13.38±0.13	3.23±0.09	0.01±0.02	1.03±0.08	5.25±0.21	3.36±0.08	99.16±1.10
27–28 cm, qub-386, pinkish/brownish, Hekla 1158								
68.21	0.50	15.11	5.61	0.46	3.17	4.34	2.29	99.68
68.52	0.52	15.10	5.61	0.46	3.25	4.25	2.27	99.98
66.25	0.50	14.62	5.52	0.46	3.12	4.50	2.21	97.18
68.30	0.52	15.03	5.61	0.48	3.16	4.57	2.17	99.84
67.43	0.50	14.83	5.57	0.49	3.12	4.51	2.17	98.62
67.09	0.47	14.92	5.73	0.46	3.25	4.40	2.24	98.55
65.58	0.48	14.48	5.46	0.46	3.04	4.15	2.00	95.65
68.35	0.50	15.09	5.60	0.49	3.15	4.63	2.26	100.06
68.26	0.42	14.88	5.63	0.47	3.06	4.24	2.19	99.15
68.46	0.55	15.06	5.65	0.49	3.12	4.28	2.31	99.91
67.77	0.52	15.02	5.69	0.47	3.12	4.50	2.27	99.35
67.62	0.57	15.03	5.68	0.48	3.25	4.41	2.31	99.33
Mean and SD								
67.65±0.94	0.51±0.04	14.93±0.20	5.61±0.07	0.47±0.01	3.15±0.07	4.40±0.15	2.22±0.09	98.94±1.32
28–29 cm, qub-387, colourless, Hekla 1158 + some Hekla 1104								
Group 1 Hekla 1104								
70.92	0.23	14.24	3.17	0.13	1.89	4.55	2.48	97.59
72.55	0.25	14.45	3.23	0.12	1.99	4.62	2.74	99.95
Group 2 Hekla 1158								
66.94	0.47	14.89	5.30	0.49	2.95	5.33	2.04	98.41
66.79	0.49	14.66	5.45	0.47	3.06	4.54	2.17	97.63
66.80	0.43	14.50	5.45	0.48	3.08	4.54	2.16	97.44
65.33	0.44	14.33	5.48	0.44	2.97	4.18	2.22	95.38
67.08	0.52	14.91	5.54	0.47	3.09	4.54	2.15	98.30
76.80	0.50	14.89	5.55	0.45	3.08	4.43	2.19	98.88
66.41	0.44	15.59	5.56	0.44	3.08	4.31	2.16	98.01
66.07	0.46	14.42	5.62	0.49	3.08	4.37	2.17	96.68
68.42	0.52	14.70	5.66	0.49	3.10	4.29	2.28	99.45
68.22	0.46	14.94	5.67	0.49	3.07	4.74	2.28	99.87
67.83	0.52	14.89	5.69	0.47	2.95	4.23	2.18	98.75
Mean and SD group 2								
67.88±3.09	0.48±0.03	14.79±0.34	5.54±0.12	0.47±0.02	3.05±0.06	4.50±0.32	2.18±0.07	98.07±1.27
31–32 cm, qub-388, Hekla 1104 + 1158								
Group 1 unknown								
72.45	0.22	14.68	2.61	0.09	2.21	5.11	2.29	99.67
Group 2 Hekla 1								
72.00	0.20	14.07	3.05	0.12	1.98	4.74	2.59	98.77
72.52	0.38	14.21	3.16	0.15	1.94	4.81	2.74	99.89
72.40	0.34	14.02	3.19	0.13	1.95	4.86	2.62	99.51
69.41	0.28	13.76	3.20	0.13	1.87	4.58	2.65	95.87
Mean and SD group 2								
71.58±1.46	0.30±0.08	14.01±0.19	3.15±0.07	0.13±0.01	1.93±0.04	4.75±0.12	2.65±0.06	98.51±1.82
Group 3 unknown								
66.86	0.44	15.90	4.39	0.36	3.46	5.32	1.96	98.70
Group 4 Hekla 1158								
68.06	0.45	14.31	5.15	0.47	3.04	3.45	2.32	98.13
64.79	*0.39*	*14.40*	*5.16*	*0.47*	*2.99*	*4.47*	*2.00*	*94.66*
68.64	0.59	14.62	5.40	0.45	3.00	3.12	2.19	98.01
68.17	0.48	14.91	5.47	0.47	3.03	4.75	2.29	99.57
68.01	0.49	14.79	5.49	0.43	3.00	4.45	2.35	98.99
66.31	0.51	14.43	5.50	0.44	2.96	4.35	2.42	96.92
68.04	0.48	14.74	5.52	0.45	3.14	4.55	2.22	99.13

Appendix. Continued.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
65.60	0.51	14.15	5.55	0.50	2.92	4.53	2.26	96.00
68.03	0.49	14.71	5.62	0.46	3.03	4.39	2.59	99.31
68.84	0.56	14.72	5.65	0.50	3.02	4.63	2.26	100.16
68.73	0.67	14.35	5.65	0.47	2.73	4.31	2.76	99.66
67.15	0.49	14.14	5.68	0.51	2.88	4.67	2.28	97.78
68.19	0.68	14.13	5.79	0.47	2.88	4.33	2.43	98.88
Mean and SD group 4								
67.58 ± 1.26	0.52 ± 0.08	14.49 ± 0.27	5.51 ± 0.19	0.47 ± 0.02	2.97 ± 0.10	4.31 ± 0.48	2.33 ± 0.19	98.25 ± 1.59
41–42 cm, qub-389, ***c*****. AD 900 (cf. Borg Indrepollen 24 cm**)								
Group 1 unknown								
71.74	0.67	13.09	4.33	0.60	2.67	4.32	1.88	99.29
Group 2 unknown								
69.17	0.22	13.59	3.07	0.15	1.82	4.65	2.36	95.03
70.17	0.18	13.52	3.12	0.10	1.91	4.72	2.48	96.20
Group 3 cf. Borg Indrepollen 24 cm								
65.10	0.43	15.70	4.17	0.34	1.84	4.74	3.44	95.75
63.74	0.52	15.23	4.52	0.42	2.09	5.24	3.68	95.44
66.17	0.42	15.58	4.25	0.40	1.97	6.40	3.74	98.93
65.52	0.38	15.15	3.87	0.27	1.60	5.29	3.76	95.84
67.28	0.44	15.90	4.38	0.29	1.80	5.40	3.77	99.26
65.18	0.49	15.45	4.40	0.39	1.79	5.36	3.81	96.87
65.66	0.40	15.16	4.04	0.30	1.77	5.14	3.88	96.34
67.53	0.44	15.93	4.14	0.31	1.87	5.64	3.93	99.80
67.16	0.45	15.71	4.25	0.30	1.87	5.50	4.03	99.26
Mean and SD group 3								
65.93 ± 1.24	0.44 ± 0.04	15.53 ± 0.30	4.22 ± 0.20	0.33 ± 0.05	1.84 ± 0.14	5.41 ± 0.45	3.78 ± 0.17	97.50 ± 1.78
Group 4 unknown								
68.22	0.51	14.56	5.36	0.45	3.07	4.98	2.21	99.36
64.38	*0.45*	*14.12*	*5.40*	*0.43*	*3.00*	*4.46*	*2.09*	*94.32*
67.96	0.50	15.28	5.41	0.45	3.22	4.70	2.11	99.63
67.67	0.48	14.58	5.55	0.44	2.92	4.52	2.14	98.29
Mean and SD group 4								
67.06 ± 1.80	0.49 ± 0.03	14.63 ± 0.48	5.43 ± 0.09	0.44 ± 0.01	3.05 ± 0.13	4.67 ± 0.23	2.14 ± 0.05	97.90 ± 2.46
48–49 cm, qub-571, *c*. AD 875 Landnam tephra, + cf. OWB-105								
Group 1 cf. OWB-105								
74.58	0.23	11.46	1.57	0.05	0.90	3.83	3.10	95.70
72.87	0.16	12.81	1.81	0.05	1.18	4.28	2.68	95.83
72.67	0.09	12.79	1.90	0.04	1.31	4.33	2.79	95.91
Mean and SD group 1								
73.37 ± 1.05	0.16 ± 0.07	12.35 ± 0.78	1.76 ± 0.17	0.04 ± 0.01	1.13 ± 0.21	4.14 ± 0.28	2.85 ± 0.22	95.81 ± 0.11
Group 2 Landnam tephra								
69.35	0.25	14.48	2.35	0.26	0.84	4.71	4.53	96.76
69.41	0.31	14.21	2.45	0.27	0.86	4.68	4.38	96.56
69.31	0.27	14.46	2.50	0.28	0.97	5.07	4.45	97.30
69.07	0.32	14.31	2.53	0.32	0.95	4.95	4.35	96.79
71.34	0.28	14.77	2.58	0.29	0.97	4.91	4.39	99.52
70.45	0.31	14.62	2.60	0.30	1.00	4.91	4.59	98.78
69.35	0.31	14.59	2.71	0.39	1.19	4.74	4.44	97.73
Mean and SD group 2 ($n = 7$)								
69.75 ± 0.83	0.29 ± 0.03	14.49 ± 0.19	2.53 ± 0.12	0.30 ± 0.05	0.97 ± 0.11	4.85 ± 0.15	4.45 ± 0.09	97.63 ± 1.13
Group 3 unknown								
72.72	0.55	12.60	3.61	0.41	2.34	3.26	1.86	97.34
72.45	0.56	12.62	3.66	0.42	2.27	4.24	1.97	98.20
73.32	0.59	12.86	3.67	0.42	2.33	4.07	1.93	99.17
71.10	0.57	12.34	3.70	0.41	2.21	3.90	2.00	96.23
Mean and SD group 3 ($n = 4$)								
72.40 ± 0.94	0.57 ± 0.02	12.60 ± 0.21	3.66 ± 0.04	0.41 ± 0.01	2.29 ± 0.06	3.87 ± 0.43	1.94 ± 0.06	97.73 ± 1.25
Group 4 unknown								
71.61	0.72	12.83	4.46	0.63	2.59	4.15	1.87	98.86

Appendix. Continued.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
51–52 cm, qub-570, brownish + colourless mixed, unknown *c*. AD 650								
Group 1 unknown								
73.74	0.37	14.08	1.82	0.39	2.01	4.40	2.05	98.86
74.30	0.31	14.29	1.84	0.44	2.17	4.27	1.95	99.56
74.70	0.33	14.20	1.84	0.39	2.07	4.02	2.12	99.67
71.03	0.37	14.52	2.93	0.13	1.90	4.52	2.55	97.94
Mean and SD group 1								
73.44 ± 1.66	0.34 ± 0.03	14.27 ± 0.18	2.11 ± 0.55	0.34 ± 0.14	2.04 ± 0.11	4.30 ± 0.22	2.17 ± 0.27	99.01 ± 0.79
Group 2 unknown								
63.28	1.04	16.25	6.73	1.46	4.68	4.27	1.64	99.36
60.60	0.86	15.26	6.75	1.52	4.50	4.10	1.62	95.21
61.68	0.98	15.69	6.87	1.45	4.58	4.17	1.74	97.16
63.64	1.03	16.14	6.89	1.49	4.36	4.56	1.69	99.79
63.46	1.00	16.13	6.92	1.48	4.68	4.02	1.57	99.26
62.52	0.98	16.41	6.93	1.41	5.03	4.43	1.44	99.15
63.13	0.99	16.25	6.97	1.45	4.62	4.20	1.66	99.27
61.58	0.94	15.71	7.05	1.42	4.54	3.73	1.54	96.50
64.09	1.09	16.10	7.37	1.55	4.66	4.38	1.56	100.78
Mean and SD group 2								
62.66 ± 1.15	0.99 ± 0.07	15.99 ± 0.36	6.94 ± 0.19	1.47 ± 0.04	4.63 ± 0.18	4.20 ± 0.25	1.61 ± 0.09	98.50 ± 1.80
53–54 cm, qub-569, brownish + colourless mixed, unknown								
Group 1 unknown								
71.11	0.17	13.88	2.97	0.14	2.00	4.43	2.35	97.04
72.75	0.21	14.21	2.99	0.13	1.90	4.65	2.46	99.28
72.78	0.23	14.28	3.05	0.14	2.04	4.78	2.53	99.84
74.56	0.16	12.57	1.67	0.03	1.26	4.39	2.59	97.23
74.06	0.28	14.28	1.60	0.45	1.85	4.47	2.74	99.72
72.55	0.31	13.95	1.69	0.40	1.63	4.47	2.77	97.77
75.22	0.18	13.35	2.00	0.04	1.25	4.62	2.85	99.51
75.76	0.17	13.26	2.06	0.03	1.34	4.70	2.90	100.23
75.13	0.35	14.08	1.48	0.37	1.52	4.89	2.92	100.74
75.44	0.33	14.13	1.43	0.34	1.55	4.79	2.98	101.01
70.38	0.33	13.59	1.92	0.29	1.36	4.30	3.27	95.44
70.98	0.31	13.54	2.09	0.32	1.38	4.28	3.37	96.28
Mean and SD group 1								
73.39 ± 1.90	0.25 ± 0.07	13.76 ± 0.52	2.08 ± 0.60	0.22 ± 0.15	1.59 ± 0.29	4.56 ± 0.20	2.81 ± 0.31	98.67 ± 1.84
Group 2 unknown								
71.31	0.26	14.76	2.61	0.26	0.79	5.25	4.54	99.78
74.82	0.20	12.95	1.83	0.06	0.90	4.30	3.72	98.83
Group 3 unknown								
63.71	0.90	16.81	5.91	1.13	5.12	5.18	1.40	100.15
60.89	0.95	15.70	6.01	1.20	4.71	4.39	1.34	95.14
64.59	1.07	15.75	7.35	1.44	4.82	4.21	1.55	100.80
54–55 cm, qub-568, unknown								
Group 1 unknown								
71.41	0.28	14.78	0.97	0.09	2.62	4.57	2.53	97.25
77.14	0.42	11.38	1.21	0.07	0.52	3.69	3.08	97.53
Group 2 unknown								
72.02	*0.13*	*12.74*	*1.85*	*0.04*	*1.27*	*4.05*	*2.64*	*94.74*
73.31	0.12	12.75	1.91	0.00	1.30	3.97	2.82	96.16
73.74	0.32	14.14	1.96	0.43	2.11	4.13	2.14	98.97
74.65	0.37	14.00	1.98	0.42	2.11	4.51	2.20	100.23
70.64	0.35	13.79	1.98	0.32	1.21	4.02	3.19	95.50
Group 3 unknown								
69.44	*0.22*	*14.07*	*2.74*	*0.12*	*1.79*	*3.95*	*2.24*	*94.55*
71.85	0.27	14.23	2.98	0.14	2.06	4.64	2.54	98.71
73.07	0.25	14.44	3.10	0.15	1.95	4.84	2.57	100.38
72.76	0.25	14.41	3.13	0.16	2.09	4.70	2.47	99.96
Group 4 unknown								
73.59	0.46	12.66	3.94	0.47	2.40	3.82	2.11	99.44
71.10	0.35	14.85	4.14	0.30	2.56	4.70	2.37	100.36

Appendix. Continued.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
61–62 cm, qub-567, unknown, *c*. AD 400–500								
Group 1 unknown								
71.37	0.35	14.09	1.97	0.33	1.33	4.17	3.31	96.90
71.22	0.36	14.19	1.97	0.28	1.32	4.14	3.14	96.61
70.92	0.36	14.11	1.99	0.28	1.26	4.23	3.29	96.45
70.38	0.35	14.14	1.99	0.29	1.24	3.77	3.26	95.41
71.25	0.33	14.40	2.00	0.31	1.37	4.37	3.27	97.29
71.28	0.35	13.93	2.01	0.30	1.30	4.13	3.22	96.53
70.57	0.35	14.27	2.01	0.29	1.24	4.02	3.18	95.94
70.93	0.30	14.22	2.02	0.34	1.36	4.00	3.29	96.46
71.78	0.32	14.18	2.03	0.32	1.33	4.35	3.32	97.62
72.07	0.33	14.37	2.05	0.30	1.28	4.34	3.31	98.05
69.78	0.36	14.00	2.05	0.27	1.22	4.01	3.34	95.02
72.34	0.36	14.33	2.08	0.29	1.34	4.41	3.29	98.45
71.07	0.36	13.80	2.08	0.34	1.32	4.05	3.30	96.31
Mean and SD group 1								
71.15 ± 0.69	0.34 ± 0.02	14.16 ± 0.17	2.02 ± 0.04	0.30 ± 0.02	1.30 ± 0.05	4.15 ± 0.19	3.27 ± 0.06	96.69 ± 0.98
Group 2 unknown								
58.68	0.95	16.98	6.56	3.34	6.66	3.97	1.47	98.62
58.81	1.01	16.58	7.09	3.88	6.27	3.68	1.69	99.01
68–69 cm, qub-566								
Colourless, very small, thin, many flat platey shards. No analyses possible so far								
80–81 cm, qub-565, unknown								
Group 1 unknown								
67.06	0.22	17.68	1.79	0.06	1.71	7.39	2.58	98.50
Group 2 unknown								
72.92	0.23	12.18	2.56	0.00	0.36	4.25	3.87	96.37
71.80	0.24	13.28	3.27	0.00	0.70	4.97	3.90	98.15
69.78	0.24	13.30	3.28	0.05	0.81	4.44	3.53	95.44
69.08	*0.26*	*13.07*	*3.36*	*0.00*	*0.83*	*4.06*	*3.72*	*94.38*
70.56	0.30	13.25	3.39	0.00	0.81	4.55	3.69	96.55
70.37	0.55	13.31	3.40	0.00	0.74	4.49	3.48	96.35
69.34	*0.25*	*13.19*	*3.41*	*0.00*	*0.76*	*4.31*	*3.48*	*94.74*
71.73	0.34	13.85	3.51	0.11	1.18	5.54	3.71	99.96
71.11	0.61	14.26	3.84	0.35	1.23	4.47	3.84	99.84
71.27	0.37	14.05	4.06	0.13	1.23	4.96	3.67	99.74
68.51	0.40	14.05	4.29	0.25	1.43	4.80	3.29	97.02
67.19	0.40	13.66	4.35	0.24	1.54	4.10	3.57	95.05
70.65	0.41	14.15	4.35	0.19	1.49	4.88	3.81	99.92
68.09	0.41	13.82	4.35	0.24	1.48	4.58	3.32	96.29
69.25	0.46	14.42	4.39	0.24	1.56	4.88	3.47	98.66
70.79	0.41	14.34	4.39	0.19	1.48	4.66	3.69	99.94
70.56	0.45	14.44	4.49	0.26	1.46	4.96	3.36	99.97
70.60	0.42	14.32	4.51	0.25	1.51	4.74	3.66	100.01
Mean and SD group 2								
70.20 ± 1.43	0.38 ± 0.11	13.72 ± 0.61	3.84 ± 0.58	0.14 ± 0.12	1.14 ± 0.38	4.65 ± 0.37	3.61 ± 0.19	97.69 ± 2.10
107–108 cm, qub-564, Hekla 4, *c*. 2310 BC								
Group 1 Hekla 4								
72.17	0.14	13.14	1.87	0.00	1.30	4.23	2.80	95.65
71.95	0.15	13.12	1.91	0.00	1.33	3.99	2.81	95.26
72.29	0.16	13.17	1.89	0.04	1.23	4.34	2.74	95.86
71.78	0.17	13.30	1.99	0.06	1.48	4.07	2.91	95.76
71.31	0.20	13.18	1.94	0.09	1.39	4.16	2.77	95.03
71.94	0.14	13.31	1.97	0.03	1.29	4.12	2.75	95.55
73.39	0.03	13.53	1.95	0.04	1.27	4.42	2.74	97.34
73.72	0.13	13.43	1.96	0.04	1.58	4.30	2.82	97.98
71.72	0.14	13.39	1.87	0.00	1.33	4.20	2.75	95.40
71.80	0.13	13.46	1.87	0.05	1.29	4.17	2.78	95.56
72.57	0.14	13.31	1.83	0.05	1.32	4.03	2.82	96.06
73.04	0.12	13.46	1.95	0.00	1.37	4.56	2.78	97.27
72.30	0.15	13.27	1.85	0.03	1.29	4.12	2.77	95.77

Appendix. Continued.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
Mean and SD group 1								
72.31 ± 0.70	0.14 ± 0.04	13.31 ± 0.13	1.91 ± 0.05	0.03 ± 0.03	1.34 ± 0.09	4.21 ± 0.16	2.79 ± 0.05	96.04 ± 0.90
118–119 cm, qub-598								
Group 1 unknown								
73.31	0.14	12.88	1.54	0.05	1.30	3.88	2.73	95.83
73.36	0.08	13.02	1.58	0.05	1.27	3.83	2.78	95.97
72.97	0.11	12.78	1.60	0.04	1.33	3.97	2.89	95.69
Group 2 unknown								
70.00	*0.25*	*12.98*	*2.58*	*0.08*	*1.52*	*4.16*	*2.89*	*94.45*
Group 3 unknown								
66.63	0.59	16.09	2.61	0.65	1.59	5.44	3.65	97.25
66.03	0.70	16.03	2.67	0.65	1.60	5.20	3.65	96.53
Group 4 unknown								
68.91	*0.34*	*12.85*	*3.14*	*0.04*	*0.99*	*3.31*	*3.48*	*93.06*
68.88	*0.23*	*12.99*	*3.14*	*0.04*	*0.95*	*3.56*	*3.17*	*92.96*
Group 5 – single shard, cf. SILK A1								
67.51	0.46	15.38	5.27	0.46	3.09	4.27	2.38	98.80
65.61	0.44	14.82	5.27	0.43	3.17	4.19	2.27	96.20
Five tephra shards analysed, all of differing composition. High FeO shard is similar to SILK A1 with date of 3850 BC								
122–123 cm, qub-599								
Pinkish/brownish tephra. Sparse layer, no analyses possible								
133–134 cm, qub-600								
Group 1								
70.21	*0.30*	*12.74*	*1.87*	*0.12*	*0.44*	*2.98*	*4.15*	*92.80*
70.13	0.46	13.23	2.06	0.25	0.73	3.75	3.36	93.96
68.00	0.48	12.35	2.10	0.28	0.70	3.64	3.61	91.16
69.51	0.50	12.83	2.13	0.26	0.73	4.12	3.57	93.64
69.24	0.26	12.08	2.33	0.03	0.51	3.70	3.86	92.02
69.67	0.26	12.11	2.36	0.08	0.46	3.53	3.97	92.43
72.80	0.22	12.65	2.36	0.02	0.47	2.22	2.33	93.05
69.77	0.28	11.99	2.37	0.04	0.49	3.56	3.82	92.32
69.98	0.27	12.08	2.43	0.06	0.48	3.65	3.82	92.75
Group 2								
69.25	*0.26*	*12.84*	*3.32*	*0.10*	*1.05*	*2.84*	*3.01*	*92.66*
Group 3								
70.41	0.46	13.13	2.04	0.22	0.66	3.43	3.66	94.02
70.83	0.46	13.52	2.10	0.26	0.79	3.36	3.30	94.61
70.91	0.54	13.41	2.21	0.26	0.73	3.59	3.86	95.49
71.27	0.45	13.35	2.06	0.28	0.73	3.57	3.89	95.58
71.28	0.53	12.96	2.07	0.29	0.73	4.19	3.58	95.62
71.14	0.46	13.46	2.14	0.27	0.72	3.83	3.68	95.69
Mean and SD of analyses over 94% group 3 ($n = 6$)								
70.97 ± 0.33	0.48 ± 0.04	13.30 ± 0.22	2.10 ± 0.06	0.26 ± 0.02	0.72 ± 0.04	3.66 ± 0.31	3.66 ± 0.21	95.17 ± 0.69
Group 4								
67.07	0.48	15.57	6.31	0.51	3.26	3.96	2.09	99.26
153–154 cm, qub-601								
Group 1 unknown								
73.85	0.18	11.81	1.85	0.03	1.06	3.96	3.11	95.85
73.78	0.17	12.24	2.09	0.08	1.14	3.80	2.99	96.28
Group 2 unknown								
69.30	0.37	16.58	2.77	0.25	3.54	4.90	1.83	99.53
Group 3 unknown								
68.58	0.29	13.33	3.46	0.14	1.96	4.03	2.44	94.22
70.59	0.30	12.28	3.53	0.14	0.95	4.32	3.76	95.87
68.18	0.42	13.54	3.66	0.34	2.30	4.11	2.23	94.78
71.19	0.37	11.75	3.69	0.15	0.89	4.05	3.70	95.80
71.18	0.29	13.61	3.70	0.16	2.22	4.31	2.65	98.12
70.93	0.36	12.71	3.79	0.19	1.06	4.17	3.72	96.93

Appendix. Continued.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
71.29	0.25	14.00	3.88	0.16	2.32	4.03	2.32	98.25
72.05	0.35	12.69	3.89	0.16	1.08	4.36	3.71	98.29
72.97	0.29	12.67	3.91	0.16	1.09	4.08	3.75	98.94
72.45	0.33	12.48	3.92	0.18	1.14	4.27	3.80	98.58
71.97	0.32	12.81	3.94	0.17	1.11	4.45	3.80	98.56
70.90	0.41	13.57	4.22	0.26	1.63	4.50	3.32	98.80
Mean and SD group 3								
71.02 ± 1.42	0.33 ± 0.05	12.95 ± 0.66	3.80 ± 0.21	0.18 ± 0.06	1.48 ± 0.57	4.22 ± 0.17	3.27 ± 0.65	97.26 ± 1.68
165–166 cm, qub-602, cf. Hekla 5								
Group 1 cf. Hekla 5								
73.95	0.14	12.59	1.74	0.05	1.29	4.11	2.75	96.62
75.18	0.16	12.91	1.70	0.04	1.32	4.04	2.85	98.20
74.08	0.14	12.56	1.66	0.03	1.15	4.12	2.72	96.46
73.60	0.11	12.82	1.73	0.04	1.32	4.31	2.83	96.75
73.62	0.11	12.74	1.65	0.05	1.25	4.21	2.66	96.28
75.75	0.14	13.15	1.69	0.05	1.37	4.41	2.78	99.32
75.67	0.16	12.77	1.83	0.00	1.27	4.05	2.90	98.66
73.98	0.14	12.72	1.74	0.03	1.26	4.37	2.76	97.01
75.95	0.14	13.03	1.78	0.06	1.34	4.38	2.80	99.48
75.50	0.16	12.89	1.74	0.06	1.25	4.13	2.74	98.47
76.49	0.10	12.80	1.75	0.02	1.27	4.14	2.90	99.46
Mean and SD group 1								
74.89 ± 1.06	0.14 ± 0.02	12.82 ± 0.17	1.73 ± 0.05	0.04 ± 0.02	1.28 ± 0.06	4.21 ± 0.14	2.79 ± 0.08	97.88 ± 1.28
175–176 cm, qub-603, cf. Hekla 5								
Group 1								
73.51	0.15	12.62	1.62	0.06	1.29	3.80	2.75	95.80
73.92	0.15	12.68	1.64	0.06	1.27	4.00	2.74	96.45
73.64	0.11	12.90	1.66	0.05	1.32	4.17	2.82	96.67
74.15	0.08	12.51	1.67	0.05	1.36	4.09	2.83	96.73
74.76	0.15	13.15	1.68	0.05	1.28	4.13	2.83	98.02
74.05	0.11	12.59	1.69	0.05	1.24	4.01	2.70	96.41
74.57	0.14	12.53	1.70	0.05	1.27	4.03	2.75	97.04
75.66	0.12	12.99	1.73	0.06	1.29	4.15	2.80	98.79
74.64	0.11	12.90	1.78	0.05	1.35	4.09	2.84	97.76
74.96	0.13	12.75	1.78	0.05	1.27	4.02	2.75	97.71
Mean and SD group 1 ($n = 10$)								
74.38 ± 0.66	0.12 ± 0.02	12.76 ± 0.22	1.70 ± 0.05	0.05 ± 0.00	1.29 ± 0.04	4.05 ± 0.11	2.78 ± 0.05	97.14 ± 0.91
Group 2 unknown								
71.37	0.54	12.54	2.33	0.24	0.68	4.14	4.38	96.20
73.51	0.28	12.69	2.52	0.04	1.22	4.24	2.78	97.24
179–180 cm, qub-604								
Group 1 unknown								
74.71	0.11	12.41	1.59	0.06	1.24	3.52	2.62	96.25
73.23	0.12	12.85	1.62	0.06	1.24	3.64	2.62	95.39
73.68	0.13	12.92	1.69	0.05	1.34	3.78	2.72	96.32
73.72	0.14	12.66	1.72	0.04	1.23	3.70	2.72	95.92
73.70	0.15	12.73	1.66	0.05	1.23	3.56	2.82	95.91
Mean and SD of group 1								
73.81 ± 0.54	0.13 ± 0.02	12.71 ± 0.20	1.65 ± 0.05	0.05 ± 0.01	1.26 ± 0.05	3.64 ± 0.10	2.70 ± 0.08	95.96 ± 0.37
Group 2 unknown								
74.21	0.18	12.38	1.41	0.09	0.73	3.48	3.52	95.99
Group 3 unknown								
73.38	0.45	13.12	1.74	0.36	1.53	3.81	2.68	97.06
73.14	0.47	12.90	1.66	0.36	1.51	3.67	2.81	96.53
Group 4 unknown								
75.96	0.17	11.61	2.13	0.00	0.78	3.57	3.16	97.39
75.91	0.19	11.71	2.18	0.00	0.82	3.63	3.14	97.56
Group 5 unknown								
69.30	0.36	14.31	4.86	0.25	2.75	3.45	2.26	97.54

Appendix. Continued.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
188–189 cm, qub-605, Suderoy Tephra, *c*. 6050 BC								
Group 1 unknown								
73.89	0.17	10.96	1.85	0.00	0.36	4.09	4.19	95.48
Group 2 Suderoy tephra								
69.13	0.28	13.32	3.60	0.19	1.27	4.04	3.48	95.31
68.79	*0.27*	*12.97*	*3.64*	*0.16*	*1.26*	*4.23*	*3.58*	*94.90*
70.03	0.31	13.40	3.65	0.19	1.33	4.90	3.55	97.36
68.97	0.30	13.15	3.67	0.16	1.26	4.14	3.54	95.20
68.52	0.25	13.20	3.72	0.17	1.23	4.52	3.49	95.11
68.76	0.30	13.13	3.73	0.15	1.23	4.45	3.30	95.02
69.24	0.33	13.21	3.74	0.18	1.20	4.44	3.51	95.86
69.73	0.28	13.53	3.76	0.19	1.29	4.50	3.49	96.77
71.38	0.29	13.58	3.83	0.20	1.30	4.52	3.59	98.68
Mean and SD group 2 ($n = 9$)								
69.39 ± 0.88	0.29 ± 0.02	13.28 ± 0.20	3.71 ± 0.07	0.18 ± 0.02	1.26 ± 0.04	4.42 ± 0.25	3.50 ± 0.09	96.02 ± 1.31
198–199 cm, qub-606								
71.94	*0.36*	*12.83*	*2.15*	*0.17*	*0.62*	*3.38*	*3.45*	*94.89*
71.86	0.37	12.84	2.14	0.15	0.62	3.50	3.57	95.05
Two analyses from single shard, unknown								
212–213 cm, qub-608, SSn of Hafledasson								
Group 1 unknown								
73.29	*0.24*	*10.89*	*2.68*	*0.12*	*0.78*	*3.26*	*2.83*	*94.09*
73.66	*0.28*	*11.19*	*2.68*	*0.12*	*1.05*	*3.04*	*2.50*	*94.52*
72.36	*0.34*	*11.52*	*3.38*	*0.11*	*1.65*	*3.29*	*2.15*	*94.80*
Group 2 unknown								
75.39	0.09	12.09	1.15	0.02	0.85	3.20	3.49	96.25
Group 3 SSn								
73.00	0.15	12.54	1.47	0.07	0.71	3.83	3.63	95.40
74.32	0.16	12.33	1.50	0.08	0.69	3.84	3.78	96.70
73.51	0.16	12.26	1.50	0.09	0.75	3.86	3.81	95.93
73.98	0.16	12.43	1.53	0.09	0.63	3.43	3.86	96.11
73.24	0.19	12.30	1.53	0.09	0.76	3.78	3.86	95.74
73.92	0.16	12.47	1.62	0.08	0.75	3.70	3.80	96.49
73.98	0.21	12.73	1.63	0.08	0.77	3.60	3.75	96.76
74.07	0.15	12.61	1.65	0.08	0.79	3.90	3.77	97.00
73.49	0.18	12.47	1.67	0.09	0.75	3.83	3.74	96.22
Mean and SD group 3 ($n = 9$)								
73.72 ± 0.44	0.17 ± 0.02	12.46 ± 0.15	1.57 ± 0.07	0.08 ± 0.01	0.73 ± 0.05	3.75 ± 0.15	3.78 ± 0.07	96.26 ± 0.52
SSn from Hafledasson								
74.28	0.13	12.26	1.59	0.08	0.71	3.64	3.97	
Group 4 unknown								
70.69	0.27	12.69	3.48	0.03	0.82	3.63	3.64	95.21
225–226 cm, qub-620, mixed Askja (10 000 BP ^{14}C) and Vedde								
Group 1 Askja								
73.05	0.35	12.01	2.46	0.24	1.59	3.63	2.52	95.85
74.24	0.34	12.15	2.47	0.24	1.57	3.99	2.52	97.51
75.17	0.33	12.39	2.50	0.26	1.68	4.07	2.50	98.89
74.87	0.31	12.50	2.52	0.24	1.54	3.89	2.58	98.45
74.97	0.32	12.43	2.58	0.25	1.60	4.03	2.53	98.71
74.22	0.36	12.11	2.60	0.27	1.63	4.05	2.49	97.72
73.25	0.36	11.97	2.61	0.24	1.57	3.77	2.57	96.32
75.68	0.33	12.33	2.63	0.28	1.58	3.78	2.56	99.16
73.43	0.34	12.00	2.68	0.25	1.59	3.51	2.31	96.13
75.91	0.45	12.19	2.72	0.36	1.67	3.52	2.54	99.36
Mean and SD group 1								
74.48 ± 1.01	0.35 ± 0.04	12.21 ± 0.19	2.58 ± 0.09	0.26 ± 0.04	1.60 ± 0.04	3.82 ± 0.22	2.51 ± 0.07	97.81 ± 1.32
Mean and SD Askja 10 000								
74.18 ± 0.88	0.31 ± 0.01	11.79 ± 0.18	2.51 ± 0.04	0.26 ± 0.01	1.59 ± 0.05	3.18 ± 0.21	2.49 ± 0.04	96.58 ± 0.90

Appendix. Continued.

SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
Group 2 unknown								
71.51	0.25	12.30	3.43	0.09	1.80	3.76	2.42	95.56
Group 3 Vedde								
69.79	0.26	13.31	3.56	0.13	1.18	4.29	3.33	95.86
69.25	0.30	13.33	3.61	0.16	1.36	4.14	3.49	95.63
68.78	*0.32*	*13.07*	*3.65*	*0.16*	*1.29*	*4.07*	*3.33*	*94.67*
69.48	0.33	13.32	3.66	0.23	1.27	4.59	3.24	96.11
70.74	0.31	13.42	3.78	0.23	1.39	5.02	3.39	98.29
70.43	0.30	13.46	3.84	0.16	1.39	4.50	3.63	97.70
71.17	0.35	13.86	3.85	0.19	1.43	4.54	3.51	98.90
71.92	0.26	13.96	3.96	0.23	1.38	5.12	3.56	100.38
Mean and SD group 3								
70.20 ± 1.06	0.30 ± 0.03	13.47 ± 0.30	3.74 ± 0.14	0.19 ± 0.04	1.34 ± 0.08	4.53 ± 0.38	3.43 ± 0.13	97.19 ± 1.94
Mean and SD Vedde								
70.02 ± 0.88	0.28 ± 0.04	13.37 ± 0.22	3.72 ± 0.14	0.14 ± 0.03	1.27 ± 0.07	4.56 ± 0.28	3.44 ± 0.14	96.86 ± 1.07