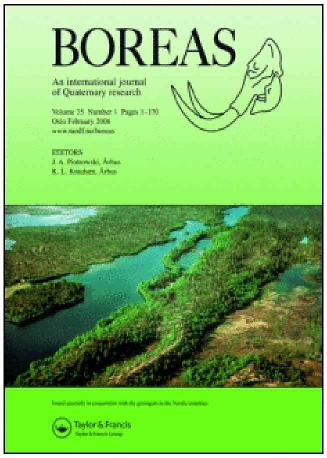

# Boreas
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Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713735669

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Online Publication Date: 01 January 2007
To cite this Article: Lawson, Ian T., Gathorne-Hardy, Frederick J., Church, Mike J., Newton, Anthony J., Edwards, Kevin J., Dugmore, Andrew J. and Einarsson, Árni (2007) 'Environmental impacts of the Norse settlement: palaeoenvironmental data from Mývatnssveit, northern Iceland', Boreas, 36:1, 1 - 19
To link to this article: DOI: 10.1080/03009480600827298
URL: http://dx.doi.org/10.1080/03009480600827298

# Environmental impacts of the Norse settlement: palaeoenvironmental data from Mývatnssveit, northern Iceland

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BOREAS

Lawson, I. T., Gathorne-Hardy, F. J., Church, M. J., Newton, A. J., Edwards, K. J., Dugmore, A. J. & Einarsson, Á. 2007 (January): Environmental impacts of the Norse settlement: palaeoenvironmental data from Mývatnssveit, northern Iceland. *Boreas*, Vol. 36, pp. 1–19. Oslo. ISSN 0300-9483.

The first stratigraphically continuous pollen profile spanning the Norse and Medieval periods from the archaeologically-rich Mývatnssveit region of northern Iceland is presented. Detailed analyses were made of the tephra, sediment characteristics, pollen and chironomids of a 3 kyr sediment sequence from Helluvaðstjörn, a small, shallow lake. The pollen data show a steady decline in the percentage abundance of tree birch (*Betula pubescens*) pollen between the Norse settlement (*landnám*, *c.* AD 870) and *c.* AD 1300, a pattern that contrasts with the abrupt fall in birch pollen percentages immediately following the Norse colonization at almost all previously studied sites in Iceland. Some lines of evidence suggest that the gradual birch decline could be a result of reworking of soil pollen, but independent evidence suggests that this may not necessarily be the case. The pollen record indicates that birch woodland was replaced by acidophilic taxa (notably *Empetrum nigrum* and *Sphagnum*), again contrasting with the more usual pattern of Poaceae expansion seen in post-*landnám* pollen diagrams from mires close to farm sites. Chironomid and *Pediastrum* accumulation data show that the limnic environment became more productive immediately after *landnám*, probably because of anthropogenic disturbance. An increase in sedimentation rate after *landnám* appears initially to have been caused by increased lake productivity, while reworked inorganic soil materials became a significant contributor to the sediments after *c.* AD 1200. The data suggest that the impact of settlement on terrestrial vegetation may have been more variable than previously thought, while freshwater ecosystems experienced significant and rapid change.

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The region of Mývatnssveit in northern Iceland (Fig. 1) is one of the most intensively studied regions of Iceland from the point of view both of archaeology and ecology (see McGovern *et al.* (in press) for a comprehensive review). Numerous Norse and early Medieval farm sites are known from the area, not least the important site of Hofstaðir, which is centred on the largest Norse longhouse yet excavated in Iceland (Friðriksson *et al.* 2004). The archaeological wealth of the area has driven intensive, multidisciplinary investigations of a number of individual sites, as well as wider surveys of the landscape. Mývatnssveit's ecological interest rests primarily on the lake of Mývatn itself, famed for its vast populations of migratory birds during the summer months. Consequently, the ecosystems of Mývatn and its surrounding area are understood in considerable detail (e.g. Jónasson 1979; Ólafsdóttir 2001; Einarsson *et al.* 2004).

Palaeoenvironmental studies in Iceland profit from the fact that the first human colonization – the *landnám* (Old Norse, meaning land-take) – occurred relatively recently, traditionally dated to around AD 870. The modification of the wholly natural environments of Iceland to their modern state took place over a relatively short period of time, most of which is well documented both archaeologically and historically. This presents an unusual opportunity to analyse the interplay between the intentional and unintentional changes that occurred to the environment, and the development of the Norse and medieval society and economy. The present study forms part of this larger research effort and was undertaken with specific research aims: (1) to establish the nature of the pre-*landnám* landscape and the resources available to the first settlers of Mývatnssveit; and (2) to assess the timing and degree of changes to vegetation, soils and aquatic ecosystems since *landnám*. Other lines of archaeological and palaeoenvironmental evidence from Mývatnssveit are used to contextualize the present study.

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DOI 10.1080/03009480600827298

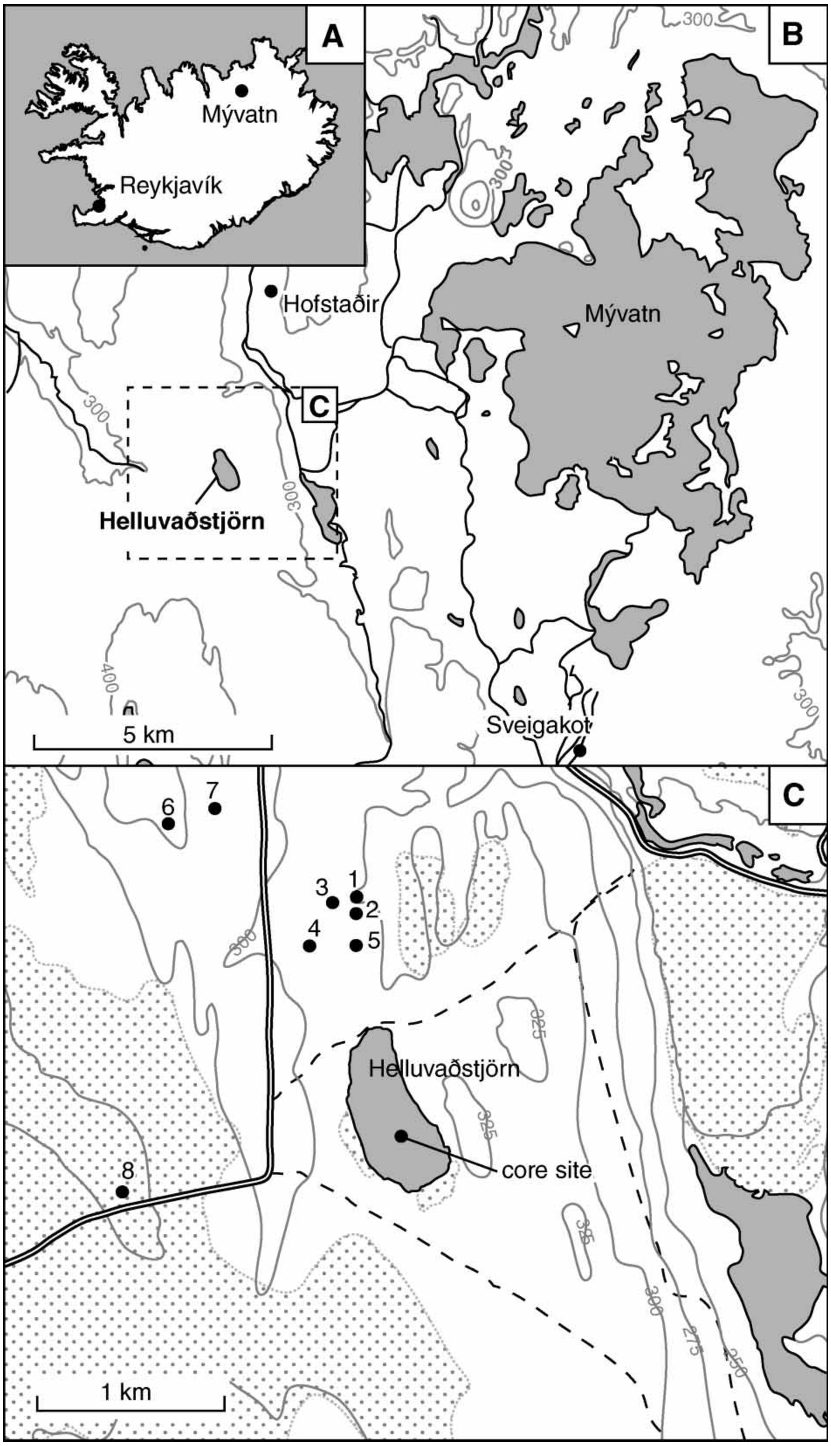

*Fig. 1.* Location maps. Contours are in metres throughout. A. Iceland. B. Part of Mývatnssveit showing the location of Helluvaðstjörn and other sites mentioned in the text. C. Sketch map of the site. Stipple: mires; double lines: roads; dashed lines: tracks. Numbered dots refer to the soil profiles shown in Fig. 5.

## Study area

Mývatnssveit has a more continental climate than many parts of Iceland, with relatively little rain- or snowfall (Einarsson 1979). Precipitation decreases markedly inland from the coast. At the present day, the boundary between vegetated and desertified land lies less than 10 km to the east of Helluvaðstjörn, and remains of settlements and sheep-pens in the desert areas attest to the migration of the erosion front to the northwest during the historical period (Simpson *et al.* 2004). Most of the vegetated area is used for sheep-grazing, with intensively cultivated hay fields around farms; the rangeland vegetation is a mosaic of Poaceae/

Cyperaceae-dominated herbaceous communities, dwarf-shrub (*Empetrum nigrum*, *Betula nana*, *Salix*) communities and *Carex*/*Eriophorum* mires (vascular plant nomenclature follows Stace (1997) and Kristinsson (1998)). In a few areas where grazing is restricted, *Betula pubescens* ssp. *tortuosa* scrub occurs, particularly on the rough lavafields to the east of Mývatn. Tall herb communities (*Angelica sylvestris*, *A. archangelica*, *Geum rivale*) also exist on some less accessible slopes and on flood-plains.

Helluvaðstjörn (Figs 1, 2; 65°35′N, 17°10.5′W, *c.* 310 m above sea level) is a small (800 × 400 m) lake which appears to occupy a glacially carved bedrock basin situated in a rangeland area 5 km southwest of Mývatn. Till underlies andisols on the gentle slopes of the catchment, and, with the exception of occasional sheep scrapes, there are few erosion scars. The lake has a maximum depth of 1.2 m and supports widespread and dense communities of *Potamogeton* spp. and *Myriophyllum alterniflorum*, while Cyperaceae fens occur in places around its shore. There are at present no substantial fluvial inputs to the lake and there is no surface outflow. The catchment is vegetated with dwarf-shrub communities dominated by *Salix phylicifolia*, *Betula nana*, *Vaccinium uliginosum* and *Empetrum nigrum*. Although there has been some erosion of the till around the edges of the lake, especially on the eastern shore, it appears likely that the dominant source of allogenic sediment and pollen is aeolian input. The lake was chosen for this study as its size, organic-rich sediments and relatively stable catchment make it an appropriate site to address the research aims.

## Materials and methods

### *Sampling and sediment characterization*

A 130-cm-sediment succession was collected from an anchored dinghy close to the centre of the lake using a 5-cm-diameter Russian corer. The cores were subsequently stored at 4°C. The sediments were described using a modification of the Troels-Smith system (Aaby & Berglund 1986) using Munsell Color charts (Munsell Color 1975), then X-rayed using a Muller 150 kV CP Be unit. The resulting X-rays were scanned and corrected for distortion, then used to identify accurately the overlap positions between each 0.5-m core section by matching prominent inwash bands and tephra layers. Samples of 1 $cm^3$ of gyttja were analysed for dry bulk density after drying at 105°C for 24 h, and for loss-on-ignition at 550°C for 4 h (Dean 1974; Heiri *et al.* 2001). These samples were generally taken at 1-cm contiguous intervals, except where discrete tephra layers occurred, in which case the sampling resolution was increased to 0.5 cm. Relative changes in magnetic susceptibility were measured at low frequency (0.46 kHz) using a Bartington Instruments MS-2 meter and MS-2f probe, with measurements contiguously at 1-cm intervals.

Subsamples for tephra identification were taken from 18 levels where visual examination of both the cores and the X-rays indicated a concentration of tephra. Pretreatments for microprobe analysis followed Dugmore *et al.* (1995a). Tephra samples were mounted in resin and then ground, polished and carbon coated. Analyses were undertaken on a five spectrometer Cameca SX100

*Fig. 2.* Photograph of Helluvaðstjörn, viewed from the west.

electron microprobe, using an accelerating voltage of 20 kV. A beam with a 4 nA current and a 10-μm raster was used to reduce sodium migration found in the more silicic tephra layers. Peak count times were 10 s per suite of elements (total count time of 45 s). The instrument was calibrated using a mixture of pure metals and simple silica compounds and counter deadtime; fluorescence and atomic number effects were corrected using Cameca's PAP correction programme. Total iron is expressed as FeO. Reference material and comparative data sets included Tephrabase (http://www.tephrabase.org), Larsen *et al.* (2002) and unpublished reference profiles from the Mývatn area.

### *Pollen, spore and* Pediastrum *analysis*

Samples were processed for pollen analysis using standard techniques (Berglund & Ralska-Jasiewiczowa 1986): 1 cm$^3$ samples were treated with 10% HCl, 10% NaOH, 60% HF and acetolysis. Tablets of *Lycopodium* spores were added to the samples to allow assessment of pollen concentrations (Stockmarr 1971). A minimum of 300 grains of indigenous terrestrial pollen taxa was counted for each sample (cf. Maher 1972; Rull 1987). Identifications followed Punt (1984), Moore *et al.* (1991), Komárek & Jankovská (2001) and John *et al.* (2002), making use of the pollen reference collection at the University of Aberdeen. Grain-size statistics were collected throughout for *Betula* and for selected samples for *Isoetes*. *Betula* grains larger than 20 μm were assigned to *B. pubescens* and the remainder assigned to *B. nana* (cf. Mäkelä 1996; Caseldine 2001). Pollen preservation was systematically recorded for the first 30 *B. pubescens*-sized grains encountered in each sample, scoring each grain for evidence of corrosion, degradation, crumpling and breakage (definitions following Cushing 1964), allowing for the possibility that individual grains might show more than one type of damage. Charcoal was only intermittently present at very low abundances and is not shown in the diagrams.

### *Chironomid analysis*

Chironomid head capsules were extracted using the methods of Lang *et al.* (2003). Samples were deflocculated for 15 min in a 10% KOH solution at 85°C, and then sieved through a 90-μm mesh. The residue was dispersed in 100 ml water and treated in an ultrasonic bath for 10 s. It was then re-sieved and the residue sorted using a grooved plastic sorting tray under a binocular microscope at ×35 magnification. Chironomid heads were mounted using Hydro-Matrix®.

Chironomids were identified using Hofmann (1971), Cranston (1982), Wiederholm (1983) and Rieredevall & Brooks (2001), and related to the Norwegian training set at the Natural History Museum, London. Tanytarsini were identified using an unpublished key (S. Brooks, unpubl. data).

## Age model

Appendix A presents the results from the EPMA analysis of individual tephra shards from the 18 possible tephra layers identified from the X-rays. Positive identification of tephra isochrons was based on the clarity of layers observed within the X-ray, the homogeneity of magma source from a shard assemblage analysed by the EPMA (e.g. Fig. 3), and the relative position of tephra layers of one magma source compared to the known regional tephrochronology.

The generic label of the '*landnám* complex' was given to the multiple layers of tephra inwash identified between 92 and 87.5 cm (Fig. 4). This horizon is a product of the multiple tephra falls from principally Veiðivötn and Grímsvötn eruptions in the 9th and early 10th centuries AD. These appear within a mixed horizon in the lake sediment due to the landscape instability occurring at *landnám*, indicated by the erosional discontinuities in the tephra profiles from the slopes of the wider catchment of the lake (Fig. 5). Virtually all of the soil profiles in Fig. 5 show erosion back into prehistoric times, with the landscape stabilizing (at least where the profiles are found) sometime in the 15th century, coinciding with the deposition of the distinctive Veiðivötn 1477 layer. The lack of Veiðivötn 1717 tephra above the 1477 layer and the evidence of reworked material in the upper part of most of the soil profiles suggest that the wider landscape after this time was still experiencing erosion. Mixing and redeposition of tephra have been observed in lake profiles elsewhere in Iceland (Thompson *et al.* 1986; Boygle 1999;

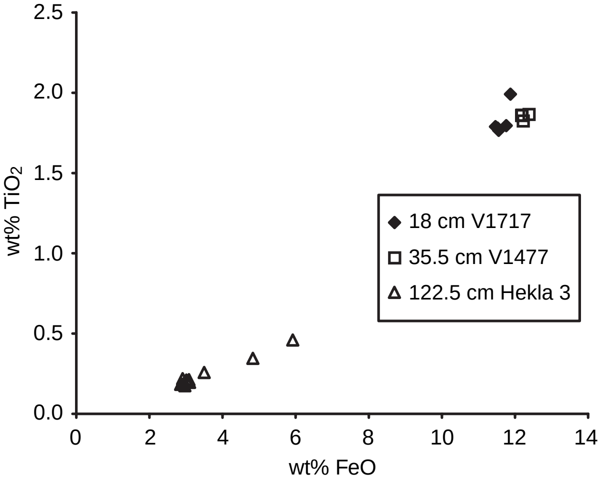

*Fig. 3.* Homogeneity of magma source indicated for Hekla 3, V1477 and V1717 based on the EPMA results of single shards, differentiated in this example using TiO$_2$ and FeO.

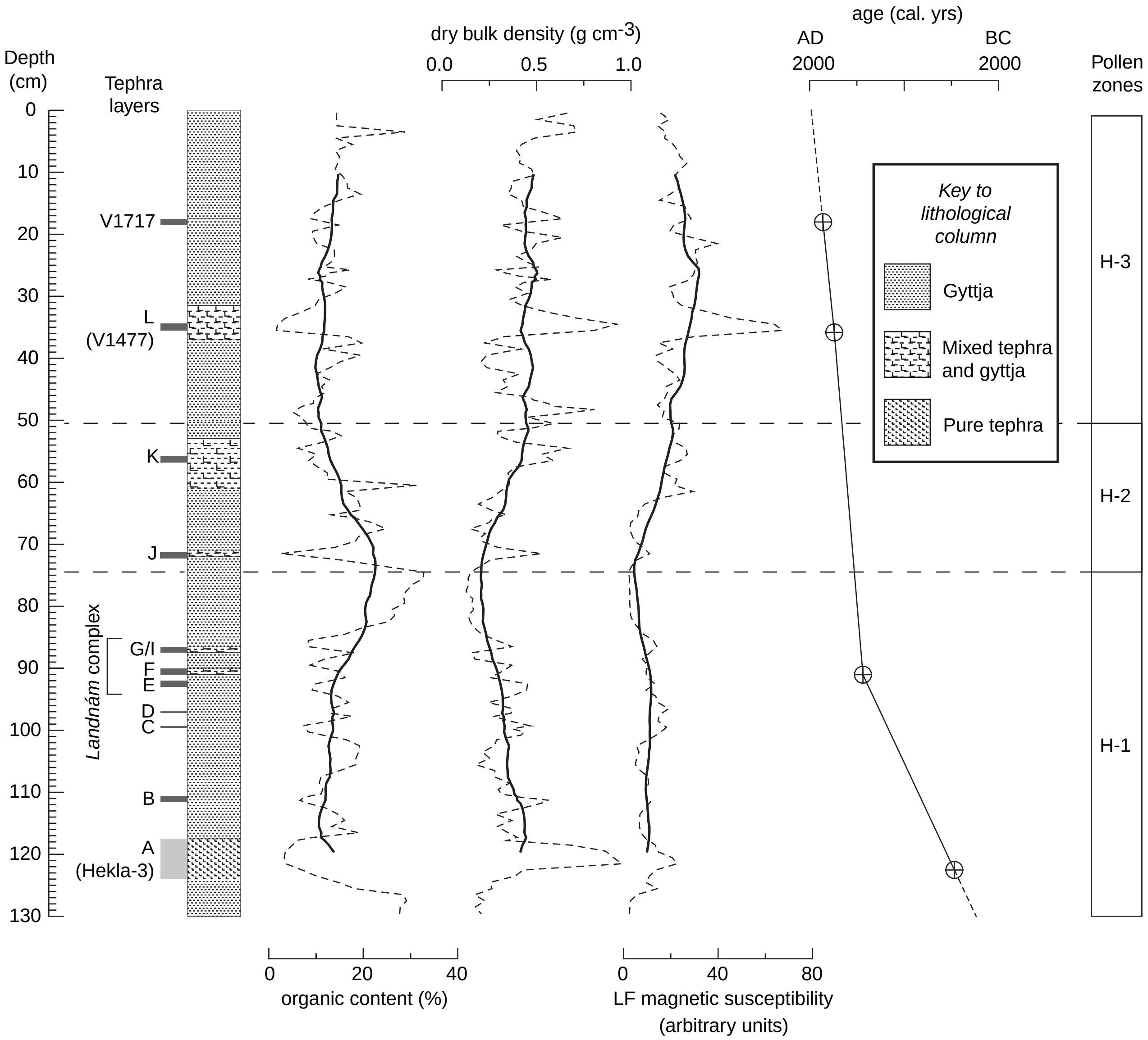

*Fig. 4.* Lithostratigraphy and tephra horizons, proxy sedimentological data and age model for the Helluvaðstjörn succession. Trendlines were calculated by unweighted linear regression using a 20-cm-wide moving window to allow for changes in sampling resolution.

Andrews *et al.* 2002) and presumably account for those tephra layers which appeared diffuse in the X-rays and gave EPMA results indicating a range of geochemistries from more than one source (for example at Layer F, 90.5–89.5 cm; Table 1). However, the geochemically homogeneous, discrete tephra layer I at 88–87 cm, at the top of the *landnám* complex, has been positively identified as a Veiðivötn layer. It is likely that this represents the Veiðivötn tephra that fell in the area during the 10th century AD (G. Larsen, pers. comm. 2004). Soil profiles throughout this area show this 10th-century layer more prominently than the 9th-century tephras.

The age model for the Helluvaðstjörn succession (Fig. 4) is based on linear interpolation between the base of four tephra layers of known age: 122.5 cm, Hekla-3 (radiocarbon dated to 2879 ± 34 yr BP: Dugmore *et al.* 1995b, calibrated to 1210–920 BC using OxCal (Bronk-Ramsey 2003) with a 95% confidence interval as shown by the horizontal bar in Fig. 4); 91 cm, base of the *landnám* tephra complex (AD 871 ± 2: Grönvold *et al.* 1995); 35.5 cm, Veiðivötn 1477 (AD 1477); 18 cm, Veiðivötn 1717 (AD 1717). The sedimentation rate apparently increased by a factor of 6 after *landnám*, then remained approximately constant to the present day.

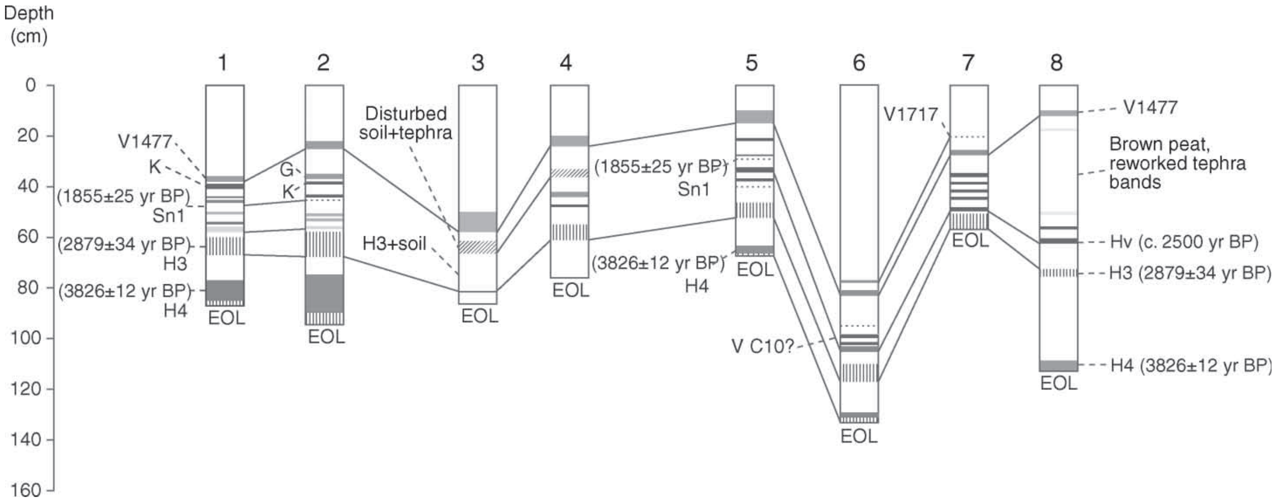

*Fig. 5.* Tephrostratigraphy of the soil profiles shown in Fig. 1C. Key to shading: vertical stripes, pale (silicic) tephras; grey bands, grey tephras; black bands, black tephras; diagonal stripes, mixed soil and tephra. Tephra nomenclature and dating follow Tephrabase (http://www.tephrabase.org); radiocarbon dates are uncalibrated with errors at the 1σ level. EOL: end of log.

## Results and interpretations

### *Sedimentology*

Proxy indicators of sediment composition – loss-on-ignition, dry bulk density and magnetic susceptibility – all co-vary to a considerable extent (Fig. 4). This is particularly the case where tephra layers occur; in most cases the resulting drop in organic content is mirrored by an increase in magnetic susceptibility, reflecting the increased proportion of mineral fraction within the sample. Some variation in the degree of coupling between these two parameters does occur – for example, the magnetic susceptibility increase across the Hekla-3 tephra is substantially smaller than across V1477, although loss-on-ignition shows a similar decrease in organic content; this is presumably attributable to variations in geochemistry between the relatively silicic Hekla-3 and the more basic V1477 (cf. Gonzalez *et al*. 1999; Ashburn *et al*. 2003). Many smaller discrepancies may be due to the fact that even a 1-cm sampling resolution is insufficient to capture the fine-scale variation in tephra content through the sequence, as indicated by the identification of sub-centimetre-scale lenses of material within the X-rays.

Long-term patterns, reflecting changes in the underlying sedimentation regime, are picked out by the trendlines in Fig. 4. Although the high degree of smoothing required to cancel out the effect of the tephras on the sediment parameters leads the trendlines to under-represent the true magnitude and speed of these changes, it is clear that there is a region of increased organic content and decreased magnetic susceptibility between *c.* 85 and 65 cm depth (*c.* AD 950–1150). The soil and tephra logs from test pits within the geomorphological catchment of the lake suggest a general acceleration of erosion and re-deposition of tephra at some point between *landnám* and AD 1477, and a further acceleration since AD 1477 (Fig. 5; cf. Simpson *et al*. 2004), although soil accumulation rates vary considerably from one test pit to the next.

### *Terrestrial pollen*

The pollen data (Fig. 6) have been divided into three assemblage zones using CONISS (Grimm 1987) as a guide. Throughout the sequence, assemblages are dominated by herbaceous taxa, with only one important tree taxon, *Betula pubescens.* The major stratigraphic feature of the pollen data is a change from high percentage values of *Betula pubescens* (mean 33.2%) and *Juniperus* (6.4%) in zone H-1 (130–74.5 cm, approx. 1500 BC–AD 1050) to much lower values (means 13.0 and 1.6%, respectively) in zone H-3 (50.5–1 cm, approx. AD 1225-present), with the transition occupying the whole of the intervening zone H-2. First Cyperaceae, then *Empetrum nigrum* and Poaceae percentages increase substantially in compensation for the decline in *B. pubescens* and *Juniperus.* Other than this transition, the pollen assemblages are remarkably stable.

A few shrub taxa, notably *Betula nana*, *Juniperus*, *Salix* and *Empetrum nigrum*, occur in moderate quantities throughout the data set, although the low pollen production of many taxa that are common in the heath around Helluvaðstjörn today, such as *Arctostaphylos uva-ursi* and *Salix* spp., means that the full diversity of heath communities is probably not well documented in the pollen record (cf. Rymer 1973; Pennington 1980). *B. nana* and *Salix* percentages hardly change between zones, while *Empetrum nigrum* values increase substantially from H-1 to H-3.

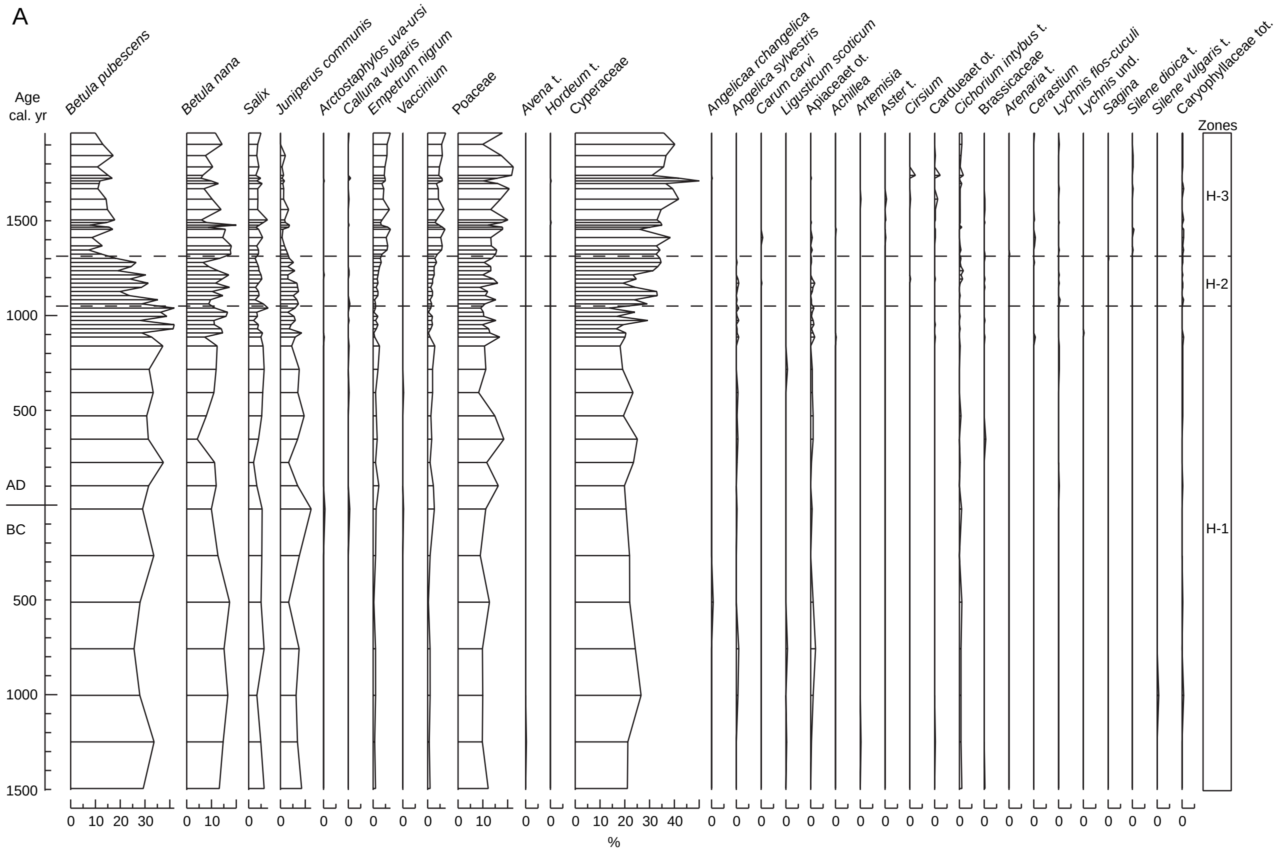

*Fig. 6.* Pollen percentage data from Helluvaðstjörn. Black dots indicate presence of a taxon at less than 0.5%. Percentage calculations are based on a sum of total land pollen (TLP) for terrestrial pollen taxa, and TLP+total spores for the Pteridophyta and *Sphagnum*.

Herbs are dominated by Cyperaceae and Poaceae, with *Thalictrum* also numerically important, although several other taxa are present continuously or nearly so, including members of the Apiaceae, Caryophyllaceae and Asteraceae, *Rumex acetosa* and *Ranunculus acris*-type. Few of the herb taxa show clear stratigraphic patterns; exceptions are the Apiaceae, especially *Angelica sylvestris*, which is present almost continuously in zones H-1 and H-2 but absent from H-3, and the Rubiaceae, which are more abundant in zone H-3 than in the lower zones.

Of the three taxa which dominate the terrestrial spore assemblages, *Lycopodium annotinum* shows little stratigraphic change, while both *Selaginella selaginoides* and *Sphagnum* show a marked decline towards the base of H-2 and a substantial increase throughout H-3. Small quantities of alien tree taxa (not shown, always $<1\%$ in total, and excluded from the pollen sum) can be attributed to long-distance transport.

Total pollen concentrations are relatively low before *landnám*, averaging 9970 grains cm$^{-3}$, rising to 13 220 grains cm$^{-3}$ for the remainder of zone H-1, and averaging 10 830 and 15 130 grains cm$^{-3}$ for H-2 and H-3, respectively. These quite minor changes in concentration translate into much larger changes in pollen influx (pollen accumulation rate) when sedimentation rate variations are taken into account, the most significant change being from a pre-*landnám* average influx of 162 grains cm$^{-2}$ yr$^{-1}$ to 1210 grains cm$^{-2}$ yr$^{-1}$ for the remainder of zone H-1. These influx rates are comparable to those from the mire site of Vesturárdalur (Wastl *et al.* 2001), but considerably lower than those recorded at the lake site of Efstadalsvatn (Caseldine *et al.* 2003), which has mid-Holocene influxes of the order of 2000–10 000 grains cm$^{-2}$ yr$^{-1}$ (in zone Efs 8, 6100–3800 yr BP, the uppermost zone in the succession). Efstadalsvatn is stream-fed, and the relatively low pollen influx in Helluvaðstjörn (and the generally excellent state of preservation of the pollen before AD 1200) supports the view that the majority of the pollen entering the lake was airborne, at least during zone H-1.

### *Chironomids and aquatic palynomorphs*

The chironomids are dominated by the Orthocladiinae *Psectrocladius sordidellus* group. High numbers of *Chironomus* are also found, as are members of the *Tanytarsus lugens* group. *Dicrotendipes* is present in low numbers through most of the core. Other species are

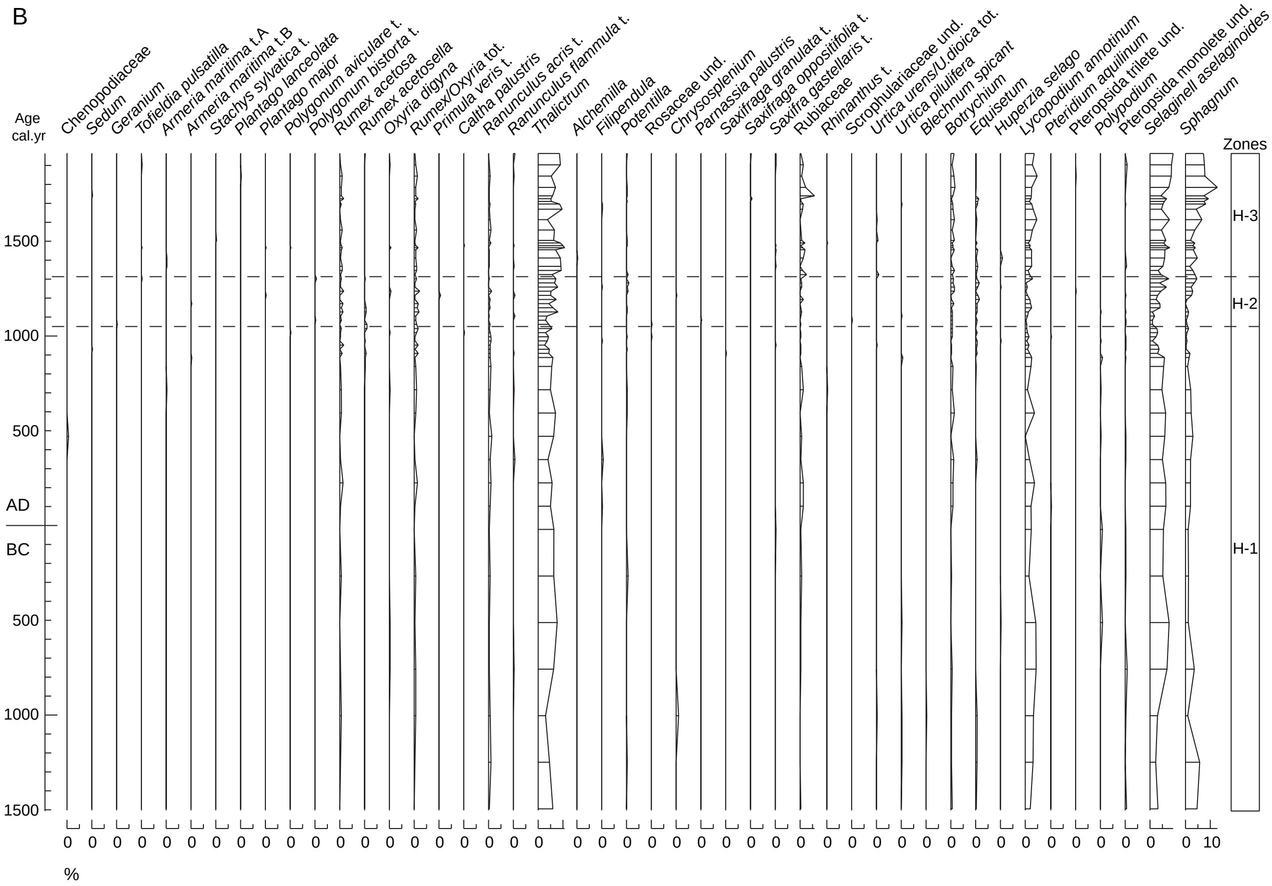

*Fig. 6* (Continued)

rare. Head capsule concentrations are low in the core (approximately an order of magnitude lower than in Efstadalsvatn; Caseldine *et al.* 2003), and the samples from each pollen zone have been amalgamated to ensure a meaningful sample size for the calculation of percentages (Heiri & Lotter 2001). Little change in chironomid percentages is evident through the succession (Fig. 7). Total chironomid concentration and accumulation rate (Figs 7, 8) both change substantially, the former increasing by a factor of 2 following *landnám*, the latter increasing at the same time by an order of magnitude. After *c.* AD 1200, concentrations subside once more, although the high sedimentation rate means that the accumulation rate remains high. This high concentration/accumulation rate phase after *landnám*, and especially between *landnám* and AD 1200, is mirrored by the planktonic alga *Pediastrum* (Fig. 8). In this case, a slight shift in species assemblage is noticeable after AD 1200, when *P. angulosum* becomes less important.

With regard to the pollen and spores of aquatic macrophytes, *Myriophyllum alterniflorum* and *Isoetes* (probably entirely *I. echinospora* on the basis of spore size measurements, which are unimodal, longest exine diameter 21.5 ± 2.4 μm for 943 measurements; cf. Birks 1973) are the dominant taxa throughout the succession. In terms both of their influx rates (Fig. 8), as well as concentrations and percentages (not shown), both taxa show considerable expansion in the upper part of the succession. *Myriophyllum* expands just above the *landnám* complex, along with *Pediastrum* and chironomids, but high values are not maintained; instead the values oscillate, with a decline in abundance at *c.* AD 1100 followed by a second peak between AD 1250 and 1600. This pattern largely matches changes in *Pediastrum* abundance. *Potamogeton* and *Isoetes* expand between the two *Myriophyllum* peaks.

## Discussion

### Vegetation changes

One of the most intriguing aspects of the Helluvaðstjörn palaeoenvironmental record is the evidence for a gradual decline of birch woodland. The pollen data suggest stable birch woodland before *landnám* (*c.* AD 870), with very little variation in *B. pubescens* pollen percentages or, indeed, any aspect of the composition

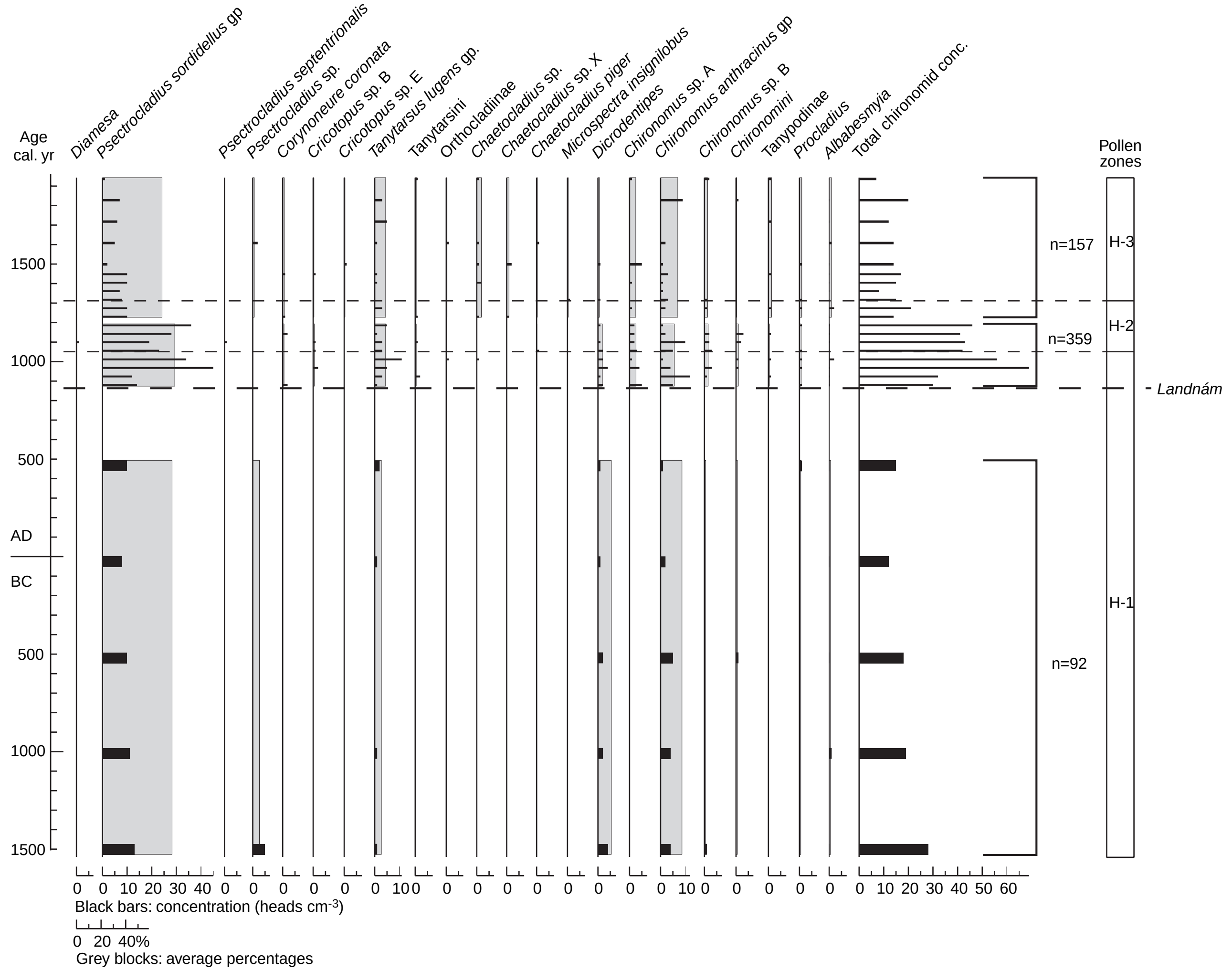

*Fig. 7.* Chironomid concentration and percentage data from Helluvaðstjörn. Concentrations are shown as solid black bars. Concentrations are generally low in the Helluvaðstjörn succession, and sample sizes are consequently small, so percentages have not been calculated for individual samples, but for groups of samples (shown as pale grey bars). Despite the loss of stratigraphic resolution, these percentages show clear trends in the data as discussed in the text.

of the pollen spectra. However, this stability in the pollen percentage data continues for some time after *landnám*; the percentages suggest that birch began to decline in the landscape around AD 1050, with a restabilization of the birch scrub at close to its present extent around AD 1300. Some of the variability of the birch pollen percentages during this period falls outside the confidence limits attributable to counting error (Fig. 9A), suggesting that the process of decline may have been episodic with periods of regrowth.

Given the independent evidence for landscape instability in the historical period, the possibility that the pollen percentage record is distorted by reworking from catchment soils must be considered. Various lines of evidence give conflicting indications. Pollen that has been reworked from soils normally shows signs of decay due to the effects of bacterial and fungal attack, and oxidation while in the soils, resulting in conditions usually described as corrosion and degradation, and mechanical damage during transport resulting in crumpling and breakage (Havinga 1964, 1967; Cushing 1964, 1967; Lowe 1982; Wilmshurst & McGlone 2005). The preservation data for *Betula pubescens* are shown in Fig. 9B. Despite high sample-to-sample variability that is likely to be partly a consequence of the relatively small sample size, it is clear that the frequency of corrosion, degradation and crumpling increases towards the top of the sequence, but only after *c.* AD 1200; the crucial period between *landnám* and AD 1200 shows no substantial change in the preservation state of the pollen compared with the pre-*landnám* situation. Breakage shows no obvious stratigraphic pattern.

Another effect that is commonly observed in conjunction with reworking is a bias in the assemblages towards particularly robust palynomorphs, such as *Cichorium intybus*-type pollen and monolete Pteropsida

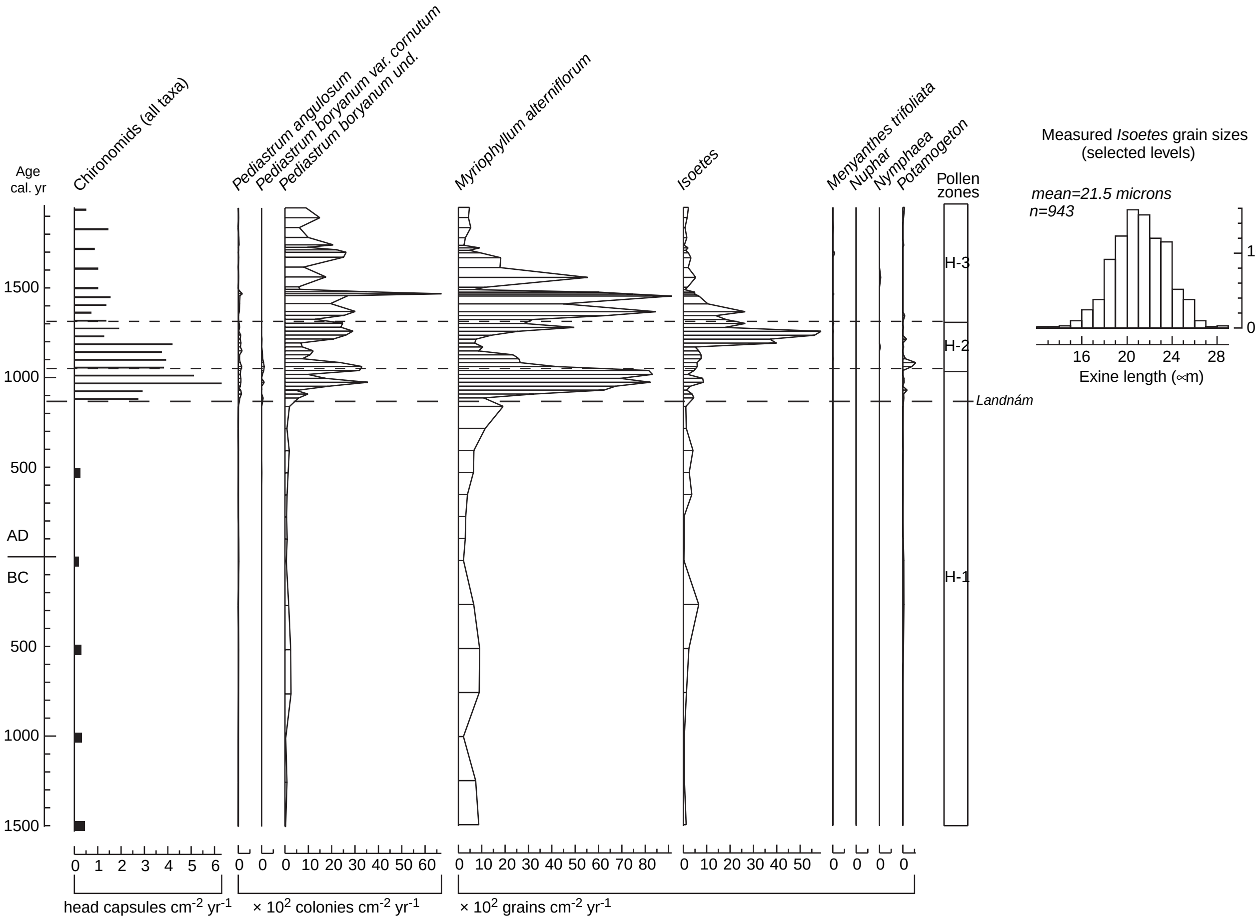

*Fig. 8.* Chironomid influx, *Pediastrum* and aquatic pollen/spore data from Helluvaðstjörn.

spores. The relevant percentage data show only a very small increase in the former after *landnám* and no change in the latter. Both lines of evidence would thus suggest that reworking does not significantly distort the pollen-vegetation relationship in the Helluvaðstjörn, at least not until AD 1200, since when reworked *B. pubescens* pollen appears to have made a steadily increasing contribution to the assemblages.

On the other hand, pollen concentrations and influx values for all taxa increase substantially and rapidly after *landnám* (the data for *B. pubescens* are shown in Fig. 9C), suggesting a significant change in the mechanism by which pollen grains were deposited in the lake. This could be consistent with remobilization of pollen in eroding soils, assuming that the first soils to be reworked were of such a character as to preserve pollen in an excellent state. However, even the highest birch influx rates observed here are within the range found by a study of aerial birch pollen deposition in northernmost Finnish and Norwegian woodlands (Hicks 2001), so other explanations which do not involve reworking may account for the data equally well. One model would be that, as the woodland began to be opened up, the increased effectiveness of pollen transport by wind in a partly deforested environment (Tauber 1965) led to higher pollen loadings in the lake. The possibility that increased flowering, for example as a consequence of management techniques such as coppicing, is responsible for the sustained *B. pubescens* values (cf. Edwards 1993) seems unlikely as the influx of most pollen taxa, not just *B. pubescens*, increases after *landnám.* Given the uncertainties in the interpretation of the available data, and the almost total absence of information about the taphonomy of pollen in the Icelandic environment (which is likely to be unusual in terms of the importance of aeolian soil transport and the conditions for pollen preservation in its soils), it would be unwise to draw firm conclusions about this issue from the pollen data alone.

A number of independent lines of evidence suggest that the first interpretation, that the data genuinely represent a gradual decline of birch woodland, could be the correct one. Several hundred charcoal production pits have been identified by aerial and walk-over archaeological survey in the region. Excavation and radiocarbon dating of charcoal from a group of these pits near the farm of Hoskulsstaðir, 30 km north of Helluvaðstjörn, has established that they were in use in

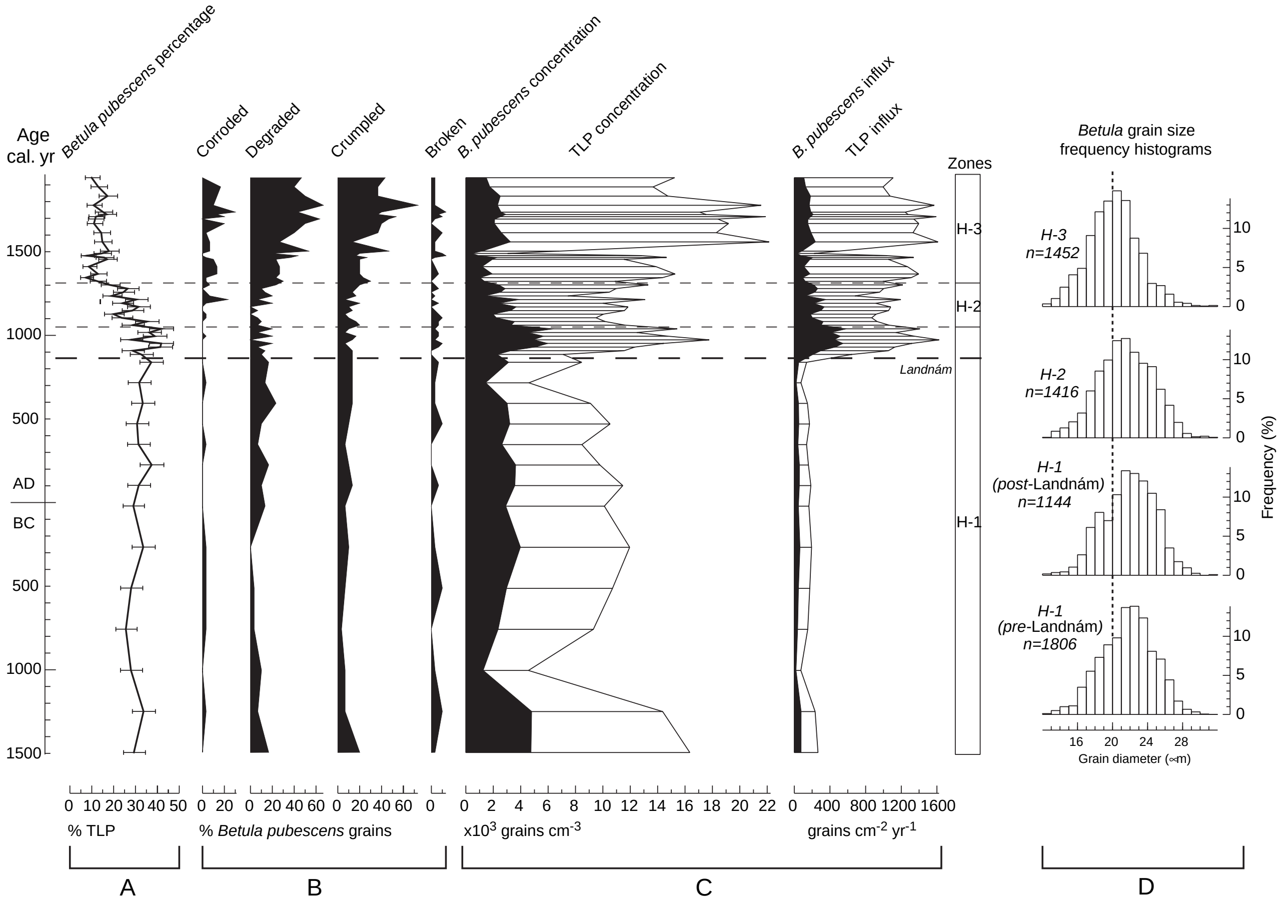

*Fig. 9.* A. Pollen percentage data for *Betula pubescens* as in Fig. 5, with confidence intervals at the 2σ level calculated using the formulae given by Maher (1972). B. Preservation state of *B. pubescens* grains expressed as the percentage of *B. pubescens* grains recorded as substantially corroded, degraded, crumpled and/or broken, from a subsample of 30 *B. pubescens* grains in each level. C. *B. pubescens* pollen concentration and influx. D. Size statistics for all measurable *Betula* grains.

the 11th and 12th centuries cal. AD (Church *et al.* 2006). The charcoal assemblage from these pits was dominated by charcoal of birch branchwood. Research on fuel ash residues at the Norse/early medieval farm sites of Hofstaðir and Sveigakot indicates the continued use of birch as fuel at the higher-status site (Hofstaðir) until at least the late 10th century AD (Simpson *et al.* 2003; Vésteinsson & Simpson 2004). Birch charcoal is also ubiquitous throughout the stratigraphy from the two sites. This not only demonstrates that there was still enough birch left in the landscape for it to be used as firewood, but also suggests that access was being controlled, with lower-status sites such as Sveigakot having to make do with less valuable sources of fuel. Elsewhere in Iceland, for example in Reykholtsdalur, western Iceland (Smith 1995) and Eyjafjallsveit, southern Iceland (Dugmore *et al.* 2006), historical sources point to a similarly gradual contraction of woodland in the face of farm expansion and collection of wood for charcoal-making and iron-working.

The conclusion that birch woodland declined slowly over the course of 400 years in the landscape around Helluvaðstjörn would contrast with the conclusions of most previous pollen studies in Iceland. At almost all sites the birch pollen decline is rapid, taking place in less than a century (where age models are adequate to gauge this) and often with the bulk of the change taking place from one sample to the next across the *landnám* tephra complex (e.g. Thórarinsson 1944; Einarsson 1961, 1963; Hallsdóttir 1987, 1996). For example, at the mire sites of Mosfell and Þrándarholt in southwest Iceland, two of the most detailed records available, Hallsdóttir (1987) found a decline in birch pollen percentages from *c.* 45 to *c.* 12% and *c.* 58 to *c.* 10%, respectively, between the deposition of the *landnám* ash and AD 1000. Other sequences with less robust chronologies for this period appear to show the same pattern, e.g. Vatnsmýri I (Hallsdóttir 1987) and Vestra Gíslholtsvatn (Hallsdóttir & Caseldine 2005). One exception to this pattern is the site of Viðey, a medieval farm on a small island by Reykavík

(Hallsdóttir 1993). In one of three peat successions analysed (Viðey EFG), the *B. pubescens* decline is very rapid, but occurs several centimetres above the Vö-900 tephra (Hallsdóttir's terminology; identical to the AD 871±2 *Landnám* tephra of Grönvold *et al.* 1995), below a tephra dated to AD 1226. The other two successions from Viðey, taken from within a few metres of the EFG site, do not include the Vö-900 tephra, but appear to show different patterns of change. The first (Viðey CD) shows a gradual decline from 30% at the (undated) base of the succession to less than 5% at AD 1226, while the second (Viðey ABH) shows a rise from almost zero to 50% *Betula*, followed by a decline to less than 10% at AD 1226. The extreme heterogeneity of the closely situated records from this site suggests that they are sensitive to vegetation change on a very fine spatial scale, on the order of a few metres, typical of many mire sites (Bunting 2003). In many regions the dissimilarity between mire vegetation and dry-land vegetation is sufficiently strong that mire records can be reasonably interpreted in terms of landscape-scale changes in the abundance of at least some taxa (trees, for example), but this is not the case in Iceland where, with few exceptions, mire and dry-land communities are practically impossible to separate given the taxonomic precision available to palynologists. Nonetheless, the Viðey records do suggest the survival of at least some birch trees at this site for some centuries after *landnám*, probably disappearing around AD 1200.

The large majority of pollen data sets covering the *landnám* period in detail are from mires situated close to early farms. This sampling pattern could be expected to miss areas where woodland may have persisted into the medieval period. Mires present difficult growing conditions for tree birch (Davy & Gill 1984; Atkinson 1992) and, consequently, any birch populations growing at these sites would be vulnerable to even slight detrimental impacts, for example through grazing. With their pollen assemblages dominated by immediately local taxa, mires would tend not to record changes in birch populations further afield on drier ground. Furthermore, the land closest to *landnám*-era farms would presumably be the first to be cleared for cultivation, either deliberately for fuel and building materials, and/or through the introduction of grazing mammals. Therefore the absence of clear and widespread evidence for a delayed deforestation after *landnám* could well be an artefact of the location of existing sites, their generally low temporal resolution, and the emphasis on mires (Hallsdóttir & Caseldine 2005). Lake sites such as Helluvaðstjörn, on the other hand, have the potential to recruit pollen from a wider area that is more representative of the landscape as a whole (Jacobson & Bradshaw 1981; Sugita 1993), and may help to develop a more complete record of landscape-scale vegetation change, taphonomy and temporal resolution permitting.

Even after AD 1300, *Betula* pollen falling into the size class of *B. pubescens* still constituted around 13% of the total. Based on the pollen preservation data, a considerable proportion of this birch pollen is likely to be reworked from catchment soils. Although no tree birch exists today in the hydrological catchment of Helluvaðstjörn, substantial areas of birch scrub do occur to the southeast of Mývatn where a rough surface of broken lava makes it difficult for sheep to graze. Mire sites across Iceland usually show lower post-*landnám* birch proportions than at Helluvaðstjörn, which is perhaps not surprising in view of the differences in taphonomy between lakes and mires and the potentially marginal nature of mire surfaces for birch growth. A perhaps related point is that there is no evidence at Helluvaðstjörn for a gradual decline in birch in the centuries leading up to *landnám*, as has been shown at many other sites across Iceland (Einarsson 1963; Hallsdóttir 1987, 1995; Hallsdóttir & Caseldine 2005) and is thought likely to be of climatic origin (Gudmundsson 1997; Eiríksson *et al.* 2000; Castañeda *et al.* 2004); again, it could be that birch growing on mires may be particularly sensitive to climatic deterioration, while the birch in the wider landscape was not affected to the same degree.

Another unusual feature of the Helluvaðstjörn pollen record is the response of the vegetation to the removal of birch/juniper woodland. At the majority of Icelandic pollen sites, Poaceae is the first taxon to expand in response to the clearance, often together with cereal-type (e.g. Hallsdóttir 1996). This is usually taken to reflect the use of the cleared land close to farms for hay production and, to a lesser extent, the cultivation of *Avena* and *Hordeum*. At Helluvaðstjörn, however, the initial response is an expansion of Cyperaceae. This difference may relate to the marginal nature of the land around the lake, which shows no evidence of having been intensively managed in the past. Following this initial expansion of Cyperaceae, *Empetrum*, *Sphagnum* and other heath taxa such as *Potentilla* and *Selaginella selaginoides* gradually increase after *c.* AD 1300. These taxa are acidophilic, suggesting that the soils around the lake became increasingly leached over time, perhaps as a consequence of deforestation (Smith 1995). This implies that as soil fertility declined and relatively nutritious grasses were replaced by less nutritious heath and mire taxa, the productivity of the grazing land must have declined, even where erosion and desertification did not remove the soil cover completely. Successive generations of Mývatnssveit farmers may have seen the yield of their grazing lands fall as the soil system adjusted to the removal of the woodland.

There is little evidence of other forms of agriculture. Only two grains assigned to *Hordeum*-type (following Andersen 1979) have been found in the post-*landnám* samples from Helluvaðstjörn; again, this small proportion relative to other pollen sites is consistent with the situation of the site. The single find of a grain ascribed to *Avena*-type well below the *landnám* layer is likely to derive from a wild grass.

Other changes in the herbaceous taxa may be attributable to grazing. A tall herb component of the vegetation is represented in zone H-3 by several members of the Apiaceae, most notably *Angelica sylvestris.* These taxa decline during H-2 and are virtually absent in H-1. The Apiaceae are not by necessity part of the woodland ecosystem, being common today in open situations, so their decline is not necessarily tied directly to the loss of birch and juniper from the landscape. More likely, tall herb pollen production declined as a result of grazing by domestic mammals. The expansion in zones H-2 and H-3 of *Rumex acetosa* and Rubiaceae may also reflect grazing-related disturbance.

Sampling resolution was increased around the V1477 and V1717 tephra layers in order to investigate the possibility of a vegetational response to the deposition of these thick ash deposits (cf. Edwards *et al.* 1994, 2004). Changes in major taxa such as Cyperaceae and Poaceae across the tephra layers are difficult to interpret, as the fluctuations in these taxa are within their range of sample-to-sample stochastic variation through the rest of the succession. More statistically robust are the changes in relatively minor taxa, particularly Rubiaceae and *Thalictrum*, both of which show small peaks contemporaneous with the tephra falls. Such a response could be taken to indicate a reduction in grazing pressure, as recorded in relation to some historical eruptions that resulted in death of livestock through various causes, including fluorosis (Gunnlaugsson *et al.* 1984; Karlsson 2000). Precise age control in the Helluvaðstjörn record is lacking, but any vegetational response to tephra deposition appears to have been a short-lived perturbation with no long-term effects, or has been muted by processes of lake sediment mixing.

### *Freshwater ecosystem and catchment soils*

In the lake sediment record, substantial changes are seen in the freshwater ecosystem across the settlement horizon. Prior to *landnám*, chironomid and algal productivity (estimated using accumulation rates as a proxy) are both low (Fig. 8). At *landnám*, accumulation rates of both increase dramatically. The implied increase in productivity is not merely an artefact of the changing sedimentation rate used to calculate the accumulation rate data as shown in Fig. 8, as the concentration of both *Pediastrum* and chironomids in the sediment also increases. Given that the productivity of most lakes is limited by nutrient availability (generally phosphate; Wetzel 2001), an increase in nutrient supply is perhaps the most likely explanation. This interpretation is supported by a change in the *Pediastrum* assemblages: *P. angulosum*, which is thought to prefer oligotrophic conditions (Nielsen & Sørensen 1992), declines in favour of more cosmopolitan species. However, although chironomid concentrations increase just after *landnám*, the species composition does not change significantly. *Chironomus*, which favours more eutrophic conditions (Brooks *et al.* 2001), does not increase in relative abundance, nor does the relative abundance of *Tanytarsus*, which prefers oligotrophic conditions, decrease. It seems that although the increased nutrient loading allowed an expansion of chironomid numbers and of *Pediastrum* spp., the lake remained oligotrophic with clear waters. Macrophytes such as *Isoetes* continued to thrive, as did the chironomid *Dicrotendipes*, which prefers to live among them (Hofmann 1984).

The exact nature of the process of nutrient loading into Helluvaðstjörn during this period is difficult to determine from the current evidence. Two possible explanations seem to us to be likely. One is that the steady infilling of the lake over time eventually passed a threshold whereby internal nutrient loading via wind-driven resuspension of the sediment increased rapidly (Wetzel 2001). The second possibility is that human impact is involved, a conclusion tenuously supported by the coincidence of this change with the *landnám* horizon. Data from lakes elsewhere in Iceland (Vatnskotsvatn in Skagafjörður, northern Iceland: Á. Einarsson, unpubl. data; Breiðavatn near Reykholt, western Iceland: E. Erlendsson, unpubl. data), and in the Faroes (Eiði: Hannon *et al.* 2001, 2005; Gróthúsvatn: Lawson *et al.* 2005), showing similar abrupt changes in a variety of limnological indicators in conjunction with the Norse settlement horizon, support the tentative conclusion that human activity is likely to be linked to the observed changes in Helluvaðstjörn.

While a pattern of increased nutrient loading around *landnám* in lakes like Helluvaðstjörn seems to be emerging, the precise causal mechanism remains unclear. Soil erosion, a well-established consequence of deforestation and grazing in Iceland (Arnalds 2005), is one potential vector for nutrient transport. However, the pollen preservation data showing little reworking of soils until *c.* AD 1200 and the high organic content of the sediments in this part of the succession suggest that this may not be the principal contributor, although this possibility cannot be ruled out. Alternatively, increased rates of nutrient leaching from soils as the forest canopy began to be opened up could result in a greater flux of nutrients to the lake, but the similar response of at least some lakes in the Faroes where there was never any significant woodland cover (Hannon *et al.* 2005) suggests that other factors could be at work, perhaps related to the introduction of cattle and other animals by the settlers (McGovern *et al.* in press; Hannon *et al.* 2001).

The evidence for rapid change in the limnological system immediately after *landnám* stands in contrast to the data from both terrestrial pollen and sedimentology for gradual deforestation and soil erosion. It is not clear that these data should be interpreted as indicating that human impact on the limnic environment was much swifter and more severe than it was on land. A more reasonable interpretation is that the different proxies have differing sensitivities to change (cf. Whittington *et al.* 2003). The initial introduction of grazing mammals, for instance, might have had a patchy impact on vegetation which could have been obvious to a contemporaneous observer but which is lost in a spatially imprecise pollen record. Even a small increase in the nutrient loading of a highly oligotrophic lake, on the other hand, could conceivably cause *Pediastrum* populations to expand by an order of magnitude. Studies have shown that shallow lake nutrient dynamics can display hysteresis, resulting in abrupt, step-like transitions in nutrient availability in response to changes in nutrient loading (Scheffer *et al.* 1993; Karst & Smol 2000). The complex mechanisms linking nutrient availability to aquatic productivity are also frequently non-linear (e.g. Wetzel 2001: p. 348).

The strong similarities between this palaeolimnological record and others from Iceland and the Faroes suggest that many oligotrophic lakes in similar rangeland contexts across northern Europe may have been substantially altered by human impact in their catchments. A challenge for future research in those North Atlantic islands where settlement took place relatively recently is to gauge the degree to which apparently unperturbed freshwater ecosystems like Helluvaðstjörn owe their character to anthropogenic pressures potentially dating back, in mainland Europe, well into prehistory.

## Conclusions

The pollen percentage data from Helluvaðstjörn suggest that *Betula pubescens* woodland in Mývatnssveit declined gradually over the course of *c.* 400 years following the Norse *landnám*, differing from the majority of Icelandic pollen sites which show a much more rapid decline across the settlement horizon. This may be accounted for by reworking of pollen from soils, but not all of the available data point to the same conclusion. Independent lines of evidence from Mývatnssveit and elsewhere (e.g. Smith 1995), including historical sources and the distribution of charcoal pits in time and space, suggest that the process of deforestation was gradual, at least in some places.

The pollen data show an expansion of sedges and acidic heathland taxa following the deforestation, rather than the increase in Poaceae more usually found in Icelandic pollen diagrams. This may relate to the location of the site away from the infields, where cultivation of hay would be reflected in increased Poaceae pollen. The expansion of sedge mires and heaths may prove to be a typical response to the hydrological consequences of deforestation on more marginal land, and implies a long-term decline in the productivity of grazing land even where soil erosion and desertification are not important.

Increasing concentrations and accumulation rates of chironomids and *Pediastrum* at *landnám* suggest an abrupt, and perhaps immediate, response in the aquatic environment to human activity, probably through an elevation in nutrient loading to the lake.

Sedimentation rates also increased at *landnám*. Various lines of evidence suggest that this may have been due primarily to higher aquatic productivity in the first instance, and that soil erosion became an increasingly important contributor after *c.* AD 1200.

*Acknowledgements.* – The Leverhulme Trust is gratefully acknowledged for funding this research as part of the project 'Landscapes circum-*Landnám*'. The logistical support kindly provided by the Icelandic Archaeological Institute (Fornleifastofnun Íslands) and the North Atlantic Biocultural Organization is gratefully acknowledged. Critical comments from the reviewers, Steve Brooks and Chris Caseldine, have significantly improved the paper. We also thank Maureen Lamb and Julie Mitchell for technical support, and Andy Casely and Nick Hulton for help with coring.

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*Appendix.* EPMA data (wt%) for analyses of individual tephra shards from 18 levels in the Helluvaðstjörn succession. All data are available at http://www.tephrabase.org.

| Depth (m) | Tephra | Source | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.17–0.18 | H | Veiðivötn 1717 | 49.84 | 1.99 | 13.85 | 11.88 | 0.20 | 5.99 | 10.22 | 2.62 | 0.27 | 0.26 | 97.11 |
| | | Veiðivötn 1717 | 49.80 | 1.78 | 13.74 | 11.52 | 0.20 | 6.74 | 11.34 | 2.60 | 0.16 | 0.20 | 98.08 |
| | | Veiðivötn 1717 | 49.72 | 1.77 | 13.67 | 11.55 | 0.23 | 6.97 | 11.53 | 2.44 | 0.19 | 0.17 | 98.24 |
| | | Veiðivötn 1717 | 49.40 | 1.80 | 13.67 | 11.76 | 0.19 | 6.69 | 11.24 | 2.49 | 0.14 | 0.23 | 97.60 |
| | | Veiðivötn 1717 | 49.25 | 1.79 | 13.65 | 11.47 | 0.26 | 6.83 | 11.32 | 2.41 | 0.17 | 0.21 | 97.34 |
| 0.33–0.36 | L | Veiðivötn 1477 | 49.58 | 1.82 | 13.49 | 12.23 | 0.19 | 6.82 | 11.39 | 2.50 | 0.19 | 0.16 | 98.36 |
| | | Veiðivötn 1477 | 49.37 | 1.86 | 13.33 | 12.19 | 0.18 | 6.68 | 11.41 | 2.63 | 0.19 | 0.14 | 97.98 |
| | | Veiðivötn 1477 | 49.15 | 1.87 | 13.61 | 12.39 | 0.18 | 6.69 | 11.15 | 2.41 | 0.22 | 0.17 | 97.83 |
| | | Veiðivötn 1477 | 48.71 | 1.86 | 13.56 | 12.18 | 0.17 | 6.47 | 11.03 | 2.39 | 0.19 | 0.14 | 96.69 |
| | | Grímsvötn | 48.86 | 3.01 | 13.07 | 13.85 | 0.19 | 5.13 | 9.53 | 3.23 | 0.36 | 0.34 | 97.56 |
| 0.455–0.46 | | ? | 54.22 | 2.03 | 13.55 | 12.10 | 0.20 | 4.31 | 8.32 | 3.19 | 0.66 | 0.27 | 98.85 |
| | | Grímsvötn | 50.62 | 2.85 | 12.70 | 15.10 | 0.27 | 4.79 | 8.94 | 2.65 | 0.53 | 0.30 | 98.73 |
| | | Grímsvötn | 50.29 | 2.13 | 13.25 | 13.11 | 0.22 | 5.79 | 9.94 | 2.81 | 0.41 | 0.25 | 98.19 |
| | | Grímsvötn | 49.38 | 2.51 | 13.35 | 13.96 | 0.21 | 5.68 | 9.93 | 2.67 | 0.44 | 0.29 | 98.42 |
| | | Grímsvötn | 49.32 | 2.52 | 13.67 | 12.44 | 0.27 | 6.43 | 10.99 | 2.71 | 0.36 | 0.27 | 98.96 |
| | | Grímsvötn | 49.20 | 2.55 | 13.28 | 13.97 | 0.27 | 5.56 | 10.14 | 2.79 | 0.45 | 0.32 | 98.52 |
| | | Grímsvötn | 49.09 | 2.70 | 13.07 | 13.28 | 0.24 | 5.63 | 9.96 | 2.97 | 0.45 | 0.30 | 97.70 |
| | | Grímsvötn | 49.06 | 2.30 | 13.73 | 13.14 | 0.25 | 6.23 | 10.50 | 2.59 | 0.39 | 0.23 | 98.44 |
| | | Grímsvötn | 49.00 | 2.63 | 13.40 | 12.61 | 0.15 | 6.47 | 10.84 | 2.66 | 0.32 | 0.29 | 98.37 |
| | | Veiðivötn | 49.52 | 1.89 | 13.44 | 12.84 | 0.21 | 6.30 | 10.38 | 2.72 | 0.35 | 0.21 | 97.85 |
| 0.51–0.515 | | Katla | 46.96 | 4.21 | 12.83 | 14.50 | 0.17 | 5.28 | 9.72 | 3.21 | 0.81 | 0.52 | 98.19 |
| | | Grímsvötn | 49.56 | 3.49 | 12.98 | 14.61 | 0.28 | 4.79 | 8.80 | 3.08 | 0.56 | 0.42 | 98.57 |
| | | Grímsvötn | 48.75 | 3.14 | 12.76 | 14.06 | 0.25 | 5.44 | 9.66 | 2.93 | 0.44 | 0.37 | 97.79 |
| | | Grímsvötn | 48.51 | 3.12 | 12.47 | 14.79 | 0.27 | 4.63 | 9.06 | 3.06 | 0.67 | 0.43 | 97.00 |
| | | Grímsvötn | 48.53 | 3.04 | 12.36 | 13.78 | 0.26 | 5.28 | 9.11 | 2.91 | 0.43 | 0.36 | 96.05 |
| | | Veiðivötn | 52.27 | 1.95 | 14.55 | 12.72 | 0.25 | 3.47 | 8.28 | 3.47 | 0.38 | 0.36 | 97.70 |
| | | Veiðivötn | 51.93 | 1.61 | 13.30 | 12.93 | 0.28 | 6.38 | 9.11 | 2.59 | 0.42 | 0.25 | 98.80 |
| | | Veiðivötn | 50.58 | 1.83 | 13.63 | 11.59 | 0.22 | 5.63 | 9.91 | 2.88 | 0.46 | 0.22 | 96.95 |
| | | Veiðivötn | 50.15 | 1.80 | 11.84 | 11.02 | 0.24 | 5.42 | 9.16 | 2.41 | 0.31 | 0.18 | 92.52 |
| | | Veiðivötn | 49.72 | 1.97 | 13.41 | 12.55 | 0.18 | 6.07 | 10.31 | 2.61 | 0.32 | 0.20 | 97.33 |
| | | Veiðivötn | 49.66 | 1.83 | 13.35 | 12.50 | 0.21 | 6.89 | 11.06 | 2.57 | 0.23 | 0.17 | 98.47 |
| | | Veiðivötn | 49.20 | 1.82 | 13.78 | 12.62 | 0.25 | 7.00 | 11.46 | 2.54 | 0.19 | 0.18 | 99.04 |
| | | Veiðivötn | 49.15 | 1.85 | 13.66 | 12.57 | 0.27 | 6.60 | 11.19 | 2.52 | 0.21 | 0.17 | 98.19 |
| | | Veiðivötn | 48.94 | 1.89 | 13.19 | 12.44 | 0.24 | 6.68 | 11.31 | 2.48 | 0.22 | 0.17 | 97.55 |
| | | Veiðivötn | 48.90 | 1.79 | 13.53 | 12.27 | 0.20 | 6.99 | 11.47 | 2.46 | 0.23 | 0.20 | 98.03 |
| | | Veiðivötn | 48.70 | 1.90 | 13.49 | 12.90 | 0.20 | 6.52 | 10.97 | 2.60 | 0.25 | 0.17 | 97.70 |
| | | Veiðivötn | 48.56 | 1.86 | 13.68 | 12.59 | 0.25 | 6.91 | 11.36 | 2.50 | 0.26 | 0.14 | 98.11 |
| | | Veiðivötn | 48.42 | 1.86 | 13.15 | 12.48 | 0.21 | 6.76 | 11.12 | 2.50 | 0.26 | 0.19 | 96.95 |
| 0.555–0.56 | K | Veiðivötn | 49.71 | 1.75 | 13.53 | 11.97 | 0.20 | 6.89 | 11.24 | 2.78 | 0.19 | 0.17 | 98.43 |
| | | Veiðivötn | 49.48 | 1.77 | 13.65 | 11.88 | 0.22 | 6.52 | 10.92 | 2.68 | 0.26 | 0.14 | 97.50 |
| | | Veiðivötn | 49.37 | 2.05 | 13.24 | 12.51 | 0.22 | 6.24 | 11.06 | 2.64 | 0.22 | 0.15 | 97.70 |
| | | Veiðivötn | 49.22 | 1.62 | 14.11 | 10.57 | 0.19 | 7.59 | 12.45 | 2.34 | 0.13 | 0.15 | 98.38 |
| | | Veiðivötn | 49.16 | 1.77 | 13.72 | 11.40 | 0.18 | 7.06 | 11.76 | 2.32 | 0.13 | 0.17 | 97.68 |
| 0.65–0.655 | | Grímsvötn | 50.80 | 3.14 | 12.18 | 15.62 | 0.31 | 4.20 | 8.22 | 3.10 | 0.55 | 0.37 | 98.49 |
| | | Grímsvötn | 48.91 | 2.63 | 13.46 | 12.92 | 0.23 | 5.83 | 10.17 | 2.85 | 0.41 | 0.30 | 97.72 |
| | | Veiðivötn | 48.92 | 2.14 | 13.24 | 13.23 | 0.22 | 6.09 | 10.58 | 2.73 | 0.25 | 0.21 | 97.61 |
| | | Veiðivötn | 49.87 | 2.14 | 13.34 | 13.30 | 0.21 | 5.87 | 10.29 | 2.90 | 0.34 | 0.20 | 98.45 |
| | | Veiðivötn | 49.53 | 2.13 | 13.24 | 13.08 | 0.20 | 6.05 | 10.25 | 2.79 | 0.35 | 0.22 | 97.83 |
| | | Veiðivötn | 48.71 | 2.11 | 13.14 | 13.44 | 0.20 | 6.09 | 10.62 | 2.76 | 0.24 | 0.18 | 97.48 |
| | | Veiðivötn | 49.96 | 2.08 | 13.52 | 13.21 | 0.26 | 6.08 | 10.46 | 2.74 | 0.31 | 0.21 | 98.83 |
| | | Veiðivötn | 49.30 | 2.07 | 13.02 | 12.99 | 0.23 | 5.92 | 10.36 | 2.62 | 0.25 | 0.21 | 96.96 |
| | | Veiðivötn | 48.97 | 2.06 | 13.33 | 13.52 | 0.26 | 6.35 | 10.56 | 2.58 | 0.26 | 0.19 | 98.08 |
| | | Veiðivötn | 49.21 | 2.05 | 13.38 | 13.55 | 0.26 | 6.28 | 10.71 | 2.63 | 0.28 | 0.18 | 98.52 |
| | | Veiðivötn | 49.03 | 2.03 | 13.43 | 13.46 | 0.24 | 6.26 | 10.74 | 2.68 | 0.21 | 0.23 | 98.32 |

*Appendix.* Continued.

| Depth (m) | Tephra | Source | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.68–0.685 | | Grímsvötn | 48.13 | 3.47 | 12.10 | 15.24 | 0.29 | 4.78 | 8.94 | 3.22 | 0.49 | 0.36 | 97.02 |
| | | Grímsvötn | 49.02 | 2.33 | 13.69 | 12.30 | 0.22 | 6.60 | 11.11 | 2.71 | 0.30 | 0.22 | 98.49 |
| | | Grímsvötn | 48.49 | 2.32 | 13.46 | 12.05 | 0.24 | 6.65 | 11.05 | 2.64 | 0.33 | 0.21 | 97.43 |
| | | Grímsvötn | 49.15 | 2.29 | 13.82 | 12.16 | 0.19 | 6.75 | 11.34 | 2.64 | 0.33 | 0.24 | 98.91 |
| | | Grímsvötn | 49.13 | 2.28 | 13.98 | 12.10 | 0.23 | 6.74 | 11.32 | 2.63 | 0.32 | 0.23 | 98.95 |
| | | Grímsvötn | 48.70 | 2.26 | 13.83 | 12.23 | 0.21 | 6.66 | 11.24 | 2.66 | 0.33 | 0.22 | 98.35 |
| | | Grímsvötn | 48.72 | 2.23 | 13.88 | 11.99 | 0.23 | 6.74 | 11.34 | 2.60 | 0.33 | 0.22 | 98.28 |
| | | Grímsvötn | 48.56 | 2.13 | 13.85 | 11.58 | 0.20 | 7.24 | 11.69 | 2.63 | 0.31 | 0.19 | 98.38 |
| | | Grímsvötn | 48.84 | 2.02 | 13.73 | 11.33 | 0.18 | 7.51 | 12.00 | 2.59 | 0.25 | 0.21 | 98.65 |
| | | Grímsvötn | 48.52 | 2.01 | 14.04 | 11.27 | 0.17 | 7.43 | 12.03 | 2.47 | 0.33 | 0.19 | 98.45 |
| | | Grímsvötn | 48.73 | 1.99 | 13.98 | 10.97 | 0.18 | 7.45 | 11.85 | 2.49 | 0.29 | 0.17 | 98.09 |
| 0.72–0.725 | J | Grímsvötn | 50.09 | 2.52 | 13.58 | 11.90 | 0.18 | 5.54 | 9.86 | 2.85 | 0.37 | 0.29 | 97.17 |
| | | Grímsvötn | 49.46 | 2.25 | 13.83 | 11.52 | 0.20 | 6.40 | 11.08 | 2.81 | 0.28 | 0.24 | 98.04 |
| | | Grímsvötn | 49.29 | 2.74 | 13.51 | 12.38 | 0.17 | 5.71 | 10.05 | 2.95 | 0.37 | 0.31 | 97.47 |
| | | Grímsvötn | 49.16 | 2.36 | 13.50 | 11.48 | 0.18 | 5.98 | 10.65 | 2.76 | 0.34 | 0.26 | 96.66 |
| | | Grímsvötn | 48.90 | 2.30 | 13.67 | 11.53 | 0.17 | 6.50 | 10.84 | 2.77 | 0.33 | 0.24 | 97.25 |
| 0.78–0.785 | | Hekla | 71.33 | 0.18 | 14.21 | 2.92 | 0.10 | 0.12 | 1.94 | 4.87 | 2.59 | 0.02 | 98.28 |
| | | ? | 60.52 | 0.72 | 15.56 | 7.41 | 0.21 | 0.91 | 5.00 | 4.90 | 1.27 | 0.31 | 96.79 |
| | | Grímsvötn | 49.06 | 2.77 | 13.47 | 13.19 | 0.23 | 5.62 | 9.85 | 2.80 | 0.41 | 0.31 | 97.71 |
| | | Grímsvötn | 48.39 | 2.06 | 12.72 | 14.58 | 0.22 | 5.92 | 10.27 | 2.52 | 0.32 | 0.18 | 97.16 |
| | | Katla | 47.26 | 4.57 | 12.56 | 13.96 | 0.23 | 5.01 | 9.59 | 3.27 | 0.84 | 0.61 | 97.88 |
| 0.815–0.82 | | Hekla | 72.77 | 0.53 | 12.58 | 3.77 | 0.08 | 0.44 | 2.27 | 4.10 | 2.08 | 0.06 | 98.66 |
| | | Hekla | 69.91 | 0.69 | 12.88 | 4.80 | 0.18 | 0.82 | 3.00 | 4.02 | 1.80 | 0.15 | 98.24 |
| | | Hekla | 66.29 | 1.09 | 13.27 | 6.50 | 0.10 | 1.50 | 4.26 | 4.01 | 1.45 | 0.30 | 98.76 |
| | | Hekla | 61.47 | 0.92 | 14.59 | 9.55 | 0.25 | 1.08 | 4.63 | 4.42 | 1.57 | 0.36 | 98.84 |
| | | Grímsvötn | 48.88 | 3.23 | 13.29 | 14.04 | 0.29 | 4.92 | 9.21 | 3.11 | 0.67 | 0.38 | 98.02 |
| | | Grímsvötn | 49.61 | 2.52 | 13.24 | 13.80 | 0.29 | 5.67 | 9.99 | 2.73 | 0.44 | 0.28 | 98.57 |
| | | Grímsvötn | 48.43 | 2.69 | 12.86 | 13.52 | 0.25 | 6.05 | 10.25 | 2.85 | 0.45 | 0.28 | 97.63 |
| | | Veiðivötn | 49.59 | 1.83 | 13.97 | 12.06 | 0.22 | 7.02 | 11.44 | 2.41 | 0.23 | 0.21 | 98.98 |
| | | Veiðivötn | 49.44 | 1.97 | 13.60 | 12.87 | 0.20 | 6.39 | 10.82 | 2.60 | 0.26 | 0.17 | 98.31 |
| | | Veiðivötn | 49.05 | 1.79 | 13.73 | 12.10 | 0.24 | 7.20 | 11.91 | 2.36 | 0.21 | 0.19 | 98.77 |
| | | Veiðivötn | 48.85 | 1.78 | 13.59 | 11.82 | 0.18 | 7.24 | 11.84 | 2.47 | 0.23 | 0.19 | 98.20 |
| | | Veiðivötn | 48.81 | 1.82 | 13.60 | 12.25 | 0.22 | 7.12 | 11.68 | 2.42 | 0.20 | 0.19 | 98.30 |
| | | Veiðivötn | 48.79 | 1.36 | 13.98 | 10.24 | 0.23 | 8.43 | 13.20 | 2.05 | 0.15 | 0.12 | 98.55 |
| | | Veiðivötn | 48.60 | 1.78 | 13.71 | 12.15 | 0.25 | 7.03 | 11.72 | 2.35 | 0.29 | 0.17 | 98.04 |
| | | Veiðivötn | 48.04 | 1.86 | 13.65 | 12.10 | 0.19 | 7.32 | 11.90 | 2.33 | 0.30 | 0.19 | 97.87 |
| 0.87–0.88 | I | Veiðivötn | 49.34 | 1.70 | 13.82 | 11.26 | 0.16 | 7.00 | 11.71 | 2.35 | 0.16 | 0.18 | 97.67 |
| | | 10th century | 49.28 | 1.79 | 13.80 | 10.96 | 0.19 | 7.30 | 11.95 | 2.35 | 0.14 | 0.19 | 97.95 |
| | | 10th century | 49.11 | 1.66 | 13.83 | 11.44 | 0.27 | 7.46 | 12.01 | 2.38 | 0.14 | 0.16 | 98.46 |
| | | 10th century | 48.90 | 1.98 | 13.07 | 12.39 | 0.21 | 6.82 | 11.53 | 2.40 | 0.16 | 0.20 | 97.65 |
| | | 10th century | 48.87 | 1.74 | 13.74 | 11.33 | 0.16 | 7.38 | 12.02 | 2.33 | 0.13 | 0.13 | 97.83 |
| | | 10th century | 48.82 | 1.88 | 13.93 | 12.57 | 0.19 | 6.53 | 11.87 | 2.22 | 0.20 | 0.18 | 98.38 |
| | | 10th century | 48.78 | 1.83 | 13.62 | 11.57 | 0.20 | 7.07 | 12.03 | 2.30 | 0.14 | 0.22 | 97.76 |
| | | 10th century | 48.73 | 1.69 | 13.84 | 11.52 | 0.26 | 7.24 | 12.21 | 2.36 | 0.13 | 0.16 | 98.13 |
| | | 10th century | 48.47 | 1.74 | 13.38 | 11.17 | 0.19 | 7.29 | 11.97 | 2.28 | 0.13 | 0.20 | 96.82 |
| 0.875–0.88 | G | Grímsvötn | 49.38 | 2.44 | 13.62 | 12.29 | 0.20 | 5.92 | 10.41 | 2.76 | 0.33 | 0.27 | 97.61 |
| | | Grímsvötn | 49.16 | 2.68 | 13.28 | 12.56 | 0.22 | 5.55 | 10.07 | 2.81 | 0.34 | 0.29 | 96.96 |
| | | Grímsvötn | 49.09 | 2.52 | 13.44 | 12.09 | 0.19 | 5.73 | 10.45 | 2.82 | 0.29 | 0.32 | 96.95 |
| | | Grímsvötn | 48.99 | 3.24 | 12.69 | 13.85 | 0.24 | 5.07 | 9.09 | 3.06 | 0.37 | 0.36 | 96.96 |
| | | Grímsvötn | 48.94 | 2.47 | 13.41 | 12.04 | 0.18 | 6.08 | 10.63 | 2.82 | 0.32 | 0.21 | 97.08 |
| | | Veiðivötn | 49.16 | 1.75 | 13.71 | 11.61 | 0.19 | 6.99 | 11.90 | 2.43 | 0.13 | 0.19 | 98.05 |
| | | Veiðivötn | 49.08 | 1.85 | 13.19 | 12.20 | 0.23 | 7.09 | 12.00 | 2.32 | 0.15 | 0.20 | 98.31 |
| | | Veiðivötn | 48.94 | 1.37 | 14.07 | 10.08 | 0.19 | 8.43 | 12.95 | 2.12 | 0.09 | 0.15 | 98.39 |
| | | Veiðivötn | 48.37 | 1.78 | 13.38 | 12.11 | 0.18 | 7.40 | 12.04 | 2.26 | 0.16 | 0.20 | 97.90 |
| | | Veiðivötn | 47.65 | 4.52 | 13.00 | 13.84 | 0.19 | 4.75 | 9.38 | 2.95 | 0.77 | 0.53 | 97.57 |

*Appendix.* Continued.

| Depth (m) | Tephra | Source | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.895–0.905 | F | Veiðivötn | 49.39 | 1.90 | 13.08 | 13.53 | 0.10 | 5.82 | 10.19 | 2.40 | 0.31 | 0.17 | 96.88 |
| | | Veiðivötn | 49.20 | 1.49 | 16.11 | 10.37 | 0.13 | 6.08 | 12.45 | 2.68 | 0.19 | 0.14 | 98.83 |
| | | Veiðivötn | 49.15 | 1.75 | 15.64 | 10.71 | 0.12 | 5.77 | 12.18 | 2.54 | 0.18 | 0.19 | 98.23 |
| | | Veiðivötn | 48.95 | 1.69 | 13.53 | 11.74 | 0.12 | 7.14 | 11.62 | 2.43 | 0.19 | 0.13 | 97.52 |
| | | Veiðivötn | 48.87 | 1.80 | 13.35 | 11.66 | 0.12 | 7.13 | 11.60 | 2.57 | 0.18 | 0.19 | 97.45 |
| | | Veiðivötn | 48.82 | 1.76 | 13.81 | 11.51 | 0.13 | 7.22 | 11.96 | 2.56 | 0.17 | 0.15 | 98.08 |
| | | Veiðivötn | 48.70 | 1.48 | 14.04 | 10.58 | 0.08 | 7.64 | 12.12 | 2.33 | 0.18 | 0.07 | 97.21 |
| | | Veiðivötn | 48.40 | 1.82 | 12.20 | 11.42 | 0.14 | 9.39 | 12.90 | 2.03 | 0.22 | 0.19 | 98.70 |
| | | Grímsvötn | 49.07 | 2.83 | 13.23 | 13.89 | 0.11 | 5.53 | 10.15 | 2.80 | 0.37 | 0.31 | 98.29 |
| | | Katla | 47.07 | 4.43 | 12.82 | 13.87 | 0.12 | 4.86 | 9.45 | 3.36 | 0.82 | 0.52 | 97.33 |
| 0.92–0.92.5 | E | Veiðivötn | 50.15 | 2.09 | 13.98 | 11.52 | 0.14 | 5.46 | 9.78 | 2.89 | 0.37 | 0.24 | 96.62 |
| | | Veiðivötn | 48.72 | 1.73 | 13.90 | 11.67 | 0.13 | 7.14 | 11.89 | 2.39 | 0.19 | 0.20 | 97.96 |
| | | Veiðivötn | 48.71 | 1.74 | 13.27 | 11.57 | 0.04 | 7.22 | 11.68 | 2.53 | 0.18 | 0.14 | 97.07 |
| | | Veiðivötn | 48.61 | 1.65 | 13.65 | 11.03 | 0.12 | 7.30 | 12.05 | 2.51 | 0.17 | 0.16 | 97.26 |
| | | Veiðivötn | 48.50 | 1.69 | 13.45 | 11.70 | 0.11 | 7.27 | 11.76 | 2.32 | 0.17 | 0.11 | 97.09 |
| | | Veiðivötn | 48.45 | 1.70 | 13.94 | 11.70 | 0.07 | 7.13 | 11.89 | 2.44 | 0.18 | 0.15 | 97.65 |
| | | Veiðivötn | 48.33 | 1.67 | 13.60 | 11.37 | 0.16 | 7.11 | 11.88 | 2.53 | 0.16 | 0.15 | 96.94 |
| | | Katla | 47.98 | 4.41 | 12.78 | 13.98 | 0.11 | 4.90 | 9.54 | 2.87 | 0.88 | 0.54 | 97.99 |
| | | Katla | 47.06 | 4.45 | 12.74 | 14.13 | 0.17 | 4.98 | 9.31 | 3.56 | 0.81 | 0.56 | 97.76 |
| | | Katla | 46.52 | 4.48 | 12.41 | 14.42 | 0.14 | 4.68 | 9.41 | 3.32 | 0.84 | 0.57 | 96.78 |
| | | Katla | 47.35 | 4.32 | 12.82 | 13.91 | 0.22 | 4.75 | 9.10 | 3.26 | 0.82 | 0.52 | 97.08 |
| | | Katla | 47.34 | 4.42 | 12.89 | 13.96 | 0.20 | 4.95 | 9.50 | 3.43 | 0.76 | 0.52 | 97.96 |
| | | Katla | 47.30 | 4.85 | 12.90 | 14.39 | 0.17 | 4.76 | 9.38 | 2.82 | 0.85 | 0.56 | 97.99 |
| | | Katla | 47.06 | 4.33 | 12.86 | 13.74 | 0.20 | 5.02 | 9.26 | 3.42 | 0.75 | 0.50 | 97.15 |
| | | Veiðivötn | 48.98 | 1.65 | 13.79 | 11.71 | 0.18 | 7.39 | 11.88 | 2.49 | 0.14 | 0.19 | 98.40 |
| | | Veiðivötn | 48.87 | 1.76 | 13.73 | 11.92 | 0.17 | 7.19 | 11.88 | 2.44 | 0.18 | 0.14 | 98.28 |
| | | Grímsvötn | 51.26 | 3.03 | 13.62 | 13.15 | 0.23 | 4.05 | 8.18 | 3.27 | 0.72 | 0.43 | 97.92 |
| 99.5–100 | C | Katla | 47.53 | 4.48 | 12.83 | 14.16 | 0.19 | 4.88 | 9.59 | 2.92 | 1.05 | 0.54 | 98.15 |
| | | Katla | 46.98 | 4.48 | 13.02 | 14.44 | 0.17 | 4.54 | 9.40 | 3.43 | 0.90 | 0.52 | 97.89 |
| | | Katla | 46.79 | 4.55 | 12.75 | 13.68 | 0.20 | 5.03 | 9.33 | 3.26 | 0.76 | 0.52 | 96.87 |
| | | Katla | 46.68 | 4.53 | 13.03 | 13.69 | 0.19 | 4.95 | 9.34 | 3.34 | 0.74 | 0.61 | 97.11 |
| | | Veiðivötn | 51.04 | 2.07 | 13.98 | 11.59 | 0.20 | 5.33 | 9.35 | 3.21 | 0.40 | 0.24 | 97.40 |
| | | Veiðivötn | 49.50 | 1.89 | 13.73 | 11.63 | 0.24 | 6.17 | 10.61 | 2.76 | 0.30 | 0.18 | 97.00 |
| | | Veiðivötn | 48.90 | 1.74 | 13.38 | 11.74 | 0.25 | 7.30 | 11.64 | 2.46 | 0.14 | 0.12 | 97.67 |
| 1.10–1.11 | B | Veiðivötn | 50.87 | 1.82 | 13.92 | 10.99 | 0.16 | 6.15 | 10.34 | 2.81 | 0.36 | 0.18 | 97.60 |
| | | Veiðivötn | 49.90 | 1.82 | 14.12 | 12.51 | 0.17 | 6.76 | 11.46 | 2.40 | 0.20 | 0.13 | 99.46 |
| | | Veiðivötn | 49.30 | 1.75 | 13.66 | 11.73 | 0.24 | 7.38 | 11.58 | 2.41 | 0.16 | 0.13 | 98.32 |
| | | Veiðivötn | 49.09 | 1.82 | 13.61 | 11.61 | 0.19 | 6.91 | 11.24 | 2.57 | 0.20 | 0.13 | 97.37 |
| | | Veiðivötn | 48.99 | 1.75 | 13.82 | 11.84 | 0.21 | 7.18 | 11.56 | 2.61 | 0.18 | 0.13 | 98.25 |
| 1.20–1.205 | A | Hekla 3 | 70.63 | 0.19 | 13.93 | 2.95 | 0.12 | 0.13 | 1.91 | 4.45 | 2.56 | 0.04 | 96.90 |
| | | Hekla 3 | 70.47 | 0.20 | 13.86 | 3.10 | 0.09 | 0.14 | 1.96 | 4.34 | 2.54 | 0.06 | 96.76 |
| | | Hekla 3 | 70.35 | 0.22 | 14.00 | 2.91 | 0.12 | 0.13 | 1.93 | 4.46 | 2.56 | 0.02 | 96.68 |
| | | Hekla 3 | 70.06 | 0.21 | 13.76 | 3.08 | 0.11 | 0.13 | 1.91 | 4.97 | 2.64 | 0.02 | 96.89 |
| | | Hekla 3 | 69.76 | 0.18 | 13.49 | 2.97 | 0.14 | 0.13 | 1.94 | 4.50 | 2.54 | 0.02 | 95.65 |
| | | Hekla 3 | 69.57 | 0.21 | 13.60 | 3.01 | 0.15 | 0.16 | 2.01 | 5.08 | 2.37 | -0.01 | 96.15 |
| | | Hekla 3 | 69.45 | 0.18 | 13.86 | 2.85 | 0.16 | 0.14 | 2.01 | 4.77 | 2.39 | 0.04 | 95.85 |
| | | Hekla 3 | 68.84 | 0.19 | 13.80 | 2.87 | 0.11 | 0.10 | 1.89 | 4.84 | 2.38 | 0.02 | 95.05 |
| | | Hekla 3 | 68.61 | 0.26 | 14.07 | 3.50 | 0.18 | 0.13 | 2.30 | 4.61 | 2.33 | 0.03 | 96.02 |
| | | Hekla 3 | 65.60 | 0.35 | 14.39 | 4.83 | 0.20 | 0.30 | 3.05 | 4.84 | 2.08 | 0.07 | 95.70 |
| | | Hekla 3 | 64.87 | 0.46 | 14.85 | 5.92 | 0.20 | 0.51 | 3.35 | 4.30 | 1.84 | 0.13 | 96.43 |