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Lake sediment evidence for late Holocene climate change and landscape erosion in western Iceland

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Abstract Ecosystem variability must be assessed over a range of timescales in order to fully understand natural ecosystem processes. Long-term climate change, at millennial and centennial scales, is a major driver of natural ecosystem variability, but identifying evidence of past climate change is frequently confounded by human-induced impacts on the ecosystem. Iceland is a location where it is possible to separate natural from anthropogenic change in environmental archives, as the date of settlement is accepted to be around AD 874, prior to which the island was free from proven human impacts. We used a lake sediment core from Breiðavatn, near Reykholt, a major farm of the Norse period in western Iceland, to examine landscape development. A change in pollen concentration in the sediments, especially the decline in *Betula*, indicated initial landscape degradation immediately post-settlement, whereas the chironomid fauna and reconstructed temperatures were relatively complacent during this period. The pollen evidence is corroborated by ^{14}C analyses, which indicate an increase in older carbon entering the lake, inferred to have been caused by increased erosion following settlement. Further decreases in *Betula* pollen occurred around AD 1300, pre-dating a drop in chironomid-inferred temperatures (CI-T) of ~1°C over 100–200 years. The CI-T reconstruction also shows a significant cooling after ~AD 1800, likely indicative of the coldest phase of the Little Ice Age. The evidence suggests that the chironomid record was relatively unaffected by the increased landscape degradation and hence reveals a temperature reconstruction independent of human impact.

Keywords Iceland · Chironomids · Pollen · Climate change · Human impact

Introduction

Iceland is an island in the North Atlantic, and its climate is influenced by changes in both atmospheric

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and oceanic circulation patterns (Andrews and Giraudeau 2003). It is a key locality for identifying past variations in Holocene climate change (Jiang et al. 2002, 2005; Caseldine et al. 2003, 2006; Dugmore et al. 2005, 2007). If the detection of past climate changes can be clearly distinguished from human impacts, then their differential effects on the landscape can be determined (Ólafsdóttir et al. 2001; Ólafsdóttir and Guðmundsson 2002; Haraldsson and Ólafsdóttir 2003). Humans only arrived in Iceland relatively recently—approximately AD 874. The Norse colonisation (known as *landnám* or land take) caused major impacts on the natural environment. Human land-use practices and introductions of grazing animals, particularly sheep, precipitated catastrophic environmental change (Buckland et al. 1990; Edwards et al. 2005), including widespread, irreversible erosion (Ólafsdóttir and Guðmundsson 2002). Vegetation simulations suggest that total vegetation cover fell from 52% of Iceland's surface area at *landnám* to 28% in 1990, and forest cover (*Betula pubescens* >2 m tall) fell at an even greater rate, from ~7 to <1% of Iceland's surface area for the same period (Ólafsdóttir et al. 2001). This rate may have been even greater, as *landnám*-time vegetation cover has been estimated elsewhere at ~68%, with that of birch woodland alone at around 27% of the total land area (Arnalds 2005).

A core was taken from the small, upland lake of Breiðavatn, and the subfossil chironomids and pollen were examined (Erlendsson 2007) to investigate climate change during the past two millennia, as well as to examine the effects of human colonisation near the historically important settlement of Reykholt in the Borgarfjörður region of West Iceland. The chitinous head capsules of chironomid larvae are well preserved in lacustrine sediments, and identification is usually possible at least to genus and sometimes to species group and/or morphotype (Brooks et al. 2007). A range of studies on contemporary chironomid communities has shown that temperature is often the primary driver of chironomid distribution in the absence of other significant environmental factors that are more often associated with human impact, such as increased eutrophication and hypoxia (Brodersen and Quinlan 2006; Walker and Cywnar 2006; Brooks 2006). Development of chironomid-temperature transfer functions (e.g. Larocque et al. 2001; Brooks and Birks 2004) provides good estimates of the temperature optima for most taxa, facilitating temperature reconstructions from fossil assemblages. This approach has been shown to give good estimates of recent climate, particularly mean July air temperatures (Larocque and Hall 2003). Improvements in taxonomic resolution (Rieradevall and Brooks 2001; Brooks et al. 2007), larger training sets (e.g. Barley et al. 2006) and a better understanding of chironomid ecologies, are also improving the precision of Holocene temperature reconstructions (but see Velle et al. 2005a).

A multi-proxy approach was employed here. Pollen spectra from Breiðavatn were used to examine the vegetation changes since the early settlement period. This was coupled with loss-on-ignition (LOI), sediment magnetic profiles and ^{14}C dating as aids to indicate erosion that was a consequence of human landscape impacts within the catchment area. Analyses of the fossil chironomid sequence allowed us to test whether *landnám* or any subsequent human impacts had a direct effect on chironomid communities (Edwards et al. 2007; Lawson et al. 2007). Given that anthropogenic effects appeared to be negligible, we were able to utilise a recently developed Icelandic chironomid-temperature transfer function (Langdon et al. 2008) to produce a temperature reconstruction for the last two millennia.

Methods

Study site

Breiðavatn (64°40′415″N 21°15′043″W) is a small oval lake, ca. 2 km northeast of the hamlet of Reykholt, approximately 100 m above sea level and situated on a low ridge just beyond the Reykholtsdalur watershed (Fig. 1). The surrounding land is used as summer pasture, and the ground surface is much disturbed by þúfur (frost hummocks). The lake has a surface area of ~3.5 ha and a fairly flat bottom with a maximum water depth of 80 cm. There are no visible inflow or outflow streams and the lake does not dry out in summer (local sources). The nearest weather station in current use, Stafholtsey (14 m a.s.l.; ~16 km west of Breiðavatn) has a mean July temperature (1989–2001) of 11°C and receives mean precipitation of at least 768 mm per annum, although Einarsson (1992) states that because of the poor design of Icelandic rain gauges, the actual figure is likely to be around 25% higher.

According to the *Book of Settlements* (Benediktsson 1968), the Reykholtsdalur area was settled extensively. Although not noted as a major early farm, Reykholt had become an important ecclesiastical and political centre by ~AD 1000 and it maintained its status through many centuries (Sveinbjarnardóttir et al. 2007). The environmental record from the farmed areas close to Reykholt also contains clear evidence for agricultural impact in the early settlement (Norse) period (Erlendsson 2007). Farm prosperity was maintained by extensive and diverse utilisation of natural resources. This is indicated by mixed livestock and numerous shielings, summer pastures, and woodland exploitation far beyond the homefields (Þorláksson 2000; Eyþórsson 2007). Arable activity and iron-smelting appear to have been practised at least during the medieval period (Erlendsson 2007; Sveinbjarnardóttir et al. 2007). It is likely that the concentration of settlement in the area and the apparent intensity of agriculture would have put severe pressure on vegetation and soils over the wider area.

Field and laboratory methods

Three overlapping core segments were taken from a boat near the middle of the lake using a Russian-type corer (Jowsey 1966) 50 × 8 cm in size, in a water depth of 80 cm, down to 120 cm below the mud/water interface. In addition, the uppermost sediments were sampled with a gravity corer, extruded on site (although the almost liquid unconsolidated uppermost 3 cm of sediment could not be sampled), and stored at 4°C. Core sections were X-rayed and core segments were aligned using stratigraphic changes and tephra bands. All depths presented are from the top of the solid sediment.

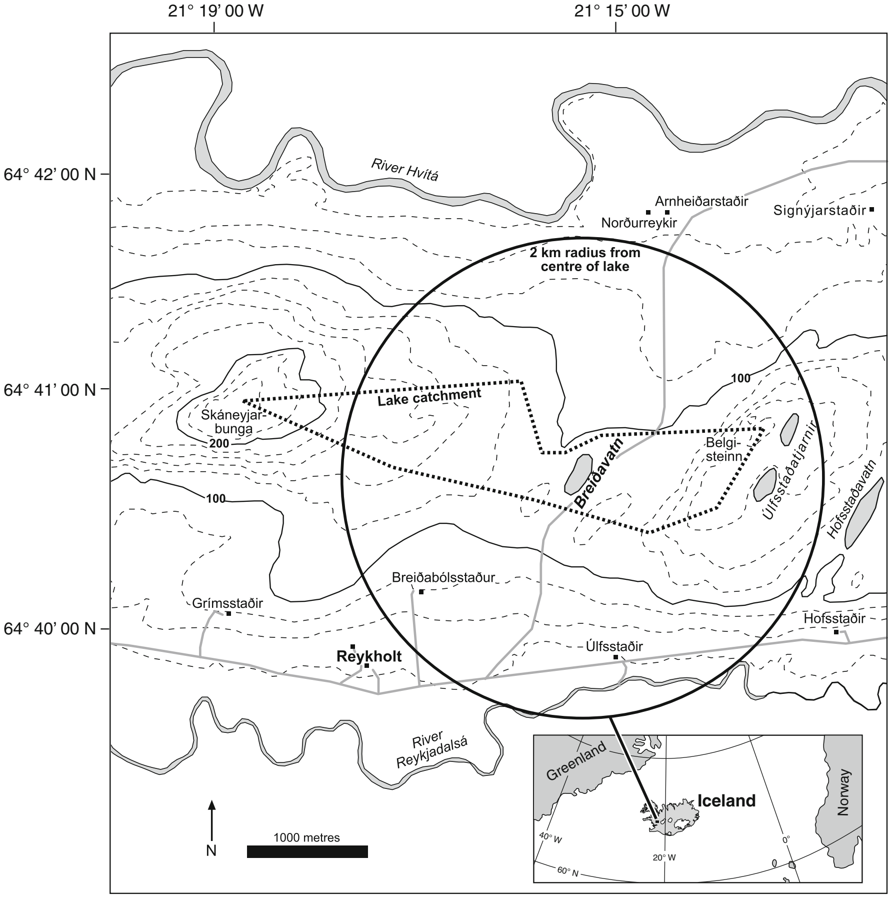


Fig. 1 Map of study site showing the location and catchment of Breiðavatn

Sediments were described using a modification of the Troels-Smith system (Aaby and Berglund 1986). Samples of measured volume were analysed for bulk dry density and LOI (Dean 1974). These samples were generally of 1 cm^3 at 1 cm contiguous intervals. Relative changes in magnetic susceptibility were measured at low frequency (0.46 kHz) using a Bartington Instruments MS-2 metre and MS-2b probe, with measurements at 1 cm contiguous intervals.

Core chronology

A combination of tephrochronology and ^{14}C dating was used to build a chronology. Too few terrestrial plant macrofossils were found in the core for dating purposes and seven samples of bulk sediment (1 cm^3 gyttja per sample) were used (Table 1). The ^{14}C dates were calibrated using OxCal, version 3.10 (Bronk-Ramsey 2005). Of the eight tephra samples that underwent geochemical analysis, only two provided sufficiently secure tephra dates. The lower (121–119 cm) is by far the most prominent tephra layer in the core. Geochemical analysis confirmed its Katla origin (Erlendsson 2007). Judging by the known tephra stratigraphy for the area, this is the Katla-E tephra, the younger of two prominent, closely-spaced Katla tephras commonly found in western and southwestern Iceland. It is chronologically constrained between the Hekla-C (~870 cal BC [calibrated ^{14}C date from Kjartansson et al. 1964]) and the Hekla-3 (~1050 cal BC [calibrated ^{14}C date from Dugmore et al. 1995]) tephras (Róbertsdóttir 1992). In the absence of a more rigorous chronological precision for this tephra date, it seems reasonable to round the age for Katla-E to 1000 cal BC. The tephra layer at 41–40.5 cm has also been analysed for geochemistry (Erlendsson 2007). It is the so-called Landnám (Veiðivötn/Torfajökull) tephra couplet, dated on Greenland ice core evidence to AD 871 ± 2 (Grönvold et al. 1995). Interpolation between the tephra-derived dates suggests that the results from ^{14}C dating consistently show ages that are too old, even before *landnám* and its associated environmental disruption. Immediately after *landnám*, the ^{14}C dates become inverted, probably due to soil erosion (either from water-borne or aeolian inputs) that allowed older carbon to enter the lake (cf. Edwards and Whittington 2001). As a consequence, reliance was placed on the two identified tephras for the construction of an age-depth model. The uppermost recovered sample is estimated to date to ~AD 1900 based on linear interpolation between the tephras and extrapolation to the surface sediments (Table 1, Fig. 2). Whilst two dates for the past three millennia may not provide the most robust chronology, we can at least be reasonably confident in these two tephra dates and the date of AD 1900 seems sensible. Interpolated dates will have some associated uncertainty, as sedimentation rates are unlikely to have been linear throughout this period. Other studies on Holocene Icelandic lake sequences (e.g. Axford et al. 2007; Lawson et al. 2007), however, have demonstrated linear sedimentation rates throughout this period.

Table 1 ^{14}C and tephra dates from the core. The ^{14}C dates were calibrated using OxCal version 3.10

Lab code	Depth (cm)	^{14}C date BP	Error (1σ)	$\delta^{13}C$	Range (cal. yr AD/BC) 1σ error
SUERC-6830	14–13	1550	35	−25	420–590 AD
SUERC-6831	25–24	1405	35	−21.8	575–670 AD
SUERC-6832	35–34	1430	35	−22.3	560–660 AD
SUERC-6833	42–41	1585	35	−24.2	400–560 AD
SUERC-6834	51–50	1660	35	−24	250–540 AD
SUERC-6835	85.5–84.5	2380	35	−23.4	730–380 BC
SUERC-6838	122–121	3000	35	−22.8	1380–1120 BC
Tephra	Depth (cm)	Date (cal. yr AD/BC)	Error (±)	Reference	
Veiðivötn/Torfajökull	41–40.5	871	2	Grönvold et al. (1995)	
Katla-E	121–119	1000	45	Róbertsdóttir (1992)	

Chironomids

Chironomids were extracted from the sediment at 4–8 cm intervals, using the methods proposed by Lang et al. (2003). The 23 samples were deflocculated for 15 min in 10% KOH solution at 85°C, and sieved through a 90 µm mesh. The residue was put into 100 ml water in a sonic bath for 10 seconds, re-sieved, and the residue sorted using a grooved perspex sorting tray under a binocular microscope at 35× magnification. Chironomid heads were mounted using Hydro-Matrix®. They were identified using Hofmann (1971), Wiederholm (1983), Rieradevall and Brooks (2001) and Cranston (1982), and related to the Norwegian and Icelandic training sets at The Natural History Museum, London and the University of Southampton. Tanytarsini were identified using an unpublished key (Brooks unpubl.) and chironomid taxonomy was synthesised with Brooks et al. (2007). Chironomid distribution was expressed as percentages of the total head count and was plotted using PSIMPOLL (Bennett 2008a). Principal references for ecological information were Wiederholm (1983), Cranston (1982), Moller-Pillot and Buskens (1990) and Brooks et al. (2007). A mean July air temperature reconstruction was carried out using a two-component WA-PLS model with $r^2_{\text{jack}} = 0.66$ and RMSEP = 1.095°C from an Icelandic training set of 52 lakes from northwestern Iceland (Langdon et al. 2008). All fossil taxa were present in the model. In order to investigate the relationships between the chironomid data and temperature, detrended correspondence analysis (DCA) was carried out using the CANOCO program version 4.51 (ter Braak and Smilauer 1998) with rare species downweighted.

Pollen analysis

Sub-samples for pollen analysis were treated by standard chemical (10% HCl, 10% NaOH, 40% HF, acetolysis) and sieving (180 µm sieves) methods (Fægri and Iversen 1975; Moore et al. 1991). Tablets of *Lycopodium clavatum* spores were added to each sample (Stockmarr 1971) enabling the calculation of palynomorph concentrations. The residue was mounted in silicone oil of 12,500 cSt viscosity. At least 300 indigenous terrestrial pollen grains were counted for each sample with primary identification based on Moore et al. (1991) and the University of Aberdeen pollen type slide collection. Pollen of *Betula pubescens* is separated from *B. nana* by size, where pollen ≥20 µm is attributed to *B. pubescens* and smaller grains to *B. nana* (Mäkelä 1996; Caseldine 2001; Karlsdóttir et al. 2007). The construction of pollen diagrams was undertaken using TILIA (Grimm 1991) and TGView (Grimm 2004) with palynomorphs expressed as percentages of the total land pollen (TLP) sum. Pollen and spore taxonomy follows Bennett (2008b) with a few amendments (Erlendsson 2007). Diagram zonation, with three local pollen assemblage zones (BR1-I to BR1-III) was aided by the use of the CONISS routine within TILIA.

Results

Chironomids

A total of 19 chironomid morphotypes were found throughout the profile (Fig. 3), which was dominated by *Psectrocladius sordidellus* type, *Chironomus, Dicrodentipes* and *Tanytarsus lugens* type. There are relative peaks in *Dicrotendipes* and *Ablabesmyia* from 32–24 cm (c. AD 1100–1300), which are among the more thermophilous Icelandic taxa according to Langdon et al. (2008), although abundances of *Dicrodentipes* and *Psectrocladius sordidellus* type fall from 16 cm (c. AD 1500), with *Dicrodentipes* having disappeared from the assemblage in the topmost sample. Meanwhile, taxa that are more commonly found in relatively cooler Icelandic lakes such as *Micropsectra, Tanytarsus lugens* type and *Heterotrissocladius grimshawi* type (ibid.) all increase after this point. The shallow water or semi-terrestrial *Limnophyes* also becomes more abundant in the top 8 cm.

Much of the core is characterised by relatively low concentrations of chironomid head capsules, with the majority of samples from 0–50 cm depth containing ~5–15 head capsules per cm^3 (Fig. 3). Because of this, several samples from different depths have been amalgamated to bring the number of head capsules per sample up to ≥50, recognised as being the minimum number required for a reliable temperature reconstruction (Heiri and Lotter 2001; Larocque 2001; Quinlan and Smol 2001). Head capsule concentration is highest at the bottom of the core, and declines with time (Fig. 3). The total number of

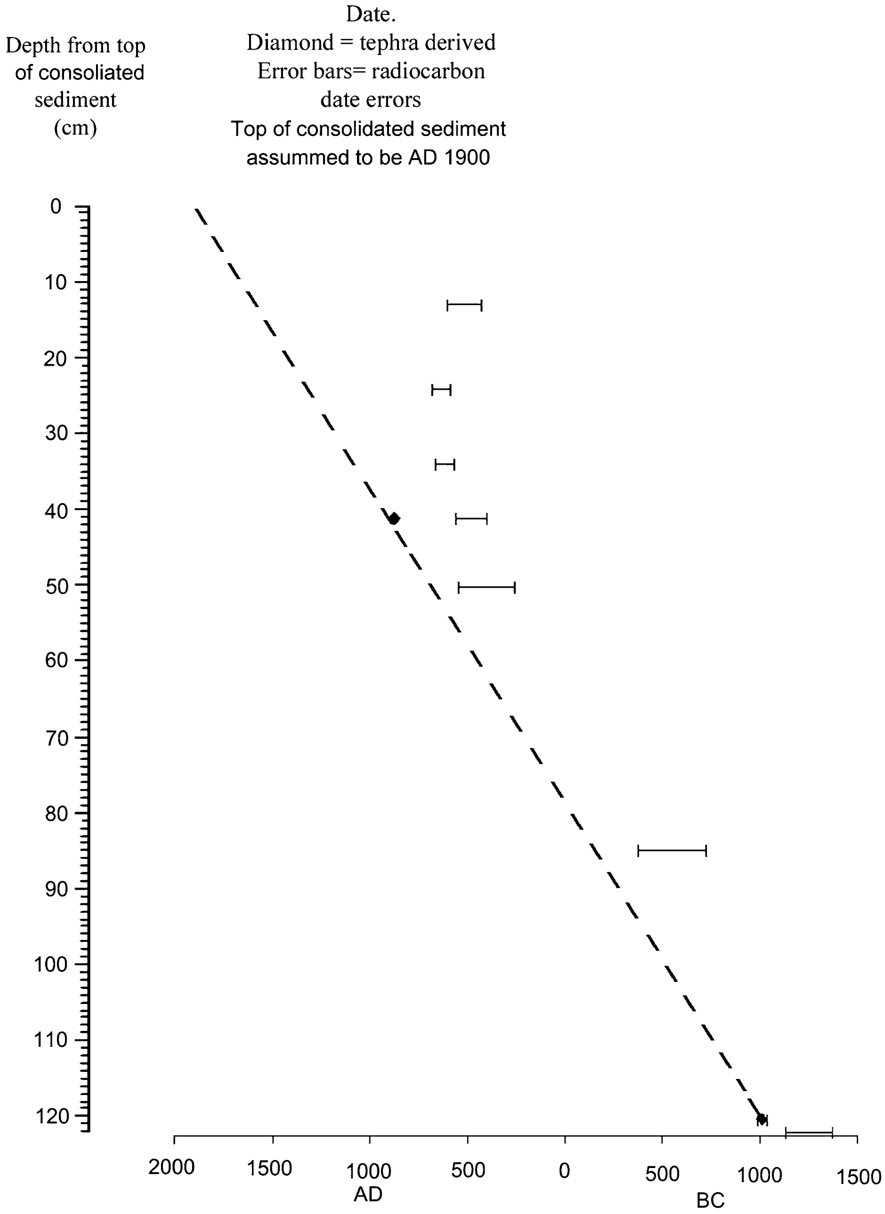


Fig. 2 Age-depth reconstruction, based only on identified tephra layers. The ^{14}C dates have been added to illustrate the inwash of increasingly older carbon post-*landnám*

chironomid taxa found per sample changes little throughout the core.

Temperature reconstruction

The temperature reconstruction (Fig. 5) suggests that mean July temperatures were fairly stable at around 9°C for most of the period covered by this core. Some increases in temperature (~0.5°C) are evident at 72 cm and also between 39 and 32 cm. Temperature declines at 16 cm (c. AD 1500), where the mean July air temperature reconstruction falls by about a degree to 8°C. There is a short period where conditions were warmer at 3 and 4 cm (AD 1825 and 1800), and then they decline again, to the coldest point in the core, at the top (7.2°C).

The DCA results show that axis 1 explains 49% of the variance of the species data, with an eigenvalue of 0.227 (Table 2). The temperature reconstruction and DCA axis 1 scores show a similar pattern, indicating

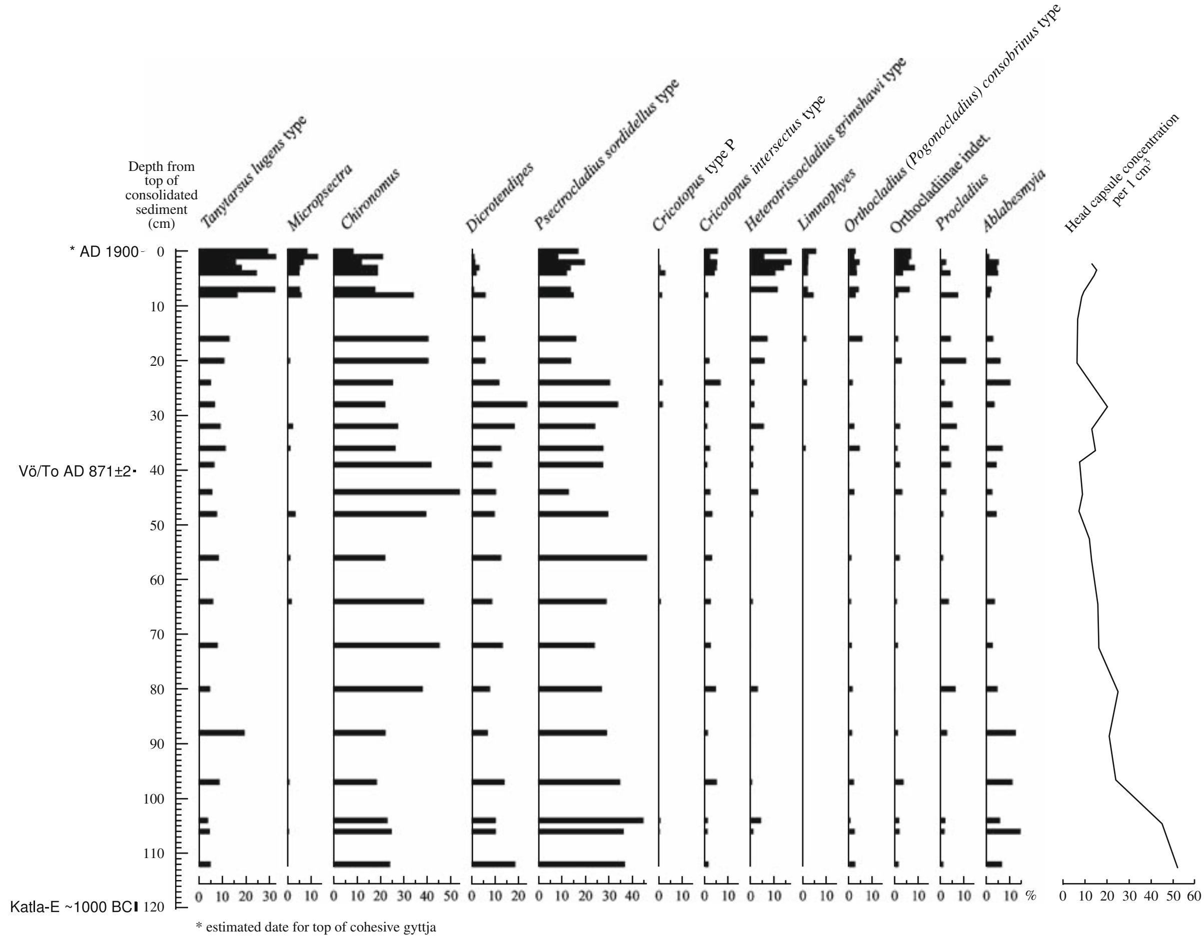


Fig. 3 Selected percentages of fossil chironomids found in Breiðavatn. The rare morphotypes are not shown

that temperature was most likely the dominant environmental variable affecting the chironomid assemblages in this core.

Pollen

The pre-*landnám* part of the core (zone BR1-I) is characterised by high relative abundances of *Betula pubescens* pollen (Fig. 4), with some *B. nana* and lesser quantities of *Salix*. Among herbaceous taxa, Cyperaceae and Poaceae are well represented. *B. pubescens* declines in relative abundance at 92 cm, and *Thalictrum alpinum* makes its first appearance at this time. By 60 cm, the relative frequency of *B. pubescens* is back to previous levels. Cyperaceae were relatively abundant in the pre-*landnám* era, as was *Sphagnum*. After *landnám,* values for well-preserved pollen of *B. pubescens* show a sudden

Table 2 Statistical results from a DCA of the chironomid sequence

Axes	1	2	3	4	Total inertia
Eigenvalues	0.227	0.043	0.013	0.008	0.466
Lengths of gradient	1.483	0.817	0.627	0.534	
Cumulative percentage					
Variance of species data	48.7	57.9	60.7	62.4	
Sum of all eigenvalues					0.466

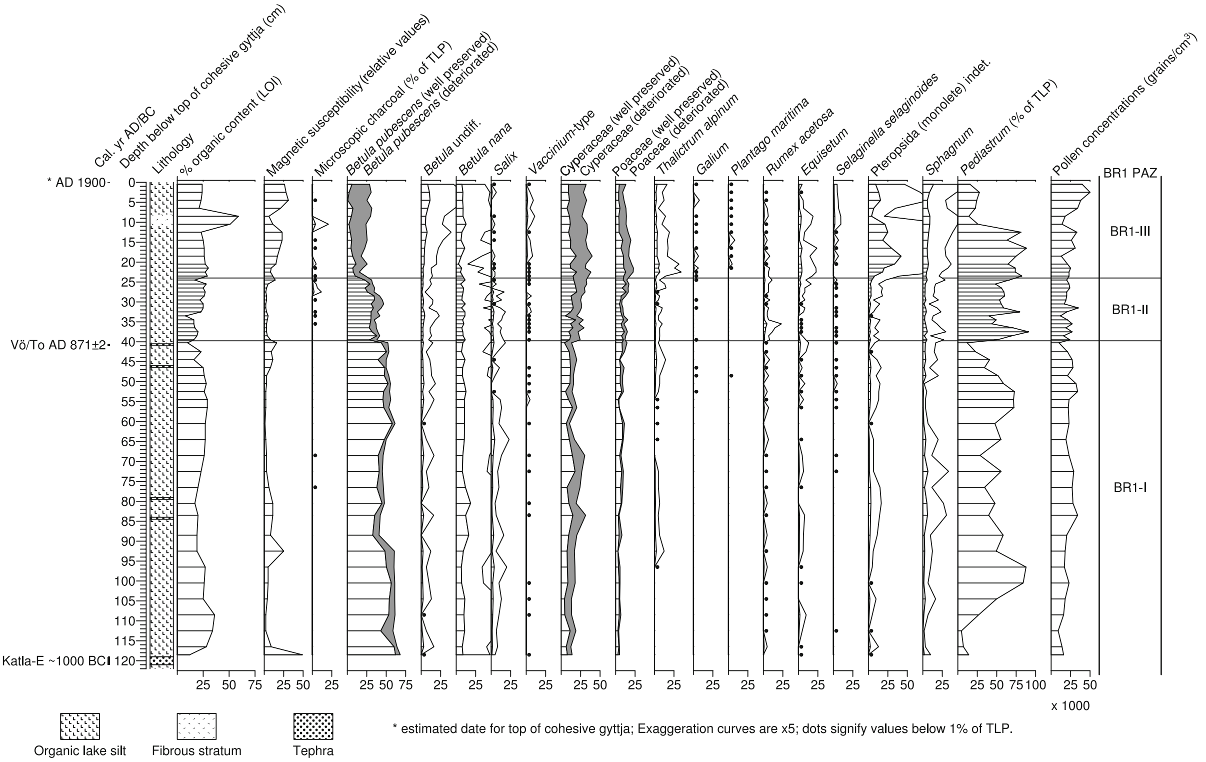
decline (zone BR1-II), and between 26 and 23 cm they fall to very low levels (zone BR1-III), which persist to the top of the profile. The apparent birch decline follows a rise in values for microscopic charcoal. Also around 24 cm, *Thalictrum alpinum*, *Galium* and *Plantago maritima* increase in relative abundance, as do the number of Pteropsida (monolete) indet. spores and, strikingly, the representation for degraded tree birch pollen. Pollen concentrations increase above 20 cm, suggesting that the rising values for these taxa are not an artifact of the percentage calculation.

Sediment

Magnetic susceptibility and LOI co-vary, largely inversely, through the pre-*landnám* section of the core (Fig. 4). There is a single spike in magnetic susceptibility before *landnám* at 92 cm. At 24 cm, magnetic susceptibility rises, and this increase is maintained (apart from a brief drop in the thick, fibrous, organic layer at 8 cm) to the top of the core. LOI oscillates around ~25% for the majority of the sequence, with brief declines (not associated with tephras) around 107, 92, 33 and 24 cm, and a significant peak associated with the thick, fibrous, organic layer at 8 cm.

Discussion

Results from the lake sediment sequence from Breiðavatn suggest that the landscape was subject to human impact, notably just after *landnám* when there was a significant decline in local woodland and a commensurate expansion of sedges. The ^{14}C dating provides further evidence for post-settlement catchment changes. Until *landnám*, the ^{14}C bulk sediment dates were all offset by ~300 years compared to the tephra dates (Fig. 2). This may be due to a natural reservoir effect in the lake, and/or inputs of older carbon to the lake. The fact that the offset is relatively consistent throughout ~2000 years (although only three dates are involved) may indicate that the



* estimated date for top of cohesive gyttja; Exaggeration curves are x5; dots signify values below 1% of TLP.

Fig. 4 Palynolgical record (selected taxa) from Breiðavatn in percentage format. Additionally, %LOI, magnetic susceptibility and charcoal abundance are shown for comparative purposes, as are total pollen concentrations and *Pediastrum* (as a % of TLP) processes controlling it probably changed little over this period. This relationship alters at *landnám*, where the ^{14}C date from immediately below the *landnám* tephra is ~400 years older than the tephra, and the disparity between dates increases through time (Fig. 2). The increase in the proportion of older carbon entering the lake suggests that the surrounding organic soil/peat was being eroded, and older material was exposed and washed or blown into the lake (cf. Edwards and Whittington 2001). The evidence from the lake sediments thus suggests that considerable changes to the environment, particularly increased erosion, followed the arrival of humans at the end of the 9th century AD. Introduction of grazing animals (especially sheep), and clearance of woodland are thought to be the major causes of this environmental change (cf. Hallsdóttir 1987).

The chironomid fauna show little variation over this period, with an increase in the relatively thermophilous *Dicrotendipes* only occurring long after both *landnám* and the change in vegetation, suggesting that the chironomid fauna was not affected directly by the initial impacts of settlement. There was, however, an increase in relative abundance of *Pediastrum* (Fig. 4), a green alga used as an indicator of nutrient levels (Lawson et al. 2005, 2007; Woodward and Shulmeister 2005) just after *landnám* from the start of zone BR1-II, but it did not rise above pre-*landnám* levels. This is quite unlike the situation in Helluvaðstjörn (also a small, spring-fed lake, in the north of Iceland, near Mývatn), where erosion of the landscape led to increased deposition of nutrient-rich matter into the lake and a locally unprecedented rise in *Pediastrum* (Lawson et al. 2007). In Helluvaðstjörn, although there was no change to the chironomid assemblage, increases in nutrients reaching the lake allowed total chironomid abundance, previously nutrient-limited, to increase dramatically (ibid.). The chironomid assemblage from Breiðavatn shows no sign of any changes associated with increased nutrient levels—indeed, taxa that are associated with increased macrophyte abundance (a potential result of increased nutrients in an oligotrophic system) such as *Dicrotendipes*, *Ablabesmyia* and *Cricotopus* (Brodersen et al. 2001; Langdon et al. in press) are all reduced throughout this phase (39-37 cm). The chironomid DCA axis 1 scores closely follow the temperature reconstruction throughout the core (Fig. 5), and the other axes explain very little of the variation in the assemblage, indicating that the assemblage composition is most likely driven largely by temperature. Hence this temperature reconstruction can be considered independent of human-induced landscape change. It appears that the erosional areas are too distant for significant nutrients to be added to the waters of Breiðavatn. Damaged pollen and spores, minerogenic soil, and deposits containing old carbon have been blown and/or washed into the lake, but not sufficiently to cause any noticeable changes to the lake biota investigated.

The chironomid-inferred temperature reconstruction shows that from c. 800 BC until c. AD 1000 (32 cm), mean July air temperatures around Breiðavatn were about 9°C, with only small (~0.5°C) fluctuations and a very slight decreasing trend. The 0.5°C fluctuations are within the boundaries of the transfer function model error, and hence must be treated with some caution, especially as there is little change in the DCA axis 1 scores over this period. More significantly though, there is an increase in relatively thermophilous taxa between 32 and 24 cm (c. AD 1100–1300), which corresponds with a rise in temperature of just <1°C. The magnitude and timing of this phase is very similar to other records from the region (Andresen and Björck 2005; Jiang et al. 2002, 2005), reflecting conditions analogous to the Medieval Warm Period (MWP). Additionally, cooler temperatures around AD 1000 (34 cm) agree with the reconstruction of Jiang et al. (2005) that show this period, though generally warmer than average, underwent several rapid cooling events.

From around AD 1200 (28 cm) the relative abundance of *Betula pubescens* pollen began to fall, and by AD 1300 (24 cm), it was at very low levels (<20%). The birch was replaced by open environment taxa (e.g. *Thalictrum alpinum*, *Galium*, *Plantago maritima*). Relative abundances of degraded birch pollen and Pteropsida (monolete) indet. spores also increase, as does magnetic susceptibility, again indicating increased erosion. The relatively low resolution of the climate reconstruction over this period means it is difficult to invoke a purely climatic cause for this second, stepped decline in birch woodland (the first being just after *landnám*), although there was perhaps an increase in summer air temperature variability throughout these centuries (Fig. 5). The decline in woodland does not appear to be associated directly with climate cooling.

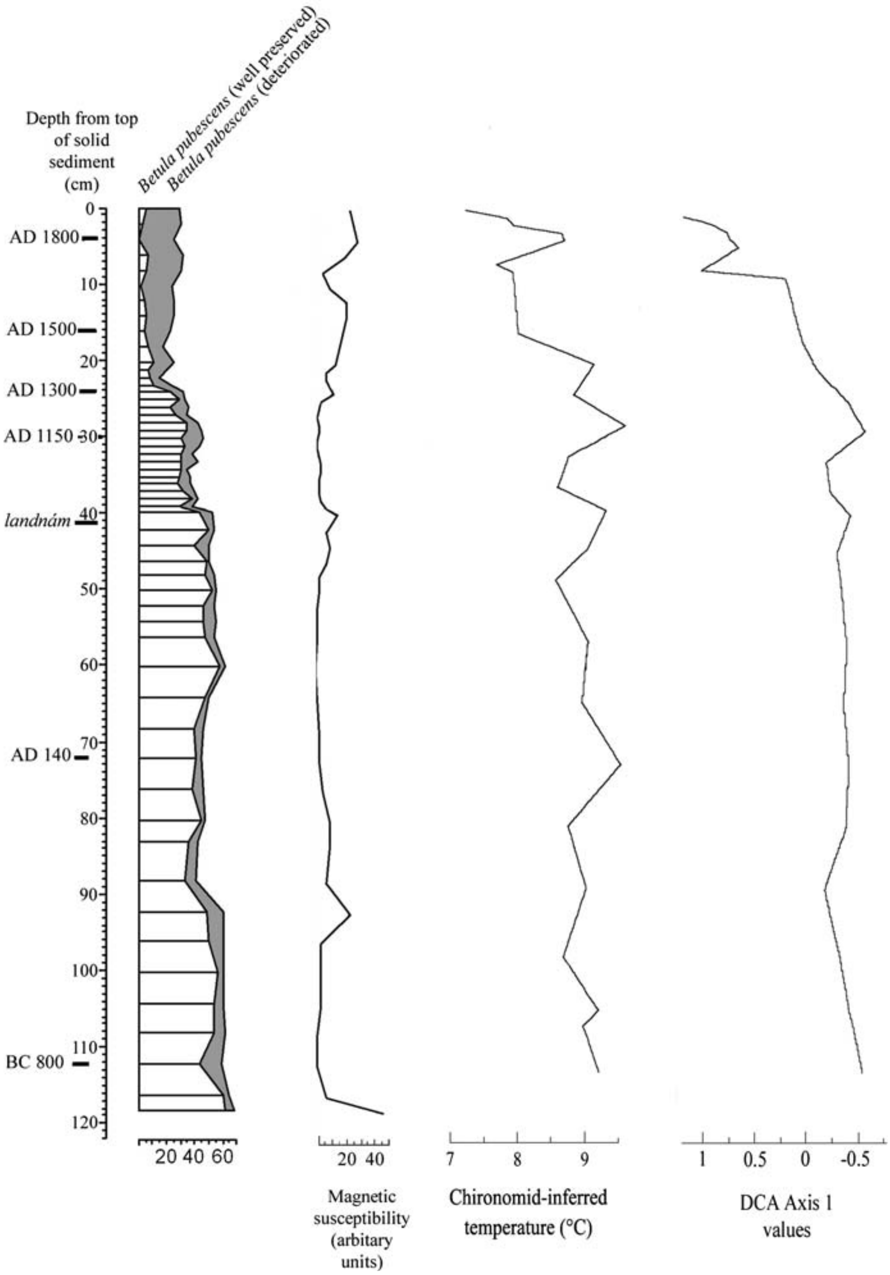


Fig. 5 Summary diagram, showing relative abundances of *Betula pubescens*, magnetic susceptibility, temperature reconstruction and chironomid assemblage DCA axis 1 scores

After AD 1500 (16 cm), tree birch levels had declined to negligible levels (<5% TLP) and remained so throughout the rest of the profile. At this time there is a significant decline in mean summer temperatures and (with the exception of two data points at 4 and 3 cm) the cooler climate remains until the top of the core. This is inferred to reflect the Little Ice Age (LIA). This temperature decline is the most severe in the whole Breiðavatn core, and evidence in the Denmark Strait area indicates that it was the most severe cooling period during the whole of the latter part of the Holocene (Andresen and Björck 2005). The Breiðavatn sequence is one of the few chironomid-inferred reconstructions that show an unambiguous LIA record (Velle et al. 2005a, 2005b; Brooks and Birks 2004). This is likely a result of the fact that the lake's topographic position means that there was no significant change in productivity after *landnám*. As the effects of changes in lake productivity and temperature on chironomid assemblages are often autocorrelated (Brodersen and Quinlan 2006), it is likely that any increase in productivity would have obscured the apparent effects of the LIA temperature decline. In fact, the generally unchanging nature of this lake's waters as well as the close correlation between DCA axis 1 scores and the temperature reconstruction, indicate that temperature is probably the key factor affecting the chironomid species assemblage, and that the reconstructed temperatures (or the trends) are reliable.

In common with other records (e.g. McKinzey et al. 2005), it appears that around Breiðavatn, there were periods of climate amelioration during the LIA, principally around the first half of the 19th century. This has been found in other studies, with Cook et al. (2002) reporting a generally positive trend in temperatures associated with changes in the North Atlantic Oscillation during the first part of the century, glaciers undergoing a retreat in the southeast (McKinzey et al. 2005), and the earliest instrumental records of temperature at Stykkishólmur showing a higher than average July temperature from about 1835–55 (Icelandic Meteorological Office). The second half of the nineteenth century, however, showed a marked temperature decline (McKinzey et al. 2005; Icelandic Meteorological Office), and the top sample of the Breiðavatn core (around AD 1900) shows the lowest reconstructed temperature at 7.2°C.

Although widespread erosion has been attributed to the LIA (Ólafsdóttir and Guðmundsson 2002; McKinzey et al. 2005), it appears that most of the changes that occurred in the Breiðavatn catchment (increased erosion and the reduction of forest cover) were set in motion before the LIA and some had occurred during the latter stages of the inferred MWP. Although generally warmer than average, the MWP can actually be characterised as a period of quite unstable climate, with frequent colder spells, as illustrated by the finer-resolution climate reconstruction in Jiang et al. (2005). The relatively low-resolution independent climate record from the chironomids does suggest more unstable climate in the last millennium compared with the previous two millennia. It is difficult, however, to resolve from these data what impact climate change may have had on promoting landscape erosion directly, as the catchment had been subjected to human impact. Most likely there is an interaction between humans and climate with respect to the magnitude of landscape erosion. For example, farmers tend to optimise stocking densities commensurate with minimal environmental degradation. With sudden cooling after a period of relative warmth, it is probable that stocking levels would not be reduced immediately to a sustainable level, allowing overgrazing to facilitate erosion. Of course, the extent of erosion around Breiðavatn was likely to have been compounded by other anthropogenic factors, such as over-exploitation of remaining woodland for fuel and charcoal production (Smith 1995; cf. Church et al. 2007).

Increases in magnetic susceptibility and the proportion of degraded *Betula* pollen throughout the uppermost core samples indicate that erosion was even more severe during the LIA. The LIA temperature decline probably compounded the negative effect of soil loss due to erosion on the agricultural economy around Breiðavatn. Mean July temperatures were at least 1°C below the pre-LIA average for most of this period (Fig. 5). This temperature drop would have generated a decline in primary productivity equivalent to a ~180 m increase in altitude, thus reducing the carrying capacity in the rangeland surrounding the lake by about 10–20% (Haraldsson and Ólafsdóttir 2003). Grazing pressure is unlikely to have dropped during this period of declining rangeland area, and this would have resulted in overgrazing and increased erosion. Although short-lived warmer episodes (e.g. around AD 1800) allowed re-expansion of farms to previously abandoned areas, these were often abandoned again as the climate worsened (McKinzey et al. 2005). Since the beginning of the 20th century, the climate has been warming. This warming and the projected 21st century increase in temperature, if coupled with cautious management of livestock densities, could allow re-vegetation of eroded land (Haraldsson and Ólafsdóttir 2003).

Conclusion

Sediment variables investigated in this lake core responded very differently to the environmental changes of the past two and a half millennia. Palynological evidence shows that the largest change to the landscape around Breiðavatn was anthropogenic, associated with post-*landnám* woodland clearance.

The ^{14}C evidence indicates increased post-*landnám* erosion, leading to the degraded environment found today. The chironomids, however, seem to have been unaffected by human-induced environmental changes, and their assemblages were influenced primarily by climate. The ability to separate climate-driven from human-induced impacts on the aquatic and terrestrial environments allowed the development of a chironomid-inferred temperature reconstruction that was relatively uncomplicated by anthropogenically-modified environmental variables. Both climate variability and human impact are likely to have contributed to the landscape erosion around Breiðavatn, with a ~1°C decline in July temperature during the LIA, which likely reduced primary productivity and would have had a profound effect on the region's farming community.

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