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Cryptotephra sedimentation processes within two lacustrine sequences from west central Sweden

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Abstract: Distal tephra horizons, particularly within lacustrine sequences, are increasingly being used as time-synchronous marker horizons within palaeoclimatic and palaeoenvironmental investigations. As sedimentary features marking the presence of these so-called cryptotephras are absent to the naked eye, it is of some importance that the stratigraphic position representing primary airfall, and likewise the timing of the volcanic event, is accurately and consistently recorded amongst these deposits. Often tephra shards from a cryptotephra deposit can be found spanning several centimetres of sediments within lacustrine and peat sequences. Very few studies, however, have looked in detail at the sedimentation and vertical distribution of cryptotephra deposits within such sequences and, more importantly, the criteria for defining the correct stratigraphic position of the volcanic event. Two sediment cores spanning the last 200 years, from Lake Spåime and Lake Getvaltjärnen, west central Sweden are employed to investigate in detail the vertical distribution of the tephra shards derived from the AD 1875 eruption of the Askja volcano in Iceland. Detailed geochemical analysis of shards from both records indicate that products of the Askja eruption are present for at least 120 years and thus emphasize the importance of carefully identifying the correct horizon that marks the timing of the volcanic event rather than shards resulting from a period of reworking or downward migration. Both sites yield contrasting shard concentration profiles and thus raise a number of questions regarding the influence of site-specific processes on cryptotephra sedimentation, particularly the role of snow-beds acting as tephra traps, the possibility of reworking, and downward migration of shards in soft sediment. A second tephra is also identified at Lake Getvaltjärnen and is believed to originate from the AD 1477 Veidivötn eruption and represents the first occurrence of this tephra outside of Iceland.

Keywords: Askja AD 1875 tephra, lacustrine deposits, cryptotephra sedimentation processes, historical volcanic eruptions, Iceland, Sweden.

Introduction

Since the pioneering work of Thorarinsson (1944), tephrochronology has long been employed as a precise correlation tool during the Quaternary period. Most studies employing this technique have been based on proximal deposits in which a primary tephra layer can be clearly identified by the sharp contact between the host sediment and the lower boundary of the volcanic horizon. When such a sedimentary feature is present, the precise timing of the volcanic event can usually be easily defined either visually by clear changes in colour or by other features eg, grain size or magnetic susceptibility. In recent years, however, tephrochronology has advanced considerably through the investigation of volcanic horizons present in sequences that

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are more distal to the volcanic source. These so-called cryptotephra horizons (Lowe and Hunt, 2001) (also referred to as microtephra) are invisible to the naked eye in the visual stratigraphy and are present in such low concentrations that an extraction technique (eg, ashing or heavy liquid separation) must be employed systematically to trace their occurrence in a sediment sequence. Recent developments in the detection of these distal tephra deposits has enhanced the potential that tephrochronology offers for correlative purposes and for deriving age control in sedimentary sequences (eg, Dugmore, 1989; Pilcher and Hall, 1992; Turney *et al.*, 1997, 2004; Wastegård *et al.*, 2000a, b; van den Bogaard and Schmincke, 2002; Davies *et al.*, 2002, 2003; Lowe *et al.*, 2004). As these horizons cannot be identified by sedimentary features visible to the naked eye, it is of fundamental importance that they are accurately defined, within a stratigraphic column, by detailed quantitative investigation of shard concentrations and geochemical analysis.

Within ombrotrophic peat deposits, cryptotephra horizons are often present in discrete millimetre- to centimetre-thick deposits (eg, Wastegård, 2002; Bergman *et al.*, 2004) and are thought to represent primary airfall material. In lacustrine sequences, the vertical spread of volcanic particles is typically much greater, possibly because of continual inwash of tephra shards from the surrounding catchment, although such observations are not exclusive to lacustrine environments (eg, Gehrels *et al.*, 2006). Cryptotephra deposits found in lacustrine material often exhibit a marked peak in shard concentration followed by a gradual tail or decline in shard concentration in the overlying sediment (eg, Turney *et al.*, 1997; Davies *et al.*, 2005). Occasionally, some sequences also have a very low concentration of shards immediately below the peak in shard concentration (eg, Turney *et al.*, 2006). Thus, cryptotephra deposits can be present over 5–10 cm or more within a stratigraphic column, which in most cases represents a considerably long period of time. If so, then care must be taken to correctly define the stratigraphic position that best represents the precise timing of the volcanic event, particularly if cryptotephra horizons are to be used as time-synchronous marker horizons on a continent-wide scale (Turney *et al.*, 2004).

Traditionally, the peak in shard concentration has been used to define the timing of the volcanic event as this is usually easy to quantitatively determine within a stratigraphic column. It can also be argued, however, that the first occurrence of volcanic particles, which may not necessarily coincide with the peak in shard concentration, truly represents the time of eruption. However, such features could also be easily interpreted as downward migration of shards within a stratigraphic column (eg, Anderson *et al.*, 1984; Beierle and Bond, 2002; Enache and Cumming, 2006) or indeed reworking (Ruddiman and Glover, 1972). Furthermore, traditionally cryptotephra investigations tend to quantitatively determine the position of the peak in shard concentration and then assume that the overlying tail of glass shards is all derived from the same volcanic eruption. There is always a possibility, however, that additional cryptotephras from subsequent eruptions may be masked within the gradual decline in glass shards of an earlier volcanic event (eg, Gehrels *et al.*, 2006). It is always useful, therefore, to geochemically analyse overlying and in some cases underlying samples as well as the horizon containing the peak shard concentration.

Very little work has actually focused on cryptotephra sedimentation patterns within lacustrine deposits, even though it represents a fundamental part of cryptotephra studies. Here we report on a comprehensive dating exercise (^{210}Pb, ^{137}Cs, radiocarbon dating and tephrochronology) undertaken as part of a multidisciplinary project investigating the timing and impact of short-term environmental changes over the last 2000 years in two lake sequences from the Swedish Scandes Mountains in southwestern Jämtland, west central Sweden. A detailed investigation of the vertical distribution (shard concentrations and geochemical analysis) of cryptotephra deposits derived from the Askja AD 1875 eruption is undertaken at Lake Spåime and Lake Getvaltjärnen. Ash from this eruption has been found extensively in central, eastern and northern Sweden (Persson, 1966, 1971; Oldfield *et al.*, 1997; Boygle, 1998, 2004; Bergman *et al.*, 2004) and a possible occurrence has been documented in peat bogs in northern Germany (van den Bogaard and Schmincke, 2002). In southwestern Jämtland, the Askja AD 1875 tephra has been recorded within the Klocka Bog site (Bergman *et al.*, 2004) and within the nearby Lake Stenjärn (Bergman, 2005; Bergman *et al.*, 2005). Indeed, historical records document eye-witness accounts of the atmospheric deposition of 'greyish dust' over western Scandinavia during and subsequent to the eruption on 28–29 March 1875, which enabled the construction of an ash distribution map by the Norwegian meteorologist H. Mohn (Mohn, 1877; Thorarinsson, 1981). High shard concentrations are present in the sediments of Lake Spåime and Lake Getvaltjärnen, but the vertical distribution of shards differs markedly between the two sites.

Study sites and methods

Lakes Spåime and Getvaltjärnen are situated in the central Scandes Mountains, southwestern Jämtland, west central Sweden (Figure 1). Both lakes are ice-covered between October and late May. Spåime is a hydrologically open lake, located in the low alpine zone at an altitude of 887 m a.s.l. The lake is *c.* 0.03 km^2 in size and has a catchment area of around 3.5 km^2. The highest parts of the catchment are situated at 1050 m a.s.l. and the mean slope gradient of the catchment is less than 0.5°. Maximum water depth is approximately 3.7 m. The surrounding vegetation is dominated by heath communities with dwarf-shrubs and willows. Moderate snow-beds (on average 0.0075 km^2) are situated in the highest part of the catchment, *c.* 2 km southwest of the lake. At present, the snow-beds melt away during July–August. Previous investigations of the Holocene record at Lake Spåime have focused upon tree-limit fluctuations and their impact on the aquatic ecosystem (Hammarlund *et al.*, 2004) and some preliminary tephra work has suggested the presence of several mid-Holocene cryptotephra horizons (Bergman, 2005).

Lake Getvaltjärnen is located in the middle alpine zone on Mount Snasahögarna, *c.* 10 km north of Lake Spåime at an altitude of 1155 m a.s.l. Herb and grass communities interspersed with exposed bedrock and boulder fields dominate the catchment, which extends over 0.2 km^2, with the highest parts situated at *c.* 1250 m a.s.l. The mean slope gradient of the catchment is around 10°. At present, perennial or semi-perennial snow beds cover approximately 0.0025 km^2 of the catchment. The size of the lake is *c.* 0.015 km^2.

Surface sediment cores (27 cm in depth at Spåime, 24 cm in depth at Getvaltjärnen) were sampled in February 2002 from the ice-covered lakes using a gravity corer (HTH-Teknik) and subsampled in the field at 0.5 cm intervals. Sediment cores were also obtained from both sites using a Russian corer to collect a continuous record of the last 2000 years. At Lake Getvaltjärnen, three overlapping Russian sediment cores (7.5 cm in diameter and 0.76, 0.70 and 0.56 cm in length) were collected *c.* 50 m from the eastern shore in the area of thickest sediment accumulation. The water depth at the coring point was 2.4 m. At Lake Spåime, two 1 m long, overlapping cores were collected at

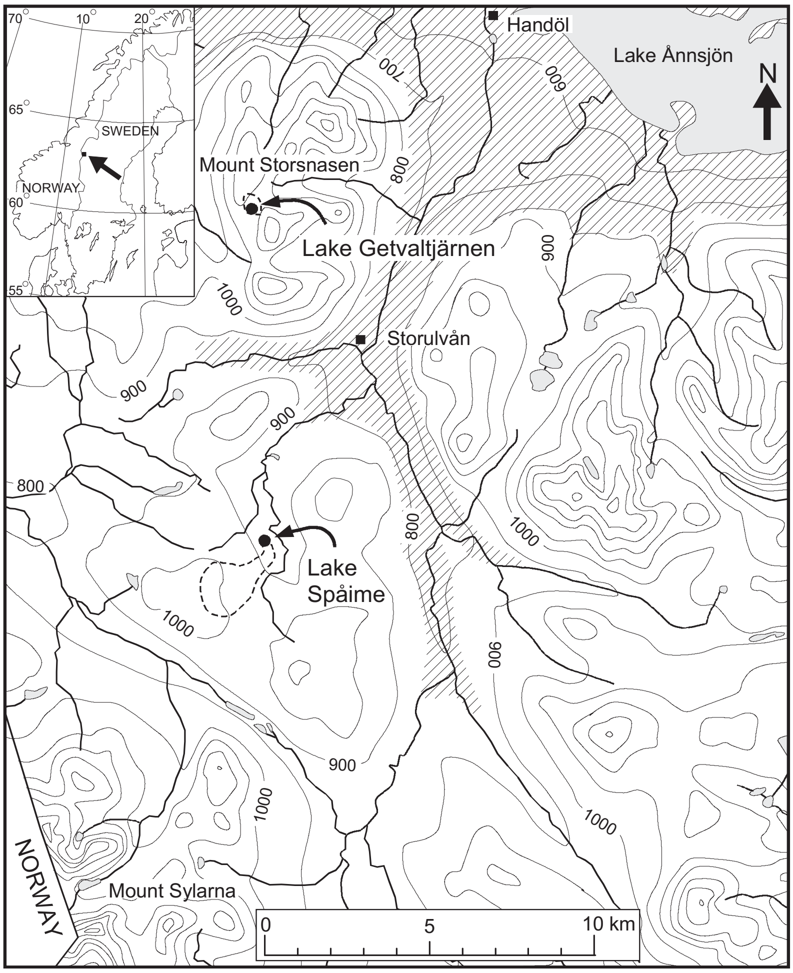

Figure 1 Map of the study area showing the locations of Lakes Spåime and Getvaltjärnen, Jämtland, west central Sweden. The hatched area indicates the distribution of subalpine forest. The catchments of both lakes are indicated by dashed lines

the deepest part of the lake. The cores were positioned down to a depth of 1.5 m below the sediment surface. All cores were carefully wrapped in plastic and transported to the laboratory at Stockholm University for cold storage and subsequent subsampling.

Tephrochronology

The entire length of both surface sediment cores (contiguous 0.5 cm samples) was investigated for the presence of cryptotephra horizons using the density separation technique for minerogenic lake sediment (Turney, 1998). Initially the samples were ashed at 550°C for 2 h before being subjected to a heavy liquid separation technique using sodium polytungstate at 2.3–2.5 g/cm^3. A NaOH (0.3M) treatment (90°C) was undertaken for 3 h to remove the biogenic silica component in the samples (Rose *et al.*, 1996). Shard concentrations were determined optically per 0.5 g dry sediment. Several samples were selected for geochemical analysis in both sequences spanning the peak and tail in shard concentration (see below) in order to determine whether the cryptotephra counts were derived from a single or several different eruptions. Samples chosen for geochemical analysis were subjected to an acid digestion treatment (sulphuric and nitric acid) to avoid any chemical alteration (Dugmore *et al.*, 1992). Geochemical analysis was undertaken by wavelength dispersive spectrometry (WDS) on a CAMECA SX-100 instrument at the Tephrochronology Analytical Unit, Department of Geology and Geophysics, University of Edinburgh. Operating conditions are given in Appendix 1.

Activity determination of radionuclides with gamma-ray spectroscopy

Contiguous 0.5 cm samples from the uppermost 6 and 8 cm from Getvaltjärnen and Spåime, respectively, were analysed for radionuclides with gamma spectrometry. Samples from the remainder of the Spåime core were analysed at 2–5 cm intervals. As the sediment from the uppermost 0.5 cm from Lake Spåime was insufficient for individual analysis, samples 0.5–1 cm and 1–1.5 cm were combined to ensure an adequate sample size. The same procedure was undertaken for the uppermost 1 cm from Lake Getvaltjärnen. Approximately 3 g of dried and homogenized sediment from each sample was placed in counting containers with Al-lined lids (Wheaton glass scintillation vials 2.5 cm i.d.) and stored for 3 weeks to ensure radioactive re-equilibrium between the gaseous ^{222}Rn and its decay-product ^{214}Pb. The activity of ^{210}Pb (total ^{210}Pb at 46.5 keV), ^{214}Pb (supported ^{210}Pb at 351.9 keV) and ^{137}Cs (at 661.5 keV) was measured on an EG&G ORTEC® co-axial low energy photon spectrometer (LEPS) containing a High-Purity Germanium detector (HPGe-detector). It was assumed that the short-lived ^{214}Pb was in equilibrium with the ^{226}Ra parent isotope. One day was sufficient for the activity measurement of the uppermost samples (0–2 cm for Spåime and 0–1 cm for Getvaltjärnen) whereas all other samples required two or more days to obtain counting statistics with low relative standard deviations. The blank sample, obtained by measuring the activity from an empty counting container, was subtracted from each sediment sample. Excess or unsupported ^{210}Pb activities were obtained by subtracting supported levels (^{214}Pb) from the total ^{210}Pb activity. Counting efficiencies for ^{210}Pb and ^{214}Pb were determined by standard additions of an externally calibrated pitchblende standard from Västergötland, Sweden, to samples with known activities.

The sedimentation rate for both lakes was derived using a simple ^{210}Pb dating model (eg, Krishnaswami *et al.*, 1971; Robbins and Edgington, 1975). Sedimentation rates in the two studied lakes were calculated from the regression line fitted to the excess ^{210}Pb data in a plot of LN ^{210}Pb excess versus depth (Berner, 1980). Intervals of near constant excess ^{210}Pb were not included in the curve fit and errors for the sedimentation rate were calculated from the obtained curve statistics (SigmaPlot 2001 Version 7.101). Age constraints could possibly have been improved by assuming a constant dry mass accumulation rate, however, in the absence of porosity and density data for the sediment cores we are unable to use a more sophisticated dating model, eg, the constant rate of supply model (CRS) (Appleby and Oldfield, 1978; Appleby, 2001).

Results

Lake Spåime

Tephrochronological investigations within the Spåime sequence reveal a distinct peak in excess of 4000 shards (per 0.5 g DW) at 12–12.5 cm (Figure 2). These shards are typically colourless, fluted and occasionally vesicular. A gradual increase to this peak is evident from *c.* 16 cm and a long declining tail in concentration is present towards the surface sediment. Five minor peaks in shard concentration are present at 11–11.5, 10–10.5, 8–8.5, 6.5–7 and 2–2.5 cm within this tail. Major element geochemistry from these horizons, the peak in shard concentration and four horizons below the peak indicate the Askja AD 1875 eruption as the sole source of the shards in this sequence (Figure 3 and Appendix 1).

The activity of unsupported ^{210}Pb decreases down to a depth of 8 cm where it reaches equilibrium with ^{214}Pb (Figure 2) and a sedimentation rate of 1.1 ± 0.05 mm/yr is determined

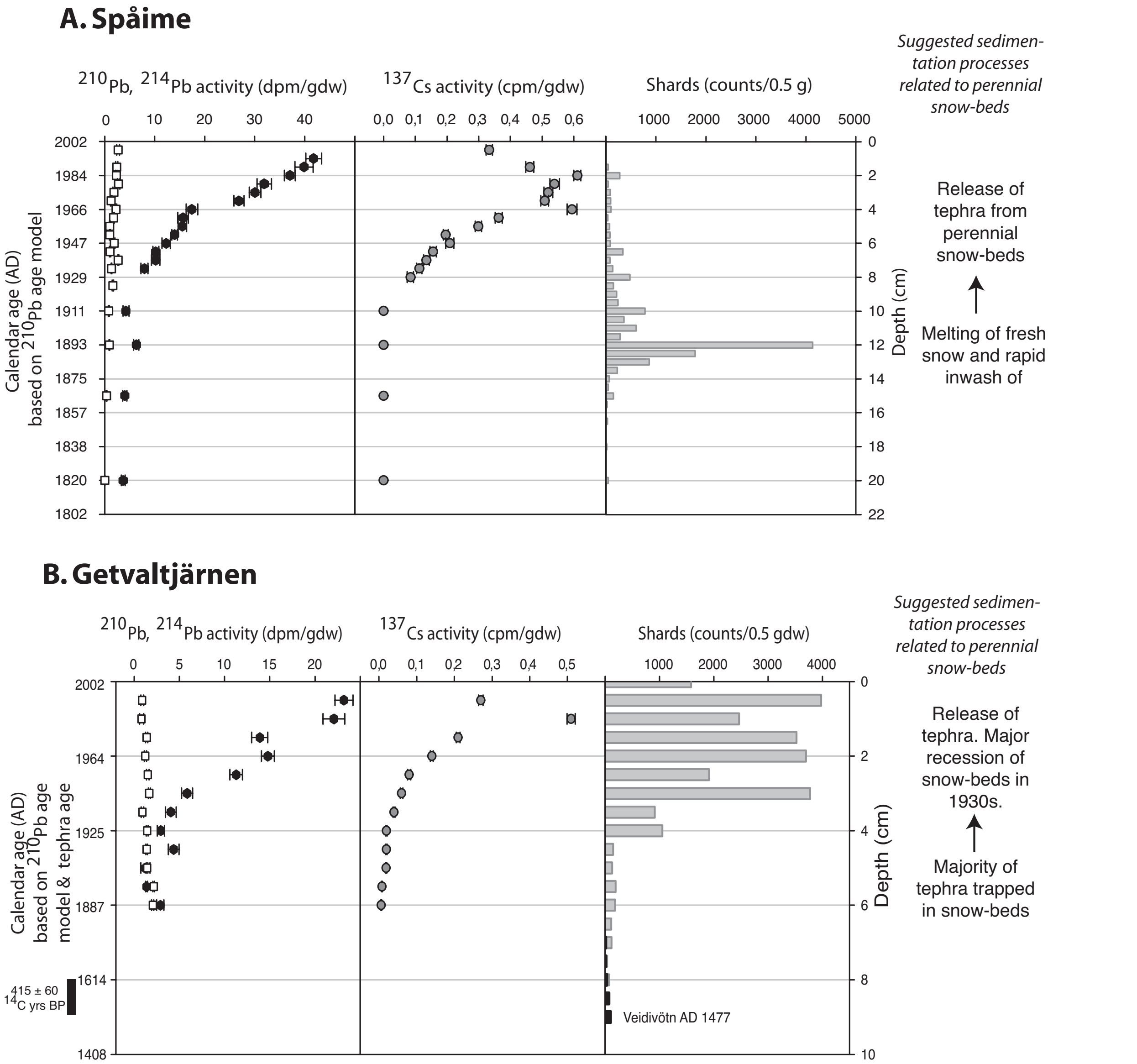

Figure 2 Vertical activity profiles of ^{210}Pb (black diamonds), ^{214}Pb (open squares), ^{137}Cs and shard concentrations for Såime (A) and Getvaltjärnen (B). Activity was measured in decays per minute per gram dry weight (dpm/gdw) and in counts per minute per gram dry weight (cpm/gdw). Error bars for the nuclides represent one standard deviation of the counting uncertainty. For Lake Getvaltjärnen the ages between 10 and 6 cm are at 1 cm intervals and calculated by assuming a constant sedimentation rate between the Veidivötn AD 1477 tephra and 1887 at 6 cm. The radiocarbon age derived for the Lake Getvaltjärnen sequence is also shown

(Figure 4; $r^2 = 0.97$; $p<0.0001$; $n=15$). Two peaks in the ^{137}Cs at 2–2.5 cm and 4–4.5 cm are thought to indicate the 1986 Chernobyl accident and the intense nuclear bomb testing that reached a distinct peak in 1963, respectively. The former falls a few millimetres outside the 1986 level as constrained by the ^{210}Pb ages (1.8 cm), but given the increased mobility of ^{137}Cs in comparison with ^{210}Pb within a sediment profile, this difference is considered to be minor. Taking into account the errors associated with the sedimentation rate determined by the ^{210}Pb ages, the 1875 level falls between 13 and 15 cm, corresponding to the low level of shards prior to the peak in shard concentration at 12–12.5 cm. Given that we have assumed a constant volumetric accumulation rate, this provides a good level of agreement.

Lake Getvaltjärnen

A clearly defined peak is absent within the shard counts for the Getvaltjärnen profile (Figure 2). Colourless and fluted rhyolitic shard counts in excess of a 1000 (per 0.5 gdw) are observed in all samples above 4–4.5 cm with no distinct tail in shard concentration as observed at Lake Spåime. A low level of rhyolitic shards is identified below the maximum concentrations at this site and geochemical results indicate that all rhyolitic shards above 7 cm are derived from the Askja AD 1875 eruption (Figure 3). Determining which depth best represents the time of eruption however, is difficult because of the absence of a peak in shard concentration.

A considerably lower sedimentation rate of 0.52 < 0.04 mm/yr (Figure 4; $r^2=0.95$; $p<0.012$; $n=6$) was derived for the Getvaltjärnen sequence based on the measured excess ^{210}Pb. Apart from the anomalous measurement at 1.5–2.0 cm, the unsupported ^{210}Pb activity decreases down to 5 cm depth where it reaches equilibrium with supported ^{210}Pb (ie, ^{214}Pb). The anomalous ^{210}Pb value at 1.5–2.0 cm may indicate the input of different types of material into the lake, eg, organic matter is important for the complexation of ^{210}Pb. A depressed value of this nuclide may reflect a larger input of terrigenous material with low concentrations of organic matter, thus, resulting in lower levels of excess ^{210}Pb (Robbins and Edgington, 1975). Alternatively, this value may represent a significant event such as a sediment slump or an increase in the sedimentation rate. In the absence of porosity data, we are unable to test this with a more sophisticated ^{210}Pb dating model. According to the ^{210}Pb ages, the 1875 level corresponds with the low level of shards between 6 and 7 cm.

A single peak in ^{137}Cs is evident between 1 and 1.5 cm, and the calculated ^{210}Pb sedimentation rate suggests that this peak comes from the nuclear testing that reached a maximum in 1963. If so, good agreement is shown between the ^{210}Pb and ^{137}Cs profiles at this depth. However, this peak could also easily represent the 1986 peak in ^{137}Cs. The absence of a second peak in ^{137}Cs may be due to the low sedimentation rate, particularly as it appears that the first sample represents 40 years.

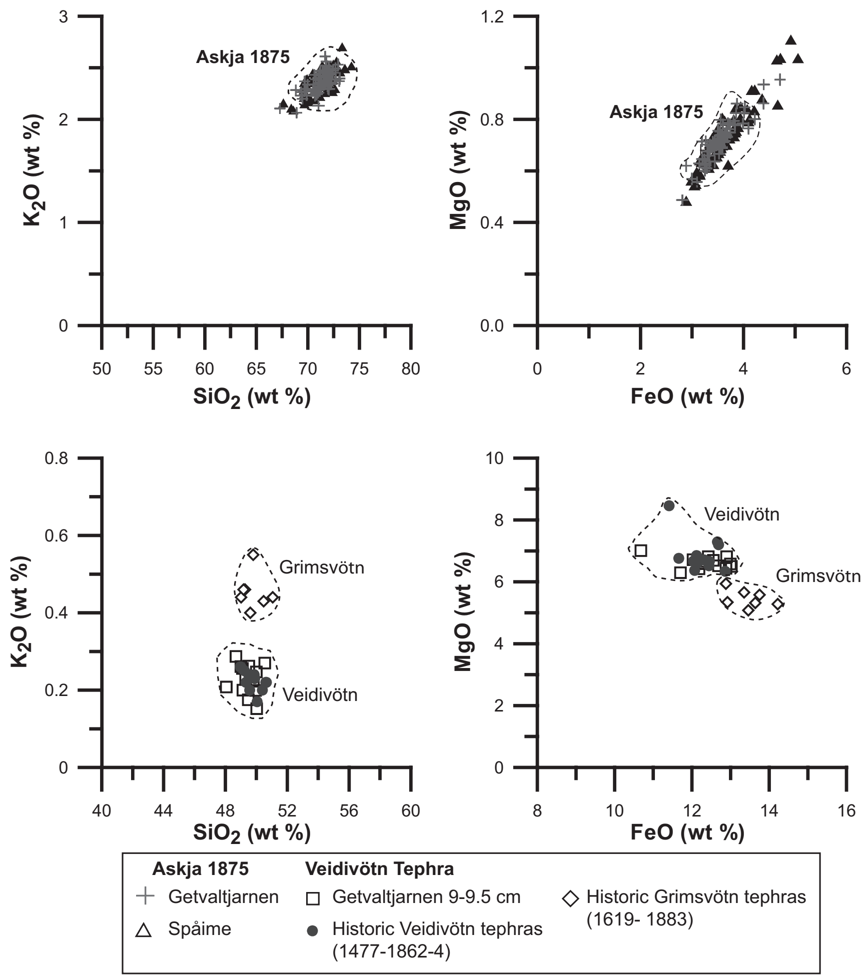

Figure 3 Major oxide biplots of the glass shards extracted from Lake Spåime and Lake Getvaltjärnen. The dashed lines represent geochemical envelopes for the Askja AD 1875 eruption reported by Larsen *et al.* (1999) and Oldfield *et al.* (1997). Some shards from Spåime and Getvaltjärnen fall outside these envelopes but show similar geochemical trends to the Askja 1875 deposits analysed by Boygle (2004) in central Sweden, indicating several phases during this eruption. Data for the historic Veidivötn and Grimsvötn tephras are derived from the Icelandic tephrochronology framework outlined by Haflidason *et al.* (2000)

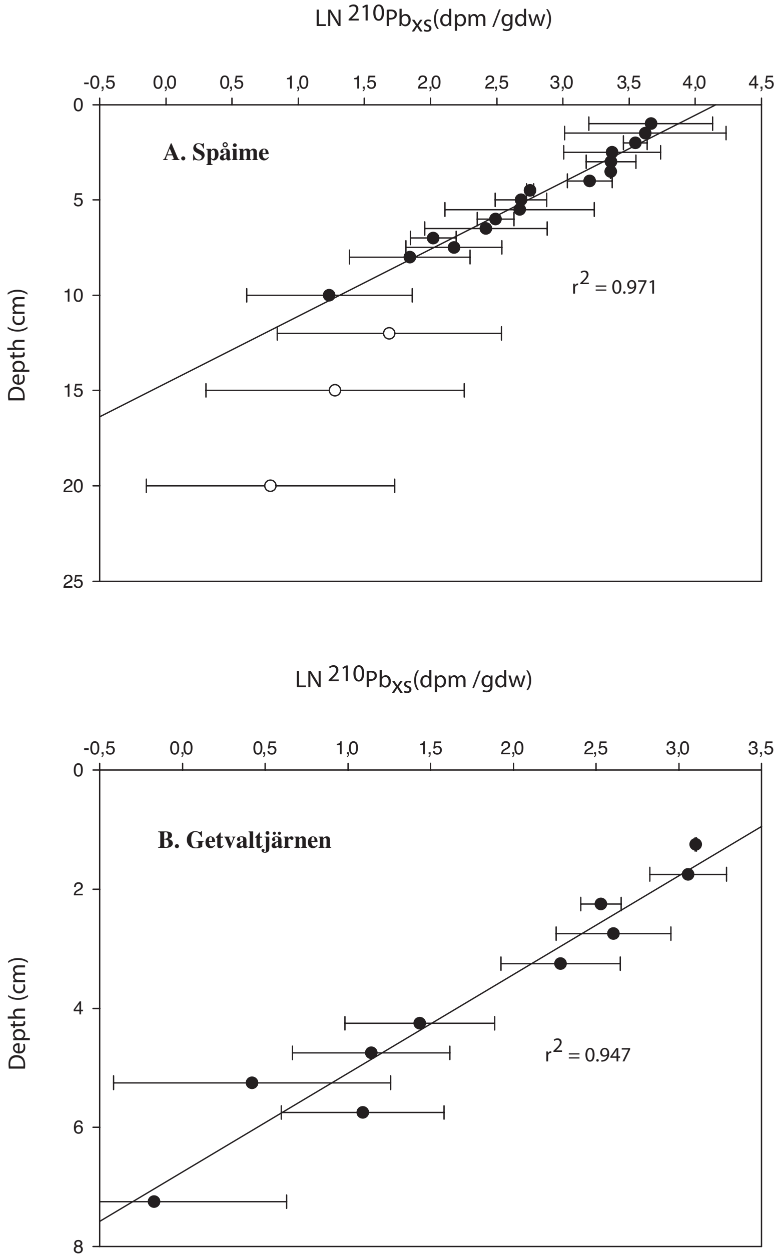

Figure 4 LN^{210}Pb versus depth for Spåime (A) and Getvaltjärnen (B). A regression line was fitted through these data (black circles only)

Indeed, an elevated concentration is evident in the uppermost sample. The use of ^{137}Cs for dating is considerably more limited than the ^{210}Pb method and is only useful when the sedimentation rate is sufficiently high (Robbins and Edgington, 1975). The generally low sediment accumulation rate at Lake Getvaltjärnen may thus be responsible for the absence of a clearly defined peak in shard concentrations within this record.

A radiocarbon date of 415 < 60 ^{14}C yr BP (LuS 6379) was also obtained on terrestrial macrofossils (*Salix* and *Empetrum* leaves) at 8–9 cm depth within the Russian core sediments from Lake Getvaltjärnen. The calibrated age range of AD 1440–1610 (1 sigma) (2 sigma: AD 1410–1640) indicates a much slower sedimentation rate downcore. The inability to use the CRS age model (Appleby, 2001) that would account for changes in sedimentation rates and possible compaction of the sediments is problematic for Lake Getvaltjärnen. This would have been particularly beneficial for the development of the chronology, since the ^{210}Pb concentrations do not decrease exponentially down the profile, owing to the absence of two distinct ^{137}Cs peaks and as the radiocarbon measurement suggests major changes in the sedimentation rate.

A second cryptotephra has also been detected between 9–9.5 and 7–7.5 cm within this sequence (Figure 2). The peak in shard concentration is marked at 9–9.5 cm and there is no evidence of any shards below this level. The dark brown and blocky morphology, typical of basaltic tephra, distinguishes this tephra from the overlying shards. An Icelandic origin and more specifically the Veidivötn fissure swarm is pinpointed as the source of this tholeiitic basaltic tephra, which is distinguished from Grimsvötn (the only other tholeiitic system in the Eastern Volcanic Zone) by the lower K_2O and slightly higher MgO concentrations (Figure 3). Veidivötn erupted no less than ten times between 1477 and 1864, producing tephra of a similar geochemical composition during each eruption (Haflidason *et al.*, 2000). As a result, it is difficult to pinpoint the exact eruption that produced this tephra. However, the radiocarbon age (AD 1440–1610 at 1 sigma) at 8–9 cm suggests that the widespread Veidivötn 1477 eruption is the most likely source of the tephra at 9–9.5 cm. If so, then this represents the first discovery of this tephra outside of Iceland (cf. Dugmore *et al.*, 1995; Langdon and Barber, 2001; Wastegård *et al.*, 2001; Hall and Pilcher, 2002; van den Bogaard and Schmincke, 2002; Bergman *et al.*, 2004). Failure to detect this tephra within the Lake Spåime sequence is probably due to the temporal resolution of the sampled record and its absence within the nearby Klocka Bog site may indicate the operation of site-specific processes contributing towards an uneven distribution of tephra, which was clearly apparent in the investigations of other tephras at this site (Bergman *et al.*, 2004). Owing to the productivity of the Veidivötn fissure swarm, a more diagnostic geochemical technique (eg, trace element analysis; Pearce *et al.*, 1999, 2004) is required in order to facilitate the use of this tephra as a time-parallel marker horizon for chronological models spanning the last 1000 years.

Discussion

Our results show that shards from one eruption can remain in a lake catchment for at least 120 years. It is of vital importance, therefore, that the position of a cryptotephra used for correlation purposes is accurately and quantitatively determined, corresponding to the best of our knowledge to the time of eruption rather than a delayed signal owing to catchment processes. Indeed, the occurrence of a diffuse zone of shards below the main peak at Spåime and below the horizons with the highest shard concentration at Getvaltjärnen raise a number of questions regarding the processes controlling the sedimentation and deposition of cryptotephra horizons in lacustrine environments. Possible explanations to account for these observations include: (1) that the first appearance of shards rather than the peak in shard concentration represent the actual eruption time; (2) catchment processes have influenced the sedimentation pattern of shards within these lakes; and (3) post-depositional processes have led to the downward movement of shards.

The age–depth models for both lakes support the first explanation, as the predicted 1875 levels correspond to the low-level of shards below the depths with the highest shard concentrations. These age–depth models, however, are not without limitations and the required precision for pinpointing the exact year of cryptotephra sedimentation within these lakes is actually beyond the capabilities of the ^{210}Pb method, particularly during the latter part of the nineteenth century which is close to its viable range. Thus, based on our age–depth models alone it is difficult to determine whether the first occurrence of shards, rather than the peak in shard concentration, best represents the timing of the Askja eruption. As mentioned above, the pattern of shard distribution within these two lakes may also have arisen because of the operation of catchment and post-depositional processes.

Catchment processes and the possible influence of snow-beds

It is possible that the initial occurrence of shards within these profiles represents the actual time of tephra deposition, as a small percentage of shards from the overhead ash cloud will be directly deposited into the lake whereas the majority of the ash will probably be deposited on the surrounding landscape and catchment. Consequently, this could enforce a delay in the majority of the ash particles reaching the lake sediments, which may well be enhanced if there are catchment characteristics that would limit the inwash of shards, eg, topography, vegetation cover and features that would act as possible sediment or tephra traps. With regards to vegetation cover, it is likely that tephra deposited in a more open landscape, eg, an open tundra landscape, is likely to be incorporated into the lake sediment at a faster rate than if it were deposited in a densely forested catchment. The two lakes investigated here can be considered sensitive in this respect as they are both located in alpine tundra environments and, thus, the vegetation cover is unlikely to have limited the transport of tephra shards into the lakes. Indeed, at Lake Getvaltjärnen, the patchy vegetation cover and the surrounding steep slopes are likely to encourage a rapid inwash of shards, whereas Lake Spåime has a larger catchment and a relatively denser vegetation cover that may have slightly delayed tephra inwash. However, these factors alone are not likely to have contributed to the puzzling nature of the shard concentration profiles in these two lakes.

A more likely scenario is that the presence of snow-beds in the surrounding catchments acted as tephra traps, particularly as the Askja tephra was deposited during the late stages of the 'Little Ice Age', when glaciers were advancing and perennial snow-beds expanding in the Sylarna-Snasahögarna area (Lundqvist, 1969). It is possible that the majority of the tephra deposited on the snow-covered catchment in late March 1875 was trapped in perennial snow-beds, and released during summers of substantial melting and snow recession. Instrumental temperature and precipitation data from the nearby town of Östersund (Dahlström *et al.*, 1995; Frich *et al.*, 1996) and the meteorological station at nearby Storlien (Alexandersson, 2002), indicate that the mean summer temperatures (June–August) in the area remained low until *c.* 1930. Furthermore, a number of studies have confirmed that the active retreat of glaciers and melting of snow fields in the Sylarna area began around 1930 (Lundqvist, 1969; Kullman, 2004a, b). The climatic regime may thus have inhibited any major recession of perennial snow until this time, and this process is likely to have been more profound at Lake Getvaltjärnen, owing to its position at a higher altitude. Following the Askja AD 1875 eruption, the tephra may have been stored in the snow-beds and released in accordance with the pattern of snow-bed recession. Small amounts of tephra may have only been released as a result of modest melting during the latter stages of the 'Little Ice Age' (hence the low level of shards below 4.5 cm). A small increase in shard concentration at 4–4.5 cm may be in accordance with the recorded elevated summer temperatures at the turn of the twentieth century, whereas the large jump at 3–3.5 cm may be a response to the further increase in summer temperatures and major recession of perennial snow during and since the 1930s. Indeed, this hypothesis and sequence of events fits in well with the ^{210}Pb chronology for Lake Getvaltjärnen, despite the limitations (Figure 2).

In contrast, at Lake Spåime, the high shard concentration relative to other horizons and the clearly defined peak at 12–12.5 cm does suggest that this is a result of a short-lived and rapid event. It is possible that the majority of ash particles were inwashed as a result of the melting of fresh snow in close proximity to the lake in the summer months following the eruption. Tephra may also have been stored in the perennial snow-beds higher up in the catchment, and released in small amounts over a number of years until the Spåime snow-beds melted away and became semi-perennial during the 1970s and 1980s. Lake Spåime has a relatively large catchment, a well-defined stream that runs through the lake, and a residence time of less than 10 days (Hammarlund *et al.*, 2004), whereas Lake Getvaltjärnen is a head-water lake with limited stream flow. These hydrological differences, together with the more alpine setting and the abundance of perennial snow-beds at Lake Getvaltjärnen, probably explain the markedly different tephra deposition histories recorded at the two sites (Figure 2). The role of snow-beds in the sedimentation of cryptotephras has not previously been fully explored and further investigation of their influence is required, especially as such features may have been particularly significant during other prolonged cold intervals in arctic and sub-arctic environments.

Post-depositional processes

Vertical displacement of shards as a result of post-depositional processes has been suggested previously with respect to cryptotephra horizons within peat bogs (Gehrels *et al.*, 2006). Such processes may have had a similar influence on the shard concentration profiles observed in this study. Reworking of older sediments caused by bioturbation and mixing at the sediment/water interface are two factors that may have disturbed both shard concentration profiles. By reference to volcanic ash deposits, vertical mixing has been shown to be a particularly dominant process in marine environments, (Ruddiman and Glover, 1972). In particular, the pattern observed in marine sediments is similar to that observed within the Spåime profile. Bioturbation cannot, therefore, be excluded. There is, however, no significant indication of this in the ^{210}Pb or ^{137}Cs profiles, although the activity of these radionuclides is fairly uniform within the sediments spanning the main peaks in tephra concentrations and thus would not be useful indicators of bioturbation.

An additional factor that may have affected tephra sedimentation within these lakes is density settling of volcanic particles. Some studies have demonstrated that tephras are in fact very mobile and prone to density settling through organic sediments (Anderson *et al.*, 1984; Beierle and Bond, 2002). Evidence for this process has been obtained from low-density organic lake sediments indicating significant displacement of tephra layers. Such processes may have contributed to the low level of shards in the lower parts of both records, particularly as the uppermost sediment in lakes is typically a soft-sediment environment. The influence of vegetation may also be significant, particularly close to the margin of lacustrine environments, in which plant roots may contribute towards the downward displacement of tephra shards (eg, Davies *et al.*, 2005). This is unlikely to have been significant in our study as the cores were both sampled close to the centre of the basins.

Core-smearing during sampling is yet another process that may have had an influence on the shard concentration patterns recorded at both sites. Such contamination is particularly difficult to control or assess within loose sediment samples obtained by gravity coring because of the potential problem of younger sediment being drawn down in the sediment core. This process may have contributed towards the downward migration of shards in this study and may account for the presence of a low level of shards below the horizons with the highest shard concentrations at both Lake Spåime and Lake Getvaltjärnen. If so, it is puzzling that this process has not influenced the shard concentration profile of the Veidivötn 1477 tephra in the same way. Nonetheless, precursors in tephra concentration records below well-defined peaks should be interpreted with caution because of this potential problem.

Defining the stratigraphic position of the Askja eruption

As these data demonstrate the possible long residence time of volcanic deposits within lake catchments and the influence of site-specific processes, it is clear that care should be taken in defining the stratigraphic position of a cryptotephra deposit. Our results show that it is difficult to ascertain whether the first occurrence of shards represents the downward migration of particles or indeed represents the precise timing of the volcanic event. It is suggested that a combination of different factors and processes are likely to have led to the observed vertical shard profiles. For instance, at Lake Spåime, the major peak in shard concentration is thought to represent the timing of the Askja eruption, which probably resulted from a short-lived inwash pulse of tephra following the melting of snow in close proximity to the lake. The low level of shards below this peak may have arisen because of downward migration of shards, core-smearing or bioturbation, whereas the long tail in shard concentration is thought to be a result of the slow release of tephra from perennial snow-beds in the catchment. The role of snow-beds is suggested to be more significant in the Lake Getvaltjärnen catchment, although downward migration and reworking may have also contributed to the shard concentration profile. As a result, it is more difficult to determine the level that best represents the time of the Askja eruption at this site. Site-specific processes are clearly significant at Getvaltjärnen, although these do not appear to have affected the vertical distribution of basaltic shards derived from the Veidivötn eruption. This may be due to a difference in the density of basaltic and rhyolitic shards, to downward sediment compaction, or to a different climatic regime – it is possible that no perennial snow-beds existed at the time.

Although not necessarily an easy task, the factors outlined require further investigation so that cryptotephra horizons can be accurately employed as time-synchronous marker horizons. A detailed investigation of the distribution of a tephra of historical age within a varved sequence may shed some light on pinpointing the correct stratigraphic position of a cryptotephra horizon. However, as shown in this investigation, the influence of site-specific processes is likely to differ and so certain criteria for defining the position of cryptotephra horizons may not be applicable to all lacustrine environments.

Conclusion

The results presented in this investigation demonstrate some of the problems that may arise in relation to using tephra horizons as precise tie-points within lacustrine deposits. Two significant trends are identified: (1) detailed geochemical analysis indicates that volcanic products from a particular eruption can be present within lacustrine sediments for at least 120 years; and (2) a low level of shards below the peak in shard concentration requires further investigation to ascertain whether or not this represents the precise timing of the volcanic event. Three main factors have been outlined that may have affected cryptotephra sedimentation in these sub-arctic lakes: (1) the role of perennial snow-beds as tephra traps; (2) bioturbation and vertical mixing of tephra; and (3) downward migration of tephra in uncompacted sediment possibly resulting from core smearing or from the density settling of shards. The shard concentration patterns for these two lakes emphasize the importance of correctly defining the position of a tephra horizon within a lake deposit and giving particular consideration to the operation of site-specific processes and catchment characteristics at the time of the eruption, which can in some instances, as shown at Lake Getvaltjärnen, limit the application of tephrochronology.

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Appendix 1:

n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
Spåime Askja 1875											
2–2.5 cm											
1	69.94	0.96	12.81	4.16	0.07	0.91	2.96	3.59	2.30	0.27	97.99
2	72.41	0.83	12.49	3.52	0.07	0.72	2.60	3.06	2.26	0.22	98.17
3	73.33	0.64	12.29	3.01	0.08	0.57	2.05	3.92	2.69	0.12	98.69
4	71.15	0.89	12.77	3.46	0.12	0.73	2.49	3.78	2.44	0.20	98.02
5	71.92	0.80	12.15	3.33	0.08	0.64	2.37	3.93	2.52	0.15	97.89
6	70.62	0.85	12.71	3.63	0.09	0.79	2.62	3.99	2.34	0.18	97.83
6.5–7cm											
1	71.01	0.82	12.50	3.47	0.05	0.72	2.60	4.02	2.31	0.17	97.69
2	71.09	0.81	12.42	3.53	0.14	0.75	2.58	4.02	2.44	0.19	97.98
3	71.41	0.88	12.30	3.27	0.10	0.67	2.22	3.92	2.51	0.14	97.41
4	71.71	0.87	12.82	3.75	0.15	0.74	2.56	3.03	2.47	0.19	98.30
5	71.33	0.80	12.83	3.81	0.08	0.80	2.74	3.85	2.38	0.24	98.86
6	69.79	0.93	12.72	4.10	0.07	0.79	2.98	3.77	2.33	0.20	97.67
7	71.42	0.75	12.61	3.67	0.05	0.74	2.70	3.88	2.50	0.18	98.50
10–10.5 cm											
1	68.59	1.10	12.97	4.92	0.12	1.11	3.46	3.53	2.08	0.30	98.18
2	69.83	0.98	12.70	4.22	0.14	0.92	2.93	3.86	2.37	0.26	98.21
3	71.65	0.85	12.53	3.84	0.11	0.75	2.68	3.65	2.35	0.12	98.52
4	71.19	0.85	12.19	3.59	0.14	0.81	2.48	4.18	2.21	0.14	97.77
5	72.31	0.80	12.47	3.61	0.11	0.71	2.45	3.87	2.48	0.19	99.00
11–11.5 cm											
1	70.17	0.96	12.90	4.12	0.09	0.80	2.82	4.10	2.20	0.27	98.42
2	72.20	0.77	12.55	3.43	0.08	0.66	2.37	3.91	2.37	0.17	98.52
3	72.78	0.79	12.68	3.29	0.11	0.64	2.37	3.54	2.55	0.12	98.87
4	72.64	0.81	12.52	3.64	0.06	0.74	2.71	4.14	2.28	0.20	99.74
5	72.09	0.82	12.76	3.68	0.09	0.70	2.47	4.19	2.42	0.17	99.40
6	73.13	0.74	12.25	3.09	0.09	0.60	2.19	4.04	2.45	0.16	98.72
7	72.35	0.82	12.51	3.59	0.10	0.70	2.53	3.93	2.28	0.13	98.93
12–12.5 cm											
1	72.68	0.78	12.18	3.22	0.10	0.64	2.21	4.20	2.44	0.14	98.59
2	73.59	0.74	12.47	3.15	0.11	0.59	2.19	3.94	2.48	0.12	99.38
3	71.72	0.90	12.75	3.86	0.16	0.76	2.69	3.98	2.36	0.23	99.40
4	71.98	0.78	12.36	3.35	0.11	0.71	2.41	4.04	2.36	0.16	98.24
5	70.79	0.94	12.76	4.21	0.09	0.84	2.89	4.07	2.36	0.25	99.19
6	73.60	0.70	12.02	2.89	0.04	0.48	1.81	4.04	2.48	0.12	98.18
7	72.16	0.82	12.55	3.48	0.10	0.66	2.46	4.08	2.37	0.18	98.85
8	71.16	0.81	12.31	3.54	0.10	0.69	2.58	3.93	2.32	0.15	97.59
9	70.08	0.90	12.69	4.07	0.14	0.84	2.83	4.01	2.16	0.23	97.94
10	74.23	0.74	12.45	3.05	0.09	0.54	2.13	3.93	2.50	0.14	99.79
11	71.89	0.79	12.61	3.51	0.11	0.67	2.37	4.02	2.34	0.17	98.49
12	69.60	1.09	12.76	5.06	0.14	1.04	3.25	3.99	2.23	0.28	99.42
13	71.98	0.77	12.31	3.30	0.14	0.61	2.34	3.84	2.43	0.16	97.88
14	71.32	0.83	12.52	3.58	0.13	0.75	2.51	4.05	2.34	0.19	98.22
15	71.32	0.91	12.90	3.89	0.09	0.77	2.69	4.08	2.33	0.20	99.18
16	71.47	0.84	12.53	3.76	0.14	0.74	2.62	4.02	2.42	0.17	98.69
17	72.16	0.82	12.70	3.55	0.14	0.69	2.51	3.91	2.35	0.18	99.01
18	72.53	0.84	12.56	3.82	0.15	0.73	2.62	3.95	2.45	0.16	99.79
19	72.61	0.80	12.70	3.54	0.11	0.70	2.37	3.90	2.47	0.14	99.34
20	72.65	0.76	12.15	3.07	0.13	0.58	2.17	3.95	2.52	0.13	98.11
21	71.34	0.80	12.71	3.69	0.13	0.73	2.70	4.02	2.41	0.16	98.69
13–13.5 cm											
1	72.41	0.80	12.58	3.55	0.10	0.68	2.57	4.05	2.38	0.17	99.28
2	71.70	0.95	12.88	3.77	0.11	0.75	2.68	4.19	2.32	0.19	99.53
3	70.64	0.96	12.61	3.94	0.11	0.81	2.88	3.87	2.26	0.30	98.37
4	71.66	0.81	12.38	3.56	0.09	0.69	2.50	4.04	2.25	0.19	98.16
5	72.40	0.80	12.49	3.33	0.09	0.61	2.26	4.02	2.37	0.15	98.52
6	72.45	0.79	12.62	3.73	0.14	0.73	2.55	3.98	2.37	0.20	99.55
13.5–14 cm											
1	69.61	0.98	12.84	4.36	0.10	0.88	3.05	4.07	2.20	0.24	98.33
2	73.06	0.78	12.26	3.14	0.13	0.59	2.21	3.83	2.45	0.13	98.59
3	72.08	0.81	12.32	3.53	0.12	0.71	2.55	4.19	2.33	0.18	98.81
4	71.78	0.83	12.81	3.63	0.13	0.71	2.65	4.20	2.31	0.16	99.20
5	72.73	0.73	12.35	3.31	0.07	0.62	2.26	4.11	2.45	0.15	98.78
6	69.67	0.94	12.96	4.66	0.17	0.86	3.01	4.02	2.14	0.27	98.69
7	71.56	0.82	12.62	3.86	0.11	0.78	2.70	4.08	2.30	0.20	99.03
8	72.15	0.79	12.55	3.53	0.11	0.72	2.46	4.29	2.51	0.14	99.24
9	72.32	0.74	12.31	3.42	0.12	0.63	2.28	3.98	2.47	0.14	98.40

(*continued*)

Appendix 1: (Continued)

n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
15–15.5 cm											
1	71.55	0.86	12.63	3.54	0.15	0.73	2.44	4.14	2.36	0.19	98.59
2	70.71	0.89	12.52	3.94	0.10	0.85	2.77	3.79	2.18	0.17	97.91
3	69.63	0.91	12.56	3.85	0.10	0.84	2.71	3.97	2.34	0.21	97.13
4	69.61	0.80	12.30	3.53	0.07	0.72	2.41	3.82	2.27	0.20	95.72
5	70.85	0.82	12.30	3.39	0.10	0.73	2.44	4.01	2.38	0.16	97.17
6	70.96	0.85	12.34	3.70	0.13	0.62	2.57	3.09	2.29	0.18	96.72
7	71.37	0.76	12.25	3.18	0.12	0.64	2.18	3.83	2.31	0.17	96.80
8	70.36	0.84	12.32	3.63	0.15	0.73	2.51	4.04	2.36	0.20	97.13
16.5–17 cm											
1	71.15	0.85	12.69	3.60	0.14	0.73	2.52	4.34	2.32	0.20	98.55
2	72.46	0.72	12.54	3.07	0.11	0.55	2.11	3.77	2.52	0.14	98.00
Mean	**71.42**	**0.84**	**12.52**	**3.65**	**0.11**	**0.73**	**2.55**	**3.93**	**2.36**	**0.19**	**98.30**
SD	1.25	0.09	0.24	0.44	0.03	0.11	0.30	0.23	0.11	0.05	0.92
Getvaltjärnen Askja 1875											
0–0.5 cm											
1	73.10	0.75	12.62	3.19	0.14	0.71	2.34	3.61	2.40	0.17	99.04
2	70.51	0.88	12.68	4.01	0.13	0.83	2.80	4.16	2.29	0.23	98.52
3	71.67	0.83	12.23	3.50	0.11	0.76	2.39	4.04	2.61	0.25	98.39
4	71.14	0.83	12.56	3.83	0.08	0.78	2.67	3.83	2.32	0.21	98.25
5	71.24	0.83	12.46	3.69	0.10	0.76	2.55	4.07	2.35	0.18	98.23
6	72.02	0.81	12.50	3.39	0.06	0.69	2.27	3.64	2.51	0.18	98.07
7	71.29	0.81	12.21	3.27	0.06	0.72	2.33	3.89	2.36	0.16	97.10
8	71.03	0.85	12.36	3.56	0.10	0.80	2.48	3.45	2.13	0.14	96.89
9	71.58	0.73	12.01	2.89	0.14	0.62	2.05	3.76	2.46	0.11	96.35
0.5–1 cm											
1	71.62	0.81	12.82	3.59	0.14	0.69	2.53	4.24	2.46	0.19	99.09
2	71.63	0.83	12.67	3.64	0.12	0.75	2.63	4.04	2.38	0.22	98.88
3	71.52	0.82	12.67	3.65	0.11	0.73	2.59	4.16	2.34	0.17	98.74
4	72.09	0.80	12.45	3.35	0.12	0.68	2.50	4.09	2.48	0.17	98.72
5	71.21	0.89	12.69	3.74	0.10	0.75	2.63	4.07	2.47	0.17	98.72
6	70.76	0.86	12.66	3.87	0.15	0.86	2.80	4.16	2.39	0.21	98.71
7	71.85	0.79	12.38	3.44	0.12	0.64	2.28	4.05	2.40	0.16	98.10
8	69.35	0.96	12.72	4.39	0.13	0.86	3.12	4.02	2.23	0.27	98.06
9	71.02	0.81	12.55	3.54	0.11	0.75	2.44	4.08	2.32	0.19	97.79
10	71.69	0.81	12.58	3.26	0.08	0.62	2.19	4.06	2.37	0.15	97.79
11	71.10	0.81	12.58	3.40	0.10	0.71	2.34	4.01	2.31	0.17	97.53
1–1.5 cm											
1	72.12	0.81	12.79	3.43	0.10	0.68	2.41	4.10	2.44	0.15	99.03
2	71.71	0.85	12.65	3.74	0.12	0.78	2.59	3.98	2.37	0.19	98.97
3	71.74	0.85	12.68	3.60	0.14	0.78	2.58	3.89	2.52	0.20	98.97
4	71.82	0.88	12.56	3.59	0.13	0.74	2.53	4.01	2.41	0.17	98.85
5	71.41	0.85	12.66	3.70	0.13	0.79	2.54	4.09	2.48	0.18	98.82
6	70.54	0.90	12.66	3.86	0.12	0.82	2.67	4.11	2.34	0.20	98.22
7	71.55	0.82	12.52	3.54	0.12	0.74	2.45	3.93	2.34	0.21	98.19
8	71.23	0.85	12.51	3.67	0.13	0.74	2.49	3.94	2.30	0.17	98.03
9	71.83	0.80	12.44	3.35	0.11	0.70	2.40	3.80	2.37	0.20	97.99
10	70.84	0.85	12.28	3.52	0.13	0.73	2.46	3.97	2.26	0.19	97.22
11	69.69	0.79	12.03	3.30	0.15	0.66	2.26	3.72	2.37	0.13	95.10
2–2.5 cm											
1	72.12	0.84	12.84	3.55	0.10	0.70	2.53	4.06	2.34	0.17	99.24
2	69.66	1.03	12.96	4.71	0.16	0.95	3.29	3.88	2.27	0.27	99.18
3	71.03	0.82	13.06	3.81	0.10	0.79	2.69	4.16	2.38	0.20	99.05
4	71.86	0.84	12.46	3.59	0.08	0.69	2.60	4.08	2.45	0.18	98.83
5	72.68	0.76	12.35	3.27	0.10	0.61	2.29	4.10	2.49	0.13	98.78
6	71.94	0.86	12.42	3.56	0.13	0.74	2.54	3.95	2.34	0.19	98.67
7	72.19	0.76	12.32	3.29	0.10	0.61	2.16	4.18	2.43	0.16	98.19
8	71.63	0.81	12.37	3.37	0.11	0.70	2.32	4.21	2.43	0.15	98.08
9	68.91	0.70	14.77	3.00	0.11	0.57	3.48	4.33	2.06	0.13	98.05
10	72.43	0.76	12.08	2.81	0.11	0.49	1.90	4.20	2.47	0.11	97.35
11	69.98	0.85	12.35	3.70	0.14	0.78	2.50	3.95	2.34	0.20	96.77
12	67.29	0.82	13.71	4.10	0.10	0.77	3.30	4.10	2.11	0.22	96.51
3–3.5 cm											
1	73.05	0.83	13.01	3.52	0.10	0.70	2.46	4.02	2.37	0.18	100.24
2	72.04	0.86	12.77	3.62	0.12	0.72	2.54	4.12	2.29	0.18	99.24
3	71.11	0.83	12.88	3.67	0.16	0.75	2.68	4.26	2.40	0.16	98.90
4	71.78	0.82	12.72	3.44	0.13	0.72	2.40	4.11	2.56	0.14	98.81

Appendix 1: (Continued)

n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
5	71.20	0.86	12.63	3.65	0.16	0.74	2.53	4.21	2.42	0.19	98.59
6	72.71	0.73	12.68	3.25	0.10	0.60	2.12	3.79	2.39	0.13	98.49
7	69.48	0.99	12.82	4.39	0.11	0.94	3.05	4.09	2.20	0.24	98.30
8	71.83	0.79	12.33	3.33	0.12	0.64	2.31	4.07	2.42	0.21	98.04
9	71.14	0.82	12.48	3.49	0.11	0.71	2.50	4.12	2.45	0.18	97.98
10	70.84	0.87	12.70	3.69	0.17	0.73	2.57	4.00	2.24	0.17	97.97
11	71.28	0.86	12.70	3.31	0.12	0.70	2.38	4.08	2.30	0.18	97.91
4.5–5 cm											
1	72.94	0.74	12.49	3.14	0.12	0.63	2.28	3.94	2.53	0.15	98.96
2	71.15	0.85	12.92	3.83	0.13	0.78	2.66	4.15	2.29	0.22	98.96
3	72.19	0.82	12.62	3.24	0.15	0.64	2.33	4.13	2.34	0.13	98.60
4	72.42	0.82	12.43	3.10	0.09	0.56	2.09	4.08	2.45	0.16	98.20
5	69.89	0.87	12.81	4.22	0.08	0.80	2.76	3.98	2.23	0.23	97.86
6	70.63	0.79	12.65	3.56	0.12	0.69	2.44	4.12	2.43	0.18	97.62
7	70.69	0.82	12.33	3.50	0.15	0.72	2.41	4.07	2.23	0.19	97.11
8	69.81	0.74	12.07	3.31	0.10	0.68	2.28	3.92	2.29	0.17	95.37
5.5–6 cm											
1	72.28	0.74	12.57	3.20	0.11	0.65	2.27	4.18	2.36	0.16	98.51
2	71.96	0.78	12.61	3.30	0.11	0.68	2.35	4.24	2.30	0.17	98.50
3	70.87	0.87	12.60	3.99	0.13	0.78	2.66	4.12	2.26	0.20	98.47
4	71.18	0.84	12.74	3.63	0.13	0.72	2.52	4.08	2.40	0.17	98.41
5	71.00	0.85	12.59	3.62	0.11	0.71	2.55	4.12	2.35	0.18	98.09
6	71.93	0.77	12.40	3.26	0.08	0.63	2.23	4.11	2.33	0.16	97.88
7	69.34	0.79	12.43	3.47	0.12	0.70	2.44	4.06	2.26	0.19	95.80
8	68.83	0.79	12.35	3.56	0.10	0.74	2.62	3.83	2.28	0.18	95.29
7–7.5 cm											
1	71.86	0.79	12.40	3.53	0.12	0.67	2.28	3.88	2.46	0.16	98.13
8.5–9 cm											
1	70.99	0.84	12.66	4.03	0.17	0.85	2.75	3.58	2.26	0.19	98.32
2	70.74	0.81	12.42	3.58	0.10	0.74	2.47	3.98	2.27	0.15	97.25
Mean	**71.24**	**0.82**	**12.60**	**3.56**	**0.12**	**0.72**	**2.50**	**4.02**	**2.36**	**0.18**	**98.12**
SD	1.05	0.05	0.36	0.33	0.02	0.08	0.27	0.16	0.10	0.03	0.96
Getvaltjärnen Veidivötn											
9-–9.5 cm											
1	50.55	1.94	13.86	12.03	0.26	6.72	11.31	2.65	0.27	0.29	99.87
2	49.81	1.73	13.84	12.43	0.23	6.82	11.47	2.48	0.22	0.33	99.36
3	50.00	1.87	13.58	12.88	0.22	6.44	11.11	2.54	0.25	0.31	99.19
4	49.52	1.89	13.52	13.00	0.18	6.58	11.31	2.58	0.26	0.33	99.16
5	49.95	1.76	13.77	12.33	0.22	6.66	11.33	2.47	0.20	0.30	98.99
6	49.48	1.79	14.83	11.70	0.19	6.30	11.64	2.48	0.18	0.29	98.85
7	50.02	1.83	14.26	10.68	0.25	7.01	11.65	2.66	0.15	0.32	98.84
8	49.13	1.94	13.43	12.90	0.25	6.81	11.11	2.63	0.20	0.30	98.70
9	49.00	1.90	13.60	12.55	0.26	6.69	11.21	2.56	0.26	0.29	98.33
10	49.10	2.01	13.30	13.02	0.27	6.50	10.93	2.58	0.26	0.31	98.26
11	49.31	1.89	13.37	12.69	0.24	6.52	10.90	2.60	0.23	0.26	98.00
12	48.68	1.94	13.25	12.18	0.17	6.42	10.55	2.58	0.29	0.34	96.42
Mean	**49.43**	**1.87**	**13.67**	**12.36**	**0.23**	**6.62**	**11.18**	**2.57**	**0.23**	**0.30**	**98.46**
SD	0.66	0.08	0.47	0.64	0.03	0.19	0.32	0.06	0.04	0.02	1.11

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Appendix 1

Major element geochemistry for the Askja AD 1875 eruption from Lake Spåime and Lake Getvaltjärnen. Operating conditions of the Cameca SX 100 electron microprobe equipped with 5 vertical WD spectrometers: accelerating voltage 15 kV, beam current 10 nA, beam diameter rastered over 10 mm. For small shards a beam current of 5 nA and beam diameter of 5 mm was used. Counting times on the peak of each element were restricted to 10 s. Sodium was measured in the first counting period and a series of standards (pure metals, synthetic oxides and silicates) were used for calibration. Any drift in the reading was monitored by analysing an andradite at regular intervals. A PAP correction was applied for atomic number, absorption and fluorescence effects (Pouchou and Pichoir, 1991).

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