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Extending the limits of the Borrobol Tephra to Scandinavia and detection of new early Holocene tephras

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Abstract

Analyses of two infilled lakes in Blekinge, southeast Sweden, indicate the presence of at least three tephra horizons of Termination 1 and early Holocene age. Geochemical analyses confirm the presence of the Borrobol Tephra, the Askja Tephra (10,000 ^{14}C yr B.P.), and one previously unreported tephra of Icelandic origin. Extending the limits of the Borrobol Tephra to Scandinavia illustrates that this ash is far more widespread than previously realized and is therefore, an important marker horizon for determining the rate and timing of the initial warming at the start of Greenland Interstade 1 (GI-1) within Europe. The relatively unknown Askja Tephra and the newly discovered Hässeldalen Tephra are stratigraphically placed at the Younger Dryas/Preboreal transition. This paper demonstrates the suitability and success associated with the extraction techniques for tracing microtephra horizons in areas distal to volcanic sources.

Introduction

Tephrochronology has long been recognized as an important correlation tool for sedimentary sequences spanning the Last Termination and the early Holocene (Westgate and Gorton, 1981; Mangerud et al., 1984; Björck et al., 1992; Haflidason et al., 2000; Lowe, 2001). Recent advances in the detection of microtephra horizons (horizons with low concentration of shards, such that the layer of ash is invisible to the naked eye) during this period of abrupt climatic change have extended the known limits of individual Icelandic ash plumes into areas much more distal to the source volcanoes than was previously the case. This includes areas such as the British Isles (Turney et al., 1997, 2001), southern Sweden (Wastergård et al., 1998, 2000a), western Russia (Wastegård et al., 2000b), and northern Germany (Merkt et al., 1993). Furthermore, the advancement of this technique has led to the discovery of previously undetected tephra horizons, such as the Borrobol Tephra (Turney et al., 1997). This tephra, dated to *ca*. 12,300 ^{14}C yr B.P., has until now only been reported in microtephra form in Scottish Late-glacial sequences (Turney et al., 1997, 2001; S. M. Davies, 2002, unpublished work) and in a marine record obtained from the North Icelandic shelf (Eiríksson et al., 2000). Here we show that the Borrobol Tephra along with a relatively unknown tephra from the Askja caldera in the Dyngjufjöll volcanic centre, dated to *ca*. 10,000 ^{14}C yr B.P. (Sigvaldason, 2002), can be traced into southern Scandinavia, and we present data for one previously unreported Icelandic tephra of early Holocene age.

Site descriptions

Hässeldala port (N 56°16′; E 15°03′) and Skallahult (N 56°14′; E 15°30′) are two small infilled lake basins in the county of Blekinge, southeastern Sweden (Fig. 1). The Hässeldala port site is situated between 60 and 65 m a.s.l., above the highest shoreline that developed during the Baltic Ice Lake stage in the early part of the Bølling pollen zone (Björck and Möller, 1987) or Greenland Interstadial 1e (GI-1e) (Björck et al., 1998). Skallahult is situated at *ca*. 50 m a.s.l. and was probably a part of the Baltic Ice Lake for some time before its isolation.

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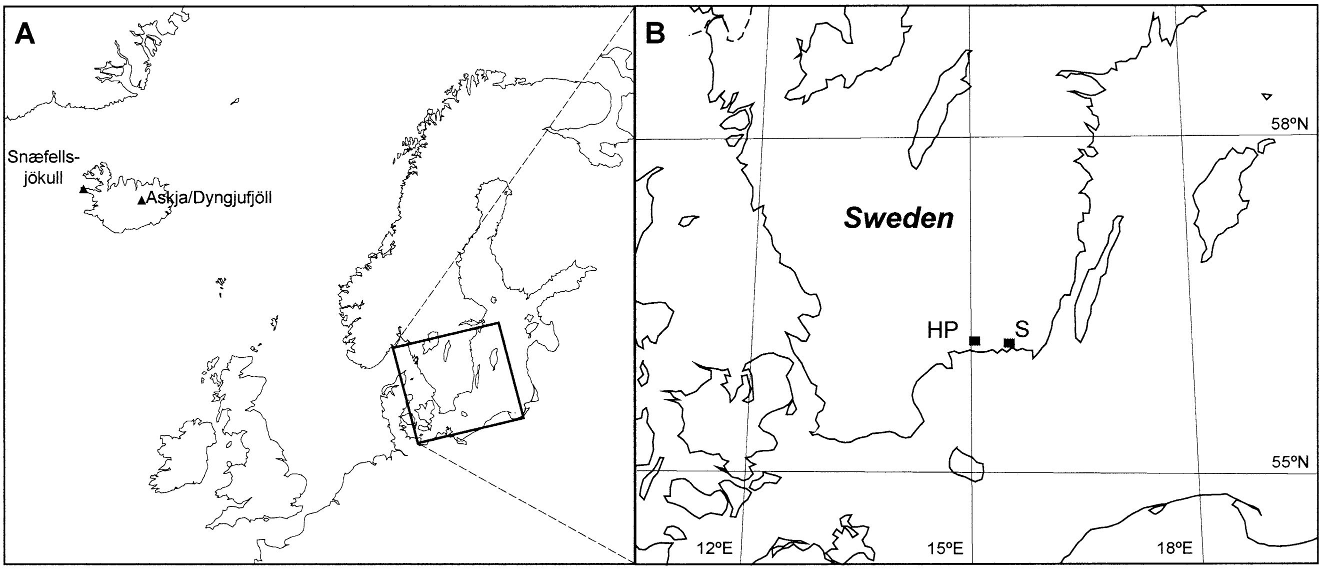

Fig. 1. Location map of Hässeldala port (HP) and Skallahult (S). The locations of the Snæfellsjökull and Askja volcanoes are also shown.

Methods

The 1-m-long cores obtained from both sites were subsampled contiguously at every centimeter for loss on ignition measurements (2 h at 550°C). Samples of 1 cm^3 were examined for the presence of tephras using a density separation technique (outlined by Turney, 1998) with all samples floated between 2.3 and 2.5 g cm^{-3} (the $<$2.3 and 2.3–2.5 g cm^{-3} fractions were retained for a search for the Laacher See Tephra (LST)). This technique was not used for the early Holocene samples that were rich in organic matter. These were ashed at 550°C (Pilcher and Hall, 1992; Pilcher et al., 1996) and treated with sodium hydroxide (0.3 M) in a water bath at 90°C for 3 h to remove biogenic silica (Rose et al., 1996). Shard concentration was determined by optical identification under a high-powered polarized light microscope and expressed per cm^3 of wet sediment. A standard acid digestion technique was used to remove the organic material for the preparation of samples prior to geochemical analysis (Dugmore et al., 1995).

Quantitative geochemical analysis of the glass shards was undertaken on a Cambridge Instruments Microscan V probe at the Tephrochronology Analytical Unit, Department of Geology and Geophysics, University of Edinburgh, UK (for analytical conditions see Tables 1 and 2).

Results

Three tephras have been clearly identified from the sequence at Hässeldala port at depths of 303, 247, and 238 cm (Fig. 2). The concentration of shards varied markedly at this site with a peak concentration of ~190 shards cm^{-3} within the horizon at 303 cm, 75 shards cm^{-3} at 247 cm, and only 9 shards cm^{-3} within the horizon found at 238 cm. The two tephras discovered at Skallahult, at depths of 367 and 318 cm in the sequence, comprise shard concentrations of 52 shards and 41 shards cm^{-3} respectively. Two other tephras were discovered at Hässeldala port at depths of 278 and 266 cm and at 336 cm at Skallahult, but due to the low number of shards present in these horizons, geochemical analysis was not possible.

The lowermost tephra found at both sites is confirmed geochemically to be the Borrobol Tephra (Table 1 and Fig. 3) dated to *ca*. 12,300 ^{14}C yr B.P. in Scotland (Lowe et al., 1999). The geochemical signature is unique for this tephra and strongly suggests an Icelandic origin from an alkaline rhyolitic system, possibly Torfajökull or Snæfellsjökull, although Hekla has also been suggested (Haflidason et al., 2000). Until now this tephra has only been discovered in microtephra form within five Scottish sites (Turney et al., 1997, 2001; S. M. Davies 2002, unpublished work) and in a marine core from the Iceland plateau (Eiríksson et al., 2000). It is clear, therefore, that this ash is probably far more widespread than previously realized, at least in microtephra form.

The geochemical data for the early Holocene tephras at 247 cm at Hässeldala port and at 318 cm at Skallahult are identical and distinctly Icelandic in provenance. This tephra has a very similar geochemistry to the Borrobol Tephra, as exemplified in the triangular diagrams (Fig. 3); however, they are distinguishable by their FeO_{tot} and CaO contents (Tables 1 and 2 and Fig. 3). Based on the lithostratigraphy, this tephra is placed at the Younger Dryas/Preboreal transition, shortly after the onset of rapid warming, with an estimated age of *ca*. 11,500 cal yr B.P. Furthermore, it occurs immediately prior to the pronounced Preboreal oscillation dated to *ca*. 11,300–11,200 cal yr B.P. in southern Sweden (Björck et al., 2002) (Fig. 2). Currently, there are no known tephras of this age with similar geochemistry, al-

Table 1
Major oxide concentrations of glass shards extracted from Hässeldala port, Blekinge

No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
					Askja Tephra (10,000 ^{14}C yr BP) Hässeldala port (237 and 238 cm)					
1	73.86	0.30	11.93	2.53	0.08	0.25	1.54	3.32	2.45	96.27
2	72.93	0.33	11.76	2.50	0.07	0.27	1.57	3.44	2.48	95.35
3	74.04	0.31	11.88	2.45	0.09	0.27	1.65	3.20	2.47	96.36
4	75.01	0.29	12.03	2.55	0.09	0.26	1.57	2.89	2.55	97.24
5	75.05	0.31	12.23	2.54	0.08	0.25	1.63	3.08	2.51	97.67
Mean	74.18	0.31	11.97	2.51	0.08	0.26	1.59	3.18	2.49	96.58
St dev	0.88	0.01	0.18	0.04	0.01	0.01	0.05	0.21	0.04	0.90
					Hässeldalen Tephra Hässeldala port (247 cm)					
1	74.22	0.07	11.80	1.21	0.02	0.03	0.52	3.49	3.96	95.31
2	74.86	0.11	11.63	1.05	0.02	0.04	0.39	3.12	4.04	95.26
3	74.73	0.09	11.60	0.96	0.03	0.04	0.40	3.04	4.26	95.15
4	74.23	0.11	11.60	1.11	0.05	0.05	0.46	3.20	3.70	94.51
5	73.95	0.11	11.79	1.13	0.01	0.06	0.47	3.12	4.06	94.70
6	73.80	0.11	11.80	1.16	0.03	0.05	0.47	3.24	3.83	94.50
7	74.39	0.10	11.62	0.98	0.01	0.01	0.43	2.77	4.07	94.38
8	73.48	0.10	11.77	1.29	0.05	0.02	0.54	3.22	3.74	94.22
9	73.51	0.09	11.84	1.21	0.03	0.02	0.55	3.24	3.67	94.16
10	73.32	0.08	11.74	1.12	0.05	0.03	0.50	3.39	3.97	94.18
Mean	74.05	0.10	11.72	1.12	0.03	0.04	0.47	3.18	3.93	94.64
St dev	0.53	0.02	0.10	0.10	0.02	0.01	0.05	0.20	0.19	0.45
					Borrobol Tephra Hässeldala port (303 cm)					
1	73.57	0.14	12.39	1.47	0.04	0.04	0.72	3.39	3.99	95.75
2	73.11	0.13	12.30	1.52	0.00	0.07	0.77	3.62	3.68	95.20
3	73.02	0.14	12.38	1.59	0.05	0.07	0.66	3.47	3.80	95.18
4	72.90	0.14	12.30	1.50	0.04	0.09	0.72	3.37	3.90	94.96
5	73.18	0.07	12.27	1.50	0.03	0.09	0.77	3.26	3.76	94.93
6	72.99	0.14	12.36	1.51	0.02	0.09	0.79	3.38	3.63	94.91
7	73.12	0.10	12.23	1.57	0.03	0.09	0.72	3.25	3.72	94.83
8	72.87	0.11	12.47	1.51	0.05	0.08	0.74	3.29	3.69	94.81
9	72.64	0.13	12.28	1.61	0.00	0.11	0.83	3.53	3.68	94.81
10	73.12	0.10	12.19	1.40	0.07	0.06	0.68	3.31	3.83	94.75
11	72.93	0.13	12.22	1.53	0.06	0.08	0.74	3.37	3.68	94.74
12	72.76	0.18	12.18	1.50	0.03	0.10	0.77	3.36	3.86	94.74
13	72.72	0.11	11.98	1.50	0.06	0.10	0.74	3.66	3.87	94.74
14	72.91	0.12	12.09	1.35	0.05	0.05	0.83	3.38	3.92	94.70
15	72.86	0.13	12.29	1.49	0.05	0.05	0.77	3.36	3.69	94.69
16	72.77	0.11	12.29	1.51	0.07	0.12	0.74	3.41	3.66	94.68
17	72.60	0.13	12.34	1.47	0.06	0.07	0.84	3.46	3.68	94.63
18	73.03	0.11	12.24	1.48	0.05	0.06	0.76	3.30	3.57	94.58
19	72.69	0.17	12.12	1.50	0.00	0.11	0.90	3.38	3.67	94.54
20	72.98	0.16	12.39	1.18	0.04	0.08	0.62	3.40	3.67	94.52
21	73.08	0.11	12.25	1.09	0.02	0.03	0.70	3.31	3.78	94.37
22	72.61	0.13	12.27	1.48	0.05	0.08	0.76	3.24	3.74	94.34
23	72.34	0.13	12.32	1.49	0.02	0.09	0.70	3.23	3.82	94.14
Mean	72.90	0.13	12.27	1.47	0.04	0.08	0.75	3.38	3.75	94.76
St dev	0.25	0.02	0.11	0.12	0.02	0.02	0.06	0.11	0.11	0.33

Note. Mean and 1 standard deviation are shown. Material from 237 and 238 cm were used to obtained sufficient shards for the analyses of the tephra at these depths. All oxides are expressed as wt%. Total iron is expressed as FeO. Analyses were obtained on an electron microprobe by wavelength dispersive spectrometry with an accelerating voltage of 20 kV, a 15-nA beam current, and a beam diameter of 1 μm. Sodium was measured in the first and last counting period to monitor the degree of mobilization. Calibration was undertaken by analyzing standards of pure metals, synthetic oxides, and silicates and an andradite was analyzed at regular intervals to monitor any drift in the readings. A ZAF adjustment was applied to correct for atomic number, absorption, and fluorescence effects (Sweatman and Long, 1969), and counter dead time was also corrected for. The data are not normalized following European convention (Hunt and Hill, 1993) and analyses with an analytical total above 94% are included.

Table 2
Major oxide concentration of glass shards extracted from Skallahult, Blekinge

No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
					Hässeldalen Tephra Skallahult (318 cm)					
1	74.77	0.05	11.58	1.23	0.08	0.07	0.55	3.77	3.95	96.05
2	74.32	0.10	11.44	1.22	0.08	0.07	0.53	3.22	4.10	95.07
3	74.03	0.08	11.83	0.75	0.05	0.03	0.41	3.90	3.72	94.80
4	74.54	0.12	11.69	0.88	0.04	0.05	0.32	3.06	4.08	94.78
5	74.61	0.08	11.19	1.02	0.03	0.06	0.38	3.07	4.28	94.72
6	74.26	0.10	11.29	1.12	0.07	0.08	0.46	3.15	3.89	94.42
7	73.84	0.08	11.61	1.15	0.04	0.06	0.45	3.26	3.81	94.31
8	73.39	0.13	11.60	1.19	0.10	0.08	0.49	3.32	3.88	94.18
9	73.79	0.10	11.56	0.94	0.05	0.04	0.38	3.11	4.15	94.12
10	73.46	0.09	11.59	1.21	0.09	0.08	0.55	3.17	3.88	94.12
11	73.56	0.11	11.78	0.87	0.02	0.05	0.46	3.03	4.22	94.10
12	73.67	0.04	11.55	1.10	0.08	0.05	0.50	3.27	3.84	94.10
13	73.77	0.09	11.55	1.07	0.05	0.05	0.42	3.11	3.91	94.02
Mean	74.00	0.09	11.56	1.06	0.06	0.06	0.45	3.26	3.98	94.52
St dev	0.46	0.03	0.18	0.16	0.02	0.02	0.07	0.27	0.17	0.57
					Borrobol Tephra Skallahult (367 cm)					
1	73.14	0.18	12.42	1.54	0.00	0.09	0.74	3.17	3.76	95.04
2	72.61	0.13	12.45	1.61	0.04	0.11	0.79	3.34	3.64	94.70
3	72.69	0.14	12.35	1.48	0.04	0.11	0.74	3.12	3.78	94.45
4	72.30	0.13	12.34	1.43	0.03	0.12	0.76	3.37	3.76	94.23
5	72.33	0.16	12.31	1.51	0.00	0.12	0.69	3.35	3.67	94.14
6	72.43	0.15	12.27	1.40	0.03	0.11	0.66	3.23	3.81	94.09
7	72.19	0.13	12.24	1.49	0.04	0.10	0.70	3.52	3.63	94.04
8	72.47	0.13	12.18	1.42	0.04	0.10	0.71	3.19	3.79	94.03
Mean	72.52	0.14	12.32	1.48	0.03	0.11	0.72	3.28	3.73	94.34
St dev	0.30	0.02	0.09	0.07	0.02	0.01	0.04	0.13	0.07	0.36

Note. Mean and 1 standard deviation are shown. All oxides are expressed as wt%. Total iron is expressed as FeO. Analyses were obtained on an electron microprobe by wavelength dispersive spectrometry with an accelerating voltage of 20 kV, a 15-nA beam current, and a beam diameter of 1 μm. Sodium was measured in the first and last counting period to monitor the degree of mobilization. Calibration was undertaken by analyzing standards of pure metals, synthetic oxides, and silicates, and an andradite was analyzed at regular intervals to monitor any drift in the readings. A ZAF adjustment was applied to correct for atomic number, absorption, and fluorescence effects (Sweatman and Long, 1969) and counter dead time was also corrected for. The data are not normalized following European convention (Hunt and Hill, 1993) and analyses with an analytical total above 94% are included.

though this ash layer has some geochemical affinites with the Svínavatn Tephra (SSn) (Boygle, 1999) dated to around 7000–6000 ^{14}C yr B.P. and the more recently reported BGMT-3 Tephra (2340 cal yr B.P.) (Langdon and Barber, 2001). Both are unlikely to the tephra reported here, due to the wide age discrepancy and to the markedly dissimilar FeO_{tot} and CaO contents. On the other hand, the Hovsdalur Tephra (Wastegård, 2002), dated to *ca*. 9300 ^{14}C yr B.P., has an identical geochemistry but differs in age, although the tephra at Hässeldala port is yet to be precisely dated. However, these four tephras may have originated from the same volcano. The highly siliceous nature and the alkali ratios close to one (Na_2O:K_2O) (Imsland, 1978) point toward the Snæfellsjökull volcano in the Snæfellsnes volcanic zone, western Iceland (Fig. 1), as the most likely common source for these three tephras. Nevertheless, it appears, that the tephra horizon discovered at these two Swedish sites has not been previously reported in the literature; it is therefore hereafter referred to as the Hässeldalen Tephra, after the site of its first discovery.

The highly siliceous nature of the ash recovered from 238 cm in the Hässeldala port sequence also indicates an Icelandic volcanic source. CaO (1.59%) and FeO (2.51%) concentrations in excess of those for the Hässeldalen Tephra and Borrobol Tephra indicate that these are not reworked shards from the previous events (Table 1 and Fig. 3). The geochemical signature of these shards seems to correlate with a relatively unknown rhyolitic tephra of 10,000 ^{14}C yr B.P. age from the Askja caldera within the Dyngjufjöll center, Iceland (Sigvaldason, 2002) (Fig. 3). There are some dissimilarities between the geochemical composition of these two populations, especially within the Na_2O and Al_2O_3 concentrations (Fig. 3). However, the stratigraphic position of this tephra within the early Holocene period, subsequent to the Younger Dryas/Holocene transition, fits well with the Askja Tephra. In view

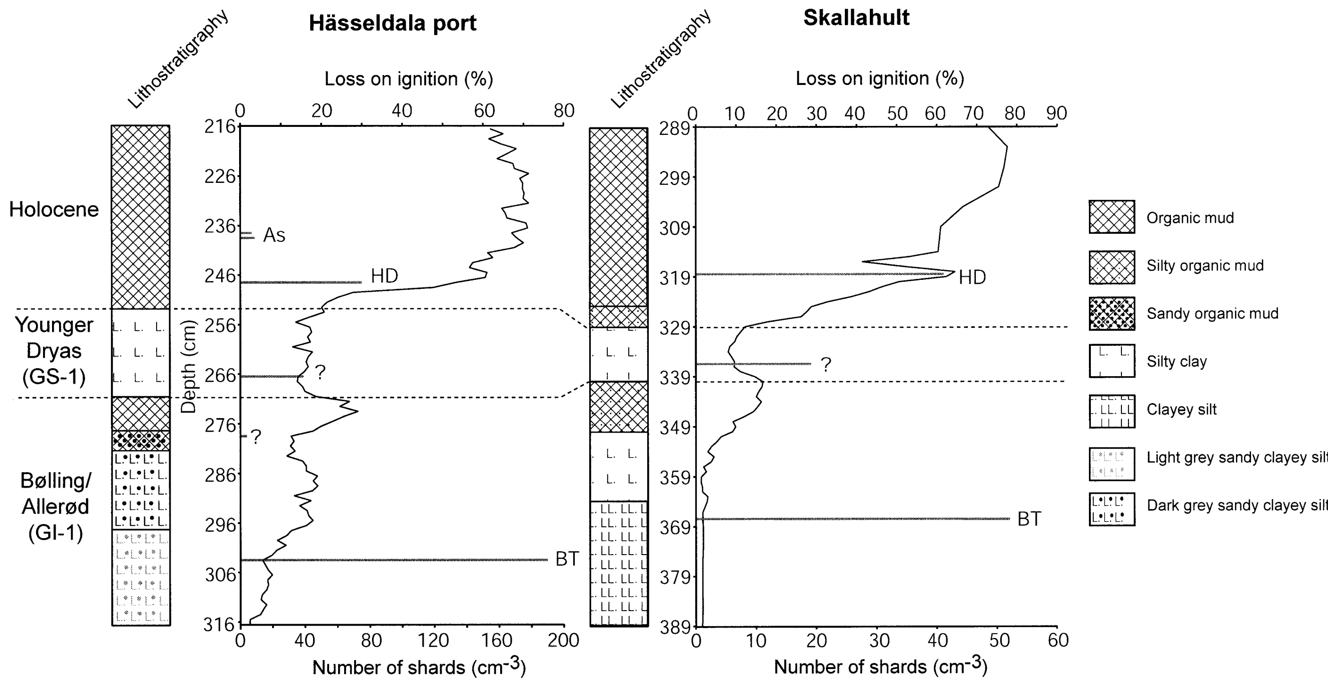

Fig. 2. Lithostratigraphy, loss on ignition, and tephra counts for Hässeldala port and Skallahult. Only the peaks for shard concentration are shown. Abbreviations are as follows: GI-1, Greenland Interstade 1; GS-1, Greenland Stade 1 following Björck et al. (1998); BT, Borrobol Tephra; HD, Hässeldalen Tephra; As, Askja Tephra (10,000 ^{14}C yr B.P.).

of the stratigraphical information and geochemical signature, this tephra is assigned to the Askja volcanic event. Until know this tephra has only been discovered in sedimentary sequences in northeastern Iceland (Sigvaldason, 2002).

Determination of the origin of the two other tephras discovered at this site is problematic in the absence of any firm geochemical evidence. These levels equate with expected stratigraphic positions of the Laacher See Tephra, dated to *ca*. 12,880 cal yr B.P. (Brauer et al., 1999), and the Vedde Ash, dated to *ca*. 12,000 GRIP ice core yr B.P. (Grönvold et al., 1995). Typically the tephra shards in the upper horizon were platy and colorless, similar to those described elsewhere for the Vedde Ash (Mangerud et al., 1984) while the few shards discovered at 278 cm were vesicle-rich, consistent with typical LST shards (van den Bogaard and Schmincke, 1985). The two sites lie within the limits of the Vedde Ash plume (Wastegård et al., 2000a) that has been traced as far as western Russia (Wastegård et al., 2000b). The northeastern plume from the Laacher See eruption, on the other hand, is known to have reached as far north as the southern Baltic region, based on the detection of visible occurrences of this tephra (Kleissle and Müller, 1969; Usinger, 1977). It has not yet been traced further afield by the detection of microtephra horizons. In the absence of geochemical analysis, however, the records of Vedde Ash and LST at Hässeldala port are equivocal.

Discussion

By extending the detection of the Borrobol Tephra into southern Sweden we have established that this ash is far more widespread than was previously realized. It therefore serves as an important marker horizon for comparing the precise timing of the initial warming at the start of GI-1 in different parts of Europe. It appears that at the time of the deposition of the Borrobol Tephra warming had not yet occurred in southern Sweden, if the loss on ignition curves are used as a crude proxy for lake productivity and hence as an indication of regional warming. In contrast, the Borrobol Tephra discovered within Scottish lakes falls shortly after the initial rise in loss on ignition that marks the start of the GI-1 period and below the minor oscillation thought to correlate with the GI-1d or Older Dryas event (Turney et al., 1997; Lowe, 2001). Over the same period, foraminiferal, lithostratigraphic, and tephrochronological data suggest that a cooling event occurred on the North Icelandic shelf at this time (Eiríksson et al., 2000). These correlations, confirmed by tephrochronology, imply that climatic change at the start of GI-1 were not synchronous within northwest Europe, supporting the conclusions reached by Coope and Lemdahl (1995), Coope et al. (1998), and Witte et al. (1998) based on fossil beetle data. However, due to the proximity of the Swedish sites to the Baltic Ice Lake, local factors may have partly obscured or prevented any changes caused by a more general, regional warming at the start of GI-1 in southern Sweden.

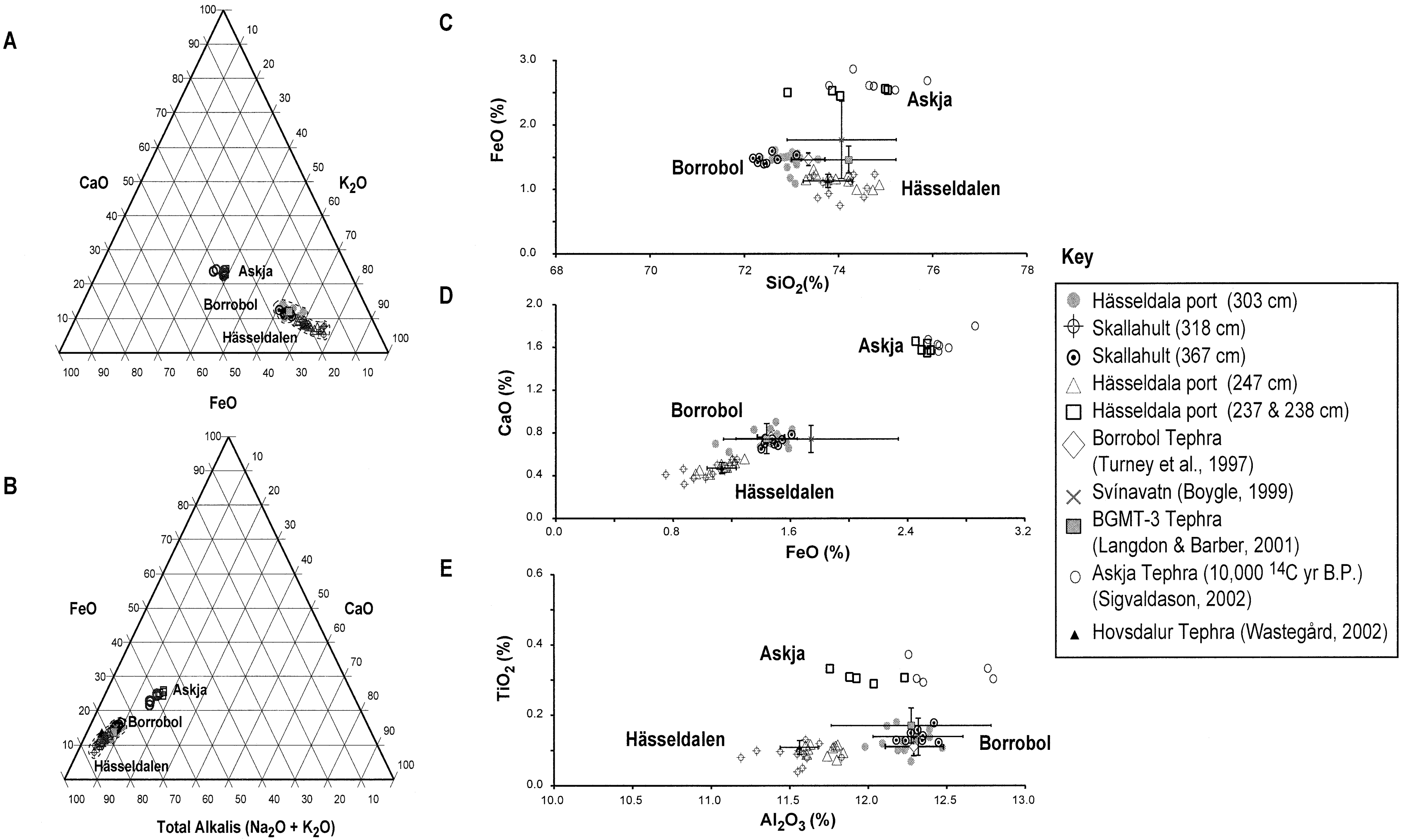

Fig. 3. Major oxide data of glass shards discovered at Hässeldala port and Skallahult. Mean compositions of the Borrobol Tephra (Turney et al., 1997), Svínavatn Tephra (Boygle, 1999), BGMT-3 Tephra (Langdon and Barber, 2001), Hovsdalur Tephra (Wastegård, 2002), and Askja Tephra (10,000 ^{14}C yr B.P.; Sigvaldason, 2001). (A) Ternary plot indicating variations in the proportions of FeO_{tot}, CaO, and K_2O. (B) Ternary plot indicating variations in the proportions of total alkalis (Na_2O + K_2O), FeO, and CaO. (C–E) Biplots of selected major element data.

The Borrobol Tephra is evidently an important marker horizon for establishing the rate and regional effects of climatic developments within Europe at the beginning of GI-1. The Askja 10,000 ^{14}C yr B.P. Tephra and Hässeldalen Tephra could also be of similar significance for the precise correlation of sediment sequences in Europe which span the Younger Dryas (GS-1)/Holocene transition if they can be detected at other European sites. If transport was predominantly in a southeasterly direction, then there is a strong possibility that these tephras could be detected within several sediment sequences located in northern Europe that span Termination 1 and the early Holocene. Furthermore, the discovery of the Hässeldalen Tephra adds to our knowledge of the sequence of Icelandic eruptions during this time and confirms that the tephrochronology framework for this region is far from complete (van den Bogaard and Schmincke, 2002). The extension of the known provenance of tephra horizons has greatly improved the potential for precisely correlating marine, terrestrial, and ice core records in order to assess the degree to which the rapid and abrupt climatic changes of this period were synchronous or asynchronous. With 29 tephras known to have been erupted from the four main European volcanic centers (Iceland, Massif Central, Eifel and Italy) during this period (Davies et al., 2002), there is considerable scope for tracing these ashes over wider areas.

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