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Distal cryptotephra found in a Viking boathouse: the potential for tephrochronology in reconstructing the Iron Age in Norway

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ABSTRACT

Distal tephra deposits from Icelandic volcanic eruptions have been found in Norway and can be used to precisely date a variety of sedimentary environments. Tephrochronology has not yet been applied to archaeological investigations in Norway because tephra are generally not found as visible layers, but are present as very low concentrations of glass shards (i.e. cryptotephra). In this study, we present results from the analysis of cryptotephras found in an Iron Age boathouse in northern Norway. The boathouse was associated with the chieftain center at Borg on Vestvågøy in the Lofoten Islands. In 2003, a trench was excavated and the stratigraphy of the boathouse was described. Radiocarbon ages from cultural deposits show that it was constructed in the Early Iron Age c. AD 540–660 and the main period of use was at the end of the Iron Age between c. AD 1030 and AD 1270. Volcanic glass shards were isolated from sediment samples collected above and below the cultural deposit representing the main period of use. Electron microprobe analysis of the glass shards showed that the lower sample resembles the AD 860 Layer B tephra and the upper sample resembles tephra erupted from the Hekla volcanic system between AD 1104 and AD 1300. These tephrochronologic dates agree with the radiocarbon-derived dates and possibly further constrain the boathouse's main period of use to c. AD 1030–1104. Our results demonstrate the value of using tephrochronology for archaeological studies in Norway and the potential for finding cryptotephra from other large explosive volcanic eruptions during the Iron Age.

1. Introduction

Tephrochronology is a dating technique based on the identification of pyroclastic deposits, typically ash (<2 mm in diameter), in sedimentary environments (Alloway et al., 2007). Tephras form time-synchronous horizons that can be geochemically matched to known volcanic eruptions or used as marker horizons to correlate between deposits. Tephras can provide age control in sediments void of material suitable for other dating techniques or can supplement existing chronologies. In particular, tephras can improve radiocarbon chronologies where reworking is suspected or where plateaus exist in the calibration curve. Tephrochronology is limited to the area covered by identifiable fallout and is typically applied proximal to volcanic centers where visible tephra layers are found. However, in some cases it is possible to isolate and identify fine-grained, finely-dispersed, tephra deposits (primarily glass shards) that are not visible as distinct layers. These deposits are known as cryptotephras, a term derived from the Greek *kryptein*, which means to hide (Alloway et al., 2007; Lowe and Hunt, 2001).

In the North Atlantic region, the volcanic systems of Iceland have been the most significant producers of tephra. The volcanic history has been well studied and there are a number of historic and prehistoric explosive eruptions that have produced tephra which form discrete layers useful for paleoenvironmental reconstructions (Haflidason et al., 2000; Larsen and Eiríksson, 2008; Larsen et al., 1999; Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007). Archaeological investigations in Iceland take advantage of the robust tephrostratigraphy and have used tephrochronology to date settlement periods, landscape change, and soil erosion (e.g. Dugmore et al., 2000, 2005, 2009; Thorarinsson, 1981). The initial settlement of Iceland has even been constrained using tephrochronology. The timing of this event coincides with deposition of the precisely dated Landnám tephra (871 ± 2 AD; Grönvold et al., 1995) that is spread across most of Iceland marking the beginning of human occupation (Dugmore et al., 2005).

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Tephra fallout from Icelandic volcanic eruptions is not limited to local sites. The most voluminous Icelandic eruptions have deposited tephras around the North Atlantic region. Tephras have been found as visible horizons in northern Europe (Birks et al., 1996; Davies et al., 2001; Mangerud et al., 1984), but are more often found as cryptotephra. The first Icelandic cryptotephra was found in Scotland (Dugmore, 1989) and the more recent development of density separation techniques (Turney, 1998) has led to the identification of cryptotephras from specific eruptions across a wider geographic area and has expanded the use of tephrochronology to more distal regions (e.g. Davies et al., 2010; Turney et al., 2006; Wastegård and Davies, 2009).

In Norway, a few Icelandic tephras have been found as visible layers (Birks et al., 1996; Mangerud et al., 1984), but more commonly they occur as cryptotephras. An investigation of the Holocene cryptotephra stratigraphy in northern Norway identified twenty-three tephras (Pilcher et al., 2005). These results demonstrated the potential for expanding the use of tephrochronology in Norway. The use of crypto-tephrochronology has been applied to a few paleoenvironmental studies (Balascio et al., *in press*; Mills et al., 2009; Vorren et al., 2007), but we wanted to test its application to constrain the age of cultural horizons in Norway. In this study we examined cryptotephra in sediment samples collected during the excavation of a Viking boathouse in northern Norway on the island of Vestvågøy in the Lofoten Islands (Fig. 1) (Wickler and Nilsen, 2005). We isolated volcanic glass shards from two stratigraphic units, geochemically matched their major-element composition to known eruptions, and compared our results with radiocarbon ages obtained from the boathouse and similar contexts in the area.

2. Site description

The boathouse, Naust 48, is located on the western shore of Inner Borgpollen (68°14.94'N; 13°46.69'E) at the settlement of Borg on the island of Vestvågøy in the Lofoten Islands (Fig. 1). Borg was the location of an Iron Age chieftain center and Borgpollen provided a protected natural harbor around which the remains of c. 20 Iron Age boathouses have been recorded (Munch et al., 2003; Nilsen, 1998). Previous investigations have examined the local distribution of boathouses in the context of the maritime history of the islands (Nilsen, 1998; Wickler, 2004; Wickler and Nilsen, 2005). The structures around Borgpollen are currently c. 1–3 m above sea level as a result of continued glacial-isostatic rebound (Mills et al., 2009; Møller, 1986). Based on estimates of former shorelines and radiocarbon ages from excavations, these boathouses span most of the Iron Age and extend into the Medieval Period, c. AD 1–1300 (Nilsen, 1998; Wickler, 2004). A majority of the structures are large and five are over 15 m in length, although four of the structures would have housed boats less than 6 m in length.

The remains of the boathouse are visible on the surface as linear mounds marking the collapsed walls of a roughly rectangular open-ended structure constructed of stone, peat, and soil with an opening facing the water (Wickler and Nilsen, 2005). The Naust 48 boathouse is situated 8 m from the water at an elevation of 1.3 m and has interior dimensions of $\sim 16.5 \times 3.2$ m. In 2003, a 3×0.5 m trench was excavated perpendicular to the long axis of the structure between the walls near the entrance. The trench profile revealed a stratigraphic sequence with a cultural deposit up to 15 cm in thickness (Fig. 2). There appeared to be two distinct phases of use separated by an extensive zone of dense charcoal with fire-cracked rock interpreted as the remains of multiple hearths. Radiocarbon samples from this zone and slightly above gave dates of 902 ± 40 ^{14}C years BP and 860 ± 75 ^{14}C years BP, respectively. A second concentration of charcoal and fire-cracked rock from a hearth at the base of the cultural deposit produced a date of 1450 ± 45 ^{14}C years BP. The dates correspond with 2-sigma calibrated ages of AD 538–662 for initial construction and AD 1030–1271 for the main period of use (Table 1; Wickler and Nilsen, 2005). Two sediment samples were collected for tephra analysis. One was taken from the middle of the Layer Ib cultural deposit (CAT-6) and the other from the stratigraphic unit Layer Ia above the cultural deposit (CAT-5).

3. Tephra analysis

Samples CAT-5 and CAT-6 from Naust 48 were treated with nitric acid (HNO_3) and then placed in an 80 °C water bath for 3 h to remove the organic components of the sediment. Although tephra particles can experience chemical alteration during acid digestions (Blockley et al., 2005), the surface of each glass particle was subsequently removed during polishing in preparation for microprobe analysis and we assume that the grain interiors are less likely to have undergone alteration. Following acid digestion, the remaining material was washed in deionized water over two stacked sieves with mesh sizes of 63 μm and 20 μm to isolate grain sizes typical of distal tephra particles. Heavy liquid density separations were then performed on the 20–63 μm fraction using sodium polytungstate

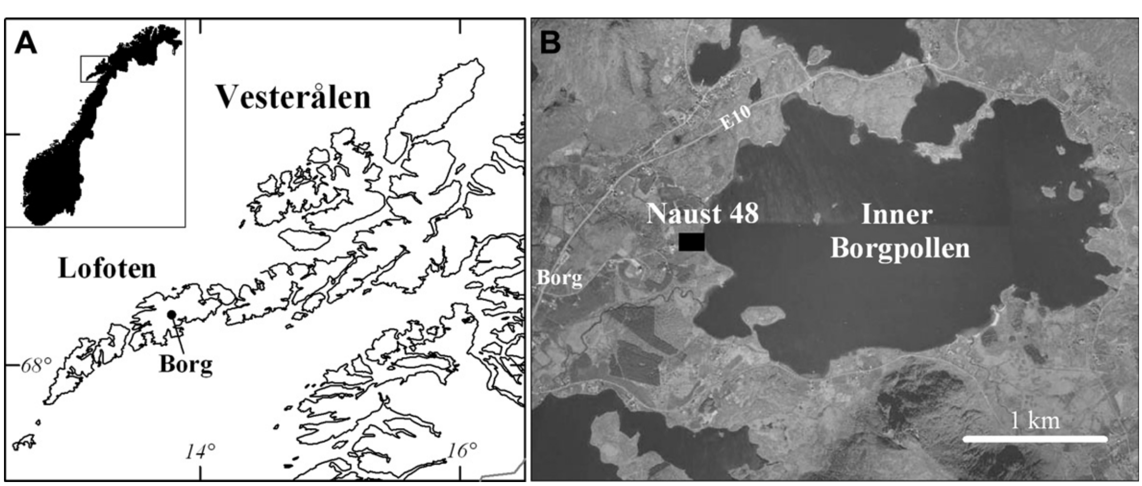

Fig. 1. (A) Location of Viking settlement at Borg on Vestvågøy in the Lofoten Islands, northern Norway. (B) Location of the boathouse Naust 48 on the western shore of Inner Borgpollen.

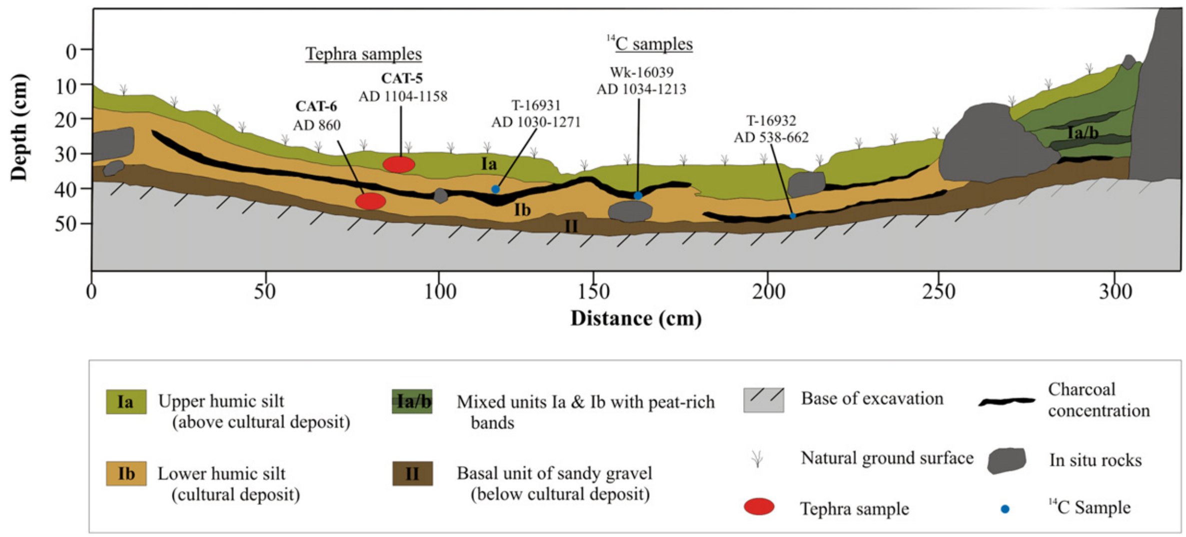

Fig. 2. East face stratigraphic profile of the Naust 48 boathouse excavation trench. Calibrated radiocarbon dates are from Wickler and Nilsen (2005), and dates on tephra samples are based on tephrochronology (this study).

($Na_6(H_2W_{12}O_{40})H_2O$) to concentrate glass shards, typically 2.3–2.5 g cm^{-3} for rhyolitic glass, from the remaining mineral grains following methods described by Turney (1998). The sediment was subjected to three floats using sodium polytungstate at 2.3 g cm^{-3}. Sediment less than 2.3 g cm^{-3} was discarded and another series of three floats was performed using sodium polytungstate at 2.5 g cm^{-3}. Following this step, the sediment that was less than 2.5 g cm^{-3} was retained, cleaned in deionized water, mounted on microscope slides in epoxy resin, and glass shards were identified using a polarizing light microscope. Slides were then polished to expose the grain interiors and then analyzed with a Cameca SX50 electron microprobe at the University of Massachusetts at Amherst using wavelength dispersal spectrometry with an accelerating voltage of 15 keV, a beam current of 10 nA, and beam size of 5–10 μm. Instrument calibration was performed using a series of silicate minerals, synthetic oxides, and glass standards. Results are reported as non-normalized major oxide concentrations. The geochemical analyses of these glass shards were then compared with those of samples of known age found in other locations around the North Atlantic region and using the *Tephrabase* database (Newton et al., 2007; http://www.tephrabase.org).

4. Results

Both CAT-5 and CAT-6 contained colorless vesicular glass shards that were 40–60 μm in diameter (Fig. 3). Shards in CAT-6 were generally smaller and had much thinner walls than those found in CAT-5, which made microprobe analysis difficult and resulted in low analytical totals for some grains. For both samples, the Na_2O contents were lower than those of potential correlatives, probably as a result of Na loss during microprobe analysis (e.g. Hunt and Hill, 2001). However within each sample, the major oxide concentrations grouped into distinct geochemical populations.

In CAT-5, nine shards were analyzed (Table 2). Results for each grain are the average of between 3 and 5 separate analyses. The number of analyses per grain depended on the size of the exposed surface area of each grain. Totals less than 96% were not included in the average. The data fall within three geochemical populations, which are distinguished mainly by their SiO_2, FeO (total Fe), and MgO content, with the largest group showing the highest precision (Fig. 4).

In CAT-6, seven tephra grains were analyzed (Table 2). Additional tephra shards were identified with the microprobe, but because of thin grain walls and the vesicular nature of the shards their analytical totals were too low to report (<90%). All of the results generally fall within one geochemical population with the exception of one grain that has a lower SiO_2 and higher FeO and Al_2O_3 composition (Fig. 4). There is some scatter in the data that can probably be attributed to the low analytical totals and loss of sodium, but the possibility of either magmatic heterogeneity or the mixing of two or more different tephras cannot be ruled out.

5. Discussion

The major element geochemistry of glass shards from CAT-5 and CAT-6 resemble the compositions of tephras from known volcanic eruptions that occurred around the time the boathouse, Naust 48, was in use (c. AD 540–1270; Wickler and Nilsen, 2005) (Table 3; Fig. 4).

5.1. CAT-5

The major oxide concentrations of glass shards in CAT-5 resemble those from the historic eruptions of the Icelandic Hekla volcanic system in AD 1104, AD 1158, and AD 1300 (Table 2). Fig. 4 shows CAT-5 data compared with analyses of glass from these eruptions found in Iceland, Ireland, and the UK (Boygle, 1994, 1999;

Table 1
Radiocarbon dates from boathouse Naust 48.

Context	Lab. ref.	Charcoal taxa	Sample size (g)	Conventional age (^{14}C years BP)	δ^{13}C (‰)	Calibrated age (1 σ/2 σ)[a]
Layer Ib (main cultural deposit)	T-16931	Birch, willow, aspen	3.7	860 ± 75	−27.8	AD 1151–1256/1030-1271
Layer Ib (main cultural deposit)	Wk-16039	Birch	4	902 ± 40	−27.4	AD 1044–1098/1034-1213
Layer Ib (base of cultural deposit)	T-16932	Birch	4.5	1450 ± 45	−27.3	AD 579–645/538-662

[a] Reimer et al., 2009

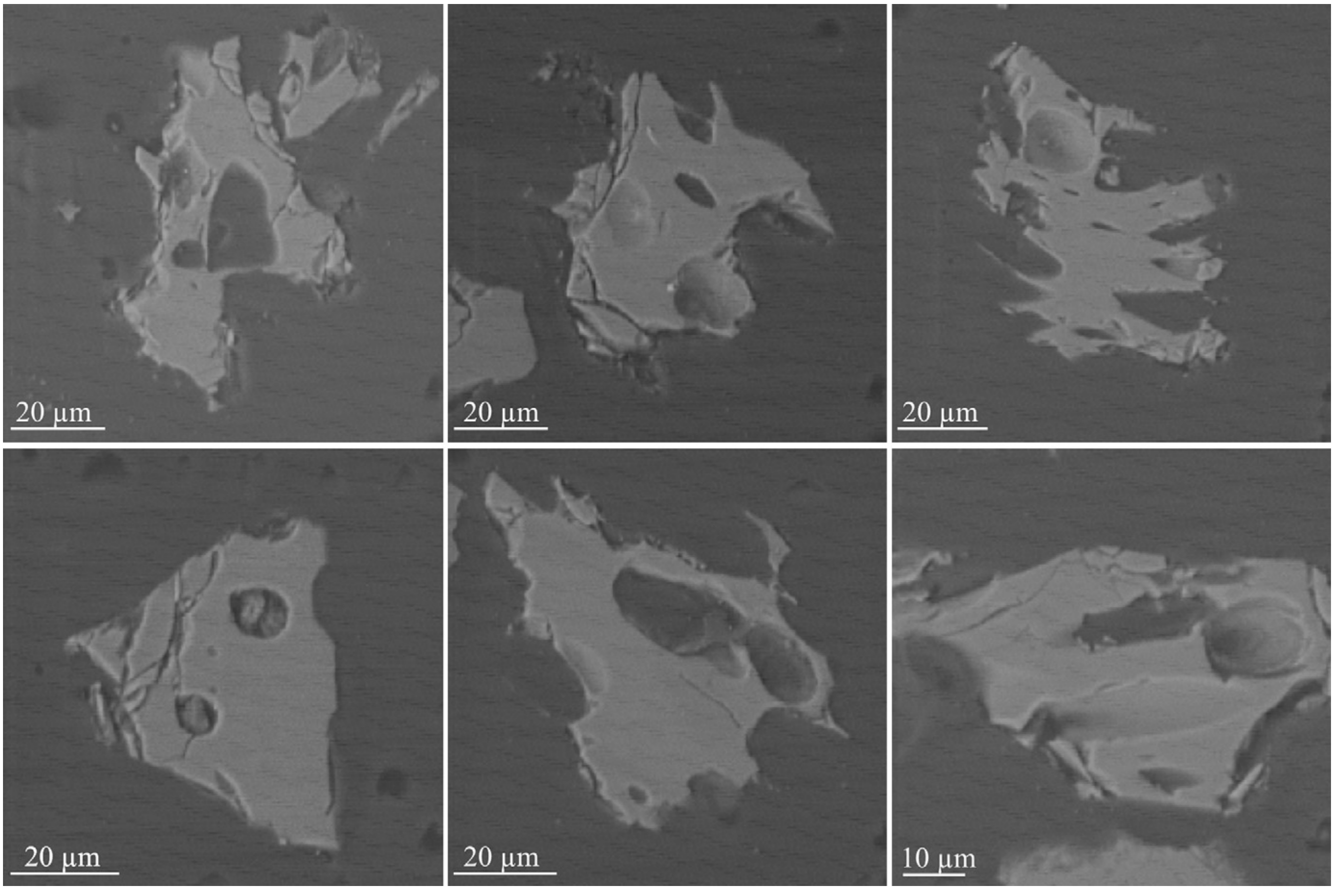

Fig. 3. Scanning electron microscope images of polished glass shards isolated from sample CAT-5.

Hall and Pilcher, 2002; Larsen et al., 1999; Pilcher et al., 1995, 1996). The glass geochemistry from these eruptions can be distinguished by differences in SiO_2, FeO, MgO, CaO, and TiO (Fig. 4). The largest geochemical population of CAT-5 clusters tightly near the compositional range of the Hekla AD 1158 tephra and supports the interpretation of the presence of this tephra as the main component of CAT-5. We speculate that two of the other shards are from the Hekla AD 1104 tephra. This tephra is distinguished from the Hekla 1158 tephra by having a higher SiO_2 and lower FeO content. There is also a single grain we attribute to the Hekla AD 1300 eruption. This interpretation is based primarily on comparison of the distinctively high FeO content of tephra from this eruption, which is not found in any of the other tephra from this period (Table 3). However, a much larger sample is required to make a more definite statement about the presence of tephra from this event.

The Hekla volcanic system is located in the East Volcanic Zone of Iceland and is one of the country's most historically active volcanoes (Thordarson and Larsen, 2007). The AD 1104 eruption was the first historic eruption of Hekla (Thorarinsson, 1967). The eruption was purely explosive and produced an estimated 2 km^3 (bulk volume) of tephra (Thordarson and Larsen, 2007). The AD 1158, and 1300 eruptions also produced significant volumes of tephra, estimated to be 0.33 km^3 and 0.5 km^3 (bulk volumes), respectively. Isopach maps of the fallout on land from these eruptions indicate that the main direction of the tephra plumes were generally to the north and northeast, ideal for transport to northern Norway (as reviewed by Haflidason et al., 2000).

We have strong evidence for the presence of the Hekla AD 1158 tephra based on the number of grains and the precision of the geochemical data within this group. There is less certainty in our attributions of the other grains to the AD 1104 and AD 1300 eruptions of Hekla. However, because of the close timing of the AD 1104 and 1158 eruptions, it is not surprising that they would both be present. Pilcher et al. (2005) also found both tephra mixed within multiple horizons and that glass from the AD 1158 eruption was in greater abundance than that from the AD 1104 eruption. The greater abundance of glass from the AD 1158 eruption in Lofoten may be the results of the difference in plume trajectories. The main axis of tephra fallout from the AD 1158 eruption was in a more northeasterly direction, oriented toward northern Norway, than fallout from the AD 1104 eruption, which was oriented to the north (Haflidason et al., 2000). However, the dispersal trajectories of ash plumes are complex, can change during the course of an eruption due to shifts in weather patterns, and are difficult to reconstruct due to site-specific processes that can unevenly distribute tephra (Davies et al., 2010).

5.2. CAT-6

The major oxide concentrations of glass shards in CAT-6 resemble those from the AD 860 Layer B tephra. Fig. 4 shows CAT-6 data compared with analyses of glass identified from this eruption found in northern Ireland (Hall and Pilcher, 2002; Pilcher et al., 1995; Swindles, 2006). The AD 860 Layer B tephra is distinguished from others in this time period by its relatively high SiO_2 and low FeO and MgO composition (Tables 2 and 3).

The AD 860 tephra was originally identified as a distal deposit in northern Ireland and was not attributed to a specific Icelandic eruption (Pilcher et al., 1995). It was found with two distinct populations, Layer A and B, and the age (AD 860 $\pm$ 20) was derived from

Table 2
Major oxide concentrations of glass shards from boathouse Naust 48 samples CAT-5 and CAT-6 arranged according to possible correlatives. Results are only reported for analyses with totals greater than 90%.

Shard no.	SiO_2	TiO_2	Al_2O_3	FeO[a]	MnO	MgO	CaO	Na_2O	K_2O	Total	n
CAT-5											
Hekla AD 1300											
1	61.33	0.89	15.67	8.80	0.23	1.35	4.97	2.79	1.66	97.70	3
Hekla AD 1158											
2	68.56	0.44	14.43	6.09	0.17	0.49	2.91	2.95	2.28	98.32	3
3	67.07	0.42	15.31	5.72	0.19	0.41	3.16	2.50	2.18	96.96	3
4	68.04	0.41	15.09	5.74	0.22	0.44	3.21	2.62	2.14	97.90	5
5	67.83	0.43	14.99	5.71	0.18	0.44	3.23	2.47	2.18	97.46	3
6	67.74	0.42	15.72	5.42	0.17	0.42	3.47	3.30	2.05	98.70	5
7	68.60	0.41	15.48	5.34	0.17	0.43	3.23	2.81	2.16	98.63	5
Mean	67.97	0.42	15.17	5.67	0.18	0.44	3.20	2.78	2.16	98.00	
Std. dev.	0.57	0.01	0.45	0.27	0.02	0.03	0.18	0.32	0.08	0.69	
Hekla AD 1104											
8	72.29	0.20	14.52	3.19	0.11	0.11	2.07	2.80	2.55	97.84	4
9	70.96	0.34	14.04	4.51	0.14	0.18	1.55	2.93	3.32	97.97	5
Mean	71.62	0.27	14.28	3.85	0.13	0.14	1.81	2.87	2.94	97.91	
Std. dev.	0.94	0.10	0.34	0.93	0.02	0.05	0.37	0.10	0.54	0.09	
CAT-6											
AD 860 Layer B											
1	68.90	0.23	13.72	1.59	0.04	0.34	2.00	2.48	3.02	92.31	1
2	72.00	0.29	13.02	2.07	0.04	0.11	1.21	1.45	3.31	93.50	2
3	71.00	0.22	13.80	3.30	0.13	0.11	1.98	2.99	2.62	96.15	1
4	72.83	0.11	12.88	2.01	0.08	0.04	1.37	2.43	2.69	94.43	1
5	71.53	0.24	13.96	1.64	0.02	0.41	2.01	2.38	3.03	95.21	1
6	72.50	0.26	14.50	1.46	0.02	0.44	1.98	2.51	2.87	96.52	1
Mean	71.46	0.22	13.65	2.01	0.05	0.24	1.76	2.37	2.92	94.68	
Std. Dev.	1.42	0.06	0.61	0.68	0.04	0.18	0.36	0.50	0.25	1.61	
Unknown											
7	65.23	0.44	16.31	4.29	0.12	0.32	2.07	3.72	3.84	96.34	1

[a] Total Fe expressed as FeO.

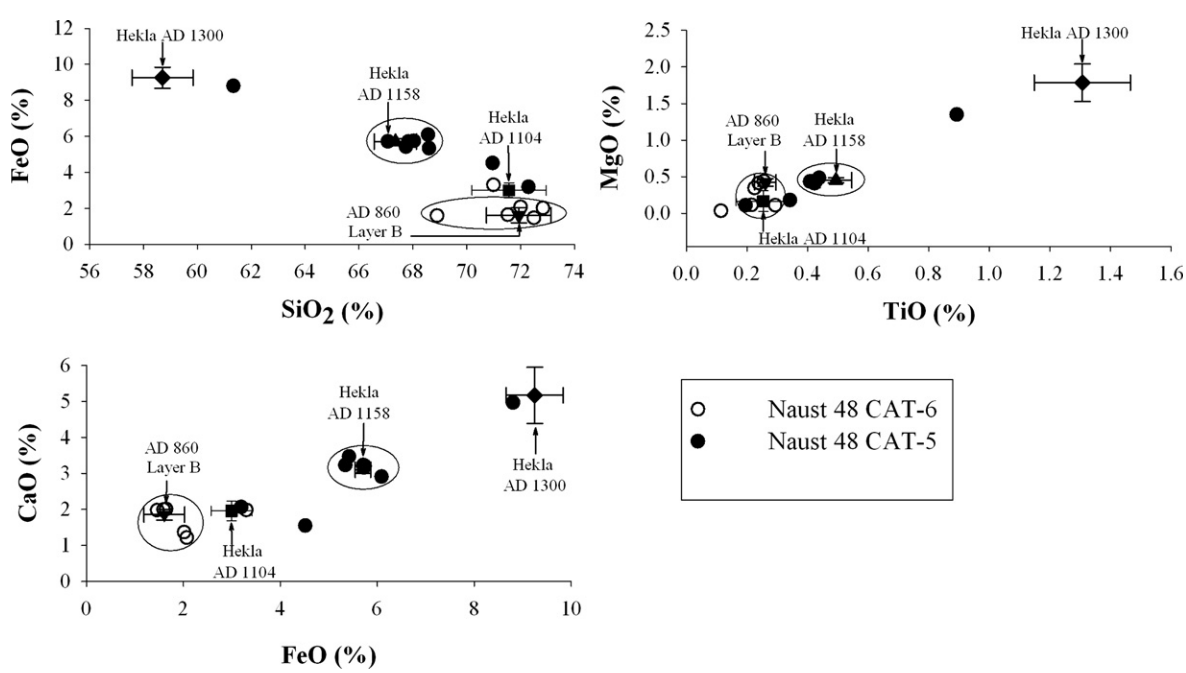

Fig. 4. Comparison of the geochemical compositions of glass shards isolated from Borg boathouse Naust 48 samples CAT-5 and CAT-6 with those from Icelandic eruptions, including: Hekla AD 1104 (Hall and Pilcher, 2002; Larsen et al.,1999; Pilcher et al., 1995, 1996), Hekla AD 1158 (Hall and Pilcher, 2002; Larsen et al., 1999), Hekla A.D. 1300 (Boygle, 1994, 1999), and AD 860 Layer B (Hall and Pilcher, 2002; Pilcher et al., 1995). The composition of glass shards from these known eruptions are presented as average values with one standard deviation ranges (see Table 3). The majority of analyses of glass shards isolated from CAT-5 resemble those from the Hekla AD 1158 eruption, and the majority of analyses of glass shards isolated from CAT-6 resemble those of the AD 860 Layer B tephra (circled).

Table 3
Geochemical compositions of tephras from explosive volcanic eruptions found around the North Atlantic that occurred during the Iron Age compiled from Tephrabase (Newton et al., 2007; http://www.tephrabase.org).

Year (AD)	Tephra		SiO_2	TiO_2	Al_2O_3	FeO	MnO[b]	MgO	CaO	Na_2O	K_2O	Total	n	Source
1362	Öraefajökull	Mean	71.66	0.26	13.42	3.18	0.10	0.04	1.03	5.15	3.40	98.16	76	Hall and Pilcher (2002),
		1 σ	1.57	0.05	0.44	0.39	0.03	0.07	0.27	0.41	0.24	1.71		Larsen et al. (1999), Pilcher et al. (1995)
1300	Hekla	Mean	58.71	1.31	15.15	9.25	0.24	1.78	5.17	4.24	1.54	97.48	40	Boygle (1994, 1999)
		1 σ	1.14	0.16	0.54	0.59	0.03	0.26	0.78	0.25	0.15	1.09		
1158	Hekla	*Mean*	67.36	0.49	14.62	5.70	0.20	0.45	3.10	4.48	2.29	98.64	16	Hall and Pilcher (2002), Larsen et al. (1999)
		1 σ	0.78	0.05	0.47	0.16	0.04	0.04	0.10	0.30	0.12	1.03		
1104	Hekla	Mean	71.57	0.25	14.25	2.99	0.12	0.17	1.96	4.63	2.65	98.49	114	Hall and Pilcher (2002),
		1 σ	1.38	0.09	0.49	0.42	0.02	0.14	0.27	0.30	0.24	1.57		Larsen et al. (1999), Pilcher et al. (1995, 1996)
c. 900	BIP-24a	Mean	65.93	0.44	15.53	4.22	–	0.34	1.84	5.41	3.78	97.50	9	Pilcher et al. (2005)
		1 σ	1.24	0.04	0.30	0.20	–	0.05	0.14	0.45	0.17	1.78		
875	Landnam[a]	Mean	70.97	0.25	14.46	2.32	0.09	0.24	0.89	4.78	4.64	98.63	23	Larsen et al. (1999)
		1 σ	0.75	0.04	0.30	0.10	0.04	0.04	0.06	0.24	0.13	0.97		
c. 860	860 Layer B	Mean	71.94	0.26	14.46	1.61	0.09	0.09	1.85	4.03	3.13	97.70	76	Hall and Pilcher (2002),
		1 σ	1.20	0.04	0.64	0.42	0.06	0.06	0.15	0.37	0.31	1.37		Pilcher et al. (1995), Swindles (2006)
c. 800	Tjørnuvík A	Mean	69.80	0.27	13.64	3.93	0.14	0.26	2.32	4.01	2.41	96.77	39	Hannon et al. (1998),
		1 σ	4.19	0.21	0.85	2.44	0.07	0.24	1.11	0.33	0.46	1.34		Wastegård (2002), Wastegård et al. (2001)
c. 800	Tjørnuvík B	Mean	63.41	1.46	13.80	6.16	0.21	1.49	3.49	4.20	2.59	96.82	3	Wastegård et al. (2001)
		1 σ	0.29	0.05	0.13	0.19	0.02	0.04	0.07	0.37	0.06	0.62		
c. 700-800	GA4-85	Mean	66.06	1.00	14.20	5.46	–	0.91	2.69	4.33	2.87	97.53	24	Hall and Pilcher (2002)
		1 σ	1.00	0.09	0.20	0.16	–	0.03	0.17	0.45	0.09	1.53		

[a] Geochemical results are only from the rhyolitic component of the Landnam tephra.
[b] MnO values not reported for all analyses: Öraefajökull ($n = 15$), Hekla 1300 ($n = 40$), Hekla 1158 ($n = 12$), Hekla 1104 ($n = 14$), Landnam ($n = 9$), 860B ($n = 9$), Tjornuvik ($n = 42$).

radiocarbon wiggle matching techniques (Pilcher et al., 1995), although it was later correlated to deposits found in Iceland (Wastegård et al., 2003). The AD 860 Layer A has only been found in northern Ireland, but Layer B is more widespread and, in addition to occurrences in Ireland (Hall and Pilcher, 2002), it has been found in northern Germany (van den Bogaard and Schmincke, 2002) and in the Lofoten Islands, within a sediment core from Inner Borgpollen (Mills et al., 2009; Pilcher et al., 2005).

5.3. *The timing of boathouse use at Inner Borgpollen*

The samples for tephra analysis were taken from the middle of the cultural deposit (CAT-6) and from above the cultural deposit (CAT-5) in Naust 48. Ages derived from these samples using tephrochronology indicate that the initial construction of the boathouse took place before AD 860 and that the main period of use was between AD 860 and AD 1104. The radiocarbon ages from this site (Table 1) had established the timing of the initial construction of Naust 48 at c. AD 538–662 and that the main period of use was from c. AD 1030–1271 (Wickler and Nilsen, 2005).

The cryptotephra analysis from CAT-6 support the calibrated radiocarbon age range for the construction of the boathouse and suggest that the main period of use may have been as early as AD 860. The cryptotephras found in CAT-5, mainly glass from the AD 1158 eruption of Hekla, provide a more precise upper limiting age and suggest a shorter period of use that ended before at least AD 1158 and probably before AD 1104. This new age range for the main period of use at Naust 48 also fits well with radiocarbon ages obtained from a second Iron Age boathouse, located c. 30 m north along the western shore of Inner Borgpollen from Naust 48. This boathouse, Naust 61, has five radiocarbon dates establishing a main period of use during the Viking Age between AD 770 and AD 1050. This structure also had an earlier use phase during the Early Iron Age with a hearth dated to 1850 ± 74 ^{14}C years BP (2-sigma calibrated age of AD 2–350) (S. Wickler, unpublished data). Both boathouses are characterized by long-term use with two temporally distinct periods of use separated by a hiatus or significant reduction in activity between them.

Overall, these results demonstrate the potential for using crypto-tephrochronology in this environment. The processing of larger sediment samples from these horizons and the analysis of more glass shards would help verify the presence and relative abundances of these tephra. The analysis of additional sediment samples from Naust 48 and Naust 61 can also be expected to produce new tephra evidence.

6. Tephrochronology during the Iron Age

Radiocarbon dating is one of the most widely used absolute dating techniques for determining the age of cultural horizons in archaeological investigations. However, to determine dates on a calendar year timescale, measured radiocarbon ages must be calibrated because of variations in the atmospheric radiocarbon content (Stuiver and Suess, 1966; Reimer et al., 2009). During the Holocene, where tree rings are used for the calibration, the errors are usually small. However, during certain intervals, "plateaus" in the calibration curve can produce a large range of statistically possible calendar dates for a given radiocarbon age and provide a temporal resolution that is insufficient for some applications (Guilderson et al., 2005). During the Iron Age and up to the early Medieval Period in Norway (c. AD 300–1200), there are two main intervals where plateaus occur in the radiocarbon calibration curve, c. AD 700–930 and c. AD 1050–1200 (Reimer et al., 2009) (Fig. 5). Radiocarbon ages that fall within these plateaus produce calibrated calendar ages with overlapping uncertainties and hamper detailed interpretations of archaeological findings. Tephrochronology can therefore supplement radiocarbon chronologies to improve temporal resolution.

A number of explosive, tephra-producing volcanic eruptions occurred during the Iron Age (Table 3; Fig. 5) (Haflidason et al., 2000; Larsen et al., 1999). Tephra from these events have distinct geochemical compositions and many of have been found in Norway, mainly as cryptotephras (Balascio et al., *in press*; Pilcher et al., 2005). This occurrence demonstrates the potential for tephra as marker horizons or for absolute age control, although the uncertainty in the ages of each tephra must be considered where ages associated with the tephras are transferred. The historic eruptions have been dated using written accounts, which can pinpoint the day or month of an eruption (e.g. Thorarinsson, 1967). Some prehistoric tephras have been found in Greenland ice cores and can be precisely dated using layer counting (Grönvold et al.,

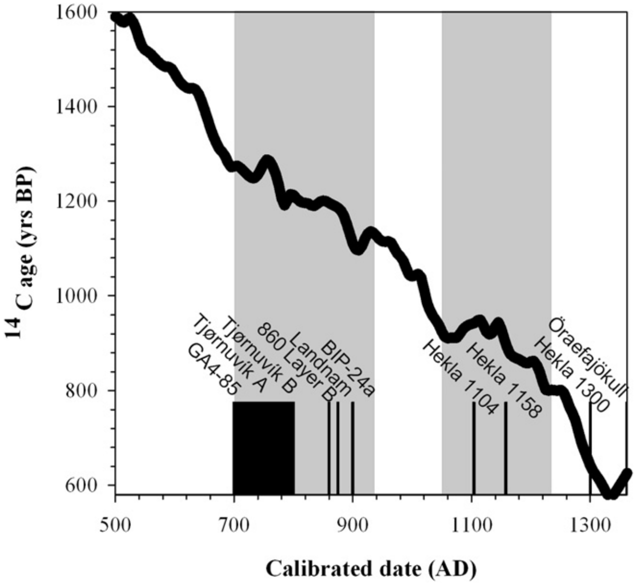

Fig. 5. Radiocarbon calibration curve around the Iron Age (Reimer et al., 2009). Gray shaded age ranges (c. AD 700–930 and AD 1050–1200) mark plateaus in the calibration curve. Icelandic volcanic eruptions with potential for tephrochronologic studies in Norway are indicated by the black vertical bars (see Table 3).

1995; Zielinski et al., 1994, 1995), while the ages of other prehistoric tephra are known from compilations of radiocarbon dates from multiple sites.

7. Conclusion

We were able to isolate volcanic glass shards from sediments in a Viking boathouse and match them using major element compositions to known Icelandic volcanic eruptions. We identified the AD 860 Layer B tephra and tephra from historic eruptions of the Hekla volcanic system in 1104, AD 1158, and AD 1300. These results helped to constrain the timing of the boathouse's use and demonstrate the potential for crypto-tephrochronology as a geochronologic tool for archaeologists in Norway.

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