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Towards a Holocene tephrochronology for the Faroe Islands, North Atlantic

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ABSTRACT

The Faroe Islands hold a key position in the North Atlantic region for tephra studies due to their relative proximity to Iceland. Several tephras have been described over the last 50 years in peat and lake sediment sequences, including the type sites for the Saksunarvatn and Mjáuvøtn tephras. Here we present a comprehensive overview of Holocene tephras found on the Faroe Island. In total 23 tephra layers are described including visible macrotephras such as the Saksunarvatn and Hekla 4 tephras and several cryptotephras. The importance of tephras originally described from the Faroe Islands is highlighted and previously unpublished results are included. In addition, full datasets for several sites are published here for the first time. The Saksunarvatn Ash, now considered to be the result of several eruptions rather than one major eruption, can be separated into two phases on the Faroe Islands; one early phase with two precursor eruptions with lower MgO concentrations (4.5–5.0 wt%) than the main eruption and a later phase with higher MgO concentrations (5.5–6.0 wt%), including the visible Saksunarvatn Ash. The Tjørnuvík Tephra, previously considered to be a primary deposit, is now interpreted as a reworked tephra with material from at least two middle Holocene eruptions of Hekla. Several of the tephras identified on the Faroe Islands provide useful isochrons for climate events during the Holocene.

1. Introduction

Tephra layers are known to be present in a wide range of climate archives in the North Atlantic region, including ice-cores, marine cores, peat and lake sediment. Tephrochronology, which is an age-equivalent dating method, exploits these often exceptionally well-dated time-synchronous markers and offers a unique possibility to test hypotheses regarding synchronous or lagged responses to climate forcing. Few, if any geochronological methods can match the precision it offers both temporally and spatially (Lowe, 2011).

A majority of tephras found in NW Europe derives from explosive volcanic eruptions in Iceland and the chronological control is often excellent for the historic part (back to the 10th Century CE) but many widely dispersed prehistoric tephras are relatively poorly dated. For example, ages for two of the largest eruptions of Hekla (Hekla 3 and Hekla 4, c. 3000 cal yr BP and 4200 cal yr BP, respectively) differ by tens to hundreds years when different dating methods (radiocarbon, dendrochronology, varves etc.) have been utilized (Baillie and Munro, 1988; Pilcher et al., 1995; van den Bogaard et al., 2002; Zillén et al., 2002; Dörfler et al., 2012). If improved numerical ages for these and other tephra layers can be obtained, tephrochronology will evolve as an even more important complement to radiocarbon dating and other geochronological methods. This will have wider implications for palaeoclimatic investigations, sea-level studies and archaeological studies as these frequently suffer from poor chronological control.

Since the first records of distal Icelandic tephra were reported in the 1960s (Persson, 1966, 1968; Waagstein and Jóhansen, 1968), an

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increasing number of papers have been published describing findings of Icelandic tephra in Scandinavia (Boygle, 1998; Bergman et al., 2004; Borgmark and Wastegård, 2008), the Faroe Islands (Mangerud et al., 1986; Wastegård et al., 2001; Olsen et al., 2010a), Germany (van den Bogaard and Schmincke, 2002; Lane et al., 2012a), the British Isles (Dugmore, 1989; Pyne-O'Donnell et al., 2008; Hall and Pilcher, 2002), Poland (e.g. Housley et al., 2013; Ott et al., 2016), Baltic states and western Russia (e.g. Wastegård et al., 2000; Stivrins et al., 2016) and even as far south as in the Mediterranean region (Lane et al., 2011a) and Romania (Kearney et al., 2018). More recently tephra from other volcanic regions has been identified in NW Europe, which indicates the possibility of distribution of tephra over even larger areas than previously thought (Coulter et al., 2012; Jensen et al., 2014). Several middle to late Holocene tephras are widespread over NW Europe but the distribution of some of the tephras from the Lateglacial and early Holocene, e.g. the Vedde Ash and Askja-S suggests that these tephras are even more widespread than those derived from the voluminous middle Holocene eruptions of Hekla (e.g. Davies et al., 2010). This may, however, be biased since more studies have focused on erecting distal tephrochronology networks for the Last Glacial-Interglacial transition (LGIT; c. 15–8 ka BP) than for the middle and late Holocene. Several reviews of the LGIT tephras in NW Europe have been published by members of the INTIMATE group (Davies et al., 2012; Blockley et al., 2014) but more comprehensive reviews of tephras from the middle to late Holocene are less numerous with notable examples by Swindles et al. (2011) and Lawson et al. (2012) who focused on the distribution and temporal occurrence of tephras rather than the geochemical composition and correlations with events on Iceland. Despite this wealth of research that has been conducted during the last c. 20 years, several recent studies have shown that our knowledge of tephra dispersal in the North Atlantic region is far from complete (e.g. Lane et al., 2012a; Lind et al., 2013; Timms et al., 2017; Plunkett and Pilcher, 2018).

The Faroe Islands hold a key position in the North Atlantic for tephra studies due to their relative proximity to Iceland. Several sources, both from historic and sedimentary archives, show that tephra fallout has been observed during historical eruptions, including Katla 1625 and 1755, Hekla 1845 and most recently, the eruption of Eyjafjallajökull 2010 (Thorarinsson, 1981; Dugmore and Newton, 1998; Stevenson et al., 2012). The tephrostratigraphy of the Faroe Islands has been described in several papers since the first studies in the 1960s, but a more comprehensive review is lacking. The aim of this paper, therefore, is to describe the terrestrial tephrostratigraphy of the Faroe Islands for the last ca 11,000 years. The importance of some tephras originally described from the Faroe Islands is highlighted and previously unpublished results are included. In addition, full datasets for several sites are published here for the first time (App. A). The tephras are described in chronological order, from oldest to youngest in the text (Table 1).

2. Material and methods

2.1. Study area

The Faroe Islands are part of the North Atlantic Igneous Province (NAIP), which stretches from Ireland to Greenland and is centered on Iceland (e.g. Saunders et al., 1997; Horni et al., 2017) (Fig. 1A). The plateau broke up during the opening of the North Atlantic Ocean and remnants exist in e.g. Northern Ireland, Scotland, the Faroe Islands and eastern Iceland. The Faroe Islands were repeatedly glaciated during the Quaternary but the Pre-Weichelian development of the Faroe Islands is poorly known, except for an Eemian section in Klaksvík that also has been investigated for tephrostratigraphy (Wastegård et al., 2005). A local ice cap or perhaps ice caps covered the islands during the Weichselian, but it is not clear when they were finally deglaciated (Humlum et al., 1996; Humlum, 1998). Moraine systems, thought to be of Younger Dryas age, occur in some areas, and a final deglaciation shortly after the Younger Dryas-Preboreal transition (c. 11.700 ka cal BP) is supported by several ^{14}C dates from the first organic lake sedimentation c. 11.5-11-3 ka cal BP (e.g. Jessen et al., 2008; Hannon et al., 2010; Lind and Wastegård, 2011).

2.2. Methods

Both visible macrotephras and cryptotephras, invisible to the naked eye, have been found on the Faroe Islands. Cryptotephras in lake sediment sequences have been concentrated using the density separation technique outlined by Turney (1998) while peat cores were treated accordning to Pilcher and Hall (1992). Tephra glass shard identification and counting were carried out optically with a polarising light microscope. Many lake sediment records on the Faroe Islands have a background of glass shards and shard concentration peaks are not always distinct. In the Høvdarhagi site, peaks in tephra shard concentration can be deciphered but there is also evidence for bioturbation and/or secondary inwash (cf. Fig. 3B in Davies, 2015). Here, and in other sites, peaks in tephra shard concentration were chosen for geochemical fingerprinting.

3. Results

3.1. The early Holocene (c. 11,500–8200 cal yr BP)

The Faroe Islands are a key area for the early Holocene tephrochronology of the North Atlantic region, and provide a detailed insight into Icelandic volcanism during this interval. Lateglacial and early Holocene tephras from Iceland are often poorly preserved in proximal localities due to the fact that much of the Icelandic landscape was covered by ice, and remained so until c. 11,000 cal yr BP (Norddahl and Pétursson, 2005; Larsen and Eiríksson, 2008). On the Faroe Islands, subarctic conditions prevailed from the deglaciation until c. 10,300 cal yr BP during which time shallow lake systems developed, and vegetation colonised lake catchments (e.g. Jóhansen, 1985). Preserved within these lake systems are the remnants of this early Holocene vegetation i.e. abundant leaves of, for example *Betula nana* and *Salix herbacea* which is a type of material which facilitates radiocarbon dating, and can be used to develop robust ages for tephra layers. Examples of this are the Hoydalar site in Tórshavn, investigated by Waagstein and Jóhansen (1968), and the Lykkjuvøtn and Høvdarhagi sites on Sandoy (Jessen et al., 2007, 2008; Lind and Wastegård, 2011) (Fig. 1B). Several of these shallow lakes were terrestrialised in the early Holocene but other larger and deeper lakes exist today on most of the 18 islands. However, only a few of these have been investigated for tephra, and usually only for visible macrotephras. Two examples are the type site for the Saksunarvatn Ash, Lake Saksunarvatn on Streymoy (Mangerud et al., 1986) and Lake Mjáuvøtn on Streymoy (Wastegård et al., 2001; Olsen et al., 2010a) (Fig. 1B).

The most complete tephra record from the early Holocene is the palaeo-lake core from Høvdarhagi bog on Sandoy, in which seven tephra layers have been found (Fig. 1B; Lind and Wastegård, 2011). Only the basaltic Saksunarvatn Ash is visible; the remaining tephras are cryptotephras extracted through heavy liquid separation (Turney, 1998). An early Holocene tephra, L3574, was also described in the Lake Saksunarvatn sequence, below the Saksunarvatn Ash (Dugmore and Newton, 1998). Two other palaeo-lake sites, Hovsdalur on Suduroy (Wastegård, 2002) and Havnardalsmyren on Streymoy (Kylander et al., 2012) have also been investigated, but

Table 1
Holocene tephras identified on the Faroe Islands, from youngest to oldest. For full description, see text. Number of sites where each tephra has been found on the Faroe Islands is shown as well as if the tephra has been found beyond the Faroe Islands (Bey. F.), (Iceland not included).

Tephra	Age ka yr (CE/BP)	Composition	Source volcano	Sites	Bey. F.
Hekla 1845	1845 CE	Andesite/Dacite	Hekla	1	Yes
Hekla 1158	1158 CE	Dacite	Hekla	1	Yes
Hekla 1	1104 CE	Dacite/Rhyolite	Hekla	1	Yes
Landnám (BAS)	877 ± 2 CE	Basaltic	Bárdarbunga-Veidivötn	3	Yes
Tjørnuvík	800s CE	Andesite/Dacite/Rhyolite	Hekla (reworked?)	3	No?[a]
Hekla 3	~3.0	Dacite/Rhyolite	Hekla	1	Yes
Hekla S/Kebister	~3.7	Andesite/Dacite/Rhyolite	Hekla	>5	Yes
Hekla 4	~4.3	Andesite/Dacite/Rhyolite	Hekla	>5	Yes
Hov	~5.9	Basaltic	Kverkfjöll?	1	No
SILK-A1?	~5.9	Dacitic	Katla (SILK composition)	1	No
Mjáuvötn	~6.6	Basaltic	Katla	3	Yes?[b]
SILK-A7/RF-2?	~7.1	Dacitic	Katla (SILK composition)	1	No
Suduroy	~8.0	Rhyolitic	Katla (rhyolitic)	1	Yes
An Druim/Høvdarhagi	~9.7	Rhyolitic	Torfajökull	1	Yes
Skopun	~9.7	Dacitic	Katla (SILK composition)	1	No
L-274/Fosen	~10.1	Rhyolitic	?	1	Yes
Saksunarvatn[c]	~10.2	Basaltic	Grímsvötn	>5	Yes
Hovsdalur[d]	~10.5	Rhyolitic	Thórðarhyrna?	1	Yes
Askja-S	~10.8	Rhyolitic	Askja	2	Yes
L3574	~11.0?	Dacitic	?	1	No
Hässeldalen	~11.3	Rhyolitic	Thórðarhyrna?	1	Yes
Sandoy A	~11.3	Basaltic	Bárdarbunga-Veidivötn	1	No
Sandoy B	~11.3	Basaltic	Bárdarbunga-Veidivötn	1	No

[a] Can possibly be correlated with the MOR-T6 tephra found on Ireland (Chambers et al., 2004).
[b] See text for possible correlatives.
[c] At least four, possibly five layers on the Faroe Island.
[d] Possibly same as Hässeldalen Tephra.

not in such detail as Høvdarhagi bog. The previous age model from Høvdarhagi bog was constructed using the OxCal 4.1.6. software (Lind and Wastegård, 2011) and has been remodelled with OxCal 4.3.2. since it has been shown that earlier attempts to use OxCal often resulted in over constraining of age depth models (Bronk Ramsey and Lee, 2013). It has also been updated to the IntCal13 calibration curve (Reimer et al., 2013).

3.1.1. Sandoy A Tephra and Sandoy B Tephra (c. 11.4–11.25 ka cal BP)

The oldest tephras at Høvdarhagi bog, the basaltic Sandoy A and Sandoy B tephras are, dated to c. 11,400–11,250 cal yr BP (Table 2). The two peaks in tephra concentration are separated by c. 8 cm which corresponds to c. 100 years and both have a tholeiitic geochemistry that suggests an origin in the Bárdarbunga-Veiđivötn volcanic system in south Iceland. There is, however, also an overlap with the Grímsvötn volcanic system in some plots (Fig. 2). Bárdarbunga-Veiđivötn is one of the most productive systems in Iceland with c. 350 eruptions since c. 7600 cal yr BP (Óladóttir et al., 2011) and at least 24 eruptions in historical time (Thordarson and Larsen, 2007), including the recent Holuhraun event in 2015. There are, however, to our knowledge, no other records of distal early Holocene tephras from Bárdarbunga-Veiđivötn, neither in marine, terrestrial or ice-core records and thus, the Sandoy A and B tephras are not possible to correlate with any known tephra deposit elsewhere.

3.1.2. Hässeldalen Tephra (c. 11.3 ka cal BP)

The Hässeldalen Tephra has emerged as one of the most important tephras from the LGIT since its first discovery in SE Sweden (Davies et al., 2003, 2012). It has recently been found in several sites in the southern Baltic region (Lilja et al., 2013; Larsen and Noe-Nygaard, 2014; Wulf et al., 2016) and most recently in two sites on Orkney (Timms et al., 2017 & 2018). It holds a key stratigraphic position in relation to climate development during the early Holocene being thought to mark the onset of the Preboreal Oscillation (PBO) (Davies et al., 2003; Larsen and Noe-Nygaard, 2014). The Hässeldalen Tephra has a rhyolitic composition with high concentration of alkalis (Figs. 3 and 4; K_2O 3.8–4.5 wt%; Na_2O 3.7–4.2 wt%) and Snæfellsjökull in W Iceland has been suggested as a source volcano (Wastegård, 2002; Housley et al., 2013). The oldest silicic tephra identified from Snæfellsjökull, however, has an estimated age of 9000–7000 ^{14}C yr BP (c. 10–8 ka cal BP) (Steinthorsson, 1967). A more probable correlation is to the Thórdarhyrna central volcano as shown in Figs. 3B and 4A. There are no geochemical data available on tephra-derived glass from this volcano, situated beneath the Vatnajökull ice-cap, so the correlation is based solely on whole rock analyses (Jónasson, 2007). Furthermore, tephras from Snæfellsjökull have a distinctive high Al_2O_3 content of 15–16 wt% (Fig. 4B e.g. Larsen and Eiríksson, 2008; Wastegård et al., 2009; Holmes et al., 2016), which separates them from the Hässeldalen Tephra, that usually ranges between 11 and 12 wt% (Fig. 4B) The findings of the Hässeldalen Tephra in Høvdarhagi bog and in the southern Baltic Sea region, but not in Norway and so far only in northernmost Scotland, suggest a rather narrow ash plume directed towards the south-east (Fig. 5). The Hässeldalen Tephra may, however, have been overlooked, especially where high concentrations of reworked Vedde Ash shards often prevail into the early Holocene and may obscure minor tephra peaks (e.g. Lind et al., 2013; Timms et al., 2017). The Hässeldalen Tephra is dated to c. 11,596–11,194 cal yr BP at Hässeldala port by Wohlfarth et al. (2006), and to c. 11,378–11,254 cal yr BP in the Høvdarhagi bog sequence, using the remodelled age-depth model (Fig. 6; Table 2).

3.1.3. L3574 Tephra (c. 11.0 ka cal BP)

This layer was described by Dugmore and Newton (1998) from the Lake Saksunarvatn sequence, as a cm-scale layer “below the Saksunarvatn Ash”. The core was taken by the Geological Survey of Denmark in 1972 and the label most probably refers to the depth where this tephra was found, 35.74 m below the sediment surface of the 36.75 m long core. The Saksunarvatn Ash (c. 10.2 ka BP) at c.

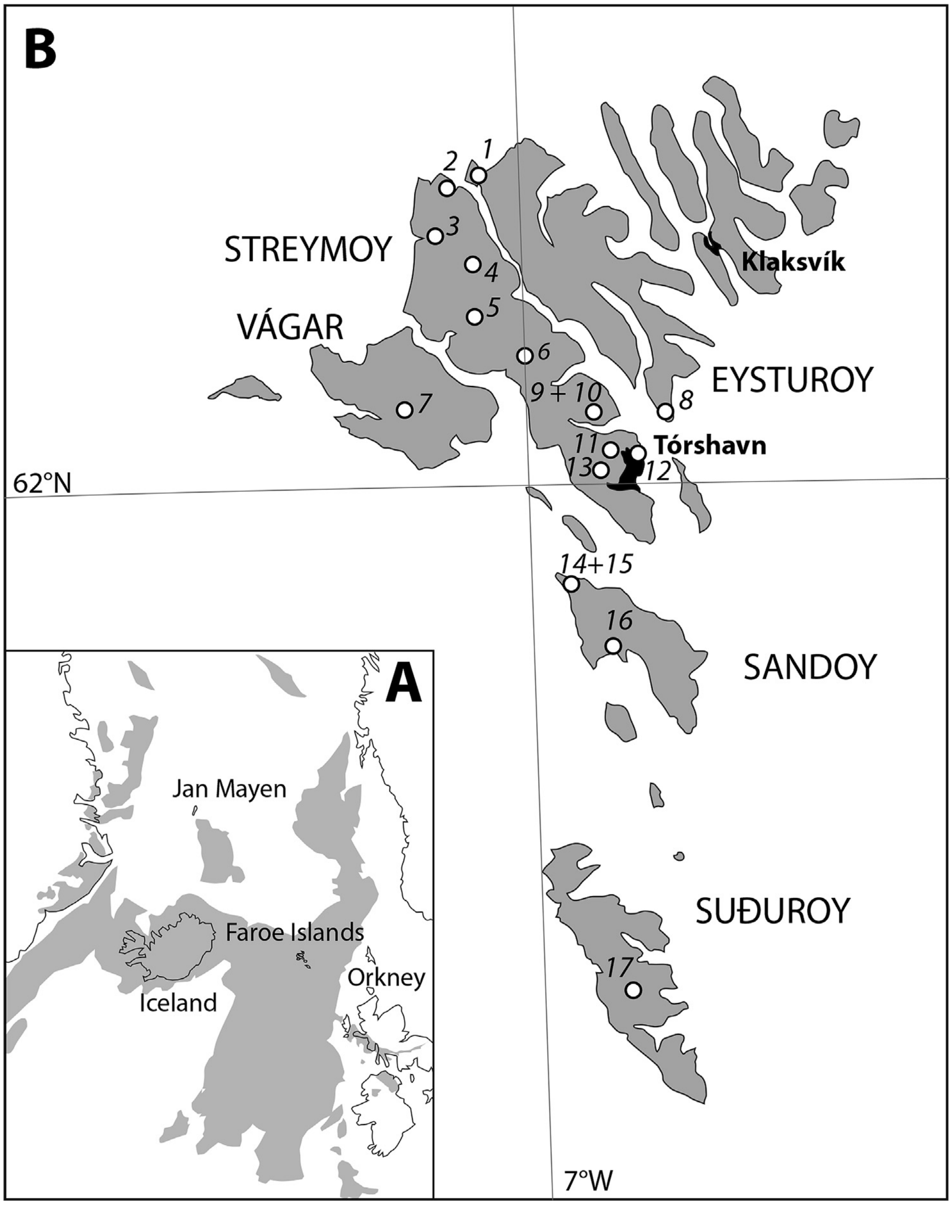

Fig. 1. A: Regional map of the North Atlantic Region. The North Atlantic Igneous province (NAIP) is marked in grey (after Horni et al., 2017)
B: Map of the Faroe Islands with sites mentioned in the text and in Appendix A (L. = lake):
1. Eidi bog (Wastegård et al., 2001, 2003, this paper)
2. Tjørnuvík (Wastegård et al., 2001, 2003, this paper)
3. L. Saksunarvatn (Mangerud et al., 1986; Dugmore and Newton, 1998)
4. Saksunmyren (Persson, 1968)
5. Myrarnar (Persson, 1968)
6. L. Mjáuvøtn (Wastegård et al., 2001, this paper; Olsen et al., 2010a; b)
7. Klovinmren
(Persson, 1968)
8. L. Starvatn (Wastegård et al., 2008, this paper)
9. L. Stóravatn (Olsen et al., 2010a)
10. L. Brúnavatn (Olsen et al., 2010a; b)
11. L. Skælingsvatn (Waagstein and Jóhansen, 1968; Dugmore and Newton, 1998)
12. Hoydalar (Waagstein and Jóhansen, 1968)
13. Havnardalsmyren (Persson, 1968; Kylander et al., 2012; Wastegård et al., this paper)
14. Høvdarhagi bog (Lind and Wastegård, 2011; Wastegård et al., this paper)
15. L. Lykkjuvøtn (Jessen et al., 2007, 2008)
16. L. Gróthúsvatn (Hannon et al., 2001; Wastegård et al., this paper)
17. Hovsdalur (Wastegård, 2002).

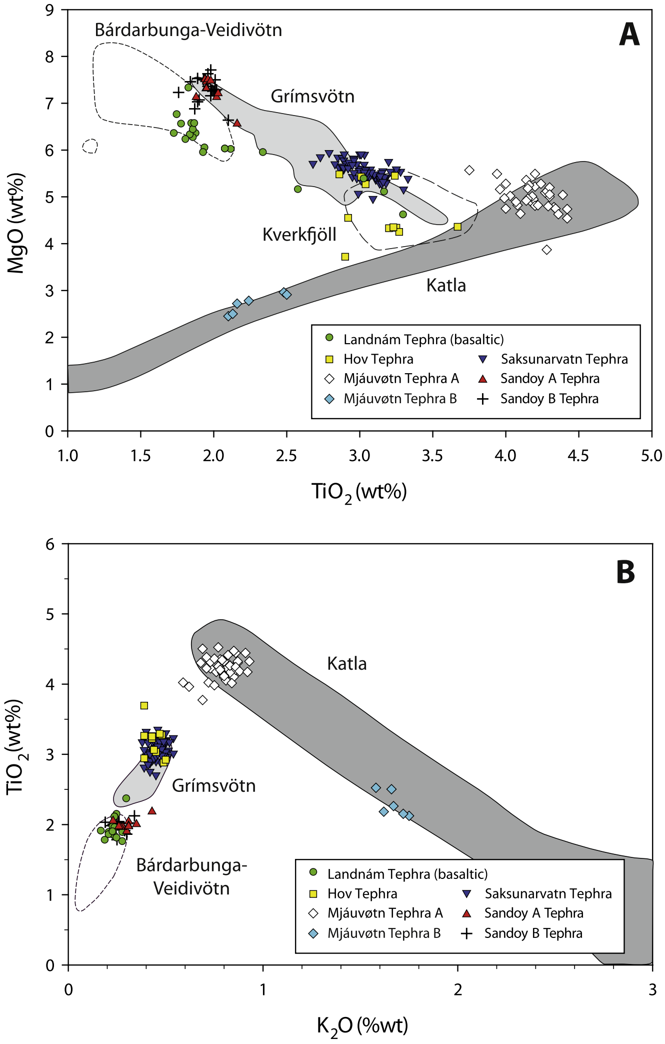

Fig. 2. Geochemical characterisation of the main basaltic tephras found on the Faroe Islands. "Saksunarvatn precursors" from Havnardalsmyren are excluded. (A) TiO_2 vs. MgO (wt%); (B) K_2O vs. TiO_2 (wt%). Geochemical field for Iceland source volcanoes are based on Óladóttir et al. (2008, 2011). The field for Katla also includes data from Boygle (1994), Larsen et al. (2001), Lane et al. (2012a), Tomlinson et al. (2012), Streeter and Dugmore (2014), Gudmundsdóttir et al. (2016) and Holmes et al. (2016) and also covers intermediate and silicic products (e.g. "SILK tephras" and the Vedde Ash). Note that there is not much intermediate material known from Katla, hence the fields for intermediate tephras (between c. 2 and 4 wt% TiO_2 in both figures) are based on few datapoints and might be revised in future.

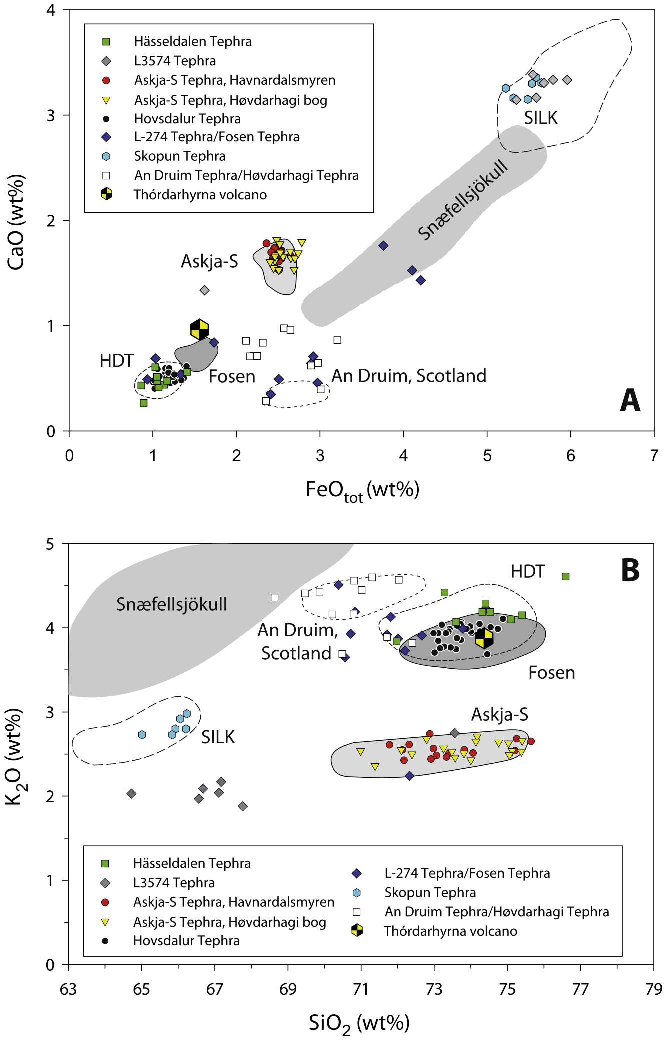

Fig. 3. Geochemical characterisation of early Holocene silicic tephras found on the Faroe Islands. (A) FeO vs. CaO (wt%); (B) SiO_2 vs. K_2O (wt%). Geochemical fields for the Hässeldalen Tephra (HDT) from Housley et al. (2013), Lilja et al. (2013) and Larsen and Noe-Nygaard (2014); Askja-S Tephra from Turney et al. (2006), Jones et al. (2017) and Kelly et al. (2017); Fosen Tephra from Lind et al. (2013) and Larsen (2014); SILK tephras from Larsen et al. (2001); Óladóttir et al. (2008) and Thorsteinsdóttir et al. (2016); An Druim Tephra from Ranner et al. (2005); Kelly et al. (2017) and Timms et al. (2017); Snæfellsjökull tephras from (Larsen et al., 2002; Wastegård et al., 2009; Holmes et al., 2016; Watson et al., 2016). Major element composition of volcanic rocks from Thórdarhyrna from Jónasson (2007).

Table 2
Ages for tephras from the Høvdarhagi bog sequence derived from the age-depth model in Fig. 5.

Tephra	Peak depth (cm)	Age, cal yr BP (mean + 1 σ)
An Druim/Høvdarhagi	217	9716 ± 120
Skopun	219	9730 ± 130
L-274	274	10,130 ± 68
Saksunarvatn[a]	286	10,210 ± 35
Askja-S	300	10,424 ± 102
Sandoy B	410	11,260 ± 47
Sandoy A	418	11,316 ± 62
Hässeldalen	418	11,316 ± 62

[a] Age for the Saksunarvatn Tephra from Lohne et al. (2013).

29.9–30.3 m (Mangerud et al., 1986) and the lowermost radiocarbon date at 31.99–32.10 m (9390 ± 150 BP; c. 10.7 ka cal BP; Jóhansen, 1977) indicates that the L3574 Tephra has an age of c. 11,000 cal BP. Most shards have a dacitic composition and show some similarities with silicic tephras from the Katla volcanic system, "SILK layers" (Larsen et al., 1999), but is lower in e.g. TiO_2 and K_2O (Fig. 3B). The L3574 Tephra has so far only been found in the Lake Saksunarvatn sequence.

3.1.4. *Askja-S Tephra (c. 10.8 ka cal BP)*

This early Holocene tephra from the Dyngjufjöll volcanic centre on Central Iceland has emerged as one of the most useful and widespread tephras from the early Holocene. The eruption occurred within the Askja caldera and the tephra is usually referred to as the 10-ka Askja Tephra or the Askja-S Tephra. The distribution on Iceland has been mapped and shows that the assumed dispersal axis was towards NNE (Sigvaldason, 2002). The volume of the Askja-S Tephra has been estimated to 1.5 ± 0.5 km^3 (DRE) which makes it one of the ten most voluminous Holocene silicic eruptions

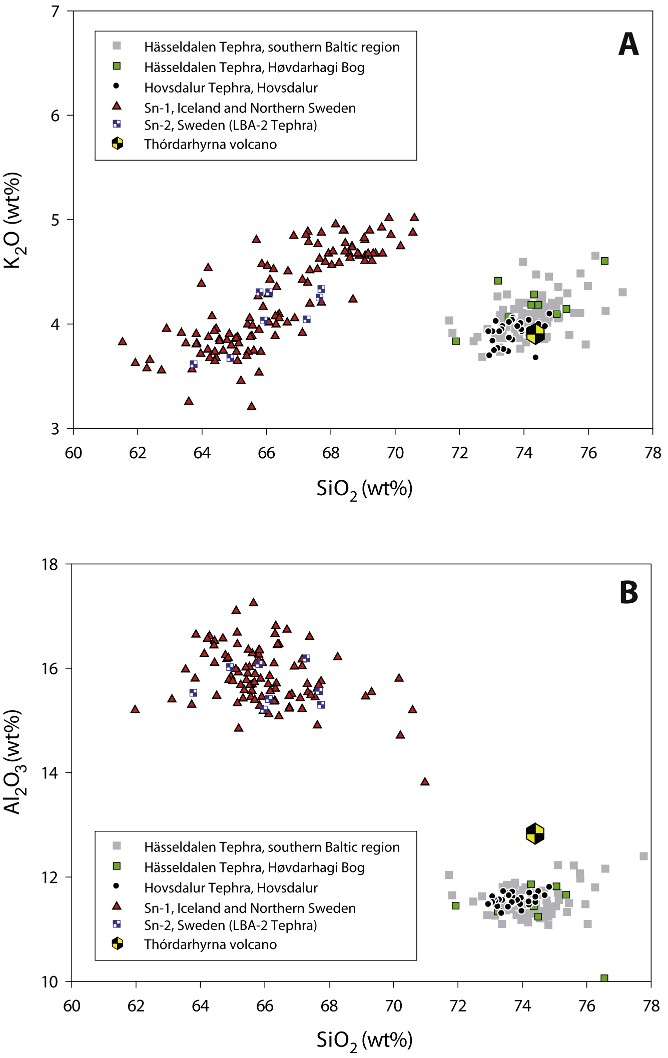

Fig. 4. Biplot of the Hässeldalen and Hovsdalur tephras from the Faroe Islands (A: SiO_2 vs. K_2O; B: SiO_2 vs. Al_2O_3) compared with published data of the Hässeldalen Tephra from Sweden, Denmark, Germany and Poland (Lane et al., 2012b; Housley et al., 2013; Lilja et al., 2013; Larsen and Noe-Nygaard, 2014) and with rhyolitic tephras from Snæfellsjökull (Sn-1: Larsen et al., 2002; Holmes et al., 2016; Watson et al., 2016); (Sn-2/LBA-2: Wastegård et al., 2009). Major element composition of volcanic rocks from Thórdarhyrna from Jónasson (2007).

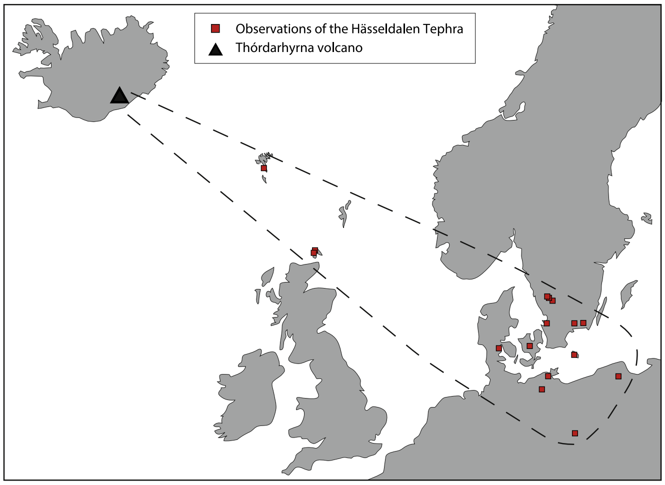

Fig. 5. Map showing reported occurrences of the Hässeldalen Tephra (e.g. Davies et al., 2003; Lilja et al., 2013; Larsen, 2014; Larsen and Noe-Nygaard, 2014; Wulf et al., 2016; Timms et al., 2017, 2018; Wohlfarth et al., 2018) and the suggested ash plume trajectory.

on Iceland (Sigvaldason, 2002). Askja-S has been found in several distal locations since its first distal discovery in SE Sweden (Davies et al., 2003), including Northern Norway, Northern Ireland, Scotland, Wales, Germany, Poland, Switzerland and most recently in Romania (Pilcher et al., 2005; Turney et al., 2006; Lane et al., 2011b; Wulf et al., 2016; Kelly et al., 2017; Jones et al., 2017; Kearney et al., 2018). Askja-S has one of the largest reconstructed distribution envelopes of all Icelandic Late Quaternary tephras (Jones et al., 2017), but seems to have a patchy distribution as many sites within the distribution envelope do not report the tephra. Jones et al. (2017) compiled positive and negative findings of the Askja-S Tephra and proposed a three plume trajectory, one towards northern Norway, one towards southern Scandinavia and Central Europe and the southernmost reaching the Faroe Islands and the British Isles. The Askja-S Tephra has a characteristic geochemistry with low contents of K_2O and higher values for CaO compared with most other rhyolitic tephras from Iceland (Fig. 3). The Askja-S has been found in two sites on the Faroe Islands, Høvdarhagi bog on Sandoy (Lind and Wastegård, 2011) and Havnardalsmyren on Streymoy (Kylander et al., 2012) (Fig. 1B). The geochemical analyses from the latter site are presented here for the first time (App. A). Askja-S has been identified in three cores from Havnardalsmyren c. 50–70 cm below the Saksunarvatn Ash.

The age of the Askja-S Tephra has been vividly discussed. It has been considered to be a result of one single eruption but different dating efforts have yielded conflicting ages, spanning over almost 1000 years. Misidentification of the less widespread 9400 year old Askja-L Tephra (Gudmundsdóttir et al., 2016) can probably be ruled out due to its younger age. The position of Askja-S in relation to early Holocene climate events such as the PBO has also been discussed (e.g. Ott et al., 2016; Kelly et al., 2017). The age estimate from Iceland is c. 10,000 ^{14}C years (Sigvaldason, 2002) which places the tephra in the early Holocene but is not precise enough to provide an exact calendar year age. Wohlfarth et al. (2006) used Bayesian modelling of radiocarbon dates at Hässeldala port, and the most robust model gave a 95% range of 11,050–10,570 cal yr BP. Bronk Ramsey et al. (2015) incorporated age constraints from Lake Soppensee which gave a calibrated range of 10,956–10,716 cal yr BP. Further age modelling, including dates from Romanian sites have produced an updated age of 10,921–10,727 cal yr BP (Kearney et al., 2018). A slightly older age was reported from the varved sediment record of Lake Czechowskie, Poland where varve counting provided an age of 11,228 ± 226 cal yr BP (Ott et al., 2016) which overlaps with the larger uncertainty range of Wohlfarth et al. (2006) but not with the more narrow uncertainty bands of Bronk Ramsey et al. (2015) and Kearney et al. (2018). The remodelled chronology of the Høvdarhagi bog sequence (Fig. 6) gives an age estimate for the Askja-S Tephra of 10,526–10,322 cal yr BP (Table 2). This is still younger than the ages reported by Wohlfarth et al. (2006), Bronk Ramsey et al. (2015) and Kearney et al. (2018). and the varve date from the Polish lake. Further radiocarbon dating of Askja-S in the Faroe sites could potentially solve this dating problem.

3.1.5. *Hovsdalur Tephra (c. 10.5 ka cal BP?)*

A rhyolitic tephra found in a core from the valley of Hovsdalur on Suduroy, c. 40 cm below the Saksunarvatn Ash was named the Hovsdalur Tephra (Wastegård, 2002). The Hovsdalur Tephra has a similar composition as the Hässeldalen Tephra (Fig. 3), but is slightly lower in alkalis (K_2O 3.7–4.1 wt%; Na_2O 3.3–3.8 wt%)

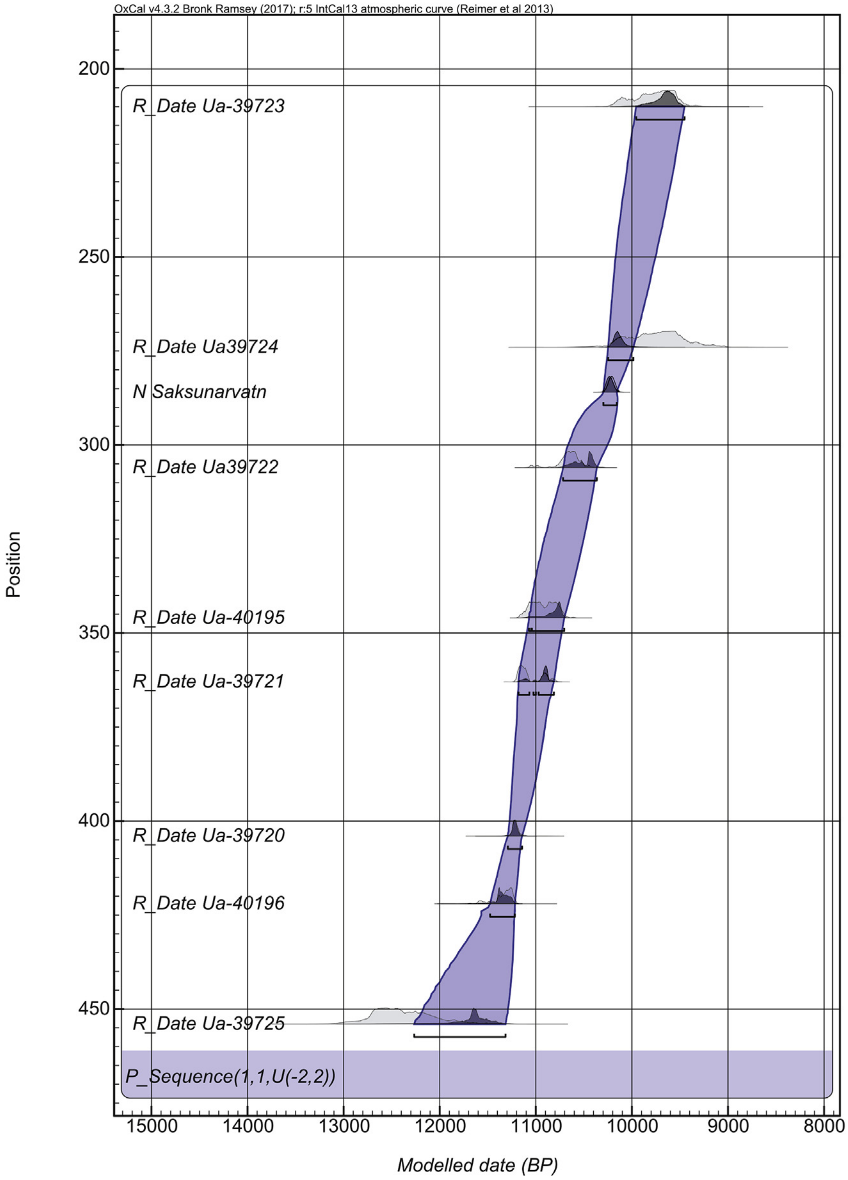

Fig. 6. Output of Bayesian age-depth modelling of the Høvdarhagi core (Lind and Wastegård, 2011), using OxCal 4.3.2. and the IntCal13 calibration curve. The age for the Saksunarvatn Tephra (10,210 ± 35 cal yr BP) is from Lohne et al. (2013). The previous age model from Høvdarhagi bog was constructed using the OxCal 4.1.6. software (Lind and Wastegård, 2011).

which, however, could be due to less refined analytical conditions when the analyses were made in the early 2000s. It is indistinguishable, however, from the Hässeldalen Tephra when analysed with the same probe conditions (e.g. Davies et al., 2003). Snæfellsjökull in W Iceland was originally suggested as a source volcano (Wastegård, 2002; Housley et al., 2013). A more probable correlation is to the Thórdarhyrna central volcano as shown in Figs. 3B and 4. The suggested age of c. 10,500 cal yr BP was based on interpolation between the Saksunarvatn Ash (c. 10.2 ka BP) and two radiocarbon dates immediately above the tephra which may underestimate the true age of the Hovsdalur Tephra. Davies et al. (2003) noted the geochemical similarity between the Hovsdalur and Hässeldalen tephras but did not suggest a correlation due to uncertain age estimates for both tephras at the time. Lind and Wastegård (2011), however, suggested that they might derive from the same eruption and that the age estimate of the Hovsdalur Tephra was several hundred years too young. The Hässeldalen and Hovsdalur tephras have not been found in the same sequence on the Faroe Islands and the fact that only one tephra with this composition was found in the Høvdarhagi sediments (Lind and Wastegård, 2011), indicates a single event. Recently, however, evidence have been presented from Quoyloo Meadow in Orkney, Scotland suggesting that the Hässeldalen and Hovsdalur tephras indeed may represent two separate events in the early Holocene (Timms et al., 2017). The tephras are there separated by 5 cm with the Askja-S Tephra in-between. Some caution, however, should be taken with the results from Quoyloo Meadow; both tephras are mixed with other components, probably due to a low sedimentation rate and an exacerbated mixing of tephra layers in the early Holocene. Furthermore, the number of analysed shards are few, and do not allow a fully secure correlation with the Hässeldalen and Hovsdalur tephras. More work is clearly needed to resolve the issue of one or two tephras with this chemical affinity in the early Holocene. The complete dataset of the Hovsdalur Tephra is here presented for the first time (App. A).

3.1.6. *Saksunarvatn Ash (c. 10.2 ka cal BP)*

This is the best-known of the tephras originally described from the Faroe Islands. It was originally reported by Waagstein and Jóhansen (1968) from the Hoydalar site close to Tórshavn and Lake Skælingsvatn on Streymoy (Fig. 1B) but it did not get its name until the publication of the paper by Mangerud et al. (1986), describing it in the eponymous type site on Streymoy, Lake Saksunarvatn (Fig. 1B). The Saksunarvatn Ash is a visible cm-scale black layer in many sites on the Faroe Islands and a valuable isochron for the early Holocene, especially for marking the 10.3 ka cal event (Björck et al., 2001). The Saksunarvatn Ash is the most voluminous Icelandic basaltic tephra deposit in the Holocene, and since its discovery it has been described from numerous sites in Iceland, the British Isles, Norway, Germany, Greenland and the North Atlantic (e.g. Björck et al., 1992; Merkt et al., 1993; Birks et al., 1996; Grönvold et al., 1995; Timms et al., 2017; Harning et al., 2018). The distribution envelope indicates a main transport direction towards NW and SE (e.g. Davies et al., 2012). The source of the Saksunarvatn Ash is the Grímsvötn volcanic system in the Eastern Volcanic Zone on Iceland which is shown by plots of e.g. TiO_2 vs. MgO (Fig. 2). The Saksunarvatn Ash is dated to 10,347 ± 45 yrs b2k in the NorthGRIP ice core (Rasmussen et al., 2006) and to 10,210 ± 35 cal yr BP in Kråkenes, Norway (Lohne et al., 2013). Several recent studies have, however, questioned the Saksunarvatn Ash as a result of one eruptive event and indeed, several closely separated layers with Grímsvötn geochemistry have been reported from Iceland, the Faroe Islands and the North Atlantic (Jóhannsdóttir, 2007; Kylander et al., 2012; Jennings et al., 2014; Harning et al., 2018). A pilot study was performed at Havnardalsmyren, Streymoy (Fig. 1B), aiming at evaluating whether XRF core-scanning can be used to identify cryptotephra deposits. In this study five separate layers with Grímsvötn geochemistry were identified, a 3–5 cm thick visible layer and four cryptotephra layers, one above the visible Saksunarvatn Ash and three layers below (Kylander et al., 2012). The full dataset from Havnardalsmyren is here presented for the first time (App. A) and is discussed in detail below.

3.1.7. *L-274 Tephra/Fosen Tephra (c. 10.1 ka cal BP)*

This tephra was found c. 13 cm above the Saksunarvatn Ash in Høvdarhagi bog on Sandoy (Lind and Wastegård, 2011). It has a mixed geochemical signature with at least three different components, represented by three to five analyses each (Fig. 3). One component has a “Borrobol-type” geochemistry similar to the Borrobol and Penifiler tephras from the Lateglacial Interstadial or GI-1 (Matthews et al., 2011; Lind et al., 2016). Another component is more similar to the An Druim Tephra (9560 cal yr BP), found in northern Scotland by Ranner et al. (2005), but is lower in K_2O (Fig. 3B). After this finding was made, two sites with early Holocene Borrobol-type tephras were described from Scandinavia, dated to c. 10,200 cal yr BP (Lind et al., 2013; Larsen, 2014). The tephra, called the Fosen Tephra, overlies the Saksunarvatn Ash in the Grønlia site on the Fosen Peninsula, W. Norway. The similar stratigraphic position and age of the L-274 Tephra on the Faroe Islands indicate that it could be a result of the same eruption from the yet unknown Icelandic volcano that produced the Borrobol-type tephras (Lind et al., 2016). The Fosen Tephra has recently also been described from eastern Iceland (Gudmundsdóttir et al., 2016) and Scotland (Timms et al., 2017) which makes it one of the most important isochrons for the Early Holocene. More analyses from Høvdarhagi bog and other sites are needed to confirm the correlation between the L-274 Tephra and the Fosen Tephra.

3.1.8. *Skopun Tephra (c. 9.7 ka cal BP)*

The Skopun Tephra is named after the village Skopun on Sandoy, c. 2 km east of the Høvdarhagi bog (Lind and Wastegård, 2011). It was found c. 2 cm below the An Druim/Høvdarhagi Tephra in the Høvdarhagi bog and the revised age model suggests similar ages for both tephras around c. 9750-9700 cal yr BP (Fig. 6; Table 2). The age model is uncertain in this part of the sequence due to a scarcity of dateable material, and a better chronology would be needed to determine the ages for both these potentially important early Holocene tephras. The Skopun Tephra has a dacitic composition and correlates with the SILK tephras layers from Katla in south Iceland (Figs. 3 and 7). The SILK tephras were erupted from vents under the ice-cap and almost 20 layers have been found in Iceland, dated between c. 8100 and c. 1675 cal yr BP (Larsen et al., 2001; Óladóttir et al., 2008; Thorsteinsdóttir et al., 2016). The Skopun Tephra is thus the oldest SILK layer that has been found and once again points out the fact that preservation of early Holocene tephras on Iceland can be poor. It also sheds new light on the Holocene evolution of the Katla volcano.

3.1.9. *An Druim Tephra/Høvdarhagi Tephra (c. 9.7 ka cal BP)*

A tephra with a bimodal alkaline rhyolite composition of Torfajökull affinity was found at 217 cm in the Høvdarhagi bog sequence (Lind and Wastegård, 2011). The layer was first called the

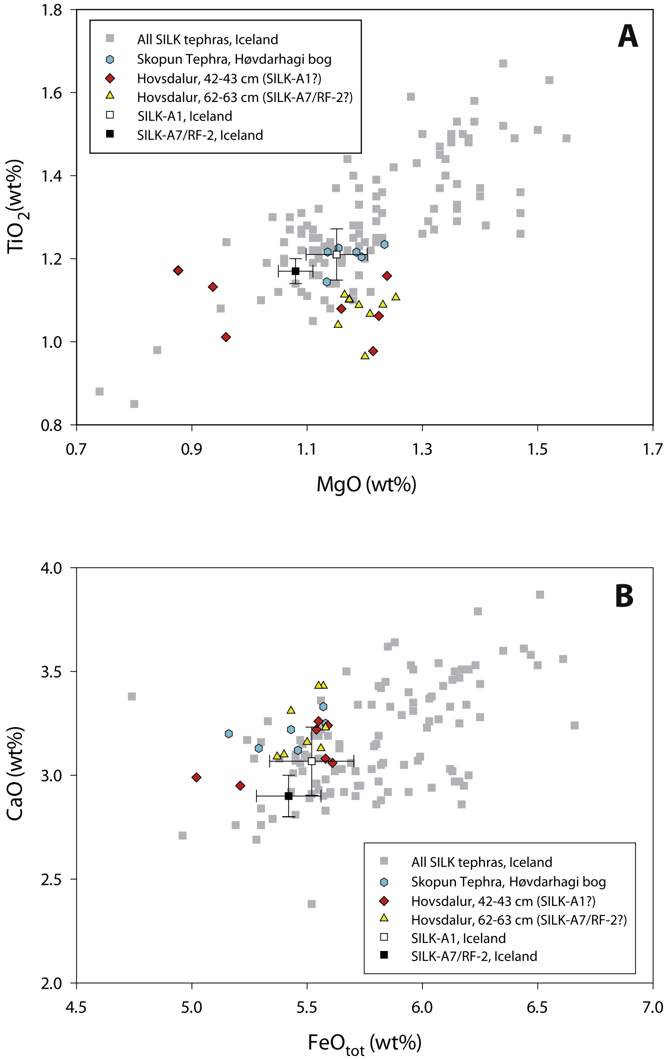

Fig. 7. Biplots of SILK tephras found on the Faroe Islands (A: MgO vs. TiO_2; B: FeO_{tot} vs. CaO) compared with published data of SILK tephras from Iceland (Larsen et al., 2001; Óladóttir et al., 2008; Thorsteinsdóttir et al., 2016); Icelandic records of SILK-A1 and SILK-A7/RF-2 are shown with 1 s.d. (Larsen et al., 2001).

Høvdarhagi Tephra but subsequent studies suggest that it probably can be correlated with the An Druim Tephra found at three sites in north Scotland (Ranner et al., 2005; Kelly et al., 2017; Timms et al., 2017). Most of the shards of the Høvdarhagi Tephra show higher concentrations of CaO than the An Druim Tephra (Fig. 3A), but this could possibly reflect that tephra from different phases of the eruption have been deposited in Scotland and the Faroe Islands, or that the absence of a bi-modal trend in the Scottish sites may be an artefact of a smaller sample size (Kelly et al., 2017). The age of the tephra in Høvdarhagi bog has been modelled to 9836–9596 cal yr BP (Table 2) which overlaps with the age of the An Druim Tephra in Scotland (9776–9565 cal yr BP; Timms et al., 2017). The An Druim Tephra is a potentially widespread tephra that can be important for the correlation of early Holocene sequences.

3.2. *The middle and late Holocene (8200 cal yr BP-present)*

Several small lakes that existed in the early Holocene were infilled and overgrown by peat in the early to middle Holocene. An example of this is the Hovsdalur site on Suduroy (Fig. 1B) where peat started to accumulate around 9000 cal yr BP (Wastegård, 2002) or even as early as before the deposition of the Saksunarvatn Ash (Edwards and Craigie, 1998). Expansion of peat has continued throughout the last 9000 years but cannot be tied to any climatic events (Lawson et al., 2007). Only a few peat records have been sampled contiguously for tephra since the pioneering work by Persson (1968) who investigated four sites, Saksunmyren, Havnardalsmyren and Myrarnar on Streymoy and Klovinmyren on Vágar (Fig. 1B), and identified around five tephra layers (Persson, 1968). Geochemical analyses were not available when Persson conducted his study and all correlations with Icelandic eruptions were based on radiocarbon dating, grain size distributions, refractive indices, and in one case pollen stratigraphy. One important effect of this is that only silicic and intermediate shards were found, despite the fact that ash fall-out from basaltic eruptions have been noted on several occasions, e.g. during the eruptions of Katla in 1625, 1660 and 1755 CE (Thorarinsson, 1981). It is possible that this reflects post-depositional processes in acidic environments, which particularly affects basaltic glass (e.g. Wolff-Boenisch et al., 2004). The lowermost two tephras in Klovinmyren were dated to 3800 ± 80 ^{14}C yr BP (c. 4200 cal yr BP) and 3450 ± 70 ^{14}C yr BP (c. 3725 cal yr BP) and can most probably be correlated with Hekla 4 (c. 4260 cal yr BP) and Hekla S (c. 3720 cal yr BP) tephras, although the latter was not known when Persson carried out his study. A further tephra higher up in the stratigraphy at Klovinmyren, was dispersed over a depth of 13 cm. A radiocarbon date of 2650 ± 75 ^{14}C yr BP (c. 2750 cal yr BP) at the bottom of the tephra indicates that it might be the Hekla 3 tephra (c. 2950 cal yr BP). The youngest peat in the sequences investigated by Persson were partly affected by peat cutting and only two tephras younger than 2000 cal yr BP were found; one at Saksunmyren dated to 1585 ± 70 ^{14}C yr BP (c. 1480 cal yr BP) and one at Myrarnar dated to 900 ± 120 ^{14}C yr BP (c. 830 cal yr BP). Without geochemical identification one can only speculate which events produced these tephras.

3.2.1. *Suduroy Tephra (c. 8.0 ka cal BP)*

The Suduroy Tephra was discovered in a core from the Hovsdalur blanket peat on Suduroy (Wastegård, 2002). The concentration was low (c. 15 shards/cm^3) and later attempts to localise the tephra in other cores from Hovsdalur have failed. The geochemistry is almost identical with the rhyolitic component of the Vedde Ash (12.1 ka cal BP) and other Vedde-type tephras (Lane et al., 2012b), except that TiO_2 is slightly lower. It is uncertain, however, if this small difference is significant. The Faroe Islands are believed to have been completely covered by an ice-cap during the Younger Dryas (Humlum, 1998) and sediment sequences with the Vedde Ash have not been found. Since its first discovery, tephras correlated with the Suduroy tephra have been reported from North Atlantic marine records (Kristjansdóttir et al., 2007; Gudmundsdóttir et al., 2012), Scotland (MacLeod, 2008; Mithen et al., 2015), North Norway (Pilcher et al., 2005) and possibly North Germany (Housley et al., 2012) but it cannot be excluded that some of these records represent reworked Vedde Ash shards. The Suduroy Tephra is dated to c. 8.0 ka cal BP and is therefore a potentially important isochron for the 8.2 ka BP event.

3.2.2. *SILK-A7/RF-2? Tephra and SILK A1 Tephra (c. 7.1 ka cal BP and 5.9 ka cal BP)*

Two further layers with Katla affinity were found in the Hovsdalur peat record at 63–64 cm and 42–43 cm, dated to c. 7.1 and 5.9 ka yr BP, respectively (Wastegård, 2002). Both layers display geochemical characteristics typical of SILK volcanism, i.e. TiO_2 contents between 1.0 and 1.1 wt%, MgO between 0.9 and 1.3 wt% and FeO_{tot} between 5.0 and 5.6 wt% (Fig. 7; App. A). Although about 20 SILK layers from Katla are known between c. 8100 and 1600 cal yr BP not all of them have been geochemically fingerprinted. Their ages are often derived from soil accumulation rates between tephras dated by radiocarbon, which makes their ages somewhat uncertain. An unambiguous correlation between the SILK layers found in Hovsdalur and the Icelandic layers cannot be made at present. It is possible, however, to speculate that the SILK-A7 Tephra is the correlative of the older tephra and SILK-A1 for the younger tephra. The SILK-A7 corresponds to SILK RF-2, dated to c. 7230 cal yr BP that was later analysed by Óladóttir et al. (2008) and the SILK-A1 Tephra dates to c. 6000 cal yr BP (Thorsteinsdóttir et al., 2016). However, further work is needed to confirm or reject these correlations.

3.2.3. *Mjáuvøtn Tephra (c. 6.6 ka cal BP)*

A mid Holocene, visible and mm-thick basaltic tephra occurs in many lake sediment sequences on the Faroe Islands and was named the Mjáuvøtn Tephra after the lake on central Streymoy, where it was first identified (Fig. 1B) (Wastegård et al., 2001). The main component, called the Mjáuvøtn Tephra A has a typical composition for basaltic tephra from the Katla volcanic system with TiO_2 contents between 3.9 and 4.4 wt% and K_2O between 0.6 and 0.9 wt% (Figs. 2 and 8). A minor component, called Mjáuvøtn Tephra B has been found at three sites and has an andesitic/trachydacitic composition with SiO_2 contents between 53.5 and 56.5 wt%, TiO_2 between 2.1 and 2.5 wt% and MgO at 2.4–3.0 wt% (Fig. 2). The Mjáuvøtn Tephra B component shares some similarities with intermediate products from the Katla volcanic system, e.g. the Solheimar ignimbrite (Tomlinson et al., 2012) and intermediate Vedde Ash shards found in Norway (Lane et al., 2012b) and we suggest that the Mjáuvøtn Tephra has a bimodal Katla composition with a main basaltic and a minor andesitic/trachydacitic composition caused by bimodal mixing of basaltic magma with silicic melts (cf. Óladóttir et al., 2008). Mixing with silicic magma is also confirmed by K_2O/P_2O_5 ratios >1.8 (cf. Óladóttir et al., 2008). The Mjáuvøtn Tephra was first given a tentative age of c. 5700-5300 cal yr BP (Wastegård et al., 2001), but age modelling of ^{14}C dates from two sites gave a significantly older and better constrained age of 6668–6533 cal yr BP (Olsen et al., 2010b). The Mjáuvøtn Tephra has a similar age as the Hekla DH Tephra (c. 6650 cal yr BP; Gudmundsdóttir et al., 2012, 2016). This predominantly intermediate tephra has some affinities with the Mjáuvøtn Tephra B, but is lower in FeO_{tot} and MgO and higher in K_2O in shards with similar SiO_2 contents.

Katla is one of the most active volcanic systems on Iceland with up to six basaltic eruptions per century in prehistoric times

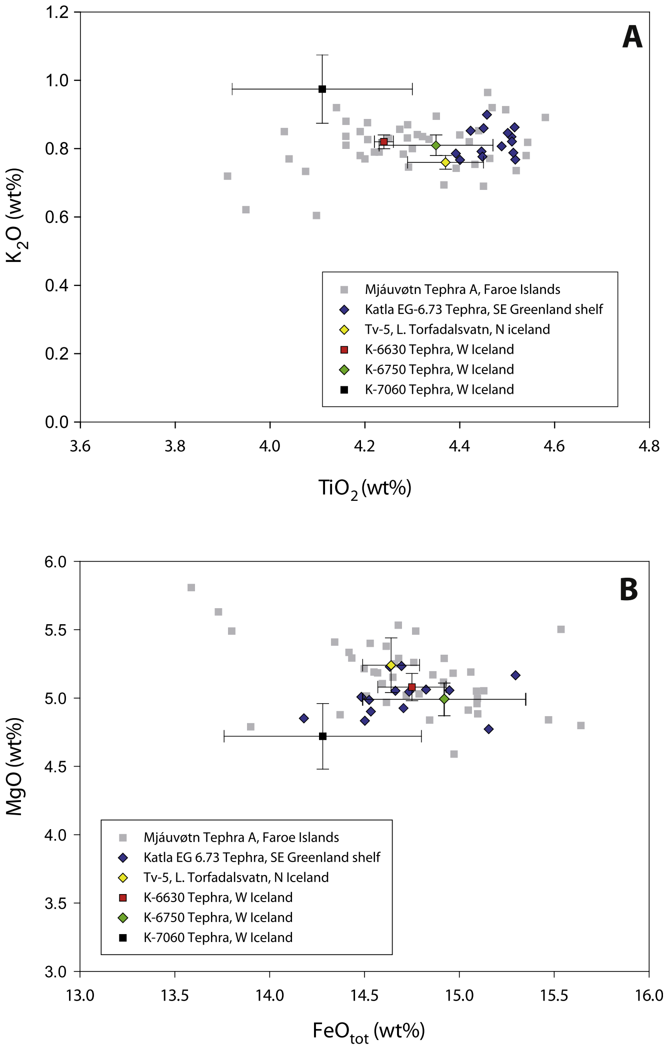

Fig. 8. Biplots of the Mjáuvøtn Tephra A (A: TiO_2 vs. K_2O; B: FeO_{tot} vs. MgO) compared with the K-6630, K-6750 and K-7060 tephras from western Iceland (means with 1 s.d.; Jóhannsdóttir, 2007), Tv-5 from Lake Torfadalsvatn, N Iceland (Björck et al., 1992) and the Katla EG-6.73 ka Tephra (= K-6750 Tephra) from the SE Greenland shelf (Jennings et al., 2014).

(Óladóttir et al., 2008). In particular, the period between c. 7500 and 6500 cal yr BP had several basaltic eruptions falling mainly into period VI (7000-6300 cal yr BP; Óladóttir et al., 2008). This period is characterized by increasing K_2O and Na_2O and decreasing CaO and MgO with time.

Some basaltic Katla layers are potentially more widespread, and Wastegård et al. (2001) suggested a correlation between the Mjáuvøtn Tephra and the Tv-5 Tephra found in the Lake Torfadalsvatn sequence in north Iceland (Björck et al., 1992). The Tv-5 Tephra is dated to 6000 ^{14}C yrs BP (c. 6850 cal yr BP) and is the only visible middle Holocene tephra in Torfadalsvatn. The Tv-5 Tephra has also been reported from a marine core from the north Icelandic shelf (Kristjansdóttir et al., 2007), suggesting a main dispersal towards the north. Several basaltic Katla layers dated between c. 7100 and 6500 cal yr BP also occur in lake cores from western Iceland and in marine cores off SE Greenland (Jóhannsdóttir, 2007; Jennings et al., 2014). The K-6750/Katla EG 6.73 Tephra (c. 6750 cal yr BP) has the highest abundance of all basaltic layers younger than the Saksunarvatn Tephra in the marine records. Jennings et al. (2014) suggested that this layer also can be correlated with Tv-5, making this one of the most widespread Icelandic Holocene basaltic tephra layers. Based on minor differences in major element geochemistry between the Mjáuvøtn, Tv-5 and K-6750 tephras, Jennings et al. (2014), however, concluded that the Mjáuvötn Tephra is an unlikely correlative with the K-6750 Tephra, also given the different dispersal directions. Geochemical plots of normalized values, however, show that the differences are small (Fig. 8) and that the Mjáuvøtn Tephra A is almost indistinguishable from the K-6750/Katla EG 6.73 Tephra as well as from the slightly younger K-6630 Tephra, also found in lake sediments in western Iceland, but distinct from the older K-7060 Tephra (Jóhannsdóttir, 2007). As mentioned above, however, several eruptions occurred in the time period in question, and correlations can not be made to a certain eruption. The minor andesitic/trachyandesitic "B" component may only be present in low numbers, and has only been found on the Faroe Islands. The Mjáuvøtn Tephra has so far only been found in lake sediments on the Faroes and not in peat.

3.2.4. Hov Tephra (c. 5.9 ka cal BP)

The Hov Tephra is one of few basaltic tephras found in peat on the Faroe Islands. It was found at the same depth as the SILK-A1 Tephra in Hovsdalur, and radiocarbon dating suggests an age around 5900 cal yr BP (Wastegård, 2002). It should be noted, however, that ages in Hovdalur are uncertain due to a low and variable peat accumulation rate. Grímsvötn has been suggested as the source volcanic system (Wastegård, 2002) but the Hov Tephra also has affinities of the Kverkfjöll volcanic system, north of Vatnajökull (cf. Óladóttir et al., 2011), e.g. MgO contents below 5 wt% for several analyses (Fig. 2A). Kverkfjöll has not erupted in historical times and is less active than most other basaltic systems on Iceland. Its highest eruption frequency was in the middle part of the Holocene, between 6000 and 5000 cal yr BP (Óladóttir et al., 2011), and especially between 5500 and 5200 cal yr BP (Gudmundsdóttir et al., 2016).

3.2.5. Hekla 4 Tephra (c. 4.3 ka cal BP)

Hekla 4 is one of the two largest eruptions of Hekla together with Hekla 3 and cryptotephra records are widely dispersed across mainland Europe (e.g. Davies et al., 2010; Lawson et al., 2012). Records of it have been made both in peat and in lake sediment on the Faroe Islands (e.g. Persson, 1968; Dugmore and Newton, 1998; Wastegård et al., 2001) and Hekla 4 is a visible horizon in lake sediment sequences and in peat cuttings together with the c. 600 year younger Hekla S Tephra (Fig. 9). Hekla has a zoned magma and rhyolitic products dominate the Plinian phase, followed by more intermediate and even basaltic products. All analyses of the Hekla 4, Hekla S and Hekla 3, Hekla 1, Hekla 1158 and Hekla 1845 from the Faroe Islands are plotted in Fig. 10, including previously unpublished results from Havnardalsmyren, Gróthusvatn and Starvatn (Fig. 1B; App. A). Intermediate and rhyolitic tephra dominate in all sites.

3.2.6. Hekla S Tephra (c. 3.7 ka cal BP)

Hekla S was originally described as Hekla 2 on Iceland (Thorarinsson, 1951), but was later found to be older than Hekla 3 and the name was changed to Hekla Selsund or simply Hekla S, after the site Selsund on Iceland c. 15 km SW of Hekla (Larsen and Thorarinsson, 1977). Hekla S has also been referred to as the Kebister Tephra on Shetland (Dugmore et al., 1995). Hekla S is one of the largest eruptions of Hekla in prehistoric time, and the tephra was dispersed mainly towards the east. Several records have been made on the Faroe Islands, Shetland and Scandinavia (e.g. Wastegård et al., 2008). The Faroe Island records cover almost the whole geochemical envelope for Hekla, from the rhyolitic shards

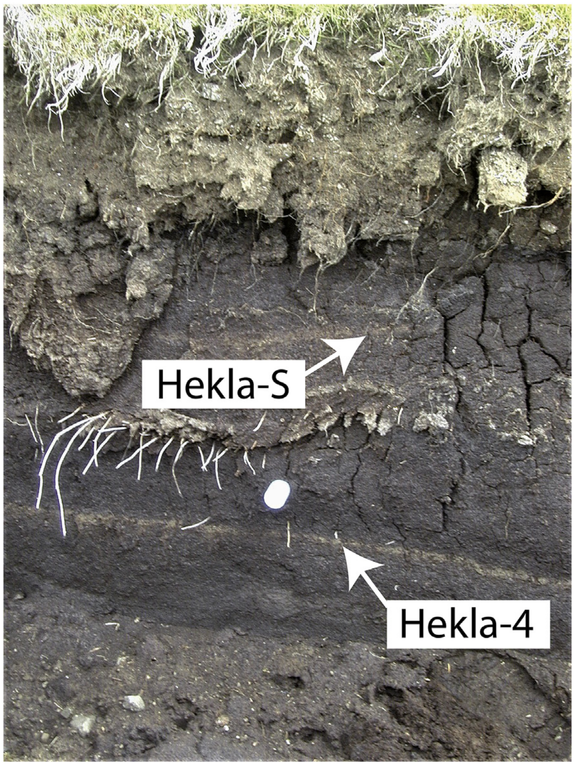

Fig. 9. Peat cutting from Streymoy with two visible tephras, Hekla 4 and Hekla S. Photo: Ian Snowball.

erupted during the initial phase, to the basaltic andesite shards from later phases (Fig. 10; App. A).

3.2.7. *Hekla 3 Tephra (c. 3.0 ka cal BP)*

Although regarded as the most voluminous eruption of Hekla, and possibly the largest Late Quaternary eruption on Iceland, the Hekla 3 Tephra is less widely dispersed than many other Icelandic tephras. Only one record has been made on the British Isles (Plunkett, 2006a) and the only Faroe record is from Brúnavatn on Streymoy (Olsen et al., 2010a). The main dispersal was to the north and northeast (Larsen and Thorarinsson, 1977) and it appears that sites south and southeast of Iceland were relatively unaffected by the ash cloud. It is also worth mentioning that none of the mid Holocene tephras from Hekla, Hekla 4, Hekla S and Hekla 3 have been found in the Greenland ice cores so far (Coulter et al., 2012).

3.2.8. *Tjørnuvík Tephra, 800s CE*

An intermediate to silicic tephra of Hekla affinity has been found in three lake and peat sequences on the Faroe Islands, close in time to the first palaeobotanical evidence of human settlement on the Faroe Islands (e.g. Hannon and Bradshaw, 2000; Wastegård et al., 2001, 2003). Furthermore, it occurs together with shards correlated with the basaltic phase of the Landnám Tephra in two sites, Tjørnuvík on Streymoy and Hovsdalur on Suduroy (Fig. 1B), suggesting an age in the second half of the 9th Century CE (Wastegård et al., 2001; Wastegård, 2002). The geochemistry, ranging from trachytic/andesitic to rhyolitic compositions suggests the Tjørnuvík Tephra is the product of a relatively large eruption from Hekla (Fig. 11). A large, late pre-Landnám rhyolitic eruption of Hekla has, however, not been identified in Iceland and the period between Hekla 3 and Landnám (c. 3000 cal yr BP-870s CE) is characterized by relatively small-scale eruptions of Hekla, dominated by tephra of andesitic-dacitic compositions (Meara, 2011). A closer look at the geochemistry of the Tjørnuvík Tephra reveals that shards similar to both Hekla 4 and Hekla S dominate at all three sites (Fig. 11), and an alternative explanation is that the Tjørnuvík Tephra consists of reworked shards from the large Hekla 4 and Hekla S eruptions. Reworking and redistribution of tephra during the Landnám phase due to soil erosion and increased mobilization of wind-blown sediment (cf. Edwards et al., 2005) is a possible explanation for the occurrence of the "Tjørnuvík Tephra" in sediments dated to the 9th Century CE on the Faroe Islands.

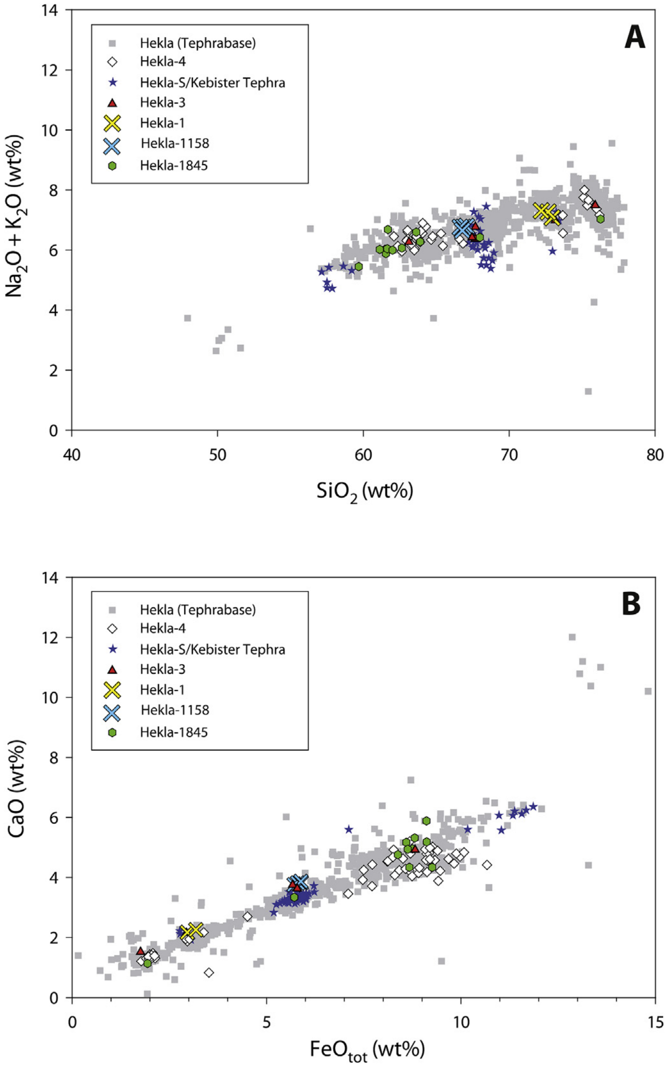

Fig. 10. Biplots of all tephras from Hekla included in this study with exception of the Tjørnuvík Tephra (Wastegård et al., 2001, 2008 and unpublished; Olsen et al., 2010a); (A: SiO_2 vs. $Na_2 + K_2O$; B: FeO_{tot} vs. CaO) compared with data from Tephrabase (www.tephrabase.org), including analyses of Hekla 5, Hekla 4, Hekla 3, Hekla S and several historical eruptions of Hekla. All analyses have been normalized to 100 wt%.

There are, however, some indications that the Tjørnuvík Tephra, or at least some parts of it, may be a primary deposit. Chambers et al. (2004) described a cryptotephra, MOR-T6 from an eruption of Hekla found in a lake sediment sequence in western Ireland, with an estimated age of c. CE 840. The geochemistry partly matches the Tjørnuvík Tephra (Fig. 11), but most analyses of the MOR-T6 Tephra are tightly clustered and do not cover the whole range from andesitic to highly rhyolitic shards. Also other Hekla eruptions have been identified in distal records between the 8th and 10th centuries CE (Pilcher et al., 2005; Plunkett and Pilcher, 2018) but until more evidence for large eruptions of Hekla at this time come forward, the

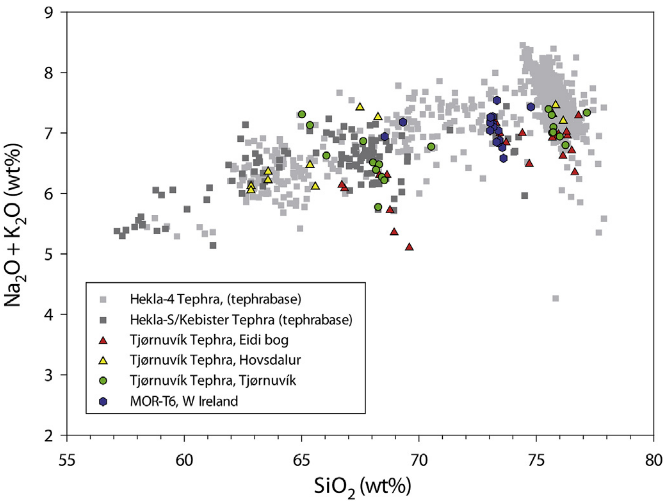

Fig. 11. Biplot of the Tjørnuvík Tephra from Eidi bog, Hovsdalur and Tjørnuvík (A: SiO_2 vs. $Na_2 + K_2O$) compared with analyses of Hekla-4 and Hekla-S/Kebister tephras from Tephrabase (www.tephrabase.org) and the MOR-T6 tephra from western Ireland (Chambers et al., 2004). All analyses have been normalized to 100 wt%.

identification of the Tjørnuvík Tephra as a primary deposit remains inconclusive.

3.2.9. Landnám Tephra, 877±1 CE

The basaltic phase of the Landnám Tephra has been reported from Tjørnuvík, Eidi bog and Hovsdalur (Fig. 1B), with highest concentration at the latter site. As mentioned above, it occurs together with the Tjørnuvík Tephra in sediments dated to the first settlement phase (e.g. Wastegård et al., 2001). The Landnám Tephra or the Settlement Tephra is a product of a simultaneous silicic and basaltic eruption of the Torfajökull and Bárdarbunga-Veiđivötn volcanic systems, dated to 877 ± 1 CE (Sigl et al., 2015; Schmid et al., 2017). The basaltic eruption is one of the largest in Iceland during the Holocene and the basaltic component has also been found in Scottish fjord sediments (Cage et al., 2011), which indicates that one axis of dispersal was directed to the south. Reworking from older deposits in the Faroe Islands cannot be excluded, as in the case with the Tjørnuvík Tephra. However, no older tephras with a geochemistry matching the Landnám Tephra have been found on the Faroe Islands, and the only tephra with Bárdarbunga-Veiđivötn affinity, the Sandoy A and Sandoy B tephras (see above), are higher in e.g. MgO and lower in FeO_{tot} (Fig. 2) and much older so reworking can probably be excluded. We therefore consider the Landnám Tephra to be a primary deposit on the Faroe Islands.

3.2.10. Hekla 1 Tephra (CE 1104) and Hekla 1158 CE Tephra

The CE 1104 event was the largest Hekla eruption in historical times (Thorarinsson, 1967), and the tephra layer is one of the most important late Holocene isochrons in Icelandic terrestrial and marine records (e.g. Larsen and Thorarinsson, 1977; Boygle, 1999; Larsen et al., 1999, 2002). It is widely dispersed and found at distal sites in Europe (e.g. Pilcher et al., 2005; Chambers et al., 2004; Watson et al., 2016). Hekla 1 can be separated from other historical Hekla tephras in plots of K_2O/TiO_2 and is more evolved than any other historical tephra from Hekla (Larsen et al., 1999). Hitherto, the only Faroe record of Hekla 1 is from Lake Brúnavatn on Streymoy (Olsen et al., 2010a). A closer look at the geochemistry, however, reveals that some shards have a more andesitic composition with CaO contents of c. 3.7–3.8 wt% and FeO_{tot} of 5.7–5.9 wt% and probably derive from the slightly younger eruption of Hekla in 1158 CE. Thus, the horizon in Brúnavatn has a mixed composition with shards from the Hekla 1 and Hekla 1158 eruptions.

3.2.11. Hekla 1845 Tephra

The youngest tephra in the Hovsdalur peat record has a predominantly andesitic composition and follows the Hekla evolution trend (Fig. 10). The explosive opening phase of the eruption lasted 1 h and produced ca 0.13 km^3 tephra (0.03 km^3 DRE) (Gudnason et al., 2018) and contemporary records describe ash fallout on Faroe Islands, Shetland and Orkney (Wastegård and Davies, 2009; Gudnason et al., 2018). Distal tephra from this eruption has also been reported from the Fallahogy peatland in Northern Ireland (Watson et al., 2015). Hekla has erupted at least 17 times since the large eruption in AD 1104 (Hekla 1) and most of the eruptives are dominated by andesitic glass with similar compositions. Tephra from the eruptions in 1158, 1510, 1845 and 1947 have so far been found in distal areas (e.g. Dugmore et al., 1995; Swindles et al., 2011; Watson et al., 2015, 2017), but it cannot be excluded that tephra from other historical eruptions, e.g. the relatively large eruptions in 1693 and 1766 also reached the European mainland. The correlation of the tephra in Hovsdalur with Hekla 1845 is corroborated by the fact that ash fallout was recorded on Suduroy, 3 September 1845 (Wastegård and Davies, 2009).

4. Discussion

4.1. Tephras in the Faroe Islands as potential isochrons

There are now 23 tephras that have been identified in Holocene sequences on the Faroe Islands (Fig. 12) and several of these have a potential for constraining leads and lags in the climate system during the Holocene. The early Preboreal climate evolution of northwestern Europe was complex, and accurate dating and comparison of palaeoclimate data is often problematic, due in part to the two radiocarbon plateaux occurring at this time (e.g. Björck et al., 1997; van der Plicht et al., 2004). Consequently the Hässeldalen, Askja-S and Saksunarvatn tephras are particularly important markers for synchronising climate records from the early Holocene, and for assessing whether climate re-organisations were synchronous/asynchronous at continental and hemispheric scales. The Hässeldalen Tephra is often reported to occur in conjunction with the PBO, c. 11.40–11.25 ka BP, although the timing and impact of this oscillation may differ between areas (e.g. Björck et al., 1997; Bos et al., 2007). The Hässeldalen Tephra has been reported from lake sediments from Denmark and Sweden (e.g. Davies et al., 2003; Lilja et al., 2013; Larsen and Noe-Nygaard, 2014; Wohlfarth et al., 2018), at most sites a few cm above the onset of the rapid warming at the Younger Dryas-Preboreal boundary, but clearly below the PBO. In the Faroe Islands it occurs near the bottom of the sequence in the Høvdarhagi bog, but a clear indication of the PBO has not been seen at this site or in Lykkjuvøtn where sedimentation began at c. 11.28 ka, i.e. during the PBO (Jessen et al., 2008). At Endiger Bruch, NE Germany, the Hässeldalen Tephra occurs after the organic matter curve has reached its Holocene levels (Lane et al., 2012a), which indicates that organic sedimentation started slightly earlier in Germany than in Scandinavia. At Lake Czechowskie, Poland, the Hässeldalen Tephra has been found in varved sediments, along with the Askja-S Tephra (Ott et al., 2016), although the time span between the tephras is in disagreement with other records being only c. 150 varve years compared to radiocarbon-based chronologies that indicate an age difference of at least 500 years (Wohlfarth et al., 2006; Lind and Wastegård, 2011). Here, the PBO is indicated by a minor increase in Ti counts, possibly indicating a response to a drier climate. In south-east Sweden PBO is bracketed by the Hässeldalen and Askja-S tephras (Davies et al., 2003; Wohlfarth et al., 2006).

The climate oscillation at c. 10.3 ka BP is less pronounced than

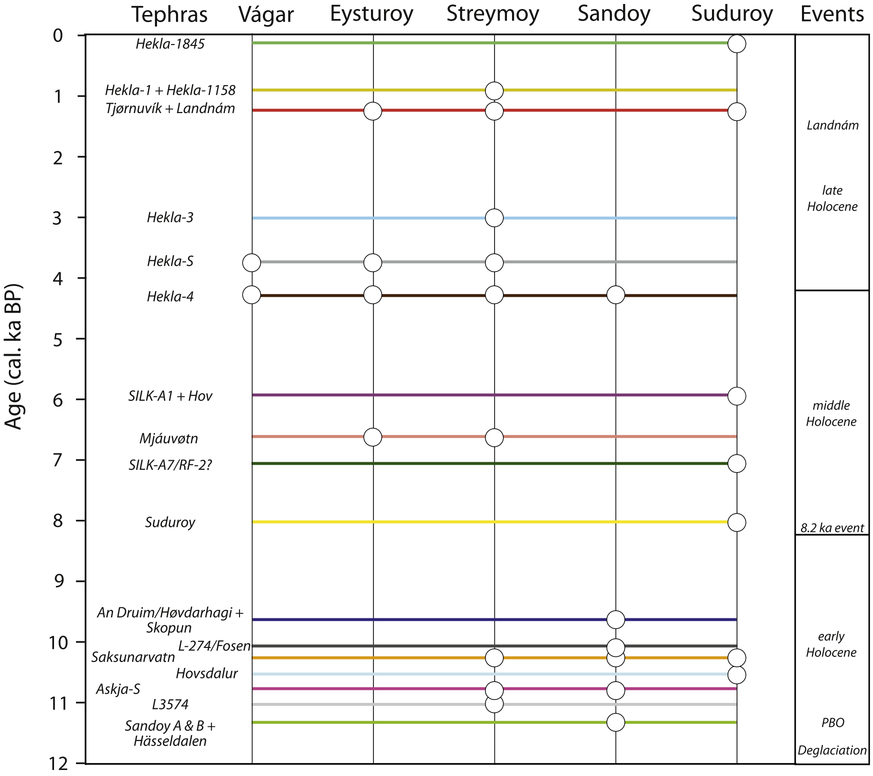

Fig. 12. Tephrostratigraphy of the Faroe Islands. Tephras found in sequences on the islands of Vágar, Eysturoy, Streymoy, Sandoy and Suduroy are represented by circles. Several of the tephras have so far only been found in single sites and it is possible that the real distribution cover more islands.

the PBO in the Greenland ice-cores (Rasmussen et al., 2007), but the lake sediment record from Lake Starvatn on Eysturoy (Fig. 1B) shows a clear climate perturbation, starting c. 50–100 years before the deposition of the Saksunarvatn Ash (Björck et al., 2001), and lasting for at least another 100 years. Evidence for a climate deterioration in connection with the Saksunarvatn Ash has also been suggested from lakes in northern Germany (Merkt et al., 1993), but elsewhere, e.g. in lake sediment records from western Norway, there is no clear evidence for a climate event close to the ash fallout (cf. Aarnes et al., 2012; Lind et al., 2013). Glacial re-advances at the Preboreal-Boreal transition in Norway, the so-called Erdalen events (10.10–10.05 ka BP and 9.7 ka BP; Dahl et al., 2002) apparently postdate the Saksunarvatn Ash and the 10.3 ka event, although the dating is uncertain. However, exact correlations using the Saksunarvatn ash are hampered by the fact that it might be a result of several eruptions close in time (e.g. Davies et al., 2012; Bramham-Law et al., 2013). It may be that the Fosen, An Druim and Skopun tephras in the future could be useful markers for the Preboreal-Boreal climate events in the North Atlantic region.

The Suduroy Tephra is a potential marker horizon for the 8.2 ka BP event (e.g. Alley et al., 1997) as well as for the Storegga tsunami event in Norway (Bugge et al., 1987; Bondevik et al., 1997), which also affected the Faroe Islands (Grauert et al., 2001). It seems to have had a widespread distribution in the North Atlantic region (e.g. Wastegård, 2002; Kristjansdóttir et al., 2007; Jennings et al., 2014), although some records may consist of reworked shards from older deposits with rhyolitic Vedde-type tephra. The Suduroy Tephra has only been traced in one site on the Faroe Islands and more work is needed to confirm that it is a primary deposit and that it can be discriminated from the 4000 year older Vedde Ash.

There are comparably few widespread Icelandic tephras in the middle Holocene, i.e. between c. 8000 and 4500 cal yr BP and a reduction in Icelandic volcanism around 5.5–4.5 ka yr BP has been suggested (Swindles et al., 2017). The Mjáuvøtn Tephra dated to c. 6600 cal yr BP (Fig. 12) has a potential to become an important marker for the middle Holocene although its relation with other middle Holocene tephras from Katla needs to be better resolved. It is, however, possible that several findings of basaltic tephra from Katla indeed can be correlated with the Mjáuvøtn Tephra, including the Tv-5 Tephra in northern Iceland and the K-6750 Tephra in western Iceland. There is, however, also the possibility that all these tephras are from different eruptions of Katla and more geochemical data is needed to confirm these links, also including analyses of minor and trace elements.

The three middle to late Holocene tephras from Hekla: "Hekla 4, Hekla S and Hekla 3" are important isochrons in north-western Europe, although relatively few studies have fully exploited these tie-points to assess regional differences/time lags in the responses of the climate system (e.g. van den Bogaard et al., 2002; Langdon and Barber, 2004; Plunkett, 2006b; Wastegård et al., 2008). Hekla 4 and Hekla S occur within a time period when several palaeoclimate archives around the North Atlantic show increasing wetness and a general cooling trend (e.g. Anderson et al., 1998; Lauritzen and Lundberg, 1999; Hammarlund et al., 2003; Mayewski et al., 2004). Hekla 4 is radiocarbon dated to c. 4260 ± 20 cal yr BP (e.g. Pilcher et al., 1995) and dated by varve counting to 4374 cal yr BP (2σ: 4417-4266 BP, Dörfler et al., 2012) which immediately predates the 4.2 ka event and the proposed mid-to late Holocene boundary at 4200 cal yr BP (Walker et al., 2012). The Faroe Islands experienced a cooling trend in climate at c. 4200 cal yr BP when lake ice occurrence and wind activity increased (Andresen et al., 2006). Hence Hekla 4 has the potential to enable detailed correlations between peat and lake sediment records around this oscillation.

The youngest tephra that has a potential to serve as a regional isochron on the Faroe Islands is the basaltic Landnám Tephra (Fig. 12). The earliest archaeological evidence for human colonization of the Faroe Islands has been dated to the 4th-6th centuries CE, some hundreds of years earlier than originally proposed by archaeologists (Hannon and Bradshaw, 2000; Church et al., 2013) and the Landnám Tephra may serve as a dating horizon for the early settlement phase on the Faroe Islands. We advise against using the Tjørnuvík Tephra as a marker horizon, since it may consist of reworked shards from the Hekla 4 and Hekla S eruptions.

4.2. *Apparently absent tephras*

Some tephras of Icelandic origin are widespread in northwestern European bogs but have not been described from the Faroe Islands. These include the Lairg A & B layers (c. 6.9 & 6.7 ka cal BP), Øræfajökull-1362 and Askja-1875 (e.g. Dugmore et al., 1995; Pilcher et al., 1996; Hall and Pilcher, 2002; van den Bogaard and Schmincke, 2002; Bergman et al., 2004; Watson et al., 2016). Only a few peat records from the Faroe Islands have been investigated in detail and there are several possible explanations for this apparent absence of these widespread tephras. One is that ash fallout never occurred on the Faroe Islands which might explain the absence of Askja-1875 that has a relatively narrow eastern dispersal from its vent (Carey et al., 2010). Another reason for tephra absence is that peat-cutting has removed younger peat, especially in areas close to human settlements (e.g. Lawson et al., 2007).

The almost total absence of basaltic tephra in peat is striking. This has been discussed elsewhere by e.g. Wastegård and Davies (2009) who suggested that post-depositional processes due to extremely acid conditions may have affected the basaltic glass in peat (Wolff-Boenisch et al., 2004; Pollard and Heron, 2008). The ombrotrophic peat sequences that have been investigated (Persson, 1968; Wastegård et al., *this paper*) have only recorded a few basaltic shards, despite the fact that historic sources have documented ash fallout during several basaltic eruptions. Basaltic tephra seems to have better preservation in lake sediment sequences in the Faroe Islands and elsewhere (e.g. Chambers et al., 2004; Davies et al., 2007). This could also explain the absence of the basaltic Mjáuvøtn Tephra in peat sequences on the Faroe Islands.

4.3. *Saksunarvatn Ash: a product of several eruptions?*

The Saksunarvatn Ash is a remarkably widespread basaltic tephra and was initially regarded to represent a single continuous volcanic event in the early Holocene (e.g. Mangerud et al., 1986; Björck et al., 1992; Birks et al., 1996). The volume has been estimated to be about 40 times bigger than the Hekla 3 and Hekla 4 eruptions, which would make it by far the largest explosive eruption of an Icelandic volcano (Thordarson, 2014). The Saksunarvatn Ash as a product of a single eruption has therefore been questioned, and studies of lake sediment cores from western Iceland have shown that three tephra layers of Saksunarvatn composition occur in close succession formed during the course of c. 120 years (Jóhannsdóttir, 2007). Recently, Harning et al. (2018) showed that three distinct Saksunarvatn-type deposits occur in a lake on the Vestfirðir peninsula, NW Iceland, dated between c, 10.3 and 10.06 ka BP. In marine cores west of Iceland, three layers with a geochemical composition consistent with the Saksunarvatn Ash were found in sediments dated between c. 10.4 and 9.9 ka BP (Jennings et al., 2014). However, most terrestrial sites in NW Europe only report one single layer (e.g. Mangerud et al., 1986; Grönvold et al., 1995; Birks et al., 1996; Björck et al., 2001; Wastegård et al., 2001; Jessen et al., 2007; Bramham-Law et al., 2013; Lind et al., 2013) Trace element compositions, however, indicate that tephras in the south-east (i.e. Faroe Islands, Scotland, Scandinavia and Germany) and north-west (i.e. Greenland ice-cores and Greenland shelf cores) probably represent separate eruption events (Davies et al., 2012; Bramham-Law et al., 2013). Furthermore, a slight offset between major element geochemistry has been observed between datasets from Greenland and a North Atlantic marine core (Davies et al., 2012).

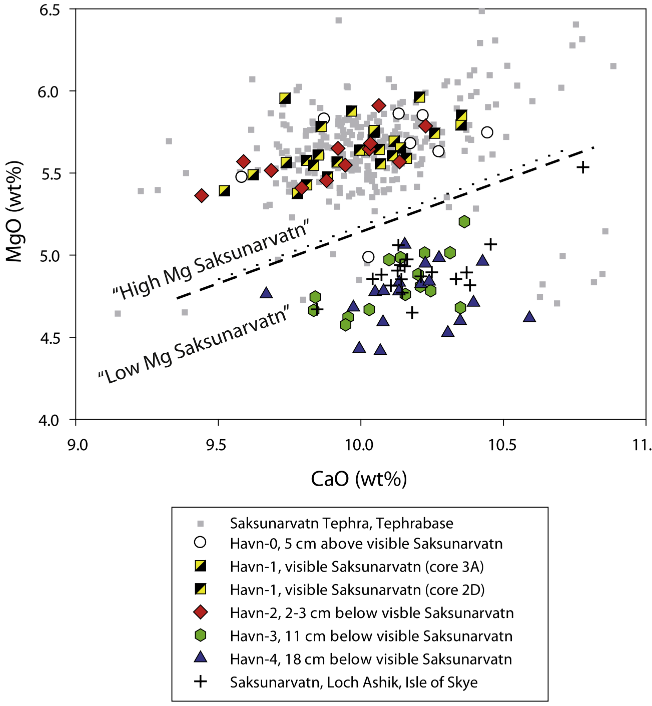

Fig. 13. Biplot of CaO vs. MgO in early Holocene Grímsvötn tephras from the Havnardalsmyren peat section compared with data from Tephrabase (www.tephrabase.org). Four basaltic cryptotephras "Havn-0, Havn-2, Havn-3 and Havn-4", from top to bottom, and a visible 2–3 cm thick, black macrotephra layer "Havn-1" was found over a core interval of c. 30 cm. The dashed line separates between "Low Mg Saksunarvatn", "Havn-3 and 4" and "High Mg Saksunarvatn" "Havn-0, 1 and 2". The Saksunarvatn Ash reported from Loch Ashik, Isle of Skye, NW Scotland is also shown (Kelly et al., 2017). Low MgO values indicate that this tephra can be correlated with the Havn-3 or 4 layers rather than with the visible Saksunarvatn Ash, "Havn-1". All analyses have been normalized to 100 wt%.

The full dataset from Havnardalsmyren is presented here for the first time (Fig. 13, Table 3, App. A). A pilot study aiming at identifying cryptotephra layers using XRF core-scanning revealed at least four basaltic cryptotephras, "Havn-0, Havn-2, Havn-3 and Havn-4" from top to bottom[1] and a visible 2–3 cm thick, black macrotephra layer, "Havn-1"[1] over a core interval of c. 30 cm. We assume that the visible layer can be correlated with other Saksunarvatn Ash deposits in the Faroe Islands, Norway and Germany. High Ti, Ca, K, Fe, Mn and Sr counts were interpreted as tephra signals concordant with peaks in tephra concentration documented by Kylander et al. (2012). The main focus of the investigation was, however, not to separate the layers geochemically, but here we conclude that there are clear differences between the two lowest cryptotephra layers "Havn-3 and Havn-4" and the other layers, including the visible macrotephra. The lower cryptotephras, "Havn-3 and Havn-4" have lower MgO values (c. 4.5–5.0 wt%) compared with the visible layer "Havn-1" and the upper cryptotephra layers "Havn-0 and Havn-2"

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[1] The Grímsvötn tephras at Havnardalsmyren were originally labelled H-1, H-2 etc. by Kylander et al. (2012) but we have avoided this terminology to avoid confusion with tephras from the Hekla volcano.

Table 3
Geochemical composition of Grímsvötn tephras from Havnardalsmyren including the visible Saksunarvatn Tephra “Havn-1” and four cryptotephras, “Havn-0, 2, 3 and 4”. Ages in cal yr BP for the cryptotephras are estimated using linear interpolation between the Saksunarvatn macrotephra horizon and the Askja-S Tephra at 385–387 cm (see Fig. 14).

Core	3A	3A	2D	2D	2D	2D
Age	c. 10.000	10 182 ± 39[a]	10 182 ± 39[a]	c, 10.200	c. 10.300	c. 10.370
Tephra peak depth	315–316 cm	320–321 cm	324–327 cm	329–330 cm	338 cm	345 cm
Layer[a]	Havn-0	Havn-1	Havn-1	Havn-2	Havn-3	Havn-4
Analyses	7	10	17	14	15	19
SiO_2	49.06 ± 0.48	49.36 ± 0.64	49.16 ± 0.43	49.04 ± 0.53	49.07 ± 0.44	49.12 ± 0.61
TiO_2	2.97 ± 0.09	3.03 ± 0.12	3.07 ± 0.11	2.94 ± 0.25	3.00 ± 0.10	2.99 ± 0.10
Al_2O_3	13.11 ± 0.25	12.91 ± 0.17	12.96 ± 0.27	12.97 ± 0.33	13.01 ± 0.22	13.02 ± 0.28
FeO	13.90 ± 0.22	14.07 ± 0.40	14.13 ± 0.31	13.84 ± 0.41	13.91 ± 0.31	13.95 ± 0.25
MnO	0.23 ± 0.01	0.24 ± 0.01	0.24 ± 0.01	0.23 ± 0.01	0.24 ± 0.01	0.23 ± 0.01
MgO	5.63 ± 0.14	5.55 ± 0.18	5.57 ± 0.15	5.63 ± 0.43	4.69 ± 0.18	4.60 ± 0.18
CaO	9.93 ± 0.29	9.75 ± 0.25	9.86 ± 0.14	9.84 ± 0.48	9.83 ± 0.14	9.87 ± 0.18
Na_2O	2.75 ± 0.07	2.70 ± 0.15	2.75 ± 0.22	2.62 ± 0.22	2.60 ± 0.12	2.48 ± 0.16
K_2O	0.42 ± 0.03	0.47 ± 0.03	0.46 ± 0.03	0.44 ± 0.07	0.47 ± 0.05	0.46 ± 0.04
P_2O_5	0.32 ± 0.03	0.32 ± 0.03	0.33 ± 0.01	0.31 ± 0.03	0.30 ± 0.02	0.30 ± 0.01
Total	**98.32**	**98.41**	**98.52**	**97.88**	**97.12**	**97.02**
Site	NGRIP	JM-96-1214/2-GC	MD99-2322	MD99-2322	MD99-2322	MD99-2275
Tephra peak depth	1409.9 m	138–140 cm	1617.5 cm	1719.5 cm	1797.5 cm	2549–2560 cm
Age	10,265–10,267	n.a.	10,031	10,186	10,390	n.a.
Reference	(1)	(2)	(3)	(3)	(3)	(4)
Analyses	13	10	17	10	22	5
SiO_2	48.80 ± 0.54	48.80 ± 0.49	49.83 ± 0.39	49.13 ± 0.53	49.27 ± 0.47	50.38 ± 0.37
TiO_2	2.77 ± 0.09	3.12 ± 0.09	3.14 ± 0.11	2.99 ± 0.14	3.11 ± 0.13	3.03 ± 0.11
Al_2O_3	13.59 ± 0.22	13.70 ± 0.30	12.99 ± 0.22	13.07 ± 0.23	12.93 ± 0.20	13.05 ± 0.19
FeO	13.68 ± 0.42	14.40 ± 0.33	14.27 ± 0.36	14.14 ± 0.32	14.14 ± 0.36	14.83 ± 0.32
MnO	0.23 ± 0.02	0.24 ± 0.01	0.24 ± 0.01	0.24 ± 0.01	0.24 ± 0.01	n.a.
MgO	5.37 ± 0.28	5.39 ± 0.06	5.36 ± 0.14	5.43 ± 0.32	5.44 ± 0.30	5.58 ± 0.10
CaO	10.29 ± 0.25	9.47 ± 0.34	9.73 ± 0.17	9.81 ± 0.24	9.80 ± 0.30	9.98 ± 0.16
Na_2O	2.44 ± 0.10	2.68 ± 0.07	2.69 ± 0.14	2.64 ± 0.09	2.62 ± 0.27	2.56 ± 0.14
K_2O	0.39 ± 0.06	0.47 ± 0.02	0.49 ± 0.03	0.42 ± 0.04	0.46 ± 0.05	0.43 ± 0.05
P_2O_5	0.31 ± 0.05	0.40 ± 0.27	0.28 ± 0.02	0.33 ± 0.03	0.30 ± 0.02	0.34 ± 0.05
Total	**97.87**	**96.92**	**99.03**	**98.18**	**98.30**	**100.11**
Site	Bjarkarlundur area	L. Torfadalsvatn	17–5P	L. Mjáuvøtn	L. Saksunarvatn	LINK14
Tephra peak depth	4 sites	10.30–10.52 m	862 cm	831 cm	29.85–30.30 m	185 cm
Age	n.a.	n.a.	10,297 ± 118	n.a.	9000^{14}C y BP	10,085–10,526
Reference	(5)	(6)	(7)	(8)	(9)	(10)
Analyses	41	9	5	16	39	10
SiO_2	48.89 ± 0.32	48.91 ± 0.45	48.69 ± 0.98	48.23 ± 0.53	49.51 ± 0.67	48.76 ± 0.44
TiO_2	3.05 ± 0.06	2.84 ± 0.16	2.95 ± 0.17	2.98 ± 0.18	2.88 ± 0.36	2.89 ± 0.17
Al_2O_3	12.86 ± 0.14	13.43 ± 0.43	12.83 ± 0.12	12.76 ± 0.25	13.08 ± 0.34	13.02 ± 0.16
FeO	14.20 ± 0.20	13.76 ± 0.23	13.84 ± 0.38	13.77 ± 0.64	14.04 ± 0.93	14.00 ± 0.42
MnO	0.25 ± 0.03	0.27 ± 0.04	0.24 ± 0.02	0.28 ± 0.04	0.23 ± 0.11	0.25 ± 0.03
MgO	5.69 ± 0.08	6.02 ± 0.29	5.72 ± 0.32	5.60 ± 0.21	5.68 ± 0.77	5.66 ± 0.21
CaO	9.79 ± 0.14	10.60 ± 0.33	10.15 ± 0.44	9.85 ± 0.48	10.04 ± 0.87	10.08 ± 0.32
Na_2O	2.81 ± 0.08	2.56 ± 0.23	2.74 ± 0.08	2.76 ± 0.17	2.50 ± 0.38	2.60 ± 0.22
K_2O	0.45 ± 0.03	0.43 ± 0.05	0.44 ± 0.04	0.44 ± 0.04	0.41 ± 0.08	0.43 ± 0.06
P_2O_5	0.33 ± 0.02	n.a.	0.32 ± 0.04	n.a.	n.a.	0.32 ± 0.03
Total	**98.32**	**98.82**	**97.98**	**96.66**	**98.37**	**98.01**
Site	Quoyloo Meadow	L. Ashik	Kråkenes	Grønlia	Potremser Moor	Eversener See
Tephra peak depth	160 cm	515–516 cm	673.5 cm	401 cm	455 cm	850 cm
Age	n.a.	n.a.	10 210 ± 35	n.a.	n.a.	n.a.
Reference	(11)	(12)	(13)	(14)	(15)	(16)
Analyses	31	19	20	16	8	16
SiO_2	49.42 ± 0.38	49.13 ± 0.43	49.81 ± 0.60	49.03 ± 0.73	49.72 ± 1.37	48.11 ± 0.56
TiO_2	3.06 ± 0.17	3.11 ± 0.11	2.80 ± 0.23	2.76 ± 0.14	2.93 ± 0.32	3.06 ± 0.13
Al_2O_3	12.99 ± 0.27	12.67 ± 0.14	12.64 ± 0.34	13.19 ± 0.42	13.11 ± 0.52	12.62 ± 0.16
FeO	14.32 ± 0.61	13.59 ± 0.32	13.46 ± 0.49	13.59 ± 0.47	13.62 ± 1.18	14.19 ± 0.53
MnO	0.23 ± 0.01	0.22 ± 0.04	0.21 ± 0.06	0.23 ± 0.02	0.24 ± 0.07	0.21 ± 0.06
MgO	5.46 ± 0.45	4.75 ± 0.18	5.47 ± 0.48	5.72 ± 0.36	5.32 ± 0.70	5.25 ± 0.18
CaO	9.85 ± 0.37	9.88 ± 0.17	10.17 ± 0.48	10.14 ± 0.36	9.55 ± 0.97	9.62 ± 0.21
Na_2O	2.81 ± 0.18	2.93 ± 0.10	2.67 ± 0.21	2.47 ± 0.21	2.23 ± 0.53	2.70 ± 0.16
K_2O	0.47 ± 0.06	0.48 ± 0.03	0.42 ± 0.07	0.41 ± 0.04	0.44 ± 0.18	0.46 ± 0.04

(*continued on next page*)

Table 3 (*continued*)

Site	Quoyloo Meadow	L. Ashik	Kråkenes	Grønlia	Potremser Moor	Eversener See
Tephra peak depth	160 cm	515–516 cm	673.5 cm	401 cm	455 cm	850 cm
Age	n.a.	n.a.	10 210 ± 35	n.a.	n.a.	n.a.
Reference	(11)	(12)	(13)	(14)	(15)	(16)
Analyses	31	19	20	16	8	16
P_2O_5	0.32 ± 0.05	n.a.	n.a.	0.29 ± 0.02	0.29 ± 0.02	n.a.
Total	**98.92**	**96.73**	**97.64**	**97.84**	**97.52**	**96.22**

Published geochemical data for the Saksunarvatn Ash (from West to East), mean and 1 s.d. except when indicated. Ages in cal yr BP except when indicated.
References: (1) Mortensen et al., 2005; age in ice core years BP SS09 timescale; (2) Jennings et al., 2002; (3) Jennings et al., 2014; (4) Eiríksson et al., 2004; (5) Lloyd et al., 2009; (6) Björck et al., 1992; (7) Thornalley et al., 2011; (8) Wastegård et al., 2001 and this paper; (9) Mangerud et al., 1986 and Bramham-Law et al., 2013; analyses shown with 2σ; (10) Rasmussen et al., 2011; (11) Bunting, 1994 and Timms et al., 2017; (12) Kelly et al., 2017, (13) Birks et al., 1996 and Lohne et al., 2013; (14) Lind et al., 2013; (15) Bramham-Law et al., 2013; analyses shown with 2σ; (16) Merkt et al., 1993. n.a. = not analysed.

[a] Age from Bronk Ramsey et al. (2015). All tephras in Havnardalsmyren were analysed in October 2010 using microprobe setting recommended by Hayward (2011) in order to avoid beam-induced chemical modification.

(Fig. 13; Table 3; App. A). The peaks in tephra concentration are situated at c. 2–3 cm “Havn-2”, 11 cm “Havn-3” and 18 cm “Havn-4″below the visible Saksunarvatn Ash “Havn-1”. Linear interpolation between the visible Saksunarvatn Ash “Havn-1” and the Askja-S Tephra, using 10.18 ka yr BP for Saksunarvatn Ash and 10.82 ka yr BP for Askja-S (Bronk Ramsey et al., 2015; Kearney et al., 2018) suggests that the “Havn-2” layer has an age of c. 10.20 ka yr BP, “Havn-3” c. 10.30 ka yr and “Havn-4” c. 10.37 ka yr BP (Fig. 14). The ages are approximate, and higher ages would be inferred if we use the age for the Askja-S Tephra suggested by Ott et al. (2016), 11,228 ± 226 cal yr BP. The uppermost layer, “Havn-0”, has a higher number of shards from other volcanic systems (Katla and Veidivötn) than the cryptotephras below the macrotephra “Havn-1” (App. A), and it suggests that this layer mainly consists of reworked tephra from the visible Saksunarvatn horizon and other tephra deposits. This layer is dated to ca. 10.00 ka yr BP (Fig. 14).

An extensive review of published proximal and distal Saksunarvatn Ash data shows that MgO values typically exceed 5.3 wt% (Table 3) and we have only found one record with comparable low MgO values and slightly elevated SiO_2 values as in the “Havn-3 and Havn-4” cryptotephras. This record is from Loch Ashik on Isle of Skye in western Scotland and was first reported by Pyne-O’Donnell (2007), although the geochemical data did not conclusively support a correlation with the Saksunarvatn Ash. A new analysis of material from the layer correlated with the Saksunarvatn Ash was presented by Kelly et al. (2017) and these data cluster more closely with other reported occurrences of the tephra. The MgO values are, however, almost 1% lower than in any other reported record of the Saksunarvatn Ash, except the “Havn-3 and Havn-4” cryptotephras in Havnardalsmyren. The Saksunarvatn Ash has a vertical spread of c. 10 cm at Loch Ashik (Fig. 2 in Pyne-O’Donnell, 2007) and it is possible that it consists of material from several eruptions, including material from the Saksunarvatn precursors, “Havn-3 and Havn-4”. Other sites in Scotland (Bennett et al., 1992; Bunting, 1994; Timms et al., 2017) report MgO values > 5 wt% in accordance with most other records of the Saksunarvatn Ash. Our results suggest that the Saksunarvatn Ash is a product of several eruptions during at least 200 years, most probably in the Grímsvötn volcanic system, but the Saksunarvatn Ash complex continues to be problematic. We suggest that all cryptotephras, including the low-Mg Saksunarvatn precursors Havn-3 and Havn-4 are from Grímsvötn, although MgO values below 5 wt% are in the low end of the range for tephra from this volcanic system (Table 3 in Óladóttir et al., 2011). The identification of the low-Mg Saksunarvatn precursors Havn-3 and Havn-4 is significant. It is the first time that major element geochemistry clearly can separate between different components of the Saksunarvatn Ash-complex, and we suggest that future investigations of sequences with the Saksunarvatn Ash aim at finding basaltic cryptotephras below and above the visible horizon. The apparent lack of low-Mg Grímsvötn tephra to the west and north of Iceland (Jóhannsdóttir, 2007; Davies et al., 2012; Jennings et al., 2014; Harning et al., 2018) suggests that this component only was dispersed towards the east and south.

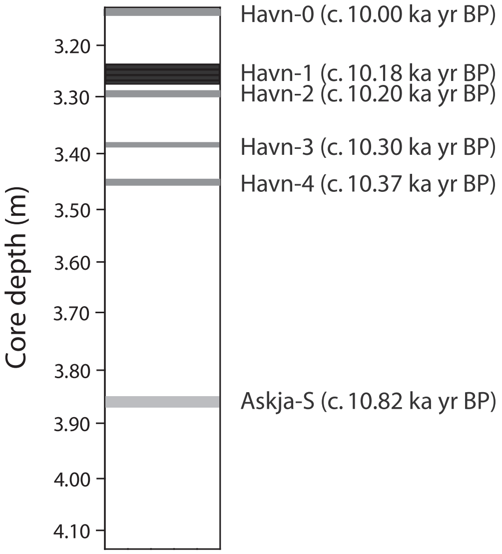

Fig. 14. Schematic drawing showing tephra layers and ages in core 2D from Havnardalsmyren on Streymoy (Kylander et al., 2012). The visible black Saksunarvatn macrotephra ("Havn-1") is shown with a black bar. Grey bars show cryptotephras.

5. Conclusions

A tephra framework is of great value for palaeoclimatic studies in distal areas. The interest in distal tephra studies has been growing over the last 20 years due to new techniques for extracting cryptotephra from minerogenic deposits (e.g. Turney, 1998) and the number of identified tephra deposits has grown as well as the number of mapped distributions of several important marker layers. The Faroe Islands hold a key position for linking the proximal tephrochronology in Iceland with distal tephra networks on the European continent and the British Isles.

Some of the key Holocene tephras are well represented on the Faroe Islands and may therefore provide more precise ages than elsewhere with further study. Examples of this are the early Holocene Hässeldalen and Askja-S tephras. Another is the Mjáuvøtn Tephra which has a potential to become an important marker for the middle Holocene although its relation with other middle

Holocene tephras from Katla needs to be better resolved (cf. Jennings et al., 2014). Tephras found in close connection with some of the most pronounced climatic events during the Holocene can provide opportunities to find time lags in the climate system and thereby increase the understanding of climate dynamics. The Hässeldalen and Askja-S tephras provide useful isochrons for the PBO, the Suduroy Tephra for the 8.2 ka BP event and Hekla 4 for the 4.2 ka BP event. The Faroe Islands is probably also the best area outside Iceland for unravelling the complex nature of the Saksunarvatn Ash complex. Results from Havnardalsmyren suggest that up to five tephras from Grímsvötn were deposited within a sediment interval of c. 30 cm equivalent of c. 300–400 years, and major element geochemistry shows that the two oldest cryptotephras have a geochemical signature which separates them from most other Saksunarvatn Ash deposits in the North Atlantic region.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2018.07.024.

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