The Saksunarvatn Ash and the G10ka series tephra. Review and current state of knowledge

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Abstract

The Saksunarvatn Ash, first found in the Faroe Islands, is a tephra produced by the Grímsvötn volcanic system in Iceland. Since its discovery in the Faroe Islands, dark tephra with a similar stratigraphic position has been described at numerous locations around the North-Atlantic region; including 46 sites in Iceland (soil and lake sediments), 37 marine sediment cores from the North-Atlantic, 23 terrestrial locations in northern Europe (Faroe Islands, Scotland, Orkney, Shetland, Norway and Germany), and 4 sites from the Greenland Ice Sheet. The chemical composition of the tephra found around the North-Atlantic is, in most cases, within the published chemical range of the Saksunarvatn Ash originally found in the Faroe Islands, i.e. tholeiitic basalt with MgO and K_2O wt% that places it in the more evolved part of the Grímsvötn chemical field. Published ages of the inferred Saksunarvatn Ash range significantly, dating from 10,625±53 to 9586±315 cal. yr BP, although the widespread usage of the ice-core age of ~10,300 yr BP has given the tephra high chronological importance. Based on the reported sites, the tephra covers an area of about 2 million km^2. However, in the last decade new studies have shown that the Grímsvötn volcanic system produced several widely distributed tephra layers of very similar chemical composition in the time period from 10,400 to 9900 yr BP. Hence, the Saksunarvatn Ash appears to be one of multiple early Holocene Grímsvötn tephra layers distributed around the North-Atlantic area. Where such tephras are identified, they therefore reflect a time interval rather than a precise marker as previously anticipated. Although still chemically indistinguishable, these Grímsvötn tephra layers represent a marker horizon around the North-Atlantic region spanning approximately 500 years, and are referred to as the G10ka series tephra. The exact number of eruptions that form the tephra marker horizon remains unknown, but up to seven have been proposed.

Highlights

1. A basaltic tephra, the Saksunarvatn Ash, was described in the Faroe Islands in 1986 CE
2. The tephra was dated and became a widely-used marker layer in the North-Atlantic

3. Recent findings shows that the tephra reflects more than one eruption from Grímsvötn
4. The new marker horizon is named the G10ka series tephra, including the Saksunarvatn Ash
5. The age of the G10ka series tephra is 10.4 to 9.9 ka

Keywords

Saksunarvatn Ash, G10ka series tephra, Grímsvötn volcano, tephra marker, basalt.

Introduction

Several explosive eruptions in the Holocene in Iceland have resulted in widespread dispersal of tephra-fall deposits that provide valuable stratigraphic markers in and around the North-Atlantic. In order to be an important marker layer, a tephra has to be traceable over large areas (e.g. the North-Atlantic region), be easily recognizable on basis of colour, physical properties and, importantly, chemical composition, as well as being accurately dated (e.g., Larsen and Eiríksson, 2008). Based on how widely the tephra is distributed, it can either serve as a regional (for large distributions) or more local (for limited distributions) marker bed. The Saksunarvatn Ash, a greyish-black to blackish basaltic tephra, that originated within the Grímsvötn volcanic system in Iceland based on its chemical composition (e.g., Mangerud et al., 1986; Kvamme et al., 1989; Dugmore and Newton, 1998), has been used as a marker layer in early Holocene strata because of its inferred wide dispersal across the northern North-Atlantic. The tephra was first identified in the Faroe Islands by Waagstein and Jóhansen (1968) and used for correlation across the islands (Jóhansen, 1975; 1978; 1982; 1985). It was named the Saksunarvatn Ash by Mangerud et al. (1986), using Lake Saksunarvatn as the type locality. Based on the above-mentioned studies that used C^{14}-dates of gyttja samples above and below the ash, Mangerud et al. (1986) estimated the age of it to about 10,200 cal. yr BP. Numerous discoveries of black basaltic tephra from similar stratigraphic positions around the North-Atlantic changed the role of the Saksunarvatn Ash from a local tephra marker to a regional one (e.g., Sjöholm et al., 1991; Merkt et al., 1993; Grönvold et al., 1995; Andrews et al., 2002a; Jennings et al., 2002).

Recently, a series of tephra layers with chemical composition and age similar to that of the Saksunarvatn Ash was described from high-resolution lake and marine sediment cores in and around Iceland and the Greenland shelf (Thordarson, 2014; Jennings et al., 2014; Neave et al., 2015). These tephra layers, referred to as the Grímsvötn 10ka series tephra or "G10ka series", were deposited from the Grímsvötn volcanic system towards the west during a period of about 500 years, i.e. between 10,400 and 9900 cal. yr BP, demonstrating the recurrenc of Grímsvötn eruptions during this time interval (e.g., Jóhannsdóttir et al., 2005a; 2005b; 2006; Jóhannsdóttir, 2007; Thordarson et al., 2012, Thordarson, 2014; Jennings et al., 2014; Neave et al., 2015; Harning et al., 2018a; Harning et al., 2019).

As these tephra layers and the Saksunarvatn Ash have very similar chemical compositions and it has not yet been possible to distinguish them, the Saksunarvatn Ash is not a unique tephra marker. Nevertheless, the G10ka series tephra (10,400-9900 cal. yr BP), which most likely includes the Saksunarvatn Ash in at least some sites, forms a useful early Holocene marker horizon spanning about 500 years. However, there is still a possibility that one of these Grímsvötn eruptions dispersed an eruption plume towards the east, and that the Saksunarvatn Ash is a single tephra marker SE of Iceland. As it has not been differentiated from other Grímsvötn eruptions from this period, its role as a unique tephra marker is unclear.

The purpose of this article is to present a comprehensive review of research on the Saksunarvatn Ash and the tephra layers of the G10ka series tephra through a detailed compilation of chronostratigraphical and major element chemical data published on the Saksunarvatn Ash and the G10ka series tephra. First, a brief overview of the Grímsvötn volcanic system and its Holocene activity is given, then the research history of the Saksunarvatn Ash is described, followed by subsequent investigations across the North-Atlantic and finally the most recent revelations on the nature of the G10ka series tephra horizon.

Terminology

The type-site locality tephra layer in the Faroe Islands was named the Saksunarvatn Ash in 1986, here referred to as the *Saksunarvatn Ash proper*. In the following years the name *Saksunarvatn Ash* was transposed to a single tephra marker identified around the North-Atlantic region and correlated to the *Saksunarvatn Ash proper* in the Faroes. This specific tephra layer originates in the Grímsvötn volcanic system that produced a series of tephra layers with very similar chemical composition during a 500-year time interval (10,400 to 9900 cal. yr BP). It has not been possible to define the geographical distribution of individual tephra layers of the series, or to distinguish the *Saksunarvatn Ash proper* as a specific layer within the series. Therefore, the term *G10ka series tephra* is used when referring to Grímsvötn tephra of this specific age. The *G10ka series tephra* most probably includes the *Saksunarvatn Ash proper*, at least in places. For simplicity we have chosen to use the old term, *Saksunarvatn Ash*, when referring to older publications although, strictly speaking, the only tephra that should really be referred to as *Saksunarvatn Ash* is the one in the Faroe Islands. Ideally, *G10ka series tephra* should replace the term *Saksunarvatn Ash* in all locations except in the type-site locality until the spatial distribution and chemical composition of the *Saksunarvatn Ash proper* can be properly identified and separated from other layers within the series.

The Grímsvötn volcanic system, Iceland

The Grímsvötn volcanic system is part of the Eastern Volcanic Zone (EVZ) in Iceland. It is about 100 km long and up to 20 km wide (Fig 1; Jakobsson, 1979; Jóhannesson and Sæmundsson, 1998) with the central volcano, Grímsvötn, capped by the Vatnajökull ice cap of up to 800 m thickness (e.g., Björnsson and Pálsson, 2008). The central volcano is composed of three calderas of possibly different ages (e.g., Gudmundsson et al., 2013), but so far no individual eruption has been correlated to the caldera formations. Grímsvötn is the most frequently erupting volcanic system in Iceland during Holocene time, having erupted more than 70 times during the last 1100 years (Thordarson and Larsen, 2007) with an estimated average of 7 eruptions/100 years (range 4–14) for the last 7600 years (Óladóttir et al., 2011a). Peaks in the Grímsvötn tephra-fall frequency are observed in the periods 7000–6000 and 2000–1000 years ago based on measured tephra sections around the volcano (Óladóttir et al., 2011a). Here, tephra-fall frequency refers to all preserved tephra layers, whereas eruption frequency refers to the estimated number of eruptions.

The great majority of volcanic material from the Grímsvötn system is tholeiitic, mostly basaltic, and only one eruption of intermediate composition is known (e.g., Sigmarsson et al., 2000). The major element chemical composition of tephra produced by the Grímsvötn system is inferred to have been confined to a distinct trend for the last ~8000 years, and possibly for the last 11,000 years, with MgO concentrations varying from 4.4–7.5 wt%, K_2O ranging from 0.2–0.6 wt% and TiO_2 values from 1.9–3.6 wt% (Óladóttir et al., 2011b). Grímsvötn tephra also displays a limited variation in trace element concentrations, where Rb values are in the range of 5.7–11.3 ppm, La of 8.6–16.9 ppm, Th of 0.59–1.26 ppm and ratios of Rb/Y from 0.23–0.27, La/Yb from 3.37–3.88 and Sr/Th from 157–365 (Óladóttir et al., 2011b). From here on, chemical composition refers to major element composition obtained by microprobe analyses on tephra glass unless otherwise stated.

Grímsvötn is distinguished from other tholeiitic systems in Iceland based on its major element composition. Askja and Bárðarbunga, both highly active volcanic systems during the Holocene, have lower MgO and higher FeO wt%, respectively, at a given TiO_2 wt% (Fig. 1b). There is a significant overlap in chemical composition between the Kverkfjöll volcanic system and Grímsvötn, but for fixed MgO and FeO wt% values, Kverkfjöll produces slightly higher K_2O and lower TiO_2 values than Grímsvötn (Fig. 1b; Óladóttir et al., 2011b). Material from Þórðarhyrna, often referred to as a second central volcano within the Grímsvötn volcanic system, can also be similar to Grímsvötn products based on major elements, but its eruption history is not well known and needs further investigation.

The most frequent eruptions within the Grímsvötn volcanic system occur at the central volcano, but two subaerial eruptions have taken place on the embryonic fissure swarm during the Holocene. The younger and larger one is the Laki eruption (1783-1784 CE), which lasted for 8 months and produced ~15 km^3 of lava (Thordarson and Self, 1993). The older one is the Lambavatnsgígar eruption that erupted a few hundred years before the Icelandic settlement, but the volume and duration is unknown (Jón Jónsson, 1983; Guðmundsson et al., 2013). Explosive basaltic eruptions occurring at the caldera rim or within the ice-capped Grímsvötn caldera complex (Larsen et al., 1998; Larsen, 2002) are most frequent within the system; e.g. the 2004 CE (e.g. Jude-Eaton et al., 2012; Oddsson et al., 2012) and 1998 CE (Gudmundsson et al., 2000) eruptions. Most of these eruptions were rather small (<0.1 km^3 uncompacted tephra volume; Thordarson and Larsen, 2007) and rarely deposited tephra outside the Vatnajökull glacier. However, every 100-200 years, larger eruptions do occur within the caldera, as observed in 2011 CE when the central volcano last erupted and produced 0.8 km^3 of freshly fallen tephra (0.27 km^3 dense rock equivalent, (DRE); Gudmundsson et al., 2012; Hreinsdóttir et al., 2014).

The discovery and first studies of the Saksunarvatn Ash

In summer of 1966, several bogs in the Faroe Islands were cored by Jóhannes Jóhansen for studies aimed at reconstructing the vegetation history of the islands (Waagstein and Jóhansen, 1968). Three tephra layers were reported; two light-coloured layers from lake Skælingsvatn and one dark-coloured layer from the Hoydalar bog, which is a paleo-lake filled with gyttja and peat (Waagstein and Jóhansen, 1968; Jóhansen 1985; Fig. 2). The two younger light-coloured layers were correlated to known eruptions in Iceland based on the refractive index of their glass shards, but the oldest one could not be assigned to a specific source or event, although an Icelandic origin was suggested (Waagstein and Jóhansen, 1968). This third and oldest layer, dark grey and 0.7 cm thick, was subsequently identified in other basins on the Faroes with an average thickness of 0.5–1.0 cm and used as a local tephra marker for correlation across the islands (Jóhansen, 1975; 1982; 1985). This layer was also identified in a core from the Saksunarvatn lake (Streymoy; Fig. 2) cored in 1972 by the Geological Survey of Denmark, where its thickness was ~45 cm (Jóhansen, 1978; 1982; 1985). This abnormal thickness is attributed to in-wash of the tephra from the entire drainage area. A geochemical description was provided by Mangerud et al. (1986), who also named the tephra the Saksunarvatn Ash. This established Saksunarvatn as the type localitywhile recognizing the correlation with the ash bed in the Hoydalar bog and other sites in the Faroe Islands (Waagstein and Jóhansen, 1968; Jóhansen 1975; 1982; 1985).

Source volcano for the Saksunarvatn Ash

Waagstein and Jóhansen (1968) suggested an Icelandic origin for the Saksunarvatn Ash proper, which was confirmed by chemical composition reported by Mangerud et al. (1986) and later by Dugmore and Newton (1998) and Wastegård et al. (2001). The compositional similarities between a basaltic component of Ash Zone I (I-THOL-2), the 1500-years-younger Saksunarvatn Ash proper in the Faroe Islands, and the Grímsvötn volcanic system in Iceland were identified by Kvamme et al. (1989). Sjöholm et al. (1991) suggested the Grímsvötn, Kverkfjöll or Askja volcanic systems as possible sources for the Saksunarvatn Ash proper, whereas Pétursson and Larsen (1992) stated that the Saksunarvatn Ash proper had the chemical characteristics of the Grímsvötn volcanic system. Dugmore and Newton (1998) reanalysed the type-site Saksunarvatn Ash, and the composition they obtained was consistent with Grímsvötn as the source volcanic system for the tephra, having an average value of 0.44±0.05 wt% K_2O, 5.72±0.31 wt% MgO, 3.02±0.16 wt% TiO_2 and 13.76±0.53 wt% FeO (Dugmore and Newton, 1998; Supplement Table 1; see chemical ranges and further discussion in later section).

The Saksunarvatn Ash used as a tephra marker in the North-Atlantic region

Mangerud et al. (1986) stated that as the Saksunarvatn Ash proper had reached the Faroe Islands, it should also be found in marine sediments between Iceland and the Faroes. Together with the Vedde Ash they further argued that it should provide a strong tool for correlation of terrestrial and marine sequences around the Pleistocene/Holocene boundary (Mangerud et al., 1984). Its dark-grey to black colour contrasts well with the commonly lighter-coloured continental sediments in Europe and in marine sediments, making it an easily observed marker layer.

The inferred presence of the Saksunarvatn Ash on mainland Europe, in the North-Atlantic marine sediments and in Greenland ice-cores changed its role to a regional marker for the whole North-Atlantic region (e.g. Bennet et al., 1992; Merkt et al., 1993, Birks et al., 1996; Fig. 2; Table 2 and more references therein). An increasing number of marine studies from the North-Atlantic then described tephra of mm-to-cm thickness that was correlated to the Saksunarvatn Ash proper as it had similar major element chemical composition or was of similar age (e.g. Andrews et al., 2002a; Fig. 2; Table 2 and references therein).

The identification of tephra similar to that of the Saksunarvatn Ash proper all across the North-Atlantic encouraged the search for such tephra on-land in Iceland, as well as in northern and central Europe (Fig. 2). Additional sites containing tephra correlated with the Saksunarvatn Ash proper (see correlation method in Table 2) were reported in the Faroe Islands (Edwards and Craigie, 1998; Wastegård et al., 2001, 2018; Hannon et al., 2003; Olsen et al., 2010; Kylander et al., 2011), Iceland (see Iceland section below), the Shetland Islands (Bennett et al., 1992; Bondevik et al., 2005), Germany (Merkt et al., 1993; Bramham-Law et al., 2013; Wulf et al., 2016), the Orkneys (Bunting, 1994; Timms et al., 2017), Scotland (Pyne-O'Donnel, 2007 (see discussion in a later section); Kelly et al., 2017) and Norway (Birks et al., 1996, Gulliksen et al, 1998; Aarnes et al., 2012, Lind et al., 2013, Lohne et al., 2013; 2014).

Except in Iceland, tThe on-land tephra layer thickness ranges from microscopic (cryptotephra, not visible to the naked eye, e.g. in Norway, Shetland, Orkney and Scotland; Table 2) to a few cm (in the Faroe Islands; Table 2). These thicknesses are similar to occurrences in the marine environment where it forms layers ranging from microscopic thickness (e.g. Norwegian Shelf, Greenland Shelf; Table

2) to tens of cm (e.g. Central North Sea and north of Iceland; Table 2) but most often 1–3 cm (see reported thickness and exact locations in Table 2).

Furthermore, tephra with a chemical composition similar to the Saksunarvatn Ash proper has been identified in four Greenland ice-cores: GRIP, GISP2, NGRIP and NEEM, located in the central and northern parts of the ice sheet (Grönvold et al., 1995; Zielinski et al., 1997; Mortensen et al., 2005; Rasmussen et al., 2013; Abbott and Davies, 2012). In the ice-cores, this tephra horizon is one of the few visible to the naked eye. In both GRIP and NGRIP it reaches a thickness of 1 mm (Grönvold et al., 1995; Mortensen et al., 2005; Table 2), suggesting that a major Grímsvötn plume extended towards the north-west, possibly from a different eruption than the one generating the plume towards the south-east to the Faroe Islands that produced the Saksunarvatn Ash proper.

Prevailing wind directions around Iceland show seasonal variations, with strong westerlies during fall and winter and weak easterlies during spring and summer (Lacasse, 2001). However, a circum-Arctic tephra transport pattern has been suggested for Icelandic tephra deposited in Greenland (e.g. Thordarson and Self, 1993; Fiacco et al., 1994; Mortensen et al., 2005; Abbott and Davies, 2012). This idea is supported by the finding of the Öræfajökull 1362 CE tephra in Greenland ice (e.g. Coulter et al., 2012), as its main dispersal axis was to the east (Thorarinsson, 1958; Palais et al., 1991). Circum-Arctic tephra transport maintains the possibility of one large and/or long-lasting Grímsvötn eruption depositing tephra to the north-east and south-west.

Age of the Saksunarvatn Ash

Ages provided for the Saksunarvatn Ash in the literature are ^{14}C ages on organic material from soil, lake or marine sediments such as diatoms, terrestrial plants and foraminifera (see Table 1), and ice-core ages from the Greenland ice (See Table 1). Ages given in the text are calibrated calendar years before 1950 (using the notation cal. yr BP) where calibration is performed using CALIB 7.1 (Stuvier et al., 2018) and the IntCal13 calibration curve (Reimer et al., 2013; for further information on ages see Table 1).

The first published age of the Saksunarvatn Ash proper, 10,630±251 cal. yr BP, is from the Hoydalar core (Waagstein and Jóhansen, 1968; Table 1). Jóhansen (1975) later obtained two more ^{14}C dates from below and above the ash in the Hoydalar bog, which gave ages of 10,441±283 and 10,215±303 cal. yr BP respectively, or a mean of ~10,300 cal. yr BP.

Jóhansen (1978) published ^{14}C dates of the 36.75-m-long Saksunarvatn Lake sediment core, where an abnormally thick Saksunarvatn Ash proper was found in the lower part at 29.85–30.30 m depth (Jóhansen, 1982). Organic material located 45 cm below and 72 cm above the ash gave the ages 10,373±149 and 9190±117 cal. yr BP (Jóhansen, 1978), respectively, bracketing the age of the tephra between ~10,400 and ~9200 cal. yr BP. Based on these two studies, Mangerud et al. (1986) estimated that the Saksunarvatn Ash proper was formed at ~10,200 cal. yr BP.

The tephra found in the Greenland ice-cores and correlated with the Saksunarvatn Ash proper in the Faroes was dated based on annual layer counting and using the GRIP ice-core age model, resulting in an ice-core age of 10,180±60 yrs BP (Grönvold et al., 1995). This age was used as the most representative age for the Saksunarvatn Ash around the North-Atlantic region for some time. Additionally, a visible tephra layer was found in the GISP2 core and correlated with the Saksunarvatn Ash proper (Zielenski et al., 1997). It was the lowest of three tephra layers whose ages span seven years, ranging from 10,275 to 10,268 (±205) yr BP (Zielenski et al., 1997). Later the NGRIP SS09 timescale gave 10,267–10,265 ice-core years BP for the presumed Saksunarvatn Ash (Mortensen et al., 2005), and a revised Greenland ice-core chronology (GICC05) for both the NGRIP and GRIP ice-cores resulted in an age of 10,347±89 b2k or ~10,300 yr BP (Rasmussen et al., 2006; see Table 1).

Relatively few attempts have been made to directly date organic material directly below (or above) the presumed Saksunarvatn Ash in both terrestrial and marine sediments from the North-Atlantic region. Rather, most studies have based correlations to the Saksunarvatn Ash proper on similar geochemical compositions and stratigraphic levels, and used the radiocarbon age from the Faroes or the ice-core age as a time marker in their age models. The few available ^{14}C ages show a wide range from ~10,600 to ~9600 cal. yr BP (Thornalley et al., 2011; Björck et al., 1992; see Table 1). This may partly be due to poorly constrained marine reservoir ages, or different material dated in soil sections and/or lake sediments, but is probably also due to dating of different Grímsvötn tephra layers from the G10ka series. Dividing the dataset into 100-year bins shows that most ages fall in the bins from 10,000–10,100 and 10,200–10,300 cal. yr BP (Supplement Table 2). The best age for the SE-plume is derived by Bayesian statistical age-depth modelling on a long series of dated samples from the Kråkenes Lake, western Norway, resulting in 10,210±35 cal.yr BP (Lohne et al 2013; 2014), recalculated to 10,176±49 cal. yr BP by using a slightly different model by Bronk Ramsey et al. (2015).

As described above, it has now been shown that more than one eruption took place within the Grímsvötn volcanic system around the time of deposition of the Saksunarvatn Ash proper (e.g. Jóhannsdóttir et al., 2005a; 2005b; Jennings et al., 2014) and the question of age has therefore changed. Tephra from these eruptions are now referred to as the G10ka series tephra, which may include tephra from the eruption that formed the Saksunarvatn Ash proper in the Faroe Islands. In the future, ages for both the individual tephra layers and the full duration of the G10ka series should be provided. For example, at present it is unknown if the dated tephra in the Greenland ice-cores is from the same eruption that formed the Saksunarvatn Ash proper.

Saksunarvatn Ash in Iceland

Icelandic eruptions have occurred on average every three to five years during historical time and about 90% of them are basaltic (e.g., Thorarinsson and Sæmundsson, 1979; Thordarson and Larsen, 2007; Thordarson and Höskuldsson, 2008), providing a large number of dark or blackish tephra layers in and around Iceland. Therefore, light-coloured silicic tephra layers, such as Hekla-3 and Hekla-4 (Larsen and

Thorarinsson, 1977; Larsen and Eiríksson, 2008) are the most easily recognisable tephra marker layers in Iceland (Fig. 3).

The numerous blackish tephra layers explain why the Early Holocene basaltic tephra originally received limited attention in Iceland, although it had occasionally been correlated to the Saksunarvatn Ash proper (Hjort et al., 1985; Björck et al., 1992; Sigurgeirsson and Leósson, 1993; Kaldal, 1993; Ingólfsson et al., 1995). However, following the characterisation of the Saksunarvatn Ash proper in the Faroes (Mangerud et al., 1986) and its confirmed source from the Grímsvötn volcanic system (e.g., Kvamme et al., 1989; Dugmore and Newton, 1998) geologists, particularly those working in the field of Quaternary sciences and paleoclimate, were encouraged to search for this tephra across Iceland.

During geological mapping of Iceland's highlands, thick deposits of late-Pleistocene to early-Holocene sediments were observed, which in places measured more than 50 m thick as revealed by a borehole close to Búðarháls in the southern highlands (Site 80, Table 2, Fig. 4; Vilmundardóttir et al., 1979). In the Búðarháls borehole the lowermost ~10 m contained pristine volcanic glass shards with a major element chemical composition that suggested an origin from the Grímsvötn volcanic system (Vilmundardóttir et al., 1979). No link to the Saksunarvatn Ash proper was made at that time, as the composition of the tephra in Saksunarvatn was unknown. However, the authors were puzzled by the amount of pristine glass from the Grímsvötn volcanic system located ~100 km from its source and speculated whether it might have been transported down an old river channel (Vilmundardóttir et al., 1979).

During the 1980s, thick black tephra deposits dating to deglacial times were found in a number of sites in Iceland and some authors suggested a correlation with the Saksunarvatn Ash proper (e.g. Björck et al., 1992; Hunt 1992; Table 2, Fig. 4 and references therein). In Hælavík in Vestfirðir, NW Iceland (Site 81, Table 2, Fig. 4), an up to 50-cm-thick tephra deposit was discovered, and its age was suggested at around 10,100 cal. yr BP (9000 ^{14}C BP; Hjort et al., 1985) based on stratigraphy and its correlation to the timing of deglaciation in the area. This tephra was linked to the Saksunarvatn Ash proper by Kvamme (1988) based on its major element chemical composition and chronostratigraphic position. In 1990, a sediment core from lake Torfdalsvatn in north Iceland (Site 82, Table 2, Fig. 4) was obtained for paleoclimate studies (Björck et al., 1992). It contained a 22-cm-thick tephra sequence close to its base, which was linked to the Saksunarvatn Ash proper on the basis of chemical composition of the lowermost 1–2-cm horizons. The tephra was intercalated between lake sediments of ages between 9920±297 cal. yr BP (below) and 9586±315 cal. yr BP (above; Table 1) indicating a younger age than that reported for the Saksunarvatn Ash proper in the Faroe Islands (Table 1).

Hunt (1992) reported an early Holocene tephra with Grímsvötn composition at Eiðar in east Iceland (Site 83, Table 2, Fig. 4), and a year later Sigurgeirsson (1993) identified an early Holocene Grímsvötn tephra in Eyjafjarðardalur, about 50 km south of Akureyri, with similar attributes (Site 84, Table 2, Fig. 4). A Grímsvötn tephra was also identified in a bog section in Sogamýri, Reykjavík (Sigurgeirsson and Leósson, 1993; Site 85, Table 2, Fig. 4). An early Holocene tephra of Grímsvötn affinity was furthermore discovered in several places in south-central Iceland, between Þórisvatn and Þjórsá (e.g. site 86, Table 2, Fig. 4). These studies confirmed a country-wide occurrence of an early Holocene tephra layer with Grímsvötn affinities (Fig. 4).

Few soil and peat sections in Iceland extend back to the lateglacial period (e.g. Larsen and Eiríksson, 2008). However, when such sections are found, the early Holocene Grímsvötn tephra exhibits highly variable thicknesses, ranging from ~1–100 cm, and often shows bedding structures and textures indicative of re-sedimentation (e.g. Vilmundardóttir et al., 1979), possibly explaining the persistent notion of a single large eruption as the source for the early Holocene Grímsvötn tephra. Large thickness variations within the same outcrop can be a clue to significant re-sedimentation, as demonstrated by the thick sequence in the borehole by Búðarháls (Site 80; Vilmundardóttir et al., 1979) and the tephra banks in the Búðarháls area (Site 86; Kaldal, 1993; Fig. 4). On the other hand, re-sedimentation may also produce several apparent tephra layers from one original tephra fall.

From the“Saksunarvatn Ash” marker layer to the “G10ka series tephra” marker horizon

There are few soil outcrops in Iceland that show more than one blackish tephra layer of the same age as the Saksunarvatn Ash proper, suggesting multiple successive eruptions at that time interval. The confirmation of multiple eruptions within the Grímsvötn volcanic system in the early Holocene was first revealed when systematic studies on lake sediment cores in Iceland began. Three tephra layers with Grímsvötn affinities dated at 10,400 to 10,200 cal. yr BP were identified in sediment cores from three lakes in western Iceland: Hestvatn, Hvítárvatn and Haukadalsvatn (Sites 105, 106, 104; Table 2, Fig. 4; Jóhannsdóttir et al., 2005a; 2005b; Jóhannsdóttir, 2007; Harning et al., 2019).

Re-examination has improved the age models for the sediment cores from these three lakes through more thorough tephra identification as well as measurements of paleomagnetic secular variations (PSV; Ólafsdóttir et al., 2013; Harning et al., 2019). Two more Grímsvötn tephra layers were discovered by Thordarson et al. (2012), who concluded that at least five eruptions took place at Grímsvötn between ~10,400 and 9900 cal. yr BP (Fig. 5). Jennings et al. (2014) supported the idea of multiple Saksunarvatn-like eruptions and even suggested seven single eruptive events within a 500-year interval based on data from the Greenland Shelf. However, more than five tephra layers have not been reported in superposition (Jóhannsdóttir, 2007; Jennings et al., 2014; Harning et al., 2018a). Currently, it is impossible to differentiate between individual Grímsvötn tephra layers or correlate one of these layers to the Sakunarvatn Ash proper, thus, the use of the term G10ka series tephra when referring to the whole tephra series (Thordarson, 2014; Jennings et al., 2014; Neave et al., 2015; Harning et al., 2018a; 2019).

However, despite references to the Saksunarvatn Ash proper, the older literature does hold indications of several eruptions of the Grímsvötn system, although they were not interpreted as such at the time. Björck et al. (1992) described a 22-cm-thick tephra layer as being “interrupted several times by thin laminae (1 mm) of diatomite indicating a rhythmic tephra deposition over some time“.

Also, Kaldal (1993) noted how powerful the Grímsvötn volcanic system has been in historical time and questioned the origin of early Holocene blackish tephra with Grímsvötn affinities from one single eruption.

Zielenski et al. (1997) observed three early Holocene tephra layers within a seven-year-time interval in the GISP2 ice-core. The lowest of these tephra layers was macroscopically visible and associated with a volcanic sulphate peak, whereas the other two layers were cryptotephras and had no associated sulphate peaks. Hence, the conclusion drawn was that the lowest tephra horizon most likely corresponded to the Saksunarvatn Ash proper and that the other two layers were dust layers of aeolian origin (Zielenski et al., 1997). However, visible tephra layers have been identified in Antarctic ice-cores without any association with sulphate or other acid volcanogenic anomalies (Palais and Kyle, 1988; Zielenski et al., 1997). Furthermore, a few recent studies provide convincing evidence that the sulphate part of an eruption plume can be disassociated from the tephra-laden part of the plume (Kerminen et al., 2011; Tesche et al., 2012; Prata et al., 2017), implying that it is possible to produce tephra fallout onto ice-sheets without precipitation of the associated sulphate aerosols (e.g. Abbott and Davies, 2012; Coulter et al., 2012).

Additionally, Zielenski et al. (1997) observed another sulphate peak in the GISP2 ice-core about 100 years prior to the one associated with the Saksunarvatn Ash. No tephra grains were observed in the ice within this peak and the authors mention a possible correlation with the I-THOL-1 tephra (Kvamme et al., 1989). Alternatively, this sulphate peak could be related to a Grímsvötn eruption forming one of the G10ka series tephra.

Certain tephra, previously correlated to the Saksunarvatn Ash proper taken from the GRIP ice-core and the marine sediment core LINK 14 from the eastern North-Atlantic, show different trace element compositions, indicating that they stem from two different eruptions from the same volcanic system (Davies et al., 2012). Furthermore, Bramham-Law et al. (2013) found that the Saksunarvatn Ash proper and the POT-455 tephra in northern Germany have similar trace element compositions as those in the LINK 14 core, consistent with the assumption of two eruptions, one with a main plume towards the northwest and the other towards the southeast. They also mention that if the reported ages are used, the northwest dispersion (Greenland ice-core age 10,297 cal. yr BP; Rassmussen et al., 2006) is older than the southeast dispersion (10,210 cal. yr BP, Kråkenes; Lohne et al. 2013, 2014). This finding, and the current lack of additional layers with a Saksunarvatn Ash affinity to the east of Iceland, may suggest that the Saksunarvatn Ash proper represents a unique marker layer in these eastern areas, but care should be taken before correlating it with tephra layers closer to and to the west of Iceland. However, Kylander et al. (2011) considered it possible that a thick ash zone on the Faroe Islands could represent several eruptions. Wastegård et al. (2018) identified three basaltic cryptotephras below the Saksunarvatn Ash proper in the Faroes with estimated ages of 10,200, 10,300 and 10,370 yr BP based on linear age interpolation between the Saksunarvatn Ash proper (age used 10,180 yr BP) and the Askja-S tephra (age used 10,820 yr BP). Two of those three cryptotephras have notably lower MgO wt% values (average 4.6 wt%, range 4.3-5.0 wt%; Wastegård et al., 2018) than the Saksunarvatn Ash proper (average 5,7 wt%, range 5.2-6.8 wt%), previously analysed in the Faroe Islands by Dugmore and Newton, (1998) and Bramham-Law et al., (2013).

The finding of multiple Grímsvötn tephra layers with ages around the age of the Saksunarvatn Ash reduces its significance as an instantaneous time marker. However, these G10ka series tephra deposits, including the Saksunarvatn Ash, collectively define a marker horizon that only differs from a marker layer by the fact that it represents a longer period. Hence, the tephra is still a prominent marker horizon that signifies the transition between glacial and early Holocene times in and around the North-Atlantic.

^{14}C dates of the Grímsvötn tephra layers, including the Saksunarvatn Ash proper, are listed in Table 1. Studies on one lake sediment core in Vestfirðir in northwest Iceland (Harning et al., 2016; 2018a)involve ^{14}C-age determinations that address the relative age of three black tephra layers with Grímsvötn chemical characteristics. The ^{14}C-age of moss between the lower two Grímsvötn layers produces an age of 10,300±70 cal. yr BP, whereas the age obtained from moss situated just above the uppermost Grímsvötn tephra layer is 10,060±120 cal. yr BP. These ages are significantly different at the 95% confidence level. Both these age determinations lie within the age range of 10,625±53 to 9586±315 cal. yr BP (Björck et al., 1992; Thornalley et al., 2011) of tephra previously correlated to the Saksunarvatn Ash around the North-Atlantic (Table 1), as well as the proposed 10,400 to 9900 period for the G10ka series (Jennings et al., 2014).

Major element chemical affinities of tephra correlated to the Saksunarvatn Ash/G10ka series

The eruptions within the Grímsvötn volcanic system throughout the Holocene have delivered magmas that are internally coherent and consistent, although slight magma differentiation has been observed (e.g., Óladóttir et al., 2011a; 2011b; Fig. 6). Consequently, identification of individual layers based solely on chemical composition is problematic. Additionally, tephra correlations based on chemical compositions derived from different analytical instruments and operating conditions (such as changing beam current, beam size, counting time, secondary standards) must be carefully considered. Different analytical conditions augment chemical scatter, making chemical correlation even more challenging. Ideally, analyses of secondary standards should be published with other chemical analyses to facilitate comparison of data sets. This has not been the standard procedure for older publications, but publication of secondary standards is becoming more frequent today.

The major element chemical composition of the Saksunarvatn Ash proper, as published by Dugmore and Newton (1998) and Bramham-Law et al. (2013) has an average of 0.42±0.04 wt% K_2O (ranging from 0.35–0.56 wt%) and 5.67±0.29 wt% MgO (range: 5.16–6.76 wt%) which plots in the more evolved part of the Grímsvötn chemical field (Fig. 6a). The TiO_2 average value is 2.95±0.14 wt% ranging from 2.64–3.34 wt% and the average FeO value is 13.94±0.46 wt% (range: 12.23–14.84 wt%; Fig. 6a; Supplement Table 1). However, some shards within these analyses show compositions that fall outside of the Grímsvötn field (Fig. 6a; see individual analyses and operational conditions of published analyses in Supplementary Table 1).

Tephras with similar chemical compositions to the Saksunarvatn Ash proper have been found in sites around the North-Atlantic (Fig. 6b-d; Supplementary Table 1), but other chemical affinities emerge among analyses of the proposed Saksunarvatn Ash (Fig. 6e); i.e. their chemical composition does not fall within the chemical field of the Grímsvötn system and thus, these tephras may have been mistakenly correlated. The chemical composition of a tephra reported to represent the Saksunarvatn Ash in Scotland (Pyne O'Donnel, 2007) is not of Grímsvötn composition, the published K_2O and TiO_2 values (0.89±0.19 and 3.83±0.25, respectively) are too high and the FeO is too low for the reported K_2O value. However, this sample was re-analysed by Kelly et al. (2017), resulting in lower K_2O and TiO_2 (0.48±0.03 and 3.11±0.11 wt%, respectively) and slightly higher FeO and MgO values (13.59±0.31 wt% and 4.75±0.17, respectively) that approximate the Saksunarvatn Ash proper composition. However, even though the new analyses plot closer to the Grímsvötn chemical field, they are still distinguishable from the Saksunarvatn Ash proper (Fig. 6e). In fact, this layer shows a similar chemical composition to two cryptotephra layers found 11 and 18 cm below the Saksunarvatn Ash proper in Havnardalsmyren in the Faroe Islands (Wastegård et al., 2018). This type of chemical composition is not often observed in Grímsvötn tephras found in Iceland although a similar composition is known e.g. from the Grímsvötn 1934 eruption (Jakobsson, 1979).

Other assumed Saksunarvatn Ash layers for which there are partial chemical overlaps with, the Grímsvötn field are from Shetland (Bondevik et al., 2005) and marine core HM79-6.2 NE of Iceland (Koç Karpuz and Jansen, 1992; Fig. 2 and 5e), although these layers have some shards outside the Grímsvötn compositional field. The published FeO value from Shetland is too high for the given MgO value and the K_2O value is too high for the given FeO and MgO values in the marine core (Supplement Table 1). However, these "outliers" have a similar chemical composition to grains from the Saksunarvatn Ash proper that plot outside the Grímsvötn field (Dugmore and Newton, 1998; Bramham-Law et al., 2013;

Fig. 6e). Additionally, the published chemical composition of tephra from marine cores B997-325 and -329 in the Húnaflói fjord (Fig. 2 and 5e; Supplement Table 1) has MgO contents that are too low and FeO values that are too high for a given TiO_2 and K_2O concentration to be correlated to the Grímsvötn volcanic system.

Discussion

How does tephra dispersal and size of Grímsvötn 2011 compare to the G10ka series tephra?

The last Grímsvötn eruption, the G2011, is the largest explosive eruption that has been studied in real time with modern techniques, and it is interesting to compare tephra dispersal of this large historical eruption with the dispersal of the G10ka series tephra. G2011 lasted for seven days in May 2011. It was an explosive basaltic eruption that produced 0.6–0.8 km^3 of freshly fallen tephra or 0.2–0.3 km^3 DRE (Gudmundsson et al., 2012; Gudmundsson et al., 2013). This is one of the largest eruptions from the system during the last 1100 years. Tephra fall was detected in south-eastern and north eastern Iceland, and close to the source it formed deposits tens of meters thick. At a distance of 7 km from the crater the tephra thickness was 1.5 m, and 60 km away along the dispersal axis, the tephra reached 5 cm (Gudmundsson et al., 2013).

Meteorological conditions play a key role in tephra dispersal. During the Grímsvötn 2011 eruption, the weather system effects were twofold. Iin the lower part of the troposphere (0–4 km), strong northerly winds blew tephra to the south, explaining heavy tephra fall in the area south of Grímsvötn. This tephra was picked up by a low-pressure system over the Atlantic and carried over the UK. At higher altitudes, southerly winds were predominant and blew very small amounts of fine tephra to the north, reaching Greenland and Jan Mayen (e.g., Stevenson et al., 2013; Prata et al., 2017). This pattern highlights that ability of tephra produced in eruptions of moderate sizes to become widely transported and deposited, indicating that larger eruptions can deposit material over larger areas, even to the west of Iceland (i.e. the Greenland Ice Sheet). The strong northerly surface winds during the Grímsvötn 2011 eruption resulted in horizontal tephra transport close to the surface and deposition in drifts rather than classical rain-out of particles to form fall deposits. As a result, hardly any proximal tephra is preserved in non-vegetated areas. Although past wind patterns could have been different, such processes possibly also affected tephra deposition during the early Holocene eruptions (Fig. 7), explaining why the early Holocene tephra in Iceland is preserved in drifts. However, pollen studies in northern and southern Iceland indicate dense vegetation, at least in some areas, at the time of tephra deposition (Rundgren, 1998; Karlsdóttir et al., 2012; Eddudóttir et al., 2015).

The Grímsvötn 2011 tephra was detected in Jan Mayen, Scotland, England, Ireland, Shetland, Norway, Sweden and Finland. Although glass shards were detected in the air during the eruption, they have not been found on the ground in all locations and it did not form a visible layer in any of these places (Kerminen et al., 2011; Gudmundsson et al., 2012; Tesche et al., 2012; Stevenson et al., 2013). In short, the fact that the Grímsvötn 2011 eruption was fairly large (0.6–0.8 km^3 freshly fallen tephra) compared to other historical eruptions (most ≤0.1 km^3 freshly fallen) and did not form a distinctive tephra layer in the North-Atlantic region indicates that the eruptions forming the G10ka series tephra were even larger, probably by at least an order of magnitude.

Eruption dynamics of the G10ka series tephra

Assuming the same eruptive frequency in the Grímsvötn volcanic system in the early Holocene as is known from the mid- and late-Holocene (4–17 eruptions/100 years; Óladóttir et al., 2011a) implies that the system erupted ~20–85 times during the 500 years of the G10ka series (from 10,400 to 9900 years ago). Moreover, by assuming similar eruptive behaviour, most of these frequent recurring events would have been small and would mainly have deposited thin tephra layers within ~200 km from the source. However, they would still have covered the circumference of the Grímsvötn volcano within a few hundred years. As in historical times, larger eruptions would have occurred occasionally, producing tephra covering a greater area in fewer events, and in the early Holocene these larger eruptions make up the G10ka series.

The wide distribution of the G10ka series tephra (Fig. 2) suggests larger eruptions than the Grímsvötn 2011 and other historical eruptions. These early Holocene eruptions caused deposition of a visible tephra layer and at least one sulphate peak in the Greenland ice (e.g., Zielenski et al., 1997). Tephra studies of early Holocene lake sediments from west-central and eastern Iceland support high activity in addition to the G10ka series within the Grímsvötn system in the early Holocene (Jóhannsdóttir, 2007; Gudmundsdóttir et al., 2016). However, correlation of these tephra records has not yet been undertaken, and thus no volume calculations are available, leaving the productivity of the system during the early Holocene unknown. Although most of these Grímsvötn layers are similar in thickness to younger Holocene layers, i.e. mm–cm thick in Iceland (~350 km from source), some of the G10ka series layers are tens of cm thick, which probably include tephra from the Saksunarvatn Ash proper eruption (e.g., Geirsdóttir et al., 2002; Jóhannsdóttir, 2007; Larsen et al., 2012; Harning er al., 2016; 2018a; 2019). The thickness of the G10ka series units across the North-Atlantic region ranges from microscopic to a few cm at a distance of 300–1000 km from the source and forms a visible layer e.g. in northern Germany (see Table 2).

If reported thickness values for the G10ka series around the North-Atlantic are taken at face value and assumed to be the product of one eruption, the volume of erupted magma would be greater than 450 km^3 (Thordarson, 2014). This volume greatly exceeds the largest known Icelandic explosive eruptions by orders of magnitude (i.e. the Hekla-3 and Hekla-4 eruptions, ~11 and 13 km^3, respectively; Larsen and Thorarinsson, 1977; Stevenson et al., 2015) and thereby largely reduces the likelihood of a single eruption. Assuming the tephra was formed in seven eruptions (e.g. Jennings et al., 2014), each of the seven would be of a similar size as the Laki eruption, or 1–3 orders of magnitude larger than the historical eruptions. The large early Holocene Grímsvötn eruptions and their wide distribution explains deposition of thick Grímsvötn tephra around the North-Atlantic region and the miscorrelation of multiple layers, regardless of their exact number, to the Saksunarvatn Ash proper.

Environmental conditions during the G10ka series tephra deposition

Icelandic lake records containing the G10ka series provide information on the climate and environmental conditions at the time of the eruptions. The G10ka series was formed during and following recession of the Iceland Ice Sheet and thus defines the transition from a glacier-dominated to a non-glacially affected catchment (Larsen et al., 2012; Geirsdóttir et al., 2013; Harning et al., 2016, 2018b; Gunnarson, 2016). In those cases where sediment was found below the G10ka tephra series, high autochthonous lake productivity supports the argument that strong summer insolation allowed rapid lake-based biota to become established immediately following deglaciation and during the time of the tephra series deposition (e.g. Harning et al., 2016; 2018a; Gunnarsson, 2016).

The fast retreat of the Iceland Ice Sheet suggests increasing amount of meltwater and outburst floods that channelized their way from the highlands and down to the lowlands of Iceland (Geirsdóttir et al., 2000; Hannesdóttir et al., 2009). Two lake records from either side of the current Langjökull ice cap, Arnarvatn Stóra and Hvítárvatn, in the western part of Iceland's highlands, indicate that the Iceland Ice Sheet had alreadyretreated from the lakes basins by the time of the tephra deposition (Larsen et al., 2012; Gunnarson, 2016). Two other lake records, Hestvatn in the southern lowlands and Haukadalsvatn in western Iceland, show a transition from marine to freshwater sedimentation around 10.6 ka and that post-glacial isostatic rebound was already underway well before the deposition of the G10ka tephra series (Geirsdóttir et al., 2009).

Conclusion

Identification of a basaltic tephra in early Holocene sediment sequences initially in the Faroe Islands and later all around the North-Atlantic region led to the notion that the ash layer identified in Lake Saksunarvatn was a single layer distributed across the North-Atlantic. However, in the last decade or so, evidence has accumulated indicating that these basaltic tephra horizons are products of multiple eruptions from the Grímsvötn volcanic system in Iceland, and that the only tephra that can be referred to as the Saksunarvatn Ash is the one found in the Faroe Islands. Whether the others to the east are part of that tephra layer needs to be demonstrated by reasonably detailed mapping of the tephra horizons across the eastern sector. The multiple tephra layers have been named the G10ka series. The Saksunarvatn Ash proper, defined by a type locality in the Faroe Islands, is therefore one layer within the G10ka series tephra marker horizon that formed between 10,400 and 9900 cal. yr BP. This does not rule out the possibility that the Saksunarvatn Ash proper was the only layer of the G10ka series that was distributed to the far eastern areas of the G10ka extension. The G10ka series tephra in and around the North-Atlantic can still be used as a tephra marker horizon covering a period of ~500 years. In Iceland it has been used to date the transition between lateglacial and early Holocene times.

The relative positions and dispersal of individual layers forming the G10ka series remain unknown, as does the exact number of tephra layers within the series and their exact ages, calling for more detailed study of the proximal and distal parts of the tephra. The striking similarity and wide distribution of the tephra layers making up the G10ka series complicates the distinction between individual layers to determine their unique characteristics, such as distribution maps and volume calculations. However, a possible first step could be to reanalyse the North-Atlantic tephra previously correlated to the Saksunarvatn Ash using a single microbeam facility, measuring both major and trace element concentrations in order to determine the compositional variability (or lack thereof) for all of these tephra units. Additionally, both marine and lacustrine sediment cores containing the tephra should be analysed for more Grímsvötn layers of similar age, including cryptotephra, with the aim of determining the exact number of Grímsvötn eruptions forming the G10ka series tephra.

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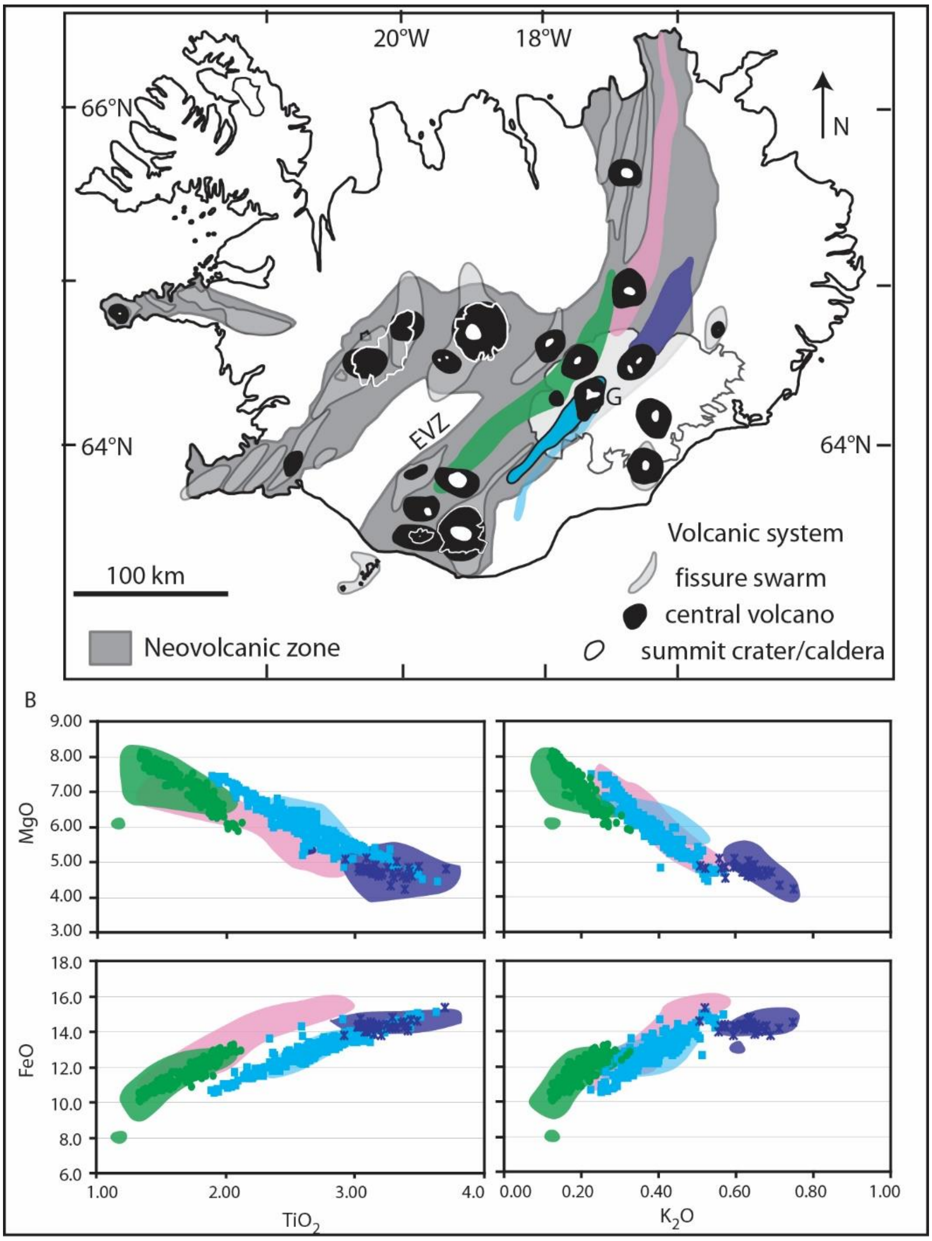


Figure 1. A) Map showing the position of the Neovolcanic Zone and volcanic systems in Iceland. The Grímsvötn system (G) is coloured blue, the Bárðarbunga system is green, Askja pink, Kverkfjöll purple and Þórðarhyrna light blue. EVZ: Eastern Volcanic Zone. B) Whole rock reference compositional fields for Grímsvötn, Bárðarbunga, Askja and Kverkfjöll shown as coloured envelopes (see colours in A) based on data from Hémond et al. (1993), Jakobsson (1979) and Kokfelt et al. (2006) and electron microprobe analyses of Grímsvötn, Bárðarbunga and Kverkfjöll shown as points (see colours in A) from Óladóttir

et al.(2011b). More data is needed to plot a reference compositional field for Þórðarhyrna. Modified from Óladóttir et al. (2011b).

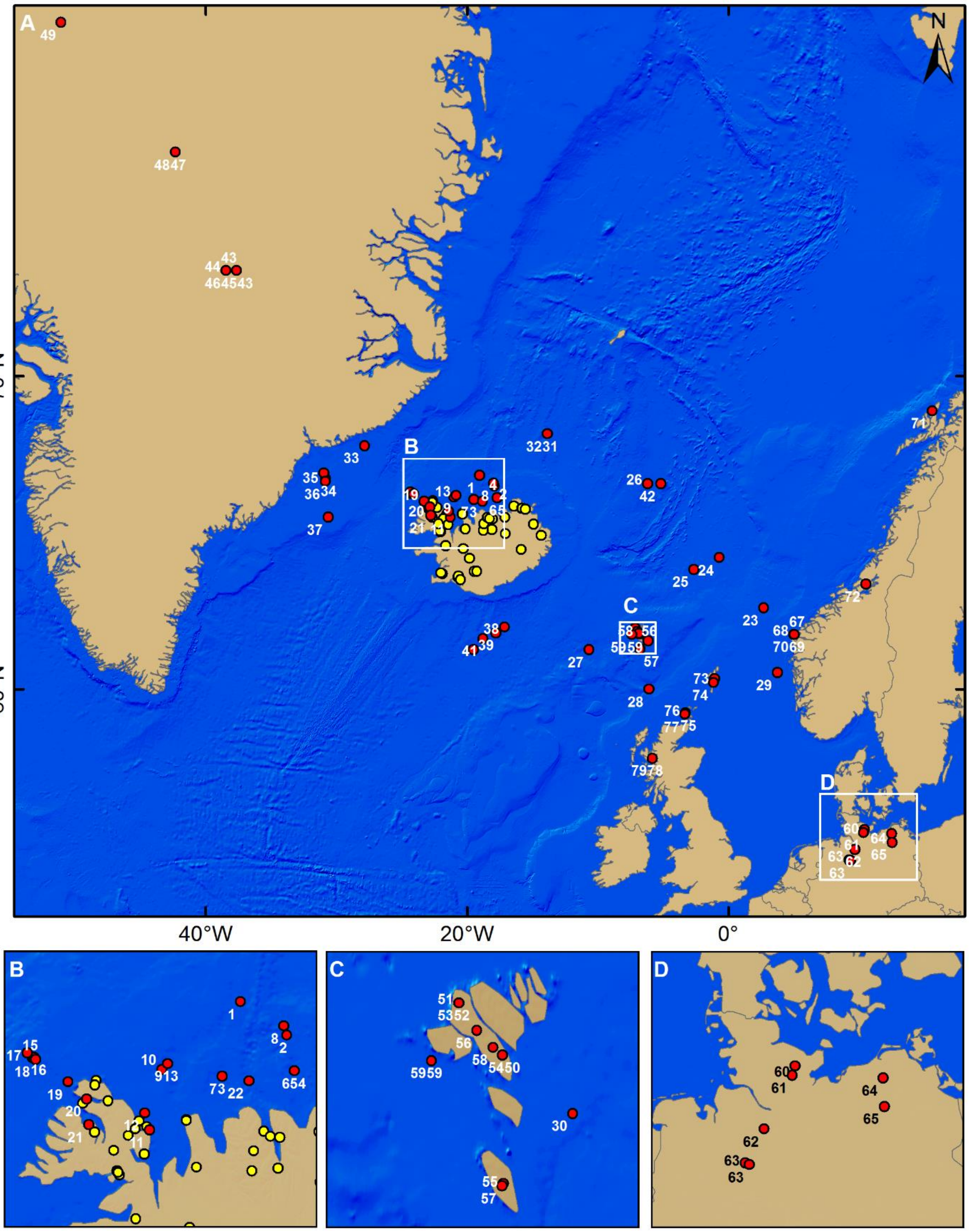


Figure 2. Locations in the North-Atlantic where parts of the G10ka series have been identified (Iceland is shown in detail in Fig. 4). Numbers refer to the list of locations in Table 2 where references are also given. The cartographic data is from GEBCO (General Bathymetric Chart of the Oceans). B, C and D are marked as boxes in A.

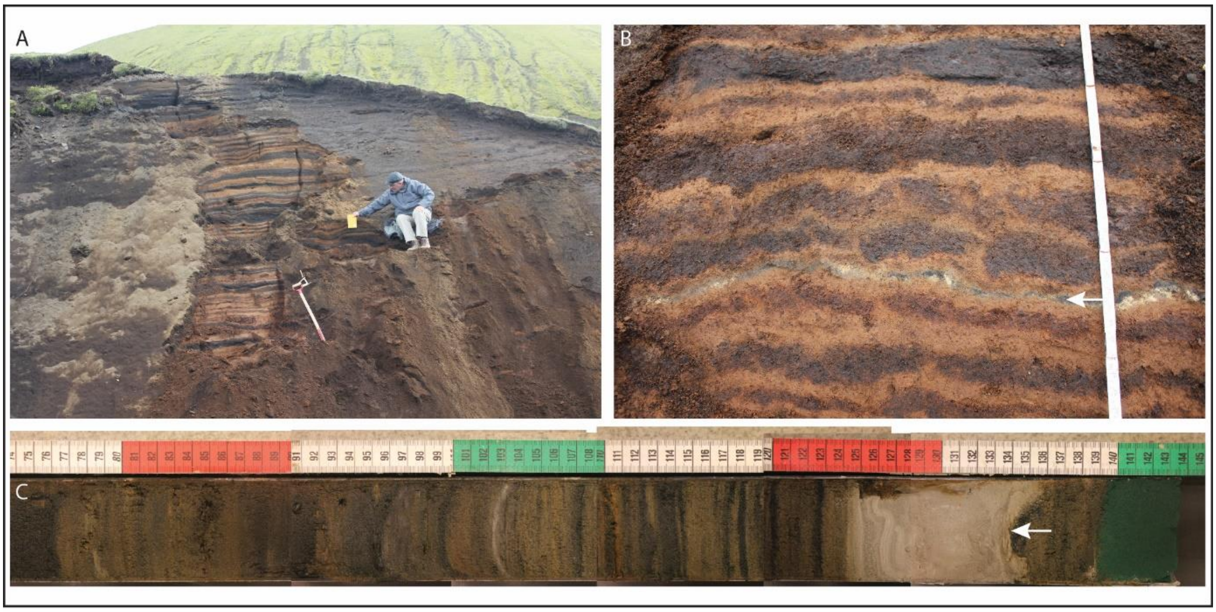


Figure 3. Tephra layers in Iceland. The majority of tephra layers are black, which explains the lack of emphasis on black layers as markers. Light-coloured tephra layers are rather few and easily distinguishable from other layers, forming ideal markers. A) Typical soil section in southern Iceland covering the last ~3000 years. Field book is 19 cm, for scale. B). The light-coloured Hekla-4 layer (white arrow) (3826±12 14C BP; ~4200 cal. yr BP; Dugmore et al., 1995) in a soil section ~70 km from the source. C) Lake sediment core from northern Iceland. The thick light-coloured layer (white arrow) is from Hekla.

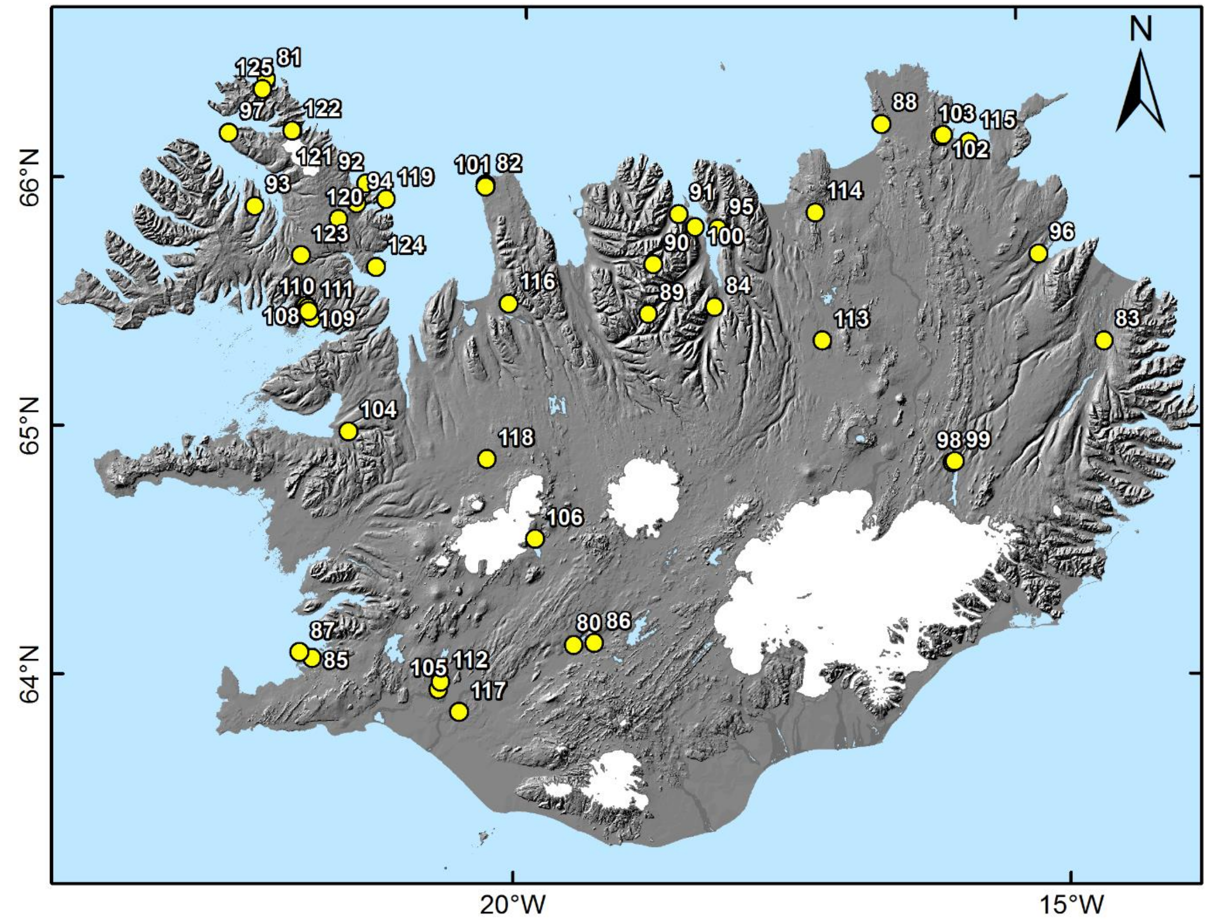


Figure 4. Locations in Iceland where parts of the G10ka series have been described. Numbers refer to the list of locations in Table 2 where references are also given. The cartographic data is from the IS50 database of the National Land Survey of Iceland.

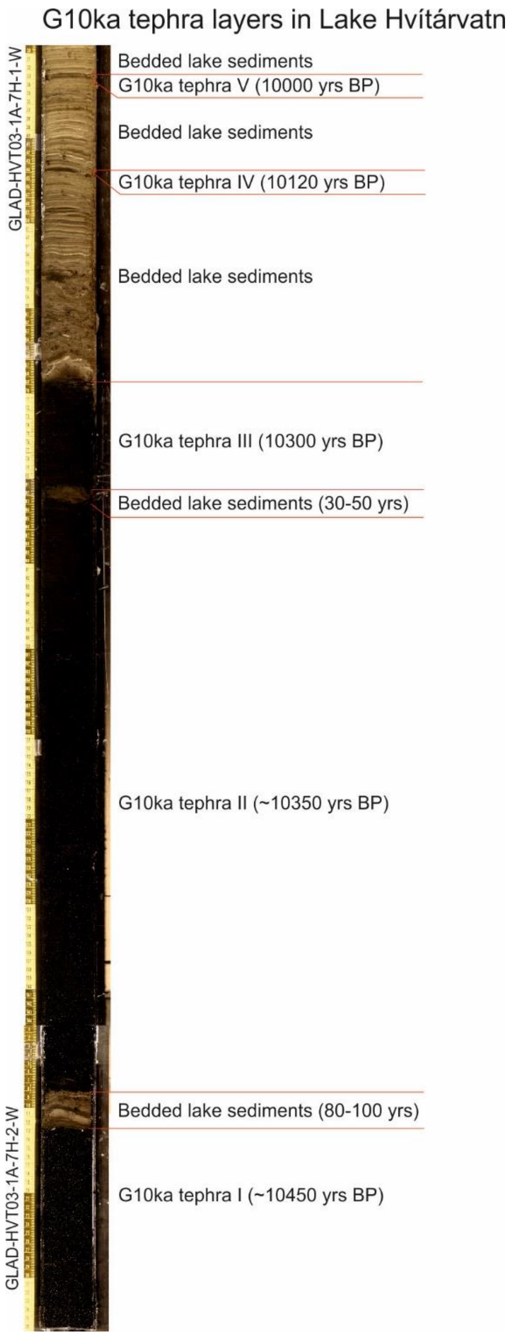
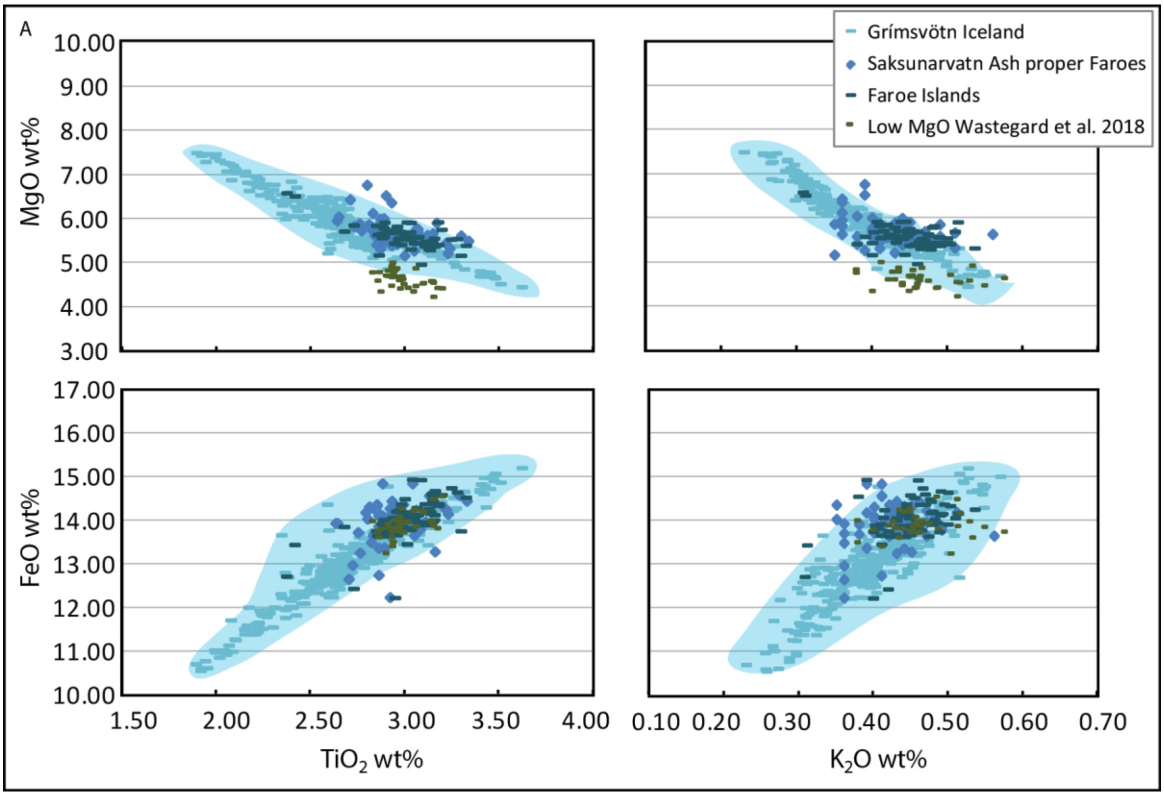
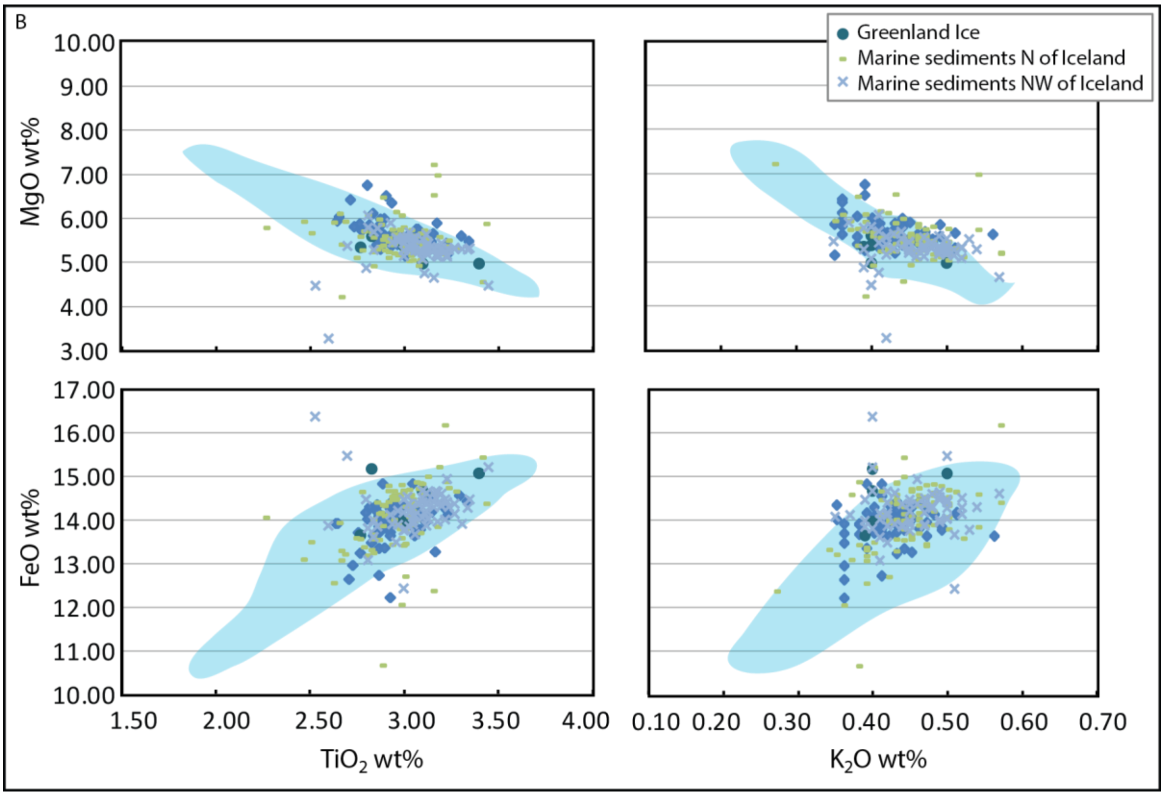
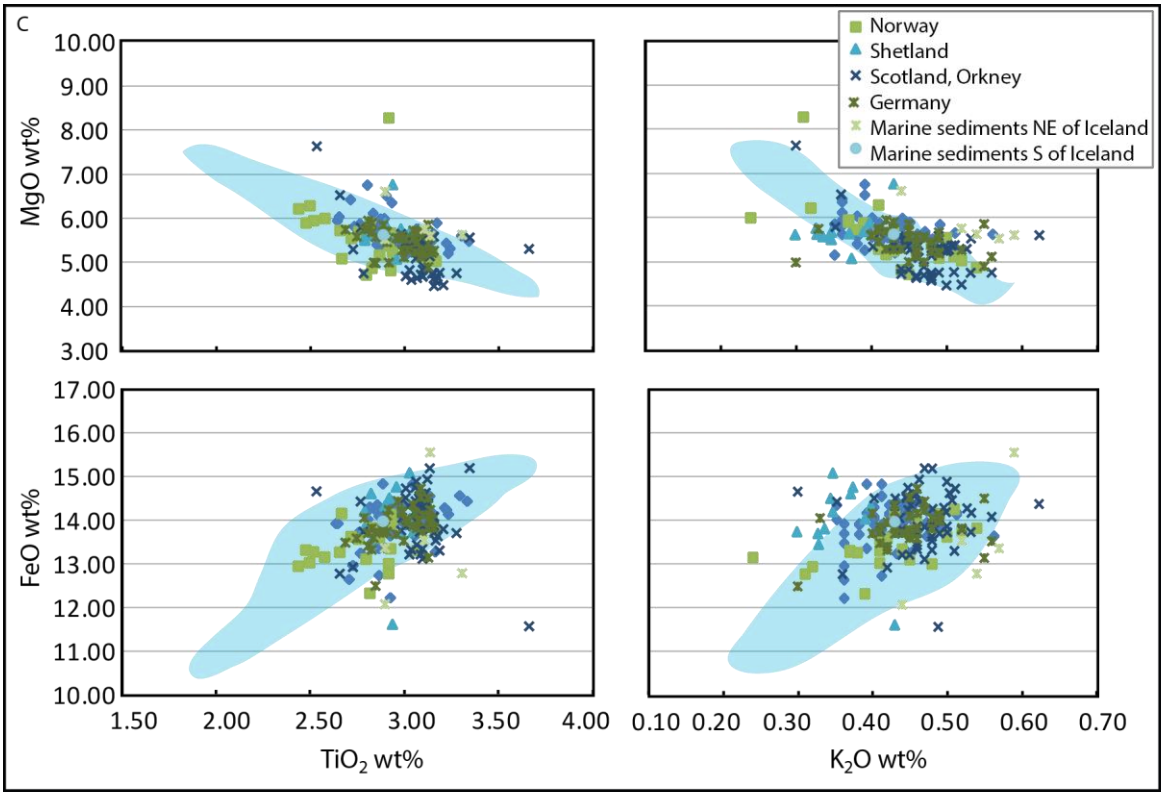
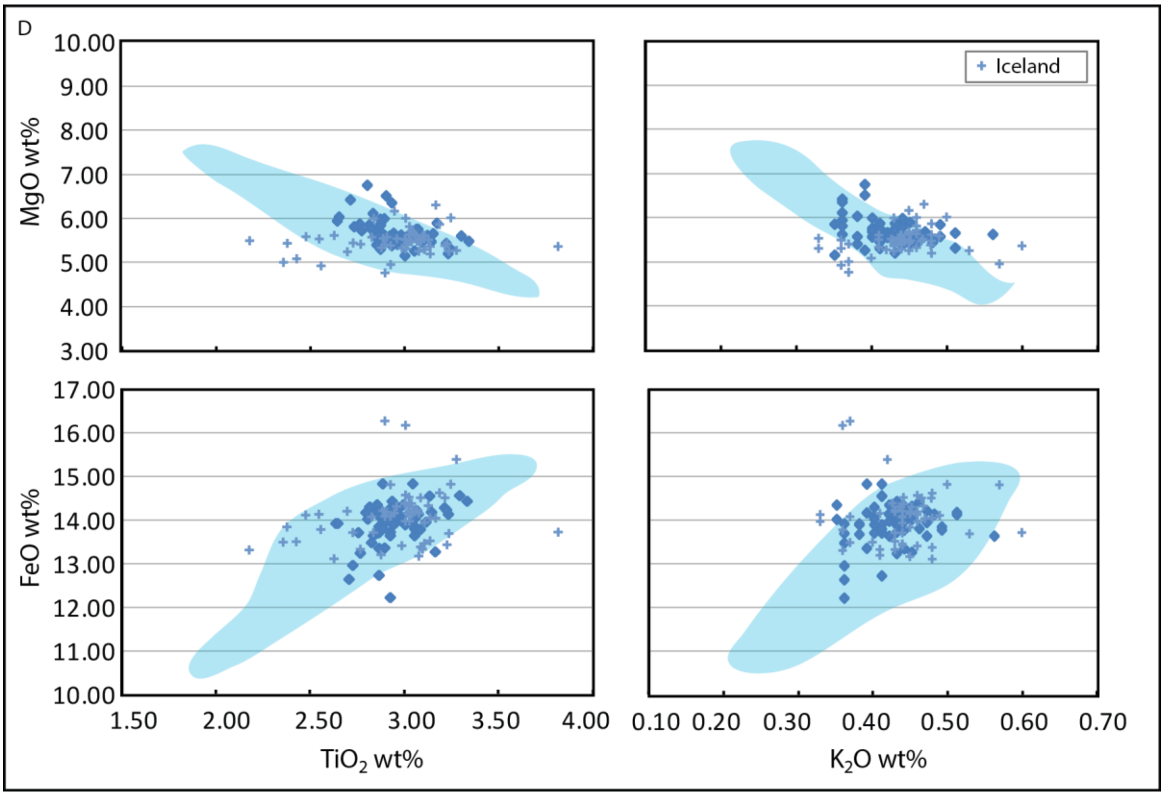


Figure 5. Sediment core HVT-1 (sections 7H-1 and 7H-2, marked on left side of core) from lake Hvítárvatn, showing sediment (indicated by red boxes in legend) between layers of the G10ka series tephras (dark colour) with a Grímsvötn composition and ages of ~10.450 to ~10.000 cal. yr BP (Jóhannsdóttir 2007; Thordarson 2014).


A
Grímsvötn Iceland
Saksunarvatn Ash proper Faroes
Faroe Islands
Low MgO Wastegard et al. 2018
MgO wt%
FeO wt%
TiO2 wt%
K2O wt%


B
Greenland Ice
Marine sediments N of Iceland
Marine sediments NW of Iceland
MgO wt%
FeO wt%
TiO2 wt%
K2O wt%


C
Norway
Shetland
Scotland, Orkney
Germany
Marine sediments NE of Iceland
Marine sediments S of Iceland
MgO wt%
FeO wt%
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
1.50 2.00 2.50 3.00 3.50 4.00
0.10 0.20 0.30 0.40 0.50 0.60 0.70
TiO_2 wt%
K_2O wt%


D
Iceland
MgO wt%
FeO wt%
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
1.50 2.00 2.50 3.00 3.50 4.00
0.10 0.20 0.30 0.40 0.50 0.60 0.70
TiO_2 wt%
K_2O wt%

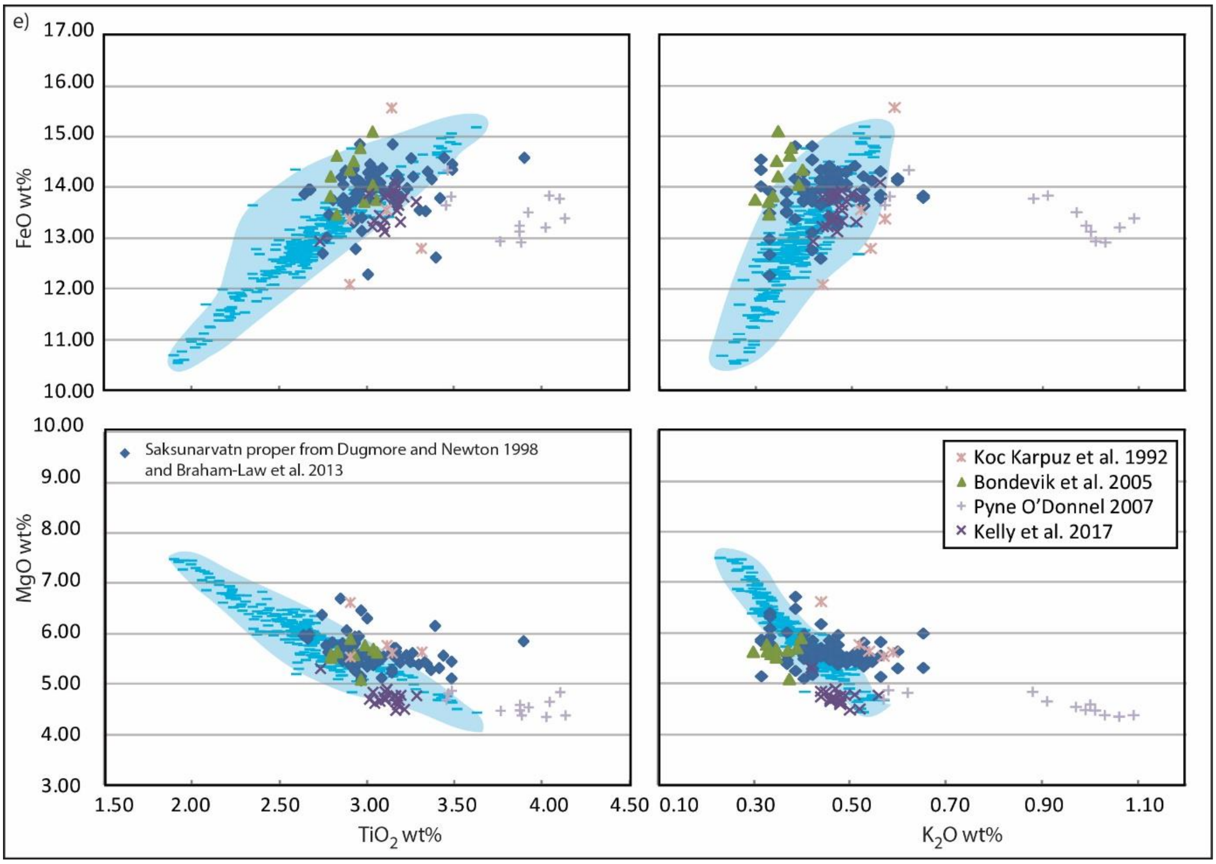


Figure 6. Chemical analyses of G10ka series previously correlated to the Saksunarvatn Ash around the North-Atlantic compared to electron microprobe analyses of Grímsvötn tephra (light blue lines: Óladóttir et al., 2011a, also indicated by the light blue field. In following figures, only the field is shown). All analyses are compiled in Supplement 1. Y-axes on figures to the right are the same as on the figures to the left and x-axes are the same for both top and bottom figures. A) Saksunarvatn Ash proper Faroes (blue diamonds): selected analyses from Dugmore and Newton, 1998 and Bramham-Law et al., 2013 and other tephra from the Faroes (dark blue lines: Wastegård et al., 2001; 2018; Olsen et al., 2010). Low MgO analyses from Wastegård et al.(2018) are shown separately (green lines). B) Tephra from Greenland ice (blue circles: Grönvold et al., 1995; Zielenski et al., 1997; Mortensen et al., 2005) and marine sediment N of Iceland (green line: Sjöholm et al. 1991 (some grains that plot outside of the field); Eiríksson et al., 2004; Söndergaard, 2005; Kristjánsdóttir et al., 2007; Gudmundsdóttir et al., 2011) and NW of Iceland (light blue x: Andrews et al., 2002a (some grains that plot outside of the field); Jennings et al., 2002; Jennings et al., 2014). C) Tephra from Norway (green boxes: Birks et al., 1996;

Aarnes et al., 2012: Lind et al., 2013), Shetland (blue triangles: Bennet et al., 1992; Bondevik et al., 2005), Scotland and Orkney (dark-blue x-es: Bunting, 1994; Kelly et al., 2017; Timms et al., 2017), Germany (dark green stars: Merkt et al., 1993: Bramham-Law et al., 2013; Wulf et al., 2016) and marine sediments NE of Iceland (light green stars: Koç Karpuzand Jansen, 1992) and SE of Iceland (blue circle: Rasmussen et al., 2011). D) Tephra from Iceland (light blue pluses: Vilmundardóttir et al., 1979; Björck et al., 1992; Sigurgeirsson and Leósson, 1993; Ingólfsson et al., 1995; Andrews et al., 2002a; Sigvaldason, 2002; Jóhannsdóttir, 2007; Lloyd et al., 2009; Eddudóttir et al., 2015; Gunnarson, 2016; Harning et al., 2016; 2018a; Brader et al., 2017; Schomacker et al., 2016). E) Tephra with chemical composition that falls outside of the Grímsvötn compositional field although close to known composition within the Saksunarvatn Ash.

Figure 7. Grímsvötn 2011 tephra deposit in Iceland (A-E) compared to an older tephra deposit in Iceland possibly correlated to the G10ka series tephra (F). A) Tephra from the Grímsvötn 2011 eruption in Skeiðarársandur, S-Iceland. No tephra is preserved on the unvegetated area, only in the lime grass dunes. Photo: Ingibjörg Eiríksdóttir. B-C) During the Grímsvötn 2011 eruption there were strong winds that blew the tephra fall directly into dunes, so near-surface lateral transport occurred during the tephra fall. D) Tephra deposited in moist environments (on a river/stream bank) resisted the wind and was not transported during and right after the eruption. E) Structure of a windblown tephra pile from

the Grímsvötn 2011 eruption, the pit is seen in Fig C. F) Structure of an old tephra deposit, probably part of the G10ka series. See further discussion in text

Table 1 Age of proposed Saksunarvatn Ash from the literature

All ages in the text are given as calibrated calendar years before 1950 (with notion cal. yr BP), unless otherwise indicated, where calibration is performed with the on-line program CALIB version 7.1 (http://calib.qub.ac.uk/calib/; Stuiver et al., 2018), and the IntCal13 calibration curve (Reimer et al., 2013). Marine samples are calibrated the same way using the "MARINE 13" curve and for simplicity "Delta R" = 0. Throughout the text we have used the 68% confidence interval for the calibrated ages and for simplicity expressed it as the midpoint plus/minus half the interval. Thus, an interval of i.e. 6500-6600 would be written 6550±50, although this is not formally a standard deviation because there is not a Gaussian probability distribution.

Table 1a 14C ages from the literature

Location	Outcrop type –Material dated	Calibration curve	Age below				Lab. Ref.	Age above				Lab. Ref.	Reference
			^{14}C BP	Range cal. yr BC[1]	Average cal. yr BP[2]	Corrected reservoir		^{14}C BP	Range cal. yr BC[1]	Average cal. yr BP[2]	Corrected reservoir		
Hoydalar Fareos	Soil-unknown	IntCal12	*9410±240*	*8933-8431*	*10632±251*		unknown						Waagstein and Jóhansen 1968
Hoydalar Fareos	Soil- gyttja rich in diatoms	IntCal13	9200±210	*8773-8208*	*10441*±283		unknown						Jóhansen 1975

Hoydalar Fareos	Soil- gyttja rich in diatoms	IntCal13						9080±210	*8568-7961*	*10215*±303		unknown	Jóhansen 1975
Kråkenes Norway	Lake- terrestrial plant macrofossils	IntCal13	9065±105	*8461-8201*	*10281±130*		Ua-3425	8930±145	*8280-7936*	*10058±172*		UA-3423	Gulliksen et al. 1998
Torfadalsvatn Iceland	Lake-bulk sample	IntCal13	8860±250	*8267-7673*	*9920±297*		UA-1891	8540±230	*7951-7321*	*9586±315*		Ua-1892	Björck et al. 199
Kagaðarhóll Iceland	Lake- Salix leaf fragment	IntCal13						9258±35	*8562-8442*	*10452±60*		SUERC-47862	Eddudóttir et al. 2015
Seltjörn Iceland	Lake-submerged peat	IntCal13	9030±110	*8344-8166*	*10205±89*		Lu-3345						Ingólfsson et al. 1995
Skorarvatn Iceland	Lake- moss	IntCal13	9145±35		10300±70^	0.5	CURL-21033	8905±35		10060±120^	12.5	CURL-21041	Harning et al. 2016; 2018a
Skorarvatn Iceland	Lake- moss	IntCal13	9145±35	*8349-8288*	*10269±31*	0.5	CURL-21033	8905±35	*8115-8054*	*10035±31*	12.5	CURL-21041	Harning et al. 2016; 2018a
HM107-05, N of Iceland	Marine-foraminifera	Marine13*	9250±70	*8220-8042*	*10082±89*	8850±70	AAR-4420	9190±80	*8183-7927*	*10005±128*	8790±80	AAR-4419	Eiríksson et al. 2000
B997-332, Húnaflói Fjord	Marine- Mollusc	Marine13*	*9480±70*	*8460-8282*	*10321±89*	9080±70	AA-35180						Andrews et al. 2002a

B997-336, Djúpáll Trough	Marine-foraminifera	Marine13*						9240±200	*8294-7759*	*9977±268*		AA-31266	Andrews et al. 2002b
RAPiD-17-5P, S of Iceland	Marine-foraminifera	Marine13*	9728 ± 39	*8728-8622*	*10625±53*		SUERC 14104						Thornalley et al 2011

Radiocarbon ages are given as conventional radiocarbon ages, i.e. corrected for isotopic fractionation to δ13C = - 25‰ and not corrected for marine reservoir age (Stuiver and Polach, 1977)

[1]68% confidence interval

[2]Midpoint ± half 68% confidence interval

^Published value, not Midpoint ± half 68% confidence interval

**Delta R=0*

Underlined: no information given on whether dated material was below or above the tephra

Italic: numbers derived from published values

Table 1b Icecore years from the literature

Location		Icecore years		
		b2k	BP	
GRIP Greenland	Ice	*10230±60*	10180±60	Grönvold et al. 1995
GRIP Greenland	Ice	10318±205	*10268±205*	Zielinski et al. 1997
GRIP Greenland	Ice	10322±205	*10272±205*	Zielinski et al. 1997
GRIP Greenland	Ice	10325±205	*10275±205*	Zielinski et al. 1997
GRIP Greenland	Ice	10347±89	*10297±89*	Rasmussen et al. 2006
NGRIP Greenland	Ice	*10316±1*	10266±1	Mortensen et al. 2005

Table 2 Published locations of the Saksunarvatn Ash. Correlation to the Saksunarvatn Ash has been based on one or more: stratigraphy (s), age, major element chemical composition (cc), morphology (m).

Marine cores										
No.	**Location**	**Core type**	**Core name**	**Lat**	**Long**	**Tephra thickness (cm)**	**Published major element chemical composition**	**Correlation method**	**Cor. unlikely**	**Reference**
1	North of Iceland, Iceland Shelf	Marine	HM107-04	67.22722222	-19.05	2-3	presented on biplots	cc		Eiríksson et al. 2000; Knudsen et al. 2004
2	North of Iceland, Iceland Shelf	Marine	HM107-05	66.90222222	-17.9052778	2-3	presented on biplots	cc		Eiríksson et al. 2000; Knudsen et al. 2004
3	North of Iceland, Iceland Shelf	Marine	MD99-2271	66.50138889	-19.5055556	6	5-point analyses	cc		Eiríksson et al. 2004
4	North of Iceland, Iceland Shelf	Marine	MD99-2275	66.55277778	-17.7108333	8	5-point analyses	cc		Eíríksson et al. 2004
5	North of Iceland, Iceland Shelf	Marine	MD99-2275	66.55277778	-17.7108333	4	44-point analyses in supplement	cc		Gudmundsdóttir et al. 2011
6	North of Iceland, Iceland Shelf	Marine	MD99-2275	66.55277778	-17.7108333		7-point analyses	cc		Söndergaard 2005
7	North of Iceland, Iceland Shelf	Marine	MD99-2271	66.50138889	-19.5055556	?	N	cc s		Knudsen & Eiríksson 2002
8	North of Iceland, Iceland Shelf	Marine	MD99-2272	66.99277778	-17.9747222	?	N	cc s		Knudsen & Eiríksson 2002
9	Húnaflói Fjord, Iceland Shelf	Marine	MD99-2269	66.62555556	-20.8527778	3	average in paper	cc m s		Kristjánsdóttir et al. 2007
10	Húnaflói Fjord, Iceland Shelf	Marine	B997-325	66.56722222	-20.9997222	2	average in paper	cc ms s	x	Andrews et al. 2002a
11	Húnaflói Fjord, Iceland Shelf	Marine	B997-329	65.96666667	-21.2986111	12	average in paper	cc ms s	x	Andrews et al. 2002a
12	Húnaflói Fjord, Iceland Shelf	Marine	B997-332	66.13638889	-21.4180556	12	average in paper	cc ms s	?	Andrews et al. 2002a

13	Húnaflói Fjord, Iceland Shelf	Marine	MD99-2269	66.62555556	-20.8527778	5	average in paper	cc ms s		Andrews et al. 2002a; 2003; Stoner et al. 2007
14	Djúpáll Trough, Iceland Shelf	Marine	B997-335	66.68666667	-24.1783333	25	average in paper	cc ms s		Andrews et al. 2002a
15	Djúpáll Trough, Iceland Shelf	Marine	MD99-2264	66.67888889	-24.1961111	30	average in paper	cc ms s		Andrews et al. 2002a; Geirsdóttir et al. 2002
16	Djúpáll Trough, Iceland Shelf	Marine	B997-336	66.68694444	-24.1616667	25	N	ms s		Andrews et al. 2002a; Geirsdóttir et al. 2002
17	Djúpáll Trough, Iceland Shelf	Marine	B997-315	66.73277778	-24.3355556	<1	N	s		Andrews et al. 2002a
18	Djúpáll Trough, Iceland Shelf	Marine	B997-337	66.66944444	-24.1272222	15	N	s		Andrews et al. 2002a
19	Ísafjarðardjúp Fjord, Iceland Shelf	Marine	MD99-2266	66.44416667	-23.3155556	1-2	average in paper	cc ms s	?	Andrews et al. 2002a
20	Ísafjarðardjúp Fjord, Iceland Shelf	Marine	MD99-2265	66.27722222	-22.8577778	2	average in paper	cc ms s		Andrews et al. 2002a; Geirsdóttir et al. 2002
21	Ísafjarðardjúp Fjord, Iceland Shelf	Marine	B997-339	66.01833333	-22.8005556	2-3	N	s		Andrews et al. 2002a, Geirsdóttir et al. 2002
22	Eyjafjarðaráll, Iceland Shelf	Marine	B997-319GGC	66.45611111	-18.84		average in paper	cc s		Andrews et al. 2002a
23	Norwegian Slope, Norwegian Sea	Marine	HM79-6.2	62.96666667	2.7	15	6-point analyses	cc	x	Koç Karpuz and Jansen 1992
24	North Sea fan, Norwegian Sea	Marine	HM79-20	64.66166667	-0.70666667		N	cc		Haflidason et al. 1998
25	North Sea fan, Norwegian Sea	Marine	HM83-06	64.28	-2.68		N	cc		Haflidason et al. 1998
26	Norway Basin, Norwegian Sea	Marine	57-17	66.98333333	-6.2		N			Haflidason et al. 1990
27	Iceland-Scotland Ridge, Central North Sea	Marine	ENAM33	61.47694444	-10.6905556	~4	N	s		Rasmussen et al. 2003
28	Wyville-Thomson Ridge, Central North Sea	Marine	59-07/276	59.99333333	-6.09166667	25-50	Y			Stoker et al. 1989
29	Norwegian Shelf, North Sea	Marine	Troll-8903	60.63361111	3.718055556	micro	N	s		Haflidason et al. 1998
30	East Faroe Shelf Trough	Marine	LINK14	61.8	-6.16666667		average in paper	cc		Rasmussen et al. 2011

31	North of Iceland, Norwegian-Greenland Sea	Marine	P57-7	68.42888889	-13.8766667		N	cc		Sejrup et al. 1989
32	North of Iceland, Norwegian-Greenland Sea	Marine	P57-7	68.42888889	-13.8766667	2	point analyses	cc s	?	Sjöholm et al. 1991
33	Grivel basin, Greenland Shelf	Marine	MD99-2317	68.09333333	-27.8355	micro	N	cc		Jennings et al. 2006
34	Kangerlussuaq Trog, Greenland Shelf	Marine	MD99-2322	67.13633333	-30.8278333	micro	N; point analyses of 3 layers	cc		Stoner et al. 2007; Jennings et al. 2014
35	Kangerlussuaq Trog, Greenland Shelf	Marine	JM96-1214/2GC	67.3	-30.9666667	2	average in paper	cc age		Jennings et al. 2002; 2006
36	Kangerlussuaq Trog, Greenland Shelf	Marine	JM96-1215/2GC	67.04666667	-30.86	2	average in paper	cc age		Jennings et al. 2002; 2006; 2014
37	Kangerlussuaq Trog, Greenland Shelf	Marine	JM96-1216/2GC	65.96277778	-30.6333333	4	average in paper	cc age		Jennings et al. 2002; 2006
38	South Iceland Rise, Iceland Shelf	Marine	RAPiD-15-4P	62.293	-17.134	micro	N	age		Thornalley et al. 2011
39	South Iceland Rise, Iceland Shelf	Marine	RAPiD-12-1K	62.0905	-17.8196667	micro	presented on biplots	cc age		Thornalley et al. 2011
40	South Iceland Rise, Iceland Shelf	Marine	RAPiD-17-5P	61.48166667	-19.536	1-2	presented on biplots	cc age		Thornalley et al. 2011
41	Mýrdalsjökull Canyon, Iceland Basin	Marine	AII94-8PC	61.88666667	-18.8016667	70*	point analyses	cc		Lacasse et al. 1998
42	South Iceland Rise, Iceland Shelf	Marine	HM57-14	66.98333333	-5.2		N			Haflidason et al. 2000

cc=chemical composition (major elements),

s=stratigraphy, m=morphology

*cc of reported Saksunarvatn ash (now G10ka series) found in a 70 cm thick horizon

micro=invisible to the naked eye

Ice-cores

No.	Location	Core type	Country	Lat	Long	Tephra thickness (cm)	Published major element chemical composition	Correlation method	Cor. unlikely	Reference
43	GRIP		Greenland	72.58333333	-37.6333333	0.1	Y	cc		Grönvold et al. 1995

No.	Location	Core type	Country	Lat	Long	Tephra thickness (cm)	Published major element chemical composition	Correlation method	Cor. unlikely	Reference
44	GISP2		Greenland	72.58333333	-38.4666667	3	average in paper	cc age		Zielenski et al. 1997
45	GISP2		Greenland	72.58333333	-38.4666667	2	average in paper	cc age		Zielenski et al. 1997
46	GISP2		Greenland	72.58333333	-38.4666667	1	average in paper	cc age		Zielenski et al. 1997
47	NGRIP		Greenland	75.1	-42.3333333	0.1	average in paper	cc age m		Mortensen et al. 2005
48	NGRIP		Greenland	75.1	-42.33		N	age		Rasmussen et al. 2006
49	NEEM		Greenland	77.45	-51.06		N	cc		Rasmussen et al. 2013
cc=chemical composition (major elements), s=stratigraphy, m=morphology										
Terrestrial cores										
No.	**Location**	**Core type**	**Country**	**Lat**	**Long**	**Tephra thickness (cm)**	**Published major element chemical composition**	**Correlation method**	**Cor. unlikely**	**Reference**
50	Hoydalar, Streymoy Island	Soil	Faroe Islands	62.03972222	-6.78111111	0.7	N	Saksunarvatn proper		Waagstein & Jóhansen 1968, Jóhansen 1975; 1982
51	Saksunarvatn, Streymoy Island	Lake	Faroe Islands	62.25222222	-7.16027778	45	13-point analyses	Saksunarvatn Ash proper		Jóhansen 1978; 1982; Mangerud et al. 1986
52	Saksunarvatn, Streymoy Island	Lake	Faroe Islands	62.25222222	-7.16027778	45	30-point analyses	Saksunarvatn Ash proper		Dugmore & Newton 1998
53	Saksunardalur, Streymoy Island	Soil	Faroe Islands	62.25222222	-7.16027778	1	N	s		Edwards & Craigie 1998
54	Ovaru Hoydalar, Streymoy Island	Soil	Faroe Islands	62.03972222	-6.78111111	1.6	N	s		Edwards & Craigie 1998
55	Hagamýra, Suduroy Island	Soil	Faroe Islands	61.50944444	-6.77222222	6.7	N	s		Edwards & Craigie 1998

56	Mjáuvøtn,Streymoy Island	Lake	Faroe Islands	62.14055556	-7.00277778	1.2	average; 16-point analyses; N	cc m s		Wastegård et al. 2001; 2018; Olsen et al. 2010
57	Hovsdalur, Suduroy Island	Soil	Faroe Islands	61.5	-6.78333333	3-5	N	s		Hannon et al. 2003
58	Stóravatn, Streymoy Island	Lake	Faroe Islands	62.070995	-6.861014	~1	9-point analyses	cc s		Olsen et al. 2010
59	Havnardalsmyren, Streymoy Island	Soil	Faroe Islands	62.01666667	-7.4	2-3	N	s		Kylander et al. 2011
59	Havnardalsmyren, Streymoy Island	Soil	Faroe Islands	62.01666667	-7.4	2-3; crypto	27-point analyses, three cryptotephra layers	cc s		Wastegård et al. 2018
60	Plußsee	Lake	Germany	54.15555556	10.40916667	0.01-0.02	average	cc		Merkt et al. 1993
61	Muggesfelder See	Lake	Germany	54.02805556	10.33805556	0.01-0.02	N	cc		Merkt et al. 1993
62	Eversener See	Lake	Germany	53.26944444	9.668055556	0.01-0.02	average	cc		Merkt et al. 1993
63	Hämelsee	Lake	Germany	52.78222222	9.218888889	0.01-0.02	N	cc		Merkt et al. 1993
64	Potremser Moor, Mecklenburg-Vorpommern	Soil	Germany	53.991213	12.49454789	micro	11-point analyses	cc s		Bramham-Law et al. 2013
65	Tiefer See	Lake	Germany	53.59166667	12.53	0.03	26-point analyses	cc		Wulf et al. 2016
66	Kråkenes, Vågsøy	Lake	Norway	62.02722222	5.00333333	micro	23-point analyses	cc		Birks et al. 1996
67	Kråkenes, Vågsøy	Lake	Norway	62.02333333	4.991111111	micro	23-point analyses	cc age		Birks et al. 1996
68	Kråkenes, Vågsøy	Lake	Norway	62.02722222	5.00333333	micro	N	cc		Gulliksen et al. 1998
69	Kråkenes, Vågsøy	Lake	Norway	62.02722222	5.00333333	micro	N	cc		Lohne et al. 2013
70	Kråkenes, Vågsøy	Lake	Norway	62.02722222	5.00333333	micro	N	cc		Lohne et al. 2014
71	Lusvatnet, Andøya	Lake	Norway	69.06666667	15.5666667	micro	average in paper	cc s		Aarnes et al. 2012
72	Grönlia fen,N-Tröndelag, Fosen peninsula	Soil	Norway	63.78444444	10.48	micro	average in paper	cc s		Lind et al. 2013

73	Dallican Water, Catte Ness	Lake	Shetland	60.39166667	-1.1	micro	average in paper	cc m		Bennett et al. 1992
74	Loch of Benston	Lake	Shetland	60.25	-1.16666667		11-point analyses	cc	x	Bondevik et al. 2005
75	Quoyloo Meadow, Mainland	Soil	Orkney	59.07055556	-3.31583333	micro	average in paper	cc m		Bunting 1994
76	Quoyloo Meadow, Mainland	Soil	Orkney	59.06567222	-3.30975	<0.8	31-point in suppl	cc		Timms et al. 2017
77	Crudale Meadow, Mainland	Soil	Orkney	59.01583333	-3.32555556	micro	average in paper	cc m		Bunting 1994
78	Loch Ashik, Isle of Skye	Lake	Scotland	57.25	-5.83333333	micro	12-point analyses	cc s	x	Pyne-O'Donnel 2007
79	Loch Ashik, Isle of Skye	Lake	Scotland	57.25	-5.83333333	micro	19-point analyses, reanalysed material from Pyne-O'Donnel 2007	cc s	x	Kelly et al. 2017
80	Sultartangalón, southern highlands	Soil	Iceland	64.21222222	-19.4686111	1100	average in report	not correlated when published		Vilmundardóttir et al. 1979
81	Hælavík, Vestfirðir Peninsula	Soil	Iceland	66.45833333	-22.6163889	50	N	s		Hjort et al. 1985
82	Torfdalsvatn, Skagi, north Iceland	Lake	Iceland	66.06666667	-20.3833333	22	average in paper	cc age s		Björck et al. 1992
83	Eiðar, east Iceland	Soil	Iceland	65.37261944	-14.3483361		N	cc		Hunt 1992
84	Eyjafjarðardalur, north Iceland	Soil	Iceland	65.57583333	-18.1186111		N	s		Sigurgeirsson 1993
85	Sogamýri, Reykjavík, south Iceland	Soil	Iceland	64.13138889	-21.8886111	3	average in paper	cc age s,		Sigurgeirsson & Leósson 1993
86	Búðarháls, West of Þórisvatn Lake, central Iceland	Soil	Iceland	64.22111111	-19.2758333	100	presented on biplots	s		Kaldal 1993
87	Seltjörn, Seltjarnarnes, south Iceland	Soil	Iceland	64.15222222	-22.0086111	2.5	average in paper	cc age s,		Ingólfsson et al. 1995

88	Snarpastaðir, Melrakkaslétta, northeast Iceland	Soil	Iceland	66.29738333	-16.41865		N	s		Pétursson 1997
89	Hörgárdalsheiði, north Iceland	Soil	Iceland	65.55	-18.7666667	~5	presented on biplots	s		Wastl 2000
90	Vesturárdalur, Tröllaskagi Peninsula, north Iceland	Soil	Iceland	65.75	-18.7166667		N	s		Wastl et al. 2001
91	Hámundarstaðarháls, north Iceland	Soil	Iceland	65.95303611	-18.4623278	~100	N	s		Wastl et al. 2001; Caseldine et al. 2006
92	Norðurfjörður, Vestfirðir Peninsula	Lake	Iceland	66.05638889	-21.5680556	8	average in paper	cc age s		Andrews et al. 2002a
93	Efstadalsvatn, Vestfirðir Peninsula	Lake	Iceland	65.94388889	-22.665	2	average in paper	cc age s		Andrews et al. 2002a; Geirsdóttir et al. 2002; Caseldine et al. 2003
94	Reykjarfjörður, Vestfirðir Peninsula	Lake	Iceland	65.97472222	-21.6527778	8	average in paper	cc age s*		Andrews et al. 2002a
95	Laufás, north Iceland	Soil	Iceland	65.8925	-18.0777778		average in paper	s		Sigvaldason 2002
96	Vopnafjörður, northeast Iceland	Soil	Iceland	65.74055556	-14.9297222		average in paper	s		Sigvaldason 2002
97	Naust, Grunnavík, Vestfirðir Peninsula	Soil	Iceland	66.2325	-22.9616667	4	N	s		Principato 2003; Principato et al. 2006
98	Kárahnjúkar ss-1, east Iceland	Soil	Iceland	64.91944444	-15.8725	20	N	s		Sæmundsson & Jóhannesson 2005
99	Kárahnjúkar ss-2, east Iceland	Soil	Iceland	64.92166667	-15.8516667	80	N	s		Sæmundsson & Jóhannesson 2005
100	Vatnamýri, north Iceland	Soil	Iceland	65.9	-18.3	~30	presented on biplots	s		Wastl 2000; Caseldine et al. 2006
101	Torfdalsvatn, Skagi, north Iceland	Lake	Iceland	66.05945	-20.38025	16	N	cc m		Axfort et al. 2007
102	Stóra-Viðarvatn, northeast Iceland	Lake	Iceland	66.2372	-15.8347167	~80	N	cc m		Axford et al. 2007
103	Litla-Viðarvatn, northeast Iceland	Lake	Iceland	66.24111111	-15.8058333	~20	N	cc m		Axford et al. 2007
104	Haukadalsvatn, west Iceland	Lake	Iceland	65.05222222	-21.6408333	12	point analyses	cc		Jóhannsdóttir 2007
105	Hestvatn, south Iceland	Lake	Iceland	64.02305556	-20.7125	35	point analyses	cc		Jóhannsdóttir 2007

106	Hvítárvatn, central Iceland	Lake	Iceland	64.63888889	-19.8427778	110	point analyses	cc		Jóhannsdóttir 2007; Black 2008; Larsen et al. 2012
107	Berufjarðarvatn, Vestfirðir Peninsula	Lake	Iceland	65.55106667	-22.1054833	2	average in paper	cc s		Lloyd et al. 2009
108	Hafrafellsvatn, Vestfirðir Peninsula	Lake	Iceland	65.50501667	-22.0464333	2 (diluted over 2 cm)	N	cc s		Lloyd et al. 2009
109	Hríshóll 1, Vestfirðir Peninsula	Soil	Iceland	65.53955	-22.0919333	3	average in paper	s		Lloyd et al. 2009
110	Hríshóll 2, Vestfirðir Peninsula	Soil	Iceland	65.54268333	-22.08455	3	average in paper	s		Lloyd et al. 2009
111	Hríshólsvatn, Vestfirðir Peninsula	Lake	Iceland	65.53045	-22.0770667	3	average in paper	cc s		Lloyd et al. 2009
112	Eyvík, southwest Iceland	Soil	Iceland	64.055	-20.6933333	5-7	N	s		Karlsdóttir et al. 2012
113	Sellandalækur, northeast Iceland	Soil	Iceland	65.43135	-17.0772		9-point analyses	s		Sæmundsson et al. 2012
114	Hvammahraun, northeast Iceland	Soil	Iceland	65.94906667	-17.1098		8-point analyses	s		Sæmundsson et al. 2012
115	Ytra-Áland, Þistilfjörður,northeast Iceland	Soil	Iceland	66.2076	-15.556	17-20	N	s		Karlsdóttir 2014
116	Kagaðarhólstjörn, north Iceland	Soil	Iceland	65.58777778	-20.1327778	1	average in paper	cc s		Eddudóttir et al. 2015
117	V-Gíslholtsvatn, south Iceland	Lake	Iceland	63.93333333	-20.5166667	4.9	N	cc		Blair et al. 2015
118	Arnarvatn-Stóra, northwest Iceland	Lake	Iceland	64.9583	-20.3101333	47	average in thesis	cc s		Gunnarsson 2016
119	Gjögurvatn, Vestfirðir Peninsula	Lake	Iceland	65.9977	-21.36171	~130	average in suppl.	cc s		Harning et al. 2016
120	Svartárgilsvatn, Vestfirðir Peninsula	Lake	Iceland	65.90846667	-21.8219667	~14	average in suppl.	cc s		Harning et al. 2016
121	Skorarvatn, Vestfirðir Peninsula	Lake	Iceland	66.25626	-22.32183	~27; 21	point analyses in suppl.	cc s		Schomacker et al. 2016, Guðmundsdóttir et al. 2018
122	Skorarvatn, Vestfirðir Peninsula	Lake	Iceland	66.25633333	-22.3270306	3 layers, from ~4-15 cm	average in suppl.	cc age		Harning et al. 2016; 2018a

123	Gedduvatn, Vestfirðir Peninsula	Lake	Iceland	65.75478333	-22.1801667	~7	average in suppl.	cc age		Harning et al. 2016; 2018a
124	Bæjarvötn, Vestfirðir Peninsula	Lake	Iceland	65.7211	-21.4362	~35	average in suppl.	cc s		Harning et al. 2016; 2018a
125	Hlöðuvík, Vestfirðir Peninsula	Lake	Iceland	66.41608333	-22.6476167	6	30-point analyses in suppl.	cc s		Brader et al. 2017

cc=chemical composition (major elements),

s=stratigraphy, m=morphology

*probably reworked material

micro=invisible to the naked eye