Stockholm University

Dynamica - SUstainable Publishing

From the ashes: a 150th anniversary review of the Askja-1875 tephra

Simon A. Larsson[1]

[1] Department of Physical Geography, Stockholm University

Abstract

The Icelandic volcano Askja's eruption in 1875 was in several respects an important moment in the history of volcanology and adjacent fields of science. A series of expeditions in the decades following the volcanic activity led to the discovery and mapping of a previously unknown volcanic system, while observations of the ashfall from the eruption's climax were used to produce the first-ever spatially and temporally detailed ash dispersal map. Later, the buried ashes on Iceland played part in the founding of the method of tephrochronology by Sigurdur Thorarinsson through his work at Stockholm University College in 1932–1944. The Askja-1875 tephra has since become a well-used marker horizon in modern tephrochronological research, providing a precise age estimate to recent natural archives. This review summarises the scientific history of studies of the eruption and the ashes it produced, and compiles and briefly examines the currently available compositional data of the Askja-1875 tephra, also providing code for a simple workflow in such statistical efforts.

Keywords: tephra, tephrochronology, volcanology, geochemistry

Correspondence: simon.larsson@natgeo.su.se

Where there's smoke: discovering a volcano

Around the annual turn of 1874–1875, several earthquakes were felt across Iceland, some supposedly lasting a full day's time (Sigurdson, 1875). In early January, steam and smoke could be seen all the way from the capital of Reykjavík to be rising from the interior of the island (Lock, 1881a; 1881b), and some ashfalls were noted locally between the time of the earthquake and late March (Lock, 1881a; Russell, 1917). The source of the activity was initially uncertain, and was reportedly first assumed to be "Skaptar Jökull" (Wight, 1885) – today known as the Laki fissures, situated southwest of the Vatnajökull ice cap – or one of several known volcanoes closer to Iceland's centre (Lock, 1881a). On February 18th, lava flows were observed by locals from Reykjahlíð in an area called the Mývatnsöræfi (Lock, 1881a; 1881b; Sigurdson, 1875), a considerable distance north of the Vatnajökull, implying one of the more central volcanoes was the culprit.

In that month of February, Jón Thorkelsson from Vidrkær set out to examine the source of the activity and found it in the mountains of Dyngjufjöll, located northwest of the Vatnajökull in east-central Iceland (Coles and Morgan 1882; Lock, 1881b; Sigurdson, 1875; Wight, 1885). Steam was seen rising from a chasm in the crater-shaped depression in the mountain known as Askja, which until that moment was not known as a volcano even to the Icelanders (Lock, 1881a). The mountain range's name of Dyngjufjöll has been translated as "mountains of the bower" (Morgan, 1882), wherein Askja's depression would likely be "the bower", implying that the feature had indeed been noted by earlier Icelanders (Lock, 1881b).

The testimony of Thorkelsson prompted an expedition to be planned by the Danish government through the University of Copenhagen (Morgan, 1882), carried out the following year and resulting in the first mapping of the crater-depression and the plain of Askja by Lieutenant Caroc of the Danish Navy (Johnstrup, 1877). Prior to this, the area had only been studied scientifically in the 1830s, when cartographer Björn Gunnlaugsson performed initial mapping, but without any closer exploration of the Dyngjufjöll (Crindle, 1885).

An explosive introduction

It was, however, on Easter Monday of 1875 – March 29th – that Askja properly introduced itself to the world. From the night of March 28th and into the following day, the volcanic activity culminated in an eruption of pumice and ash that spread with the westerly winds. The ejecta covered the land toward the east all the way to the coast (Lock, 1881b), destroying a number of farms and rendering the area uninhabitable for some time (Watts, 1876b). What's more, the finer ash fraction was evidently transported as far as Stockholm, Sweden, nearly 2000 km away from the Icelandic source; such distal deposition of volcanic ashes was at the time considered theretofore unknown (Nordenskiöld, 1876). A few ashfall observations in Norway implied that the eruption event began a day or two prior to the main spread of ashes on March 29th, which was otherwise the most commonly reported date of the climax (e.g. Lock, 1881a; Mohn, 1877).

About a dozen scientific excursions to Askja were completed in the half-century-or-so following the activity in 1875 (as summarised by Dawson, 1940), the first of which was in the summer after the main eruption when James Wight became the first foreigner to reach the volcano. His party observed the still rising steam from what had widened to a caldera in the southeast corner of the Askja plain, and he referred to it as Askjagjá (Wight, 1885). This name should mean "casket rift", as Wight made a point to correct previous translations of Askja: the correct translation of the mountain's name should be "casket" or "box", while previous translations included "oval casket" (Watts, 1876a) and "basket" (Lock, 1881b; Morgan, 1882). Later translations would include "the bowl" (Russell, 1917). The caldera of the 1875 eruption was in several cases noted under the alternative spelling "Öskjagjá" (e.g. Watts, 1876a), which would better align with the currently preferred spelling of the lake later formed within it as "Öskjuvatn". In some works, this lake is referred to as "Knebelsee" or "Knebelsvatn", in honour of a German geologist who lost his life on the lake or nearby during his study of Askja, a misfortune of which the details are unknown (Dawson, 1940; Russell, 1917).

That same summer of 1875, William Lord Watts set out to be the first to cross the Vatnajökull in an expedition where his party approached Askja from the south – which was by error, as they were aiming for Kverkfjöll further to the east (Watts, 1876b). They saw steam rising above the Dyngjufjöll, pumice covering the land eastward, and lava fields which "stretched among the neighbouring mountains like a troubled ocean of cindery stone" (Watts, 1876b, p. 5). At Öskjagjá they noted landslides and expulsions of loam, and described fissures spreading outwards "making the most horrible noise, while emitting the most nauseous smell" (Watts, 1876a, p. 91). By the time of the Danish expedition the following year, such activity had to some degree receded, and the lake of Öskjuvatn had started to form in the Öskjagjá, estimated then as reaching some 1200 m across (Johnstrup, 1877).

While Watts published the first English-written accounts of Askja, William George Lock added to (and extensively criticised) these works in an article and a book describing his expeditions in 1878 and 1880. His party approached Askja from the north by crossing the Ódáðahraun (translated to "misdeed lava-desert") and entering the Askja plain through a pass in the northwest end of the depression, named Jónsskarð after the previously mentioned Askja-discoverer Jón Thorkelsson (Lock, 1881b). Among their observations, they described the Öskjuvatn as considerably larger (and still steaming) in 1878 than what was described by Johnstrup (1877), and larger yet (but at that time of still waters) in 1880. When Þorvaldur Thoroddsen, who was part of the Danish expedition, revisited Askja in 1884, the lake had swelled to over 4000 m across, which is close to today's c. 4500 m – but during Wight's revisit in 1885, it was surprisingly noted as nearly entirely dissipated (Wight, 1885).

The scene was obviously a dynamic one in the decade following the 1875 eruption, which complicates comparisons of early work on Askja. To borrow a phrase from Morgan's (1882) description of the lava rocks of the Askja plain, there's some "extraordinary confusion" in the reports of these expeditions. Approximations of elevations, heights of the caldera walls, the area of the plain and the circumference of the mountains surrounding it, etc., vary among the sources and are in several cases considerably exaggerated compared to modern measurements (e.g. Johnstrup, 1877; Lock 1881a; 1881b; Watts, 1876b). This is of course understandable considering the limited precision of instruments and techniques utilised at the time. Still, it is amusing to note how the many exaggerations fit well with the often-hyperbolic writings about the excursions during which the observations were recorded, such as the (incorrect) description of this newly discovered volcano as the largest in Iceland (Lock, 1881a).

Askja, then and now

The current state of knowledge presents Askja as a north-to-south-reaching volcanic system in the Northern Volcanic Zone of Iceland, parallel to several other systems and stretching along the divergent plate boundary of the North American and Eurasian plates (cf. Thordarson and Larsen, 2007). The central volcano of the Askja system is located at 65°02' N 16°46' W in the Dyngjufjöll mountains, with the main caldera's walls reaching a peak elevation of 1514 m above sea level. The caldera floor – the Askja plain – sits mainly around 1100–1150 m above sea level, and the Öskjuvatn lake, filling the Öskjagjá caldera, is one of the deepest lakes in Iceland at over 250 m depth, with a surface elevation at approximately 1054 m above sea level.

A rift zone extends from the central volcano, 120 km to the north and 30 km to the south. This has been described as Askja's fissure swarm, from which the lava flows observed in early 1875 are thought to have originated (Hjartardóttir, Einarsson and Sigurdsson, 2009; Sigurdsson and Sparks, 1978). The early explorers of Askja assumed that the initial formation of Öskjagjá and the opening of the rifts to the north occurred already during the first activity in early January, or at least during the early spring, of 1875 (Lock 1881a; Watts, 1876b). Several lava flow relicts are found nearer the central volcano, already early on deemed too old to correlate to the 1875 eruption (Lock, 1881b).

It was initially suggested that the volcanic system must be stretching across a considerable distance, with the lighter, siliceous fractions of the magma escaping through calderas in the elevated, central volcano and the heavier, basaltic lava flows pouring from rifts and fissures extending from the foot of Dyngjufjöll, reaching to the north (Lock, 1881b; Watts, 1876b). This scenario has, however, been contested in modern studies, suggesting three separate plumbing systems for the Askja volcano, the northernmost lava flows, and the southernmost lava flows, although they did erupt more or less simultaneously around 1875 (Hartley and Thordarson, 2013). The northern extent of the lava flows of the 1875 eruption was first mapped by Peek (1882) during an expedition from which Morgan (1882) made his excursion to Askja. The rift zone's southern extent was initially under-estimated (Thoroddsen, 1884) and more lava flows south of Dyngjufjöll were later suggested to have originated from Askja, rather than from any other nearby volcano (Russell, 1917).

The main caldera surrounding the Askja plain was thought impossible to have formed by one single eruption event, due to its sheer size and the complex pattern of lava rocks comprising the caldera floor, interpreted as indicative of a multifaceted eruptive history (Thoroddsen, 1884). Considering this evidence of past activity, it was also suggested that eruptions may likely have occurred in historical time, observations of which being miscredited to other volcanoes in the region prior to the recognition of Askja as an active volcano (Lock 1881a). This interpretation has been confirmed in modern studies, indicating repeated activity in the last 1500 years (Hartley, Thordarson and de Joux, 2016). Regarding the formation of Askja's main caldera, it has been suggested to correlate to an eruption around ten thousand years ago, after substantial melting of glacier ice in the warming climate of the early Holocene (Sigvaldason, 2002).

During the 1875 eruption, pumice and ash were ejected from a point which the early explorers identified by the side of the Öskjagjá (e.g. Wight, 1885). Later studies of the proximal ashfall and pyroclastic flow deposits indicate a six-phase eruptive event during which the vent actually wandered across the Öskjagjá: during the vent's movement, the eruption style shifted as the vent changed in size and cut across different sources of water along its path (Carey, Houghton and Thordarson, 2009). This process caused the rare event of an eruption including both Plinian and phreatoplinian volcanism (Carey, Houghton and Thordarson, 2010). The main phases that produced the majority of the ejecta likely lasted for six hours (Sparks, Wilson and Sigurdsson, 1981) – a phreatoplinian phase lasting for an hour, followed by a half-hour pause before the larger Plinian eruption (Carey, Houghton and Thordarson, 2010) – while the final deposits were likely not produced until at least several days later (Sigurdsson and Sparks, 1981).

Because relatively small amounts of pumice were found near Askja after the eruption, in contrast to a thicker layer covering the lands eastward, strong westerly winds were assumed to have prevailed during the eruption climax (Lock, 1881b). The total volume of loose material ejecta was estimated to c. 2 km^3 by Thorarinsson and Sigvaldason (1962) and was later modelled to c. 1.8 km^3 by Carey, Houghton and Thordarson (2010). This can be compared to the 2.88 km^3 of collapse estimated in the Öskjagjá caldera (Hartley and Thordarson, 2012), though this includes collapse throughout time passed since the eruption event. These volumes are likely not matched by any Icelandic eruption in the last 600 years prior to 1875 (cf. Larsen, Dugmore and Newton, 1999, table 1).

The 1875 eruption event affected human migration from Iceland to North America, which had begun in earnest only a few years prior. In 1876, about 1200 Icelanders emigrated (more than during any previous or later year), the majority of them abandoning homes in northeast Iceland (Lalonde, 2024) where the ashfall most severely impacted farming and livelihoods. It was likely not the direct aftermath of the eruption alone that convinced all of these emigrants, however, as the event was also used in international politics to persuade would-be-emigrants to leave Iceland for other nations (Büntgen, Eggertsson and Oppenheimer, 2024).

After the 1875 eruption, the current shape of the Öskjagá caldera formed bit by bit through collapses over the next 40 years (Hartley and Thordarson, 2012). Askja was active once more in 1961, but this was only an effusive event, producing lava from a fissure and fountaining it 500 m into the air, but without any explosivity (Thorarinsson and Sigvaldason, 1962). After this eruption subsided, Askja was quiet for some time and even deflated (Rymer and Tryggvason, 1993; Sturkell and Sigmundsson, 2000) before signs of magma accumulation beneath the caldera were observed in 2007–2009 (Rymer et al., 2010). No activity commenced, however, and subsidence continued, until inflation was observed in 2021–2023 (Parks et al., 2024). As of the time of writing this review, the Icelandic Met Office presents Askja's status as "green", indicating a normal, non-eruptive state (Icelandic Met Office, 2025).

Ashes to the wind: studies of the Askja-1875 tephra

Askja's eruption in 1875 was the first time an ash dispersal event was recorded in any spatial and temporal detail. In what can be described as an early citizen-science effort, Nordenskiöld (1876) used newspaper advertisements to collect observations of the ashfall – these being for example from residents of Stockholm, Sweden, noting a yellowish staining of their clothes and on window panes, and of a fine grey dust covering the greenhouses at Haga Palace in Stockholm, in the afternoon of March 30th. Observations from other parts of Sweden as well as Norway were compiled, the location and time of each recorded, and results indicated that the ashfall occurred earlier and with greater quantities of ash in a north-westerly direction, with enough material deposited to form a nearly continuous (albeit thin) ground cover at certain locations on the western Norwegian coast in the evening of March 29th. This pattern of deposition was in agreement with wind directions recorded at weather stations at the time, and aligned well with the later observations of a pumice and ash cover stretching eastward from the volcano on Iceland.

Taken together, the observations collected by Nordenskiöld (1876) were combined with information from Johnstrup's (1877) report as well as additional observations from Norway to delineate the dispersal area and produce a map of the ashfall – the first-ever of such precision – from the volcanic source and across the North Atlantic, into middle Norway and Sweden (Mohn, 1877). This work also included discussion of the apparent complexity of the dispersal, suggesting different rates of spread in different layers of the atmosphere.

Stockholm University

Samples of the ashes fallen at Haga Palace were collected and examined under the microscope. The particles found were described as translucent and colourless, angular and glass-like, forming "elongated filaments, bent sabre-fashion, or sharp-cornered flat bodies, partly plain, partly connected together in the form of Y or T" (Nordenskiöld, 1876, p. 293), featuring also hollows described as cavities and channels. To any tephrochronologist having examined ash particles (i.e. volcanic glass shards) under the microscope, these descriptions should evoke a familiar image! A few examples of such particles stemming from the 1875 eruption, showcasing several of the features mentioned by Nordenskiöld (1876), are shown in Figure 1.

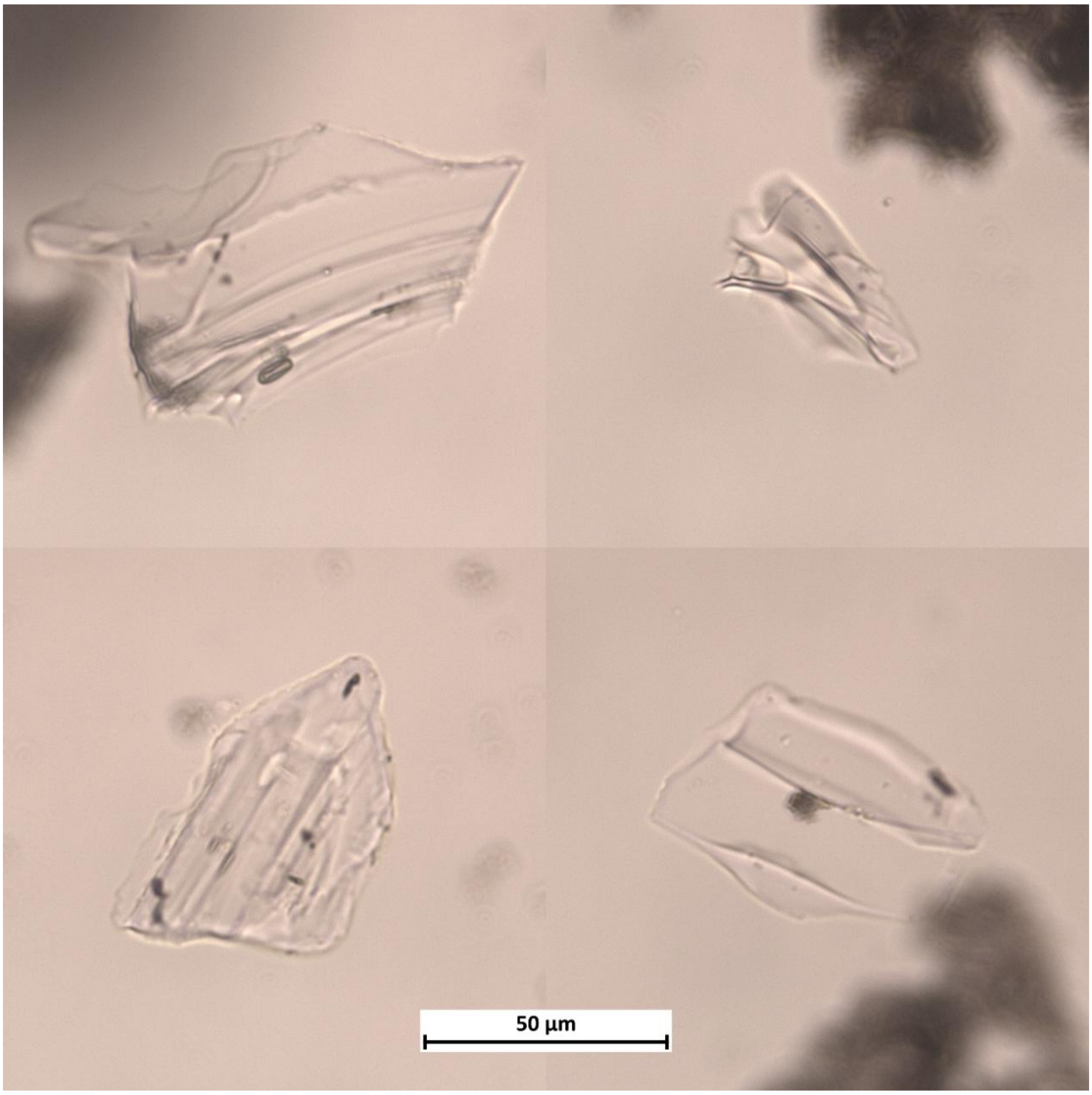

Figure 1: Transmitted-light microscope photos of glass shards extracted from sediments collected from Lake Blektjärnen, Sweden, in 2014, tentatively identified as the Askja-1875 tephra after comparison to Andersson et al. (2010).

By applying a polarisation filter, the particles from Haga were found to be isotropic (as revealed by the particles becoming dark or black), a feature of amorphic solids such as (volcanic) glass. Basic chemical tests implied that this was no locally sourced minerogenic dust, and so the conclusion was that the "pumice dust" was the result of "a so-called ash-rain" (Nordenskiöld, 1876, p. 293). The connection was made to the Dyngjufjöll eruption, while not naming Askja specifically – which is no surprise, considering Nordenskiöld's study was presented before the publishing of the first reports from excursions to the volcano, and thus before any word of Askja as an active volcano.

Stockholm University

The birth of tephrochronology

Toward the mid-20th century, ashes from the 1875 eruption preserved in Icelandic soils would, together with several other ash layers, form the basis for a study which was to become a precursor to the method of tephrochronology. While examining peat accumulations for pollen analysis, the idea came to Bjarnason and Thorarinsson (1940) that the well-defined ash layers in the soil could be dated, and that the age estimates would be applicable to the same layers at other locations. A number of ash layers were correlated to historically known eruptions by, for example, comparisons to archaeological remains of delimited ages.

Following this, Sigurdur Thorarinsson – whose father's expected birth delayed the abandoning of the family homestead in eastern Iceland during the 1875 eruption (Sigurdson, 1983) – would coin the term *tephrochronology* to describe the chronological application of volcanic ashes, or "tephra", in his doctoral research performed at Stockholm University, at the time known as Stockholm University College (Thorarinsson, 1944). Tephrochronological research would continue in Sweden following the initiation by Thorarinsson as Persson (1966) focused on the detection of distal tephra deposits in Swedish peat accumulations. Although modern geochemical analyses were unavailable at the time, tentative identifications of, amongst others, the tephra from Askja's 1875 eruption were made at a number of sites across Sweden (see Wastegård and Boygle, 2012).

Wherever the far-flown ashes produced by an eruption such as Askja's in 1875 have been buried in, for example, sediments or ice, they may offer a precise time-marker horizon. Volcanic ashes can function as what in geochronological terms is known as an isochron, meaning a feature representing a single point in time regardless of the location where it is found (and thereby enabling exact correlation between findings from such locations). In recent decades, Askja's 1875 ashes have been utilised in such a way in a range of studies, from reconstructions of past climate and environmental responses to climate change (Andersson et al., 2010; Borgmark and Wastegård, 2008; Ott et al., 2017) to investigations of anthropogenic eutrophication and hypoxia in lakes (Poraj-Górska et al., 2021; Sirota et al., 2024) to calibration of radiometric dating methods (Tylmann et al., 2016) to testing of mapping technology for use on other worlds (Shoemaker et al., 2024). When used in modern tephrochronological studies, the ashes have come to be labelled as the "Askja-1875 tephra".

Tracing tephra

As described above, the ashfall event was recorded in enough detail to produce an ash dispersal map based on contemporary observations across Scandinavia, presented by Mohn (1877). While an unprecedented feat and still relevant when studying the spread of the Askja-1875 tephra, modern tephrostratigraphical investigations have added detections of buried ashes beyond the previously mapped extent of dispersal. By detecting microscopic amounts of ash particles (now referred to as "cryptotephra", meaning "hidden ash") preserved in various sediments and accumulations (in the context known as "natural archives"), the Askja-1875 tephra has been identified across northern Europe (see Figure 2).

In addition to several sites within the dispersal area of Mohn (1877) in Sweden, these distal locations range from Germany (Sirota et al., 2024; Wulf et al., 2016) and Poland (Kinder, Wulf and Appelt, 2021; Ott et al., 2017; Tylmann et al., 2016; Watson et al., 2017; Wulf et al., 2016) in the south, to Latvia (Stivrins et al., 2016) and Finland (Kalliokoski, Guðmundsdóttir and Wastegård, 2020; Kalliokoski, Wastegård and Saarinen, 2019), and as far northeast as northwest Russia

(Vakhrameeva et al., 2020) and as far north as northern Norway (Pilcher et al., 2005). The most recently published study as of the time of writing this review added Scotland to the list of Askja-1875 tephra detections (Wang et al., 2025), significantly expanding the known dispersal area to the southwest.

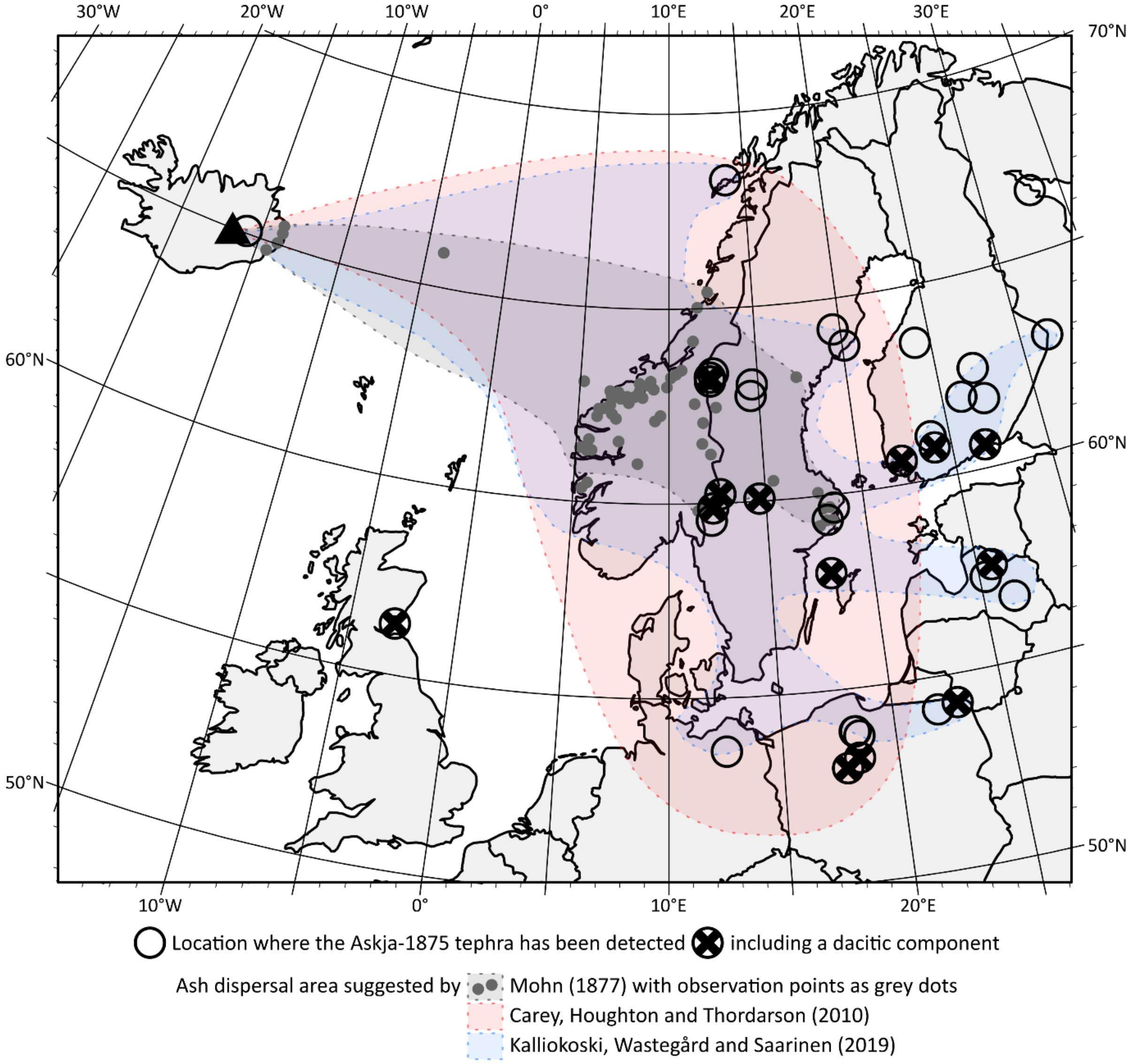

Figure 2: Map of northwest Europe displaying distal locations of tephrostratigraphical investigations where the Askja-1875 tephra has been detected, together with previously suggested ash dispersal areas. The location of Askja is indicated by the black triangle. Tephrostratigraphical investigation locations from Oldfield et al. (1997), Larsen, Dugmore and Newton (1999), Bergman et al. (2004), Boygle (2004), Pilcher et al. (2005), Wastegård (2005), Davies et al. (2007), Borgmark and Wastegård (2008), Wastegård, Andersson and Perkins (2009), Andersson et al. (2010), Stivrins et al. (2016), Tylmann et al. (2016), Watson et al. (2016), Wulf et al. (2016), Ott et al. (2017), Watson et al. (2017), Kalliokoski, Wastegård and Saarinen (2019), Kalliokoski, Guðmundsdóttir and Wastegård (2020), Vakhrameeva et al. (2020), Kinder, Wulf and Appelt (2021), Sirota et al. (2024), Müller et al. (2025), and Wang et al. (2025). Site names and coordinates are compiled in the supplementary material (provided in all data tables). Map image produced in the WGS84 coordinate system with a European equidistant conic map projection at a 1:20 000 000 scale.

It is clear that new tephra studies often bring with them the possibility to redefine the known dispersal area of the ashes from a particular eruption, and the combined map information of Figure 2 showcases this well: the dispersal maps of Carey, Houghton and Thordarson (2010), and Kalliokoski, Wastegård and Saarinen (2019) are drawn stretching farther in the directions of new findings than their predecessors and are adjusted in relation to the updated collective evidence. The detections of ashes in natural archives across vast distances away from their volcanic sources have in this way garnered important information for the understanding of ash dispersal, knowledge that in many areas of the world is vital for volcanic hazard assessments (e.g. Cashman and Rust, 2020; Lowe, 2011).

The identifications of the Askja-1875 tephra at the distal locations shown in Figure 2 were all based on certain considerations, some of which are critical in any and all efforts to identify a tephra sample. Apart from the shard morphology, i.e. the physical appearance of the ash particles, the geographical location of the sampling site (with its spatial relation to possible volcanic sources) and the stratigraphic position of the sample at the sampling site (with any chronological information) provide important clues as to what eruption the tephra may correlate to. However, another key factor in modern tephrochronological studies is in focus in the next, final part of this review.

A fiery fingerprint: geochemistry of the Askja-1875 tephra

Most known volcanic ashes are distinguishable at an eruption-event level (and possibly even an eruption-phase level) by their differing major-element compositions; they can thereby be geochemically identified, a process known as geochemical "fingerprinting" (e.g. Lowe, 2011). The very first geochemical analysis of the Askja-1875 tephra was conducted by vom Rath (1875) using a sample collected in Norway during the ashfall event. Limited by comparably crude methodology at the time, the century-and-a-half old results differ somewhat from those of modern analyses (see Table 1), which is not surprising considering the methodological differences, not to mention the different reporting standards. Regardless, it is an entertaining thought that a geochemical analysis of tephra particles was conducted more than a hundred years before the standardised use of electron probe micro-analysers in modern tephrochronological studies!

Table 1: Results of vom Rath's (1875) geochemical analysis of a Norwegian ash sample and corresponding results of Sigurdsson and Sparks' (1981, table 8) analyses of clear rhyolitic glass and the average major-element oxide composition of distal tephra findings in modern studies of the Askja-1875 tephra. All numbers presented as non-normalised weight percentages (with all iron represented as FeO). Published data used to calculate the average composition in modern studies are compiled in the supplementary material (Table S1).

vom Rath (1875)			Sigurdsson and Sparks (1981)	Modern studies
Silicic acid	68	SiO_2	73.72	72.16
Loam (bauxite)	13.55	Al_2O_3	12.81	12.51
Iron oxide	8.5	FeO	3.34	3.66
Chalk	3.75	CaO	2.31	2.56
Magnesia	1.25	MgO	0.60	0.75
Kali	1.4	K_2O	2.40	2.36
Soda (natron)	4.2	Na_2O	4.32	3.62

The geochemistry of the Askja-1875 tephra has been described as rhyolitic (e.g. Sparks, Wilson and Sigurdsson, 1981), i.e. the classification of volcanic materials with the highest silica content (cf. Le Bas et al., 1986). The vast majority of modern geochemical analyses of the Askja-1875 tephra do indeed place it as rhyolitic (see Figure 3), and it mainly sits below the lower of the two "Kuno lines", implying a comparably low-alkali tephra in the tholeiitic magma series (cf. Kuno, 1966). The data points are mostly collected in a quite well-defined data range that has been used as reference for identifications of Askja-derived tephra, and which appears quite separate from reference ranges of most other volcanic systems of Iceland producing high-silica tephra, overlapping only with

Hekla (cf. Kalliokoski, Wastegård and Saarinen, 2019; Kinder, Wulf and Appelt, 2021; Ott et al., 2017; Vakhrameeva et al., 2020; see coloured fields in Figure 3). It can, however, be quite easily distinguished from Hekla tephras by the higher TiO_2 and lower FeO content (cf. Kalliokoski, Wastegård and Saarinen, 2019, figure 6). The basaltic component of Askja is not represented in the studies referred to for data in this review, as these studies have exclusively analysed the far-flown, high-silica component produced by the 1875 eruption.

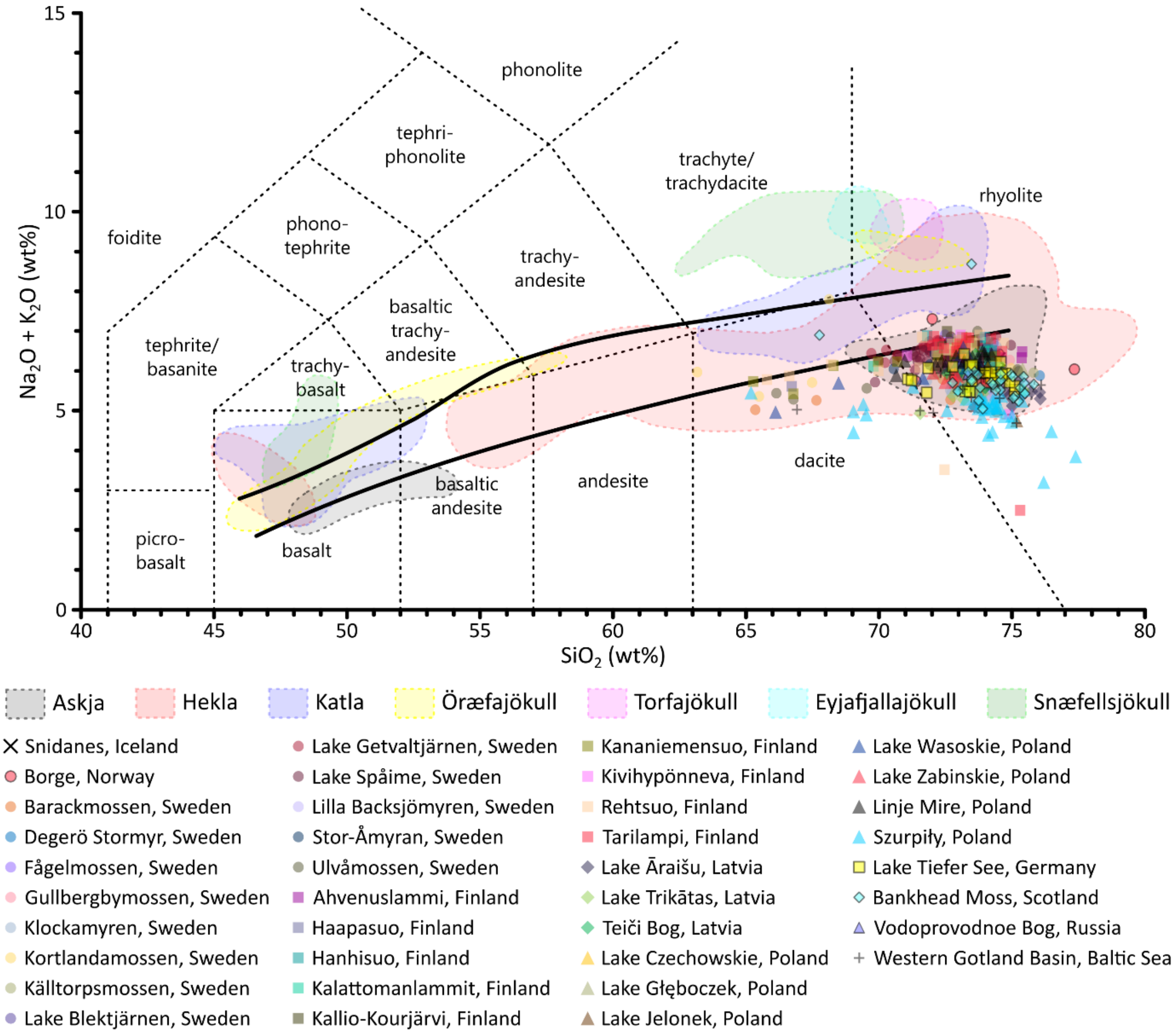

Figure 3: Total alkali-silica (TAS) plot displaying normalised data of published Askja-1875 tephra-derived glass-shard major-element oxide compositions from distal locations, presented as weight percentages. TAS classification scheme for volcanic rocks reproduced from Le Bas et al. (1986) as dotted lines between labelled fields. "Kuno lines" reproduced from Kuno (1966) as thick, black lines. Generalised reference data ranges for Icelandic volcanic systems reproduced from Kalliokoski, Wastegård and Saarinen (2019, figure 5) and Vakhrameeva et al. (2020, figure 2B) as coloured fields. Data collected from Oldfield et al. (1997), Larsen, Dugmore and Newton (1999), Bergman et al. (2004), Boygle (2004), Pilcher et al. (2005), Wastegård (2005), Davies et al. (2007), Borgmark and Wastegård (2008), Wastegård, Andersson and Perkins (2009), Andersson et al. (2010), Stivrins et al. (2016), Tylmann et al. (2016), Watson et al. (2016), Wulf et al. (2016), Ott et al. (2017), Watson et al. (2017), Kalliokoski, Wastegård and Saarinen (2019), Kalliokoski, Guðmundsdóttir and Wastegård (2020), Vakhrameeva et al. (2020), Kinder, Wulf and Appelt (2021), Sirota et al. (2024), Müller et al. (2025), and Wang et al. (2025). Published raw (non-normalised) data are compiled in the supplementary material (Table S1) together with the normalised data (Table S2).

As is visible in Figure 3, a minority component of the Askja-1875 tephra's data population appears to be dacitic, as determined by a lower silica content and/or lower sum of alkaline major elements. This dacitic component has been reported from locations across the dispersal area: the results of studies at Szurpiły, Poland (Kinder, Wulf and Appelt, 2021), Rehtsuo, Finland (Kalliokoski, Wastegård and Saarinen, 2019) and Kortlandamossen, Sweden (Boygle, 2004), stand out with six (out of thirty-seven), four (out of twenty), and four (out of seven) dacitic data points from the respective locations. Kortlandamossen, located in southwest-central Sweden, is the only location where a majority of the reported analysis results imply a dacitic geochemistry, but it should be noted that this is from a small sample size.

If the geographical spread of the dacitic component had been more limited or clearly spatially defined, it would have implied a possibility of ejecta from a certain phase of the eruption spreading differently than the main, rhyolitic component – as is, for example, ostensibly the case for the Laacher See eruption with its several phases (cf. Riede et al., 2011) – but this does not appear to be the case for the Askja-1875 tephra. The lack of any obvious geographical bimodality is in line with the previous suggestion that ejecta of both main phases of the eruption spread along nearly identical paths (Carey, Houghton and Thordarson, 2010, figure 5). It has been noted, though, that the dacitic component does not appear in any known proximal products of Askja's 1875 eruption (Kalliokoski, Wastegård and Saarinen, 2019).

A quick dip in the data

Considering the apparent dacitic component of the Askja-1875 tephra, it is motivated to end this review with a basic statistical analysis of its published geochemical composition. Like all reported tephra major-element oxides, these data are a type of compositional data, which are inherently constrained by being parts of a total sum (an issue known as the constant-sum constraint). Such data must be transformed into Euclidian space to enable mathematically sound analysis, which can be done by log-ratio transformations (see Aitchison, 1986). The centred log-ratio transformation – a comparably straight-forward variant which has been used for tephra compositional data before (e.g. Lowe et al., 2017) – is calculated as the natural logarithm of the ratio of a variable to the geometric mean of all variables. However, this cannot be done if any observations in the data contain zero values, as a geometric mean cannot be calculated for a set of values including any zeroes. Because the oldest among modern studies presenting geochemical analysis results of the Askja-1875 tephra do not report any data on P_2O_5 and sometimes also not on MnO (Bergman et al., 2004; Boygle, 2004; Larsen, Dugmore and Newton, 1999; Oldfield et al., 1997; Pilcher et al., 2005; Wastegård, 2005), these oxides were excluded from the transformation performed for this review. There is also one occasion of a zero value for MgO among later studies (Wang et al., 2025), and so this single observation was excluded.

A centred log-ratio transformation was thus performed on the remaining selection, and a principal component analysis (see Greenacre et al., 2022; Pearson, 1901) was performed on the transformed data using the R package *compositions* (version 2.0-8; van den Boogaart, Tolosana-Delgado and Bren 2008). A complete script (reusable for your own tephra compositional data!) is provided in "R code" in the supplementary material.

The principal component analysis resulted in eight principal components, where the first two components explain 87% of the variance (63.76% by component 1 and 23.47% by component 2). Plotting the principal component scores of components 1 and 2 against each other reveals a quite well-constrained cluster comprising the vast majority of the data points (see Figure 4). A somewhat less tidy spread among data points more negatively correlated with component 1 represent measurements indicating a dacitic composition, stretching to the left of the plot without any clearly separate subgrouping (similarly to when visualised in the TAS plot in Figure 3). By comparison to the variable loadings (see arrows in Figure 4), these data points appear to have positive correlations with (i.e. higher measurements of) variables MgO, FeO, CaO, and/or TiO_2, combined with negative correlations with (i.e. lower measurements of) variables K_2O, SiO_2, Al_2O_3, and/or Na_2O. This relationship agrees with dacite having a lower silica content and/or lower sum of alkaline major elements (K_2O and Na_2O) than rhyolite.

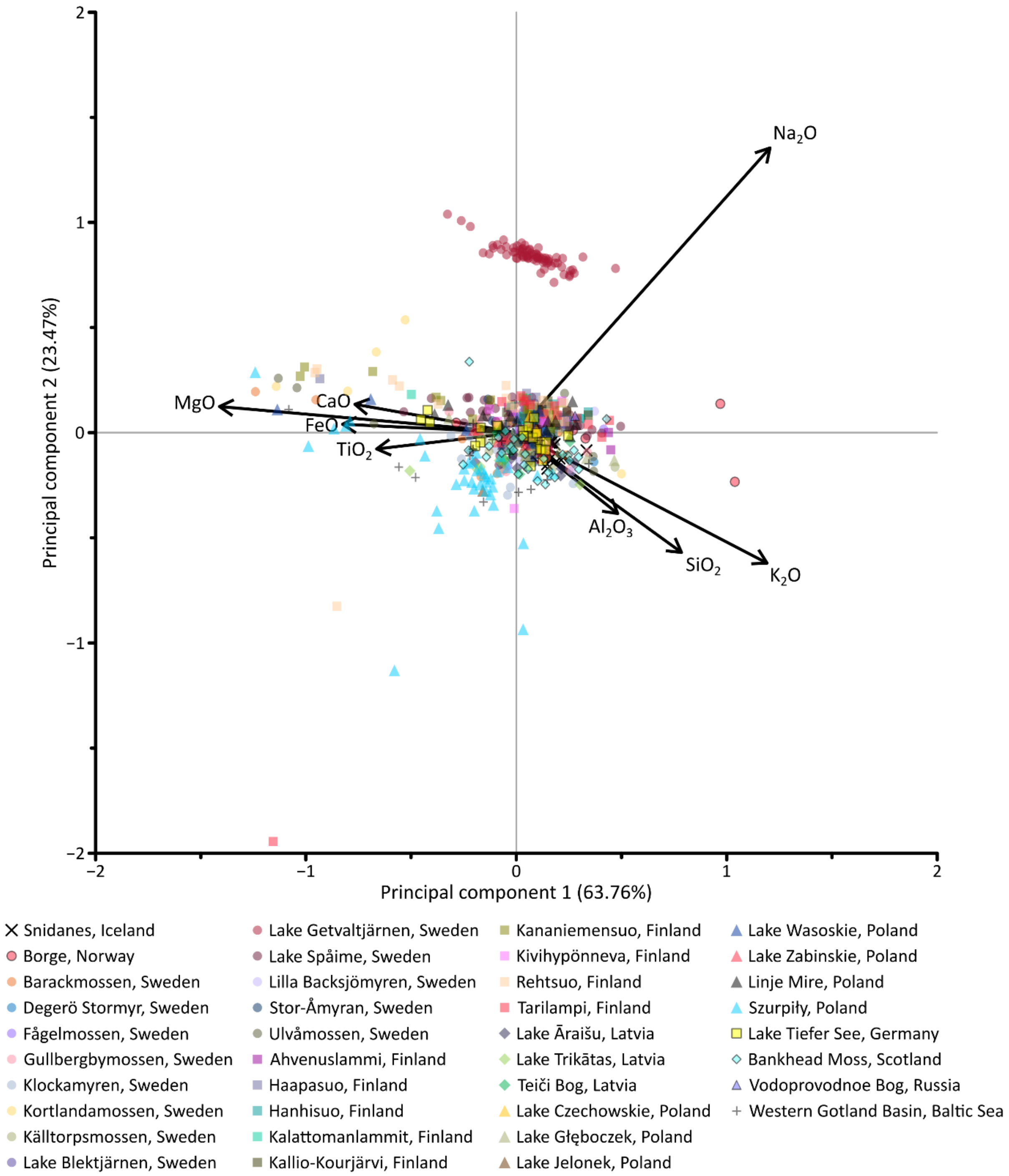

Figure 4: Biplot displaying results of principal component analysis of centred log-ratio transformed published Askja-1875 tephra-derived glass-shard major-element oxide compositions, as principal component 1 against principal component 2 (which together explain 87% of the variance). Variable loadings displayed as black arrows (exaggerated by an order of magnitude) labelled with their corresponding major-element oxides. Principal component analysis results are compiled in the supplementary material (Table S4) together with the centred log-ratio transformed selection of data analysed (Table S3).

Outside the majority cluster and the dacitic spread, five slight and one considerable outlier occur, as well as one subgroup of data points which is more positively correlated to component 2 than the majority cluster is. The individual outliers are data points from Norway (Pilcher et al., 2005), Poland (Kinder, Wulf and Appelt, 2021) and Finland (Kalliokoski, Wastegård and Saarinen, 2019). They represent observations that show some notable discrepancies from the average composition of the Askja-1875 tephra, including the lowest-ever measured contents of TiO_2 at Borge, Norway and Na_2O at Tarilampi, Finland, as well as combinations of notably high or low measurements of TiO_2, FeO, CaO or Na_2O, high Al_2O_3, or low MgO. The variable loading corresponding to Na_2O (arrow towards the top right in Figure 4) implies that low Na_2O may explain the four outliers displaced towards the bottom left of the plot (which are also quite visible in Figure 3, even though it displays the sum of Na_2O and K_2O). Looking at these measurements in the context of their original studies does not lead to any suspicions that they would be correlated to any other tephras than the Askja-1875 tephra, though. Problems in analysing Na_2O in glass using the electron probe, due to the issue known as sodium migration or sodium loss, have been well documented (e.g. Gedeon, Hulínský and Jurek, 2000; Hunt and Hill, 2001; Lowe et al., 2017).

Yet more notable is the subgroup mentioned above, which comprises data points representing all raw data on the Askja-1875 tephra published from Lake Getvaltjärnen, Sweden (Davies et al., 2007). These data points are shifted to a significantly more positive correlation with component 2 than the rest of the data (meaning they are visible as a separate cluster towards the top of the plot in Figure 4). Compared to variable loadings, this implies they may be separated in large part by high Na_2O measurements. Examining the raw data of these samples does indeed show a higher average Na_2O – 4.02% compared to the 3.63% average of all compiled data – while the averages of all other major-element oxides are quite close to the average composition of all compiled data (apart from P_2O_5, but this is the least well-constrained oxide; it was also not included in the data transformation and does not inform the principal component analysis).

The study by Davies et al. (2007) also presents data from Lake Spåime, Sweden, which are all represented within the majority cluster of the principal component analysis results, only barely skewed toward the direction of the Lake Getvaltjärnen samples. The average composition of the Lake Spåime samples is very close to the average composition of all compiled data, with only slightly higher Na_2O and P_2O_5. Considering that all analyses in the study were performed using the same instrument with the same operating conditions (see Davies et al., 2007, appendix 1), the Lake Getvaltjärnen subgroup is not so likely explained by laboratory factors such as sodium loss. The data from either site does not more closely match any other volcanic source candidate than Askja; it should also be noted that the Lake Getvaltjärnen data is decisively constrained within the Askja reference range in the TAS plot of Figure 3, despite its apparently low Na_2O values.

The two study sites are located only 10 km apart, and ^{210}Pb dating was applied to the sediments at both sites. It should be noted that the occurrence of tephra in the Lake Getvaltjärnen sediments does appear late compared to that in Lake Spåime: it does not increase to significant concentrations until what the ^{210}Pb dating suggests is around the calendar year 1925, increasing further around 1945. In the study, this is explained by the majority of the particles at Lake Getvaltjärnen being trapped in snow-beds, being released during later recession of these temporary storages (see Davies et al., 2007, figure 2). A tantalising alternative is that these particles may stem from Askja's 20th century activity, but no explosive events have been observed in this timeframe. The reason for the Lake Getvaltjärnen subgroup's separation from other Askja-1875 tephra findings thus remains uncertain. Potentially, analysis of the trace-element composition of this population and comparison to that of other Askja-1875 tephra findings could provide further clues.

Concluding remarks

The story of the Askja-1875 tephra is a story of scientific progress: from the eruption event leading to the discovery of a volcano; to the collection of observations of the ashfall leading to the first detailed ash dispersal map; to the ashes buried in peatland on Iceland sparking the idea of the method of tephrochronology; to modern studies utilising invisibly low concentrations of ash particles for age estimations of local environmental and regional climatic events. It exemplifies the relevance of tephrochronology in studies of varying aims, where this well-defined marker horizon becomes useful for dating and correlation of recent sediments and accumulations. The Askja-1875 tephra's mainly well-defined geochemistry combined with its shallow emplacement in recently formed natural archives makes it an easily identified tephra in northern Europe. The simple statistical analysis of the tephra's geochemical composition performed as part of this review exemplifies a basic workflow easily adaptable for exploration of any tephra compositional data.

Supplementary Material

The supplementary material for this article is stored on the Stockholm University Figshare, accessible via https://doi.org/10.17045/sthlmuni.29098307, and comprises a .xlsx spreadsheet file containing the following contents, divided onto separate sheets (also made available as separate .csv and .txt files):

Table S1. Compilation of published raw (non-normalised) data from geochemical analyses of glass from the Askja-1875 tephra in the form of major-element oxide compositions provided as weight percentages.

Table S2. Normalised data of published Askja-1875 tephra-derived glass-shard major-element oxide compositions.

Table S3. Centred log-ratio transformed selection of data of published Askja-1875 tephra-derived glass-shard major-element oxide compositions.

Table S4. Results of principal component analysis performed on centred log-ratio transformed selection of data of published Askja-1875 tephra-derived glass-shard major-element oxide compositions.

R code. Script used for data treatment and statistical analysis.

References. List of references for the articles presenting the published raw data compiled in Table S1.

Stockholm University

References

Aitchison, J. (1986) *The Statistical Analysis of Compositional Data*. Chapman and Hall.

Andersson, S., Rosqvist, G., Leng, M.J., Wastegård, S. and Blaauw, M. (2010) Late Holocene climate change in central Sweden inferred from lacustrine stable isotope data. *Journal of Quaternary Science* 25(8): 1305–1316. https://doi.org/10.1002/jqs.1415

Bergman, J., Wastegård, S., Hammarlund, D., Wohlfarth, B. and Roberts, S.J. (2004) Holocene tephra horizons at Klocka Bog, west-central Sweden: aspects of reproducibility in subarctic peat deposits. *Journal of Quaternary Science* 19(3): 241–249. https://doi.org/10.1002/jqs.833

Bjarnason, H. and Thorarinsson, S. (1940) Datering av vulkaniska asklager i isländsk jordmån. *Geografisk Tidsskrift* 43: 5–27.

Borgmark, A. and Wastegård, S. (2008) Regional and local patterns of peat humification in three raised peat bogs in Värmland, south-central Sweden. *GFF* 130:3: 161–176. https://doi.org/10.1080/11035890809453231

Boygle, J. (2004) Towards a Holocene tephrochronology for Sweden: geochemistry and correlation with the North Atlantic tephra stratigraphy. *Journal of Quaternary Science* 19(2): 103–109. https://doi.org/10.1002/jqs.811

Büntgen, U., Eggertsson, O. and Oppenhemier, C. (2024) Braided motivations for Iceland's first wave of mass emigration to North America after the 1875 Askja eruption. *Regional Environmental Change* 24: 48. https://doi.org/10.1007/s10113-024-02215-6

Carey, R.J., Houghton, B.F. and Thordarson, T. (2009) Abrupt shifts between wet and dry phases of the 1875 eruption of Askja Volcano: microscopic evidence for macroscopic dynamics. *Journal of Volcanology and Geothermal Research* 184: 256–270. https://doi.org/10.1016/j.jvolgeores.2009.04.003

Carey, R.J., Houghton, B.F. and Thordarson, T. (2010) Tephra dispersal and eruption dynamics of wet and dry phases of the 1875 eruption of Askja Volcano, Iceland. *Bulletin of Volcanology* 72: 259–278. https://doi.org/10.1007/s00445-009-0317-3

Cashman, K.V. and Rust, A.C. (2020) Far-travelled ash in past and future eruptions: combining tephrochronology with volcanic studies. *Journal of Quaternary Science* 35(1–2): 11–22. https://doi.org/10.1002/jqs.3159

Coles, J.M. and Morgan, E.D. (1882) *Summer travelling in Iceland: being the narrative of two journeys across the island by unfrequented routes*. John Murray.

Crindle, J.W.M. (1885) Thoroddsen on the lava-desert in the interior of Iceland. *Scottish Geographical Magazine* 1(12): 626–634. https://doi.org/10.1080/14702548508553859

Davies, S.M., Elmquist, M., Bergman, J., Wohlfarth, B. and Hammarlund, D. (2007) Cryptotephra sedimentation processes within two lacustrine sequences from west central Sweden. *The Holocene* 17(3): 319–330. https://doi.org/10.1177/0959683607076443

Dawson, F.L.M. (1940) The Cambridge (Mývatn) Iceland expedition, 1939. *The Geographical Journal* 95(6): 439–451. https://doi.org/10.2307/1788429

Gedeon, O., Hulínský, V. and Jurek, K. (2001) Microanalysis of Glass Containing Alkali Ions. *Mikrochimica Acta* 132: 505–510. https://doi.org/10.1007/s006040050050

Greenacre, M., Groenen, P.J.F., Hastie, T., D'Enza, A.I., Markos, A. and Tuzhilina, E. (2022) Principal component analysis. *Nature Reviews Methods Primers* 2: 100. https://doi.org/10.1038/s43586-022-00184-w

Hartley, M.E. and Thordarson, T. (2012) Formation of Öskjuvatn caldera at Askja, North Iceland: mechanism of caldera collapse and implications for the lateral flow hypothesis. *Journal of Volcanology and Geothermal Research* 227–228: 85–101. https://doi.org/10.1016/j.jvolgeores.2012.02.009

Hartley, M.E. and Thordarson, T. (2013) The 1874–1876 volcano-tectonic episode at Askja, North Iceland: lateral flow revisited. *Geochemistry, Geophysics, Geosystems* 14(7): 2286–2309. https://doi.org/10.1002/ggge.20151

Hartley, M.E., Thordarson, T. and de Joux, A. (2016) Postglacial eruptive history of the Askja region, North Iceland. *Bulletin of Volcanology* 78: 28. https://doi.org/10.1007/s00445-016-1022-7

Hjartardóttir, Á.R., Einarsson, P. and Sigurdsson, H. (2009) The fissure swarm of the Askja volcanic system along the divergent plate boundary of N Iceland. *Bulletin of Volcanology* 71: 961–975. https://doi.org/10.1007/s00445-009-0282-x

Hunt, J.B. and Hill, P.G. (2001) Tephrological implications of beam size—sample-size effects in electron microprobe analysis of glass shards. *Journal of Quaternary Science* 16(2): 105–117. https://doi.org/10.1002/jqs.571

Icelandic Met Office (2025) *Aviation colour code map*. https://en.vedur.is/earthquakes-and-volcanism/volcanoes/ (accessed 2025-03-28, 2025-05-20, 2025-07-22)

Johnstrup J.F. (1877) *Indberetning om den af Professor Johnstrup foretagne undersøgelsesreise paa Island i sommeren 1876*. Rigsdagstidende Kjøbenhavn.

Kalliokoski, M., Guðmundsdóttir, E.R. and Wastegård, S. (2020) Hekla 1947, 1845, 1510 and 1158 tephra in Finland: challenges of tracing tephra from moderate eruptions. *Journal of Quaternary Science* 35(6): 803–816. https://doi.org/10.1002/jqs.3228

Kalliokoski, M., Wastegård, S. and Saarinen, T. (2019) Rhyolitic and dacitic component of the Askja 1875 tephra in southern and central Finland: first step towards a Finnish tephrochronology. *Journal of Quaternary Science* 34(1): 29–39. https://doi.org/10.1002/jqs.3078

Kinder, M., Wulf, S. and Appelt, O. (2021) Detection of the historical Askja AD 1875 and modern Icelandic cryptotephras in varved lake sediments – results from a first systematic search in northern Poland. *Journal of Quaternary Science* 36(1): 1–7. https://doi.org/10.1002/jqs.3259

Kuno, H. (1966) Lateral variation of basalt magma type across continental margins and Island Arcs. *Bulletin Volcanologique* 29: 195–222. https://doi.org/10.1007/BF02597153

Lalonde, J.L. (2024) The search for a promised land: three settlement plans, three agents, and three handbooks for Icelandic migrant-settlers from 1875. *Settler Colonial Studies* 14(3): 314–340. https://doi.org/10.1080/2201473X.2024.2316921

Larsen, G., Dugmore, A. and Newton, A. (1999) Geochemistry of historical-age silicic tephras in Iceland. *The Holocene* 9(4): 463–471. https://doi.org/10.1191/095968399669624108

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A. and Zanettin, B. (1986). A chemical classification of volcanic rocks based on the Total Alkali-Silica diagram. *Journal of Petrology* 27(3): 745–750. https://doi.org/10.1093/petrology/27.3.745

Lock, W.G. (1881a) *Askja, Iceland's largest volcano: with a description of the great lava desert in the interior and a chapter on the genesis of the island.* Charlton.

Lock, W.G. (1881b) Askja, the Largest Volcano of Iceland; With a Short Description of the Ódáđahraun. *Proceedings of the Royal Geographical Society and Monthly Record of Geography* 3(8): 471–483. https://doi.org/10.2307/1800278

Lowe, D.J. (2011) Tephrochronology and its application: a review. *Quaternary Geochronology* 6(2): 107–153. https://doi.org/10.1016/j.quageo.2010.08.003

Lowe, D.J., Pearce, N.J.G., Jorgensen, M.A., Kuehn, S.C., Tryon, C.A. and Hayward, C.L. (2017) Correlating tephras and cryptotephras using glass compositional analyses and numerical and statistical methods: Review and evaluation. *Quaternary Science Reviews* 175: 1–44. https://doi.org/10.1016/j.quascirev.2017.08.003

Mohn, H. (1877) Askeregnen den 29de–30te Marts 1875. *Forhandlinger i videnskabs-selskabet i Christiania* 10: 1–12.

Morgan, E.D. (1882) Excursion to Askja, August 1881. *Proceedings of the Royal Geographical Society and Monthly Record of Geography* 4(3): 140–148. https://doi.org/10.2307/1800544

Müller, D.J.M., Neugebauer, I., Kearney, R.J., Schwab, M.J., Appelt, O., Czymzik, M., Kaiser, J., Arz, H.W. and Brauer, A. (2025) Constraining the Baltic Sea sediment chronology using tephrochronology. *Geology* (volume or number not yet available at the time of writing). https://doi.org/10.1130/G53346.1

Nordenskiöld, A.E. (1876) Distant transport of volcanic dust. *Geological Magazine* 3(7): 292–297. https://doi.org/10.1017/S0016756800154858

Oldfield, F, Thompson, R., Crooks, P.R.J., Gedye, S.J., Hall, V.A., Harkness, D.D., Housley, R.A., McCormac, F.G., Newton, A.J., Pilcher, J.R., Renberg, I. and Richardson, N. (1997) Radiocarbon dating of a recent high-latitude peat profile: Stor Åmyrân, northern Sweden. *The Holocene* 7(3): 283–290. https://doi.org/10.1177/095968369700700304

Ott, F., Kramkowski, M., Wulf, S., Plessen, B., Serb, J., Tjallingii, R., Schwab, M., Słowiński, M., Brykała, D., Tyszkowski, S., Putyrskaya, V., Appelt, O., Błaszkiewicz, M. and Brauer, A. (2017) Site-specific sediment responses to climate change during the last 140 years in three varved lakes in Northern Poland. *The Holocene* 28(3): 464–477. https://doi.org/10.1177/0959683617729448

Parks, M. M., Sigmundsson, F., Drouin, V., Hreinsdóttir, S., Hooper, A., Yang, Y., et al. (2024). 2021–2023 unrest and geodetic observations at Askja volcano, Iceland. *Geophysical Research Letters* 51(4): e2023GL106730. https://doi.org/10.1029/2023GL106730

Pearson, K. (1901) On lines and planes of closest fit to systems of points in space. *Philosophical Magazine* 2(6): 559–572. https://doi.org/10.1080/14786440109462720

Peek, C.E. (1882) Across Iceland by the Sprengisandr route. *Proceedings of the Royal Geographical Society and Monthly Record of Geography* 4(3): 129–140. https://doi.org/10.2307/1800543

Persson, C. (1966) Försök till tefrokronologisk datering av några svenska torvmossar. *Geologiska Föreningen i Stockholm Förhandlingar* 88(3): 361–394. https://doi.org/10.1080/11035896609448933

Pilcher, J., Bradley, R.S., Francus, P. and Anderson, L. (2005) A Holocene tephra record from the Lofoten Islands, Arctic Norway. *Boreas* 34: 136–156. https://doi.org/10.1111/j.1502-3885.2005.tb01011.x

Poraj-Górska, A.I., Bonk, A., Żarczyński, M., Kinder, M. and Tylmann, W. (2021) Varved lake sediments as indicators of recent cultural eutrophication and hypolimnetic hypoxia in lakes. *Anthropocene* 36: 100311. https://doi.org/10.1016/j.ancene.2021.100311

Riede, F., Bazely, O., Newton, A.J. and Lane, C.S. (2011) A Laacher See-eruption supplement to Tephrabase: investigating distal tephra fallout dynamics. *Quaternary International* 246: 134–144. https://doi.org/10.1016/j.quaint.2011.06.029

Russell, W.S.C. (1917) Askja, a volcano in the interior of Iceland. *Geographical Review* 3(3): 212–221. https://doi.org/10.2307/207661

Rymer, H., Locke, C., Ófeigsson, B.G., Einarsson, P. and Sturkell, E. (2010) New mass increase beneath Askja volcano, Iceland – a precursor to renewed activity? *Terra Nova* 22: 309–313. https://doi.org/10.1111/j.1365-3121.2010.00948.x

Rymer, H. and Tryggvason, E. (1993) Gravity and elevation changes at Askja, Iceland. *Bulletin of Volcanology* 55: 362–371. https://doi.org/10.1007/BF00301147

Shoemaker, E.S., Baker, D.M.H., Richardson, J.A., Carter, L.M., Scheidt, S.P., Whelley, P.L. and Young, K.E. (2024) Mapping ice buried by the 1875 and 1961 tephra of Askja volcano, Northern Iceland using ground-penetrating radar: implications for Askja caldera as a geophysical testbed for in situ resource utilization. *Journal of Geophysical Research: Planets* 129: e2023JE007834. https://doi.org/10.1029/2023JE007834

Sigurdson, J. (1875) Stora vulkaniska utbrott på ön Island. Arbetare-bladet: tidning för arbetare och allmoge. 13 May, pp. 1–2.

Sigurdsson, H. (1983) Sigurdur Thorarinsson 1911–1983. *EOS* 64(28): 450–450. https://doi.org/10.1029/EO064i028p00450-01

Sigurdsson, H. and Sparks, R.S.J. (1978) Rifting episode in North Iceland in 1874–1875 and the eruptions of Askja and Sveinagja. *Bulletin of Volcanology* 41(3): 149–167. https://doi.org/10.1007/BF02597219

Sigurdsson, H. and Sparks, R.S.J. (1981) Petrology of rhyolitic and mixed magma ejecta from the 1875 eruption of Askja, Iceland. *Journal of Petrology* 22(1): 41–84. https://doi.org/10.1093/petrology/22.1.41

Sigvaldason, G.E. (2002) Volcanic and tectonic processes coinciding with glaciation and crustal rebound: an early Holocene rhyolitic eruption in the Dyngjufjöll volcanic centre and the formation of the Askja caldera, north Iceland. *Bulletin of Volcanology* 64: 192–205. https://doi.org/10.1007/s00445-002-0204-7

Sirota, I., Tjallingii, R., Pinkerneil, S., Schroeder, B., Albert, M., Kearney, R., Heiri, O., Breu, S. and Brauer, A. (2024) Tracing rate and extent of human-induced hypoxia during the last 200 years in the mesotrophic lake, Tiefer See (NE Germany). *Biogeosciences* 21(19): 4317–4339. https://doi.org/10.5194/bg-21-4317-2024

Sparks, R.S.J., Wilson, L. and Sigurdsson, H. (1981) The pyroclastic deposits of the 1875 eruption of Askja, Iceland. *Philosophical Transactions of the Royal Society of London: Series A, Mathematical and Physical Sciences* 299(1447): 241–273. http://www.jstor.org/stable/36767

Stivrins, N., Wulf, S., Wategård, S., Lind, E.M., Alliksaar, T., Gałka, M., Joest Andersen, T., Heinsalu, A., Seppä, H. and Veski, S. (2016) Detection of the Askja AD 1875 cryptotephra in Latvia, Eastern Europe. *Journal of Quaternary Science* 31(5): 437–441. https://doi.org/10.1002/jqs.2868

Sturkell, E. and Sigmundsson, F. (2000) Continuous deflation of the Askja caldera, Iceland, during the 1983–1998 noneruptive period. *Journal of Geophysical Research* 105(B11): 25671–25684. https://doi.org/10.1029/2000JB900178

Thorarinsson, S. (1944) Tefrokronologiska studier på Island: Þjórsárdalur och dess förödelse. *Geografiska Annaler* 26(1–2): 1–217. https://doi.org/10.1080/20014422.1944.11880727

Thorarinsson, S. and Sigvaldason, G.E. (1962) The eruption in Askja, 1961: a preliminary report. *American Journal of Science* 260: 641–651. https://doi.org/10.2475/ajs.260.9.641

Thordarson, T. and Larsen, G. (2007) Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. *Journal of Geodynamics* 43(1): 118–152. https://doi.org/10.1016/j.jog.2006.09.005

Thoroddsen, T. (1884) Explorations in Iceland: the lava desert of Ódáðahraun. *Nature* 30: 584–585. https://doi.org/10.1038/030584c0

Tylmann, W., Bonk, A., Goslar, T., Wulf, S. and Grosjean, M. (2016) Calibrating ^{210}Pb dating results with varve chronology and independent chronostratigraphic markers: problems and implications. *Quaternary Geochronology* 32: 1–10. https://doi.org/10.1016/j.quageo.2015.11.004

Vakhrameeva, P., Portnyagin, M., Ponomareva, V., Abbott, P.M., Repkina, T., Novikova, A., Koutsodendris, A. and Pross, J. (2020) Identification of Icelandic tephras from the last two millennia in the White Sea region (Vodoprovodnoe peat bog, northwestern Russia). *Journal of Quaternary Science* 35(4): 493–504. https://doi.org/10.1002/jqs.3190

van den Boogaart, K.G., Tolosana-Delgado, R. and Bren, M. (2024) *compositions: Compositional Data Analysis*. https://doi.org/10.32614/CRAN.package.compositions (accessed 2025-04-25)

vom Rath, G. (1875) Mittheilungen an Professor G. Leonhard. *Neues Jahrbuch für Mineralogie, Geologie und Palaeontologie* 1875: 506–518.

Wang, L., Roucoux, K.H., Davies, A.L., Zhang, S., Sun, C., Streeter, R.T., Hutchison, W. and Lawson, I.T. (2025) A new tephrochronological record of a raised bog in eastern lowland Scotland. *Quaternary Geochronology* 86: 101647. https://doi.org/10.1016/j.quageo.2024.101647

Wastegård, S. (2005) Late Quaternary tephrochronology of Sweden: a review. *Quaternary International* 130: 49–62. https://doi.org/10.1016/j.quaint.2004.04.030

Wastegård, S., Andersson, S. and Hohl Perkins, V. (2009) A new mid-Holocene tephra in central Sweden. *GFF* 131(4): 293–297. https://doi.org/10.1080/11035890903452662

Wastegård, S. and Boygle, J. (2012) Distal tephrochronology of NW Europe – the view from Sweden. *Jökull* 62: 73–80. https://jokull.jorfi.is/articles/jokull2012.62/jokull2012.62.073.pdf

Watson, E.J., Kołaczek, P., Słowiński, M., Swindles, G.T., Marcisz, K., Gałka, M. and Lamentowicz, M. (2017) First discovery of Holocene Alaskan and Icelandic tephra in Polish peatlands. *Journal of Quaternary Science* 32(4): 457–462. https://doi.org/10.1002/jqs.2945

Watson, E.J., Swindles, G.T., Lawson, I.T. and Savov, I.P. (2016) Do peatlands or lakes provide the most comprehensive distal tephra records? *Quaternary Science Reviews* 139: 110–128. https://doi.org/10.1016/j.quascirev.2016.03.011

Watts, W.L. (1876a) *Across the Vatna Jökull; or, scenes in Iceland; being a description of hitherto unknown regions*. Longmans and co.

Watts, W.L. (1876b) Journey across the Vatna Jökull, in the summer of 1875. *The Journal of the Royal Geographical Society of London* 46: 1–10. https://doi.org/10.2307/1798666

Wight, J. (1885) Askja: the great volcanic crater of Iceland. *Scottish Geographical Magazine* 1(12): 613–626. https://doi.org/10.1080/14702548508553858

Wulf, S., Dräger, N., Ott, F., Serb, J., Appelt, O., Guðmundsdóttir, E., van den Bogaard, C., Słowiński, M., Błaszkiewicz, M. and Brauer, A. (2016) Holocene tephrostratigraphy of varved sediment records from Lakes Tiefer See (NE Germany) and Czechowskie (N Poland). *Quaternary Science Reviews* 132: 1–14. https://doi.org/10.1016/j.quascirev.2015.11.007

Conflict of interest statement

The author confirms that there is no conflict of interest regarding the writing of this article.

Funding statement

The author received no external financial support for the writing of this article.

Peer-review statement

The author suggested peer-reviewers from the tephra community, who have the necessary knowledge and competencies to review the more technical aspects of the article. The author did not select current or previous collaborators or themself as peer-reviewers.

Author contribution statement

This article was conceptualised and written in its entirety by the sole author, who performed the literature review and all analyses as well as produced all graphics.

Reviews for version 1

Alice Carter-Champion:

This is a succinct and interesting contribution to both the history of tephrochronology (centred around Askja) and towards a more statistical approach to examining geochemical data from distal tephra layers. It was really enjoyable to read and clear that a rigorous investigation of the historical records has occurred, blending history with science! Discussion of the 1875 eruption and discovery and subsequent mapping of the volcanic system is concise and provides excellent context for the later overview and discussion of the geochemical characteristics of the Askja 1875 eruption. There are a few minor suggestions that I include, but these are optional or very minor expression suggestions.

Comments:

Where there's smoke: discovering a volcano

Alice Carter-Champion: The scene setting is really great, but it would be helpful to also have a map of Iceland, to help contextualise some of the places that you mention - either a reproduction of one of the historical maps that I'm sure exist, or a modern one!

irst mapping of the crater-depression and the plain of Askja by Lieutenant Caroc of the Danish Navy

Alice Carter-Champion: Again, this sounds very interesting, is there any chance to reproduce/photograph this and include it?

which in

Alice Carter-Champion: which began in?

separate plumbing systems

Alice Carter-Champion: three separate plumbing systems you mean? Askja, northern lava flow, southern lava flow? Or two plumbing systems, one for the explosive stuff and one for the effusive lava flows?

produce a map of the ashfall

Alice Carter-Champion: Again, would be really nice to include a reproduction of this if it's possible!

Figure 3:

Alice Carter-Champion: It would be nice to include the proximal data from Askja-1875 from Meara, R.H., Thordarson, T.H., Pearce, N.J.G., Hayward, C. and Larsen, G., 2020. A catalogue of major and trace element data for Icelandic Holocene silicic tephra layers. Journal of Quaternary Science, 35(1-2), pp.122-142.

Figure 4:

Alice Carter-Champion: It's interesting that there is a clear distinction based on Na2O for the samples from Borge (I think?) - could there be some issue of sodium migration? Or a different probe used compared with the other data?

The reason for the Lake Getvaltjärnen subgroup's separation from other Askja-1875 tephra findings thus remains uncertain.

Alice Carter-Champion: Maybe it would be nice to mention the potential for trace elements to distinguish whether this is the case or not?

<u>David Lowe</u>:

This is an excellent paper, very well written and presented, and of interest to a wide percentage of tephrochronologists and geoscience historians. The paper should be published almost "as is" but I have suggested minor changes to the text to clarify or reduce ambiguity. These should be considered as 'changes by the author' but very minor overall.

Comments:

David Lowe: Excellent topic and abstract

1830's,

David Lowe: 1. Remove appostrophe 1830s 2. 'widened to a caldera' - is this a true caldera which is a major collapse feature (that arises because of large volume of ejecta, unlike a crater). Please check and reword to 'large crater' if appropriate.

David Lowe: Add space before 'N' and 'W' lat/long

1054 :

David Lowe: Lake level must fluctuate with evaporation etc hence suggest add approximately or similar

This

David Lowe: This scenario has, however, been...

though

David Lowe: although

David Lowe: interpretation ie This interpretation has been

was

David Lowe: were

Thi

David Lowe: This process caused...

David Lowe: Please record if the volume estimates are as loose material or dense rock equivalence

migration

David Lowe: insert 'human' ie affected human migration (initiallly I read this as volcanic migration)

Öskjagá caldera

David Lowe: Ok it seems it is a caldera

David Lowe: add comma after Sweden

This

David Lowe: This pattern of deposition was in agreement...

ash particle

David Lowe: examined ash particles (i.e. glass shards) under...

ash particles

David Lowe: ash particles is misleading here as 'ash' is a grain size term technically - the particles in the image are glass shards and should be described as such. Also, in more proximal deposits 'ash particles' can also contain crystals and lithic fragments, not just glass, So the term 'ash particle' is not synonymous for glass particles.

invisible)

David Lowe: ....becoming dark or black

the

David Lowe: delete 'the'

hough with modern geochemical analyses

David Lowe: Although modern geochemical analyses were unavailable at the time, tentative..

David Lowe: in, for example,... add commas

numbers presented as weight percentages

David Lowe: Need to note if the values are normalised or not

findings

David Lowe: use 'locations' rather than 'findings'

David Lowe: now referred to as...

lkali-Silica

David Lowe: alkali-silica

it is

David Lowe: I am

).

David Lowe: Could add here if desired a citation Lowe et al., 2017 QSR Lowe, D.J., Pearce, N.J.G., Jorgensen, M.A., Kuehn, S.C., Tryon, C.A., Hayward, C., 2017. Correlating tephras and cryptotephras using glass compositional analyses and numerical and statistical methods: review and evaluation. Quaternary Science Reviews 175, 1-44.

his

David Lowe: relationship

entred log-ratio transformed published Askja-1875 tephra major-element oxide compositions,

David Lowe: compositions of glass shards, as principal.... (add 'glass shards' as they were analysed, not whole tephra)

data

David Lowe: selection of glass-shard analytical data...

of

David Lowe: delete 'of'

David Lowe: than to the majority...

measured .

David Lowe: ..measured contents of

David Lowe: Could insert sentence before "Looking..": Problems in analysing Na2O in glass using the electron probe, usually showing reduced totals, have been well documented (e.g. Lowe et al., 2017)

ll numbers presented as weight percentages.

David Lowe: Need to add that data are normalised.

Pub

David Lowe: Also add after percentages... All iron represented as FeO.

Looking

David Lowe: Before "Looking.." could insert sentence That Na2O totals are somewhat low reflects the well known problems associated with the analysis of glass shards using the electron microprobe (e.g. Lowe et al., 2017).

ephra shards

David Lowe: tephra-derived glass shards the shards are not "tephra shards", they are glass shards

first detailed ash dispersal ma

David Lowe: first for Icelandic tephra or globally?

of the

David Lowe: ...geochemical analyses of glass from the ...

[illegible]

David Lowe: ..raw data (i.e. not normalised) from...

tephra

David Lowe: ..tephra-derived glass-shard major...

[illegible]

David Lowe: ..tephra-derived glass-shard

[illegible]

David Lowe: tephra-derived glass-shard raw data

David Lowe: ..raw glass-shard analytical

Reviews for version 2

David Lowe:

Looks great - well done

<u>Alice Carter-Champion</u>:

A nice summary of the eruptive episode and discovery of the Askja volcano and 1875 eruption. The article is well written and engaging, but would be improved with a figure detailing the context in which Askja sits, at the very least. The PCA is well produced, but some of the symbols/colours are pretty similar and so hard to distinguish without guidance in text. Finally I think you need to double check the writing around the high/low Na2O values for the Davies (2007) data - you say that the Na2O is high at one point but then low on the TAS plot. Apart from those minor comments, I would like to approve the manuscript for publication.