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AN OUTLINE FOR FINNISH HOLOCENE TEPHROCHRONOLOGY

Volcanic ash as a dating method in Finland

Maarit Kalliokoski

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Faculty of Science and Engineering
Department of Geography and Geology
Quaternary Geology
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University of Iceland

Nordic Volcanological Center
Institute of Earth Sciences
School of Engineering and Natural Sciences

Supervised by

Professor Timo Saarinen
Department of Geography and Geology
University of Turku, Finland

Professor Stefan Wastegård
Department of Physical Geography
Stockholm University, Sweden

Assistant professor Esther Ruth Guðmundsdóttir
Institute of Earth Sciences
University of Iceland, Iceland

Reviewed by

Dr Gill Plunkett
School of Natural and Built Environment
Queen’s University Belfast
Northern Ireland, UK

Assistant Professor Britta Jensen
Department of Earth and Atmospheric Sciences
University of Alberta, Canada

Opponent

Assistant Professor Nicholas Balascio
Department of Geology
College of William & Mary
Williamsburg, VA, United States

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ABSTRACT

Tephrochronology is a high-precision dating method that uses volcanic ash horizons as isochrons in correlating and dating geological records and archaeological sites. First developed in the volcanic regions of the world, tephrochronology has expanded to ever more distal areas with improved laboratory and analytical methods that have enabled the utilization of even the scarcest deposits of far-travelled cryptotephra i.e. small volcanic glass shards that are invisible to the naked eye.

The objective of this dissertation is to assess the potential of cryptotephra studies and tephrochronology in Finland. No cryptotephra studies had been conducted in Finland previously, and the ultimate aim of the work presented here was to establish a first outline for a Finnish tephrochronology that could be used as a dating tool in environmental research in the region. Cryptotephra was searched from 30 peatland and lake sites from an area that covers the whole southern and central Finland from Åland archipelago in the west to the Russian border in the east. As a result, cryptotephra deposits from at least 17 Icelandic and two Alaskan volcanic eruptions were detected and geochemically characterized from the Finnish environmental archives. The oldest identified tephra in Finland is the 7 ka Hekla 5 tephra and the youngest one is the Askja 1875 tephra. The Finnish tephrochronology therefore covers approximately 7000 years and the results of this study demonstrate that dispersal of tephra to Finland has been relatively frequent throughout this time.

Within this project, the known dispersal areas of several Holocene tephras, such as Askja 1875, Hekla 1845, Hekla 1510, Landnám (Torfajökull), White River Ash eastern lobe, Hekla Ö and Aniakchak tephra were extended significantly eastwards, and the Hekla Y tephra was identified for the first time outside of Iceland. These results indicate that Icelandic tephra can travel to Finland along complex northerly and southerly pathways in addition to a direct eastwards dispersal route. Additionally, datasets of proximal geochemistry of Hekla X, Hekla Y, Hekla Z and Hekla 1845 tephras were produced and published to be used as an aid in establishing more robust correlations between the distal and proximal tephra records. The main outcome of this study is a first outline for a Finnish Holocene tephra framework. The high number of cryptotephra horizons in the framework demonstrates that there is great potential for further cryptotephra studies and utilization of tephrochronology as a dating method in Finland.

KEYWORDS: Finnish tephrochronology, cryptotephra, tephrochronology, Hekla Y, Alaskan tephra, Icelandic tephra, Hekla 1947

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TIIVISTELMÄ

Tefrokronologia on tarkka ajoitusmenetelmä, joka perustuu tefran eli tulivuoren tuhkan muodostamien kerrosten käyttöön arkeologisten ja geologisten ympäristöarkistojen ajoittamisessa ja korreloinnissa. Tefrokronologinen tutkimus on lähtöisin maapallon tuliperäisiltä seuduilta, joilta se on vähitellen levinnyt yhä kauemmaksi distaalialueille laboratorio- ja analyysimenetelmissä tapahtuneen kehityksen myötä. Nykyään ajoitushorisontteina on mahdollista käyttää jopa paljaalle silmälle näkymättömiä kerroksia, jotka muodostuvat kauimmaksi kantautuneista, mikroskooppisista vulkaanisen lasin partikkeleista eli kryptotefrasta.

Tämän väitöskirjan päämääränä on arvioida tefrokronologian mahdollisuuksia Suomessa. Kryptotefran esiintymistä Suomessa ei ole aikaisemmin tutkittu, ja yksi työn tärkeimmistä tavoitteista oli luoda alueellinen tefrokronologinen kehys, jota voitaisiin käyttää ajoitustyökaluna suomalaisessa ympäristötutkimuksessa. Tutkimuskohteiksi valittiin 30 suota ja järveä, joista kryptotefraa etsittiin. Tutkimusalue kattaa koko Etelä- ja Keski-Suomen aina Ahvenanmaalta Venäjän rajalle saakka. Tutkimuskohteista löytyi kryptotefraa, joka on geokemiallisen koostumuksensa perusteella peräisin ainakin 17 islantilaisesta ja kahdesta alaskalaisesta tulivuorenpurkauksesta. Vanhin geokemiallisesti tunnistettu tuhkakerros on peräisin islantilaisen Hekla keskustulivuoren n. 7000 vuotta sitten tapahtuneesta purkauksesta, ja nuorin tuhkakerrostumista on kulkeutunut Suomeen islantilaisen Askja keskustulivuoren vuoden 1875 purkauksesta. Tämän tutkimuksen tuloksena rakennettu Suomen tefrokronologinen kehys kattaa siis noin 7000 vuotta, ja sen muodostavat tefrakerrostumat osoittavat, että tulivuoren tuhkaa on levinnyt Suomeen usein kyseisen ajanjakson aikana.

Tulokset osoittavat myös, että useiden holoseenin tefrojen levinneisyysalueet ovat ulottuneet huomattavasti kauemmaksi itään kuin aiemmin on ollut tiedossa. Esimerkkejä tällaisista tefroista ovat Askja 1875, Hekla 1845, Hekla 1510, Landnám (Torfajökull), White River Ash, Hekla Ö sekä Aniakchak tefra. Lisäksi Hekla Y tefraa löytyi tämän tutkimuksen tuloksena ensimmäistä kertaa Islannin ulkopuolelta. Tulokset osoittavat, että tuhkapilvet kantautuvat Islannista Suomeen sekä suoraan lännestä että pitkin monimutkaisia pohjoisia ja eteläisiä kulkeutumisreittejä. Suomessa tehdyn kryptotefratutkimuksen lisäksi tässä väitöskirjatyössä tutkittiin Hekla X, Hekla Y, Hekla Z ja Hekla 1845 tefrojen geokemiallista koostumusta proksimaalialueiden geologisissa kerrostumissa. Uuden geokemiallisen datan avulla luotiin aiempaa luotettavampia yhteyksiä proksimaali- ja distaalialueiden tefrostratigrafioiden välille. Tämän väitöskirjan tärkein tulos on ensimmäisen suomalaisen tefrokronologisen kehyksen julkaisu. Kryptotefrahorisonttien suuri lukumäärä Suomessa osoittaa, että alueella on erinomaiset mahdollisuudet kryptotefroihin kohdistuvaan jatkotutkimukseen sekä tefrokronologian käyttämiseen ajoitusmenetelmänä.

ASIASANAT: Tefrokronologia, tulivuoren tuhka, kryptotefra, Aniakchak, Hekla Y, Hekla 1947

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Abbreviations

AD	Anno Domini
AMS	Accelerator mass spectrometry
BCE	Before common era
BP	Before present i.e. radiocarbon years before the year 1950
cal BP	Calibrated or calendar years before present i.e. the calendar year 1950
CE	Common era
EMPA	Electron microprobe analysis
EPMA	Electron probe microanalysis
HAA	Haapasuo
HAN	Hanhisuo
IES	Institute of Earth Sciences
KANA	Kananiemensuo
KIVI	Kivihypönneva
KOL	Kolkansuo
LGIT	Last Glacial-Interglacial Transition
PAR	Parkusuo
PER	Pervarvikonneva
PUN	Punkaharju
REHT	Rehtsuo
SIR	Sirrajärvi
STOR	Stormossen
SUO	Suovanalanen
TAR	Tarilampi
TAU	Tephra Analysis Unit
VEI	Volcanic Explosivity Index
XRF	X-ray fluorescence
^{14}C	Radiocarbon

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Kalliokoski, M., Wastegård, S., Saarinen, T. Rhyolitic and dacitic component of the Askja 1875 tephra in southern and central Finland: first step towards a Finnish tephrochronology. *Journal of Quaternary Science*, 2019; 34: 29–39.

II Kalliokoski, M., Guðmundsdóttir, E.R., Wastegård, S. Hekla 1947, 1845, 1510 and 1158 tephra in Finland: challenges of tracing tephra from moderate eruptions. *Journal of Quaternary Science*, 2020; 35: 803–816.

III Kalliokoski, M., Guðmundsdóttir, E.R., Wastegård, S., Saarinen, T. A Holocene tephrochronological framework for Finland. *Manuscript.*

1 Introduction

1.1 Significance of tephrochronology as a dating method

Environmental archives, such as peat or soil sections, lake and marine sediments, and glacier ice have recorded the natural history of the Earth in the form of various proxies that reflect the conditions that once prevailed. These biological, chemical, or physical traces of past environments can all be used for reconstructing the palaeoenvironments and the palaeoclimate. Reconstructions of the past conditions are, however, of little use without the element of time. Without age constraints we cannot answer questions of timing, duration, rate, or frequency of events. Only by introducing time into the equation, can we align the environmental archives of geographically separate locations temporally and gain understanding on how and why complex and interconnected systems such as the environment and climate have been changing in the past. Extensive networks of well-dated paleoenvironmental records are a prerequisite for inferring the mechanisms and spatial patterns of global change, and one of the most important methods for dating and correlating the Quaternary records has proven to be tephrochronology (e.g. Lowe, 2011; Davies, 2015).

Tephrochronology is an event-based dating and correlation method that uses the horizons of volcanic particles, i.e. tephra, in environmental records as marker layers. According to the principles of tephrochronology, a tephra layer originating from an explosive volcanic eruption is deposited instantaneously in geological sense of time, and thus forms an isochron, a horizon that represents the same moment in time throughout its dispersal area (Thorarinsson, 1944). When a tephra layer has been geochemically characterized and identified as a marker layer with unique geochemical (and/or physical) properties, it can be traced from one geological sequence to another and used for correlating the sequences. If the age of the tephra-layer-forming eruption is known from historical records or determined with other dating methods, the eruption age can be applied to every location where the layer is present (e.g. Lowe, 2011). Several other dating methods exist that are relevant for the Quaternary timescale. Examples of these are radiocarbon (Libby 1961), luminescence (Huntley et al., 1985) and palaeomagnetic dating (Mackereth, 1971), as well as incremental methods that are based on growth/accumulation of annual layers on either living organisms (e.g. tree rings: Douglass, 1919) or geological archives (varved lake sediments, glacier ice, stalagmites). However, each dating method has its weaknesses and sources of error and most of them can be used only in a certain type of environment. For example, radiocarbon dating requires presence of organic material, and annual layers of glacier ice, lake sediment or tree growth are formed only in specific conditions that are present in restricted geographical areas. The strength of tephrochronology as a dating method lies in the correlation power of the geochemically unique tephras and in the fact that tephra horizons can be found in a wide range of environmental records. Tephrochronology has already proven to be an important tool for dating and correlating archaeological (e.g. Thorarinsson, 1944; Balascio et al., 2011), environmental and climate records (Lane et al., 2011, 2013) in Northern Europe. For example, the Last Glacial-Interglacial Transition (LGIT) is marked by several short climate fluctuations and rapid environmental change in Northern Europe (Dansgaard et al., 1993), and accurate and precise age control is needed for inferring the sequence of response to climatic forcing from various environmental archives for estimating synchronicity of change or leads and lags between regions. Unfortunately, radiocarbon dating of the LGIT environmental records is problematic due to perturbations in the atmospheric radiocarbon content and consequent plateaus in the radiocarbon curve that often occur simultaneously with shifts in climate (Guilderson et al., 2005; Lowe et al., 2001). Cryptotephra horizons have been successfully used as an alternative high-precision correlation and dating tool for aligning LGIT and early Holocene records temporally and inferring the order of environmental response to climatic forcing between regions (Lane et al., 2011, 2013).

1.2 History of tephrochronology

Tephra layers were first used as marker horizons in volcanic regions of the world, where they form visible deposits that can often be distinguished from each other and traced across the landscape on the basis of their physical properties (such as grain size, grain morphology and colour). First tephra correlations were undertaken already in the 1920s and 1930s in Tierra del Fuego, South America by the Finnish geologists Väinö Auer and Martti Salmi (Thorarinsson, 1944), but tephrochronology as a discipline was established with the research of Sigurður Thorarinsson in Iceland in the 1930s and 1940s. Thorarinsson was the first one to define the terminology used in tephrochronology today and to realize the potential of Icelandic tephra to be transported overseas and remain preserved as microscopically thin and scarce deposits in environmental archives of northern Europe (Thorarinsson, 1944). Observations of ash-fall originating from Icelandic volcanic eruptions had been recorded in Scandinavia already in the 17th century (Thorarinsson, 1981), and the first contemporary tephra fall-out maps from northern Europe are the ones depicting the dispersal areas of Askja 1875 (Mohn 1877, in Thorarinsson, 1981) and Hekla 1947 (Salmi, 1948) tephras. However, it was not before the 1960s that the research of Christer Persson of the Stockholm University resulted in first cryptotephra findings from peat bogs in Scandinavia. At the time, geochemical analysis of the small volcanic glass particles was not feasible, and Persson used information such as occurrence depths of the cryptotephra layers, ^{14}C-dates of the peat, and properties of the volcanic shards for establishing correlations between sites (Persson, 1966, 1967). Later, as analytical techniques improved and geochemical fingerprinting of volcanic glass by electron microprobe analysis (EMPA) was enabled (Smith & Westgate, 1969; Larsen, 1981), more robust correlations of distal cryptotephra findings to source eruptions could be established (Dugmore, 1989; van den Bogaard et al., 1994). Since then, tephrochronology as a dating method has rapidly gained ground and the method has expanded from proximal to distal and even ultra-distal areas (Lowe, 2011; Davies, 2016; Plunkett & Pilcher, 2018).

1.3 Northern European tephra framework

Tephrochronology is best utilized when well-dated and geochemically well-characterized tephra layers form a tephra framework and identification and ages of tephra horizons at individual sites get support from stratigraphic relations to the other tephras in the framework. Regional (crypto)tephra frameworks are well established in areas where tephra studies have been conducted already for many decades, such as Iceland (e.g. Thorarinsson, 1944, 1967; Larsen & Thorarinsson, 1977; Björck et al., 1992; Larsen et al., 1999; Larsen & Eiríksson, 2008; Óladóttir et al., 2008, 2011; Guðmundsdóttir et al., 2011, 2016), the Faroe Islands (Persson, 1968; Wastegård, 2002; Wastegård et al., 2018), Sweden (Persson, 1966; Wastegård et al., 1998; Boygle, 1998, 2004; Bergman et al., 2004, Zillén et al, 2002; Wastegård, 2005), Germany (van den Bogaard et al., 1994, 2002; van den Bogaard & Schmincke, 2002; Lane et al., 2012; Wulf et al., 2016; Jones et al., 2016), Ireland (Pilcher & Hall, 1992; Pilcher et al., 1996) and the UK (Dugmore, 1989; Dugmore et al., 1995, 1996; Pilcher & Hall, 1996; Jones et al., 2019). The number of cryptotephra studies in northern Europe has been rapidly increasing during the recent years with advances in laboratory and analytical methods as well as a growing realization of the benefits of the method. For example, improved EMPA protocols (Hayward, 2012) and introduction of techniques to concentrate volcanic glass grains by picking them individually with a micromanipulator and an attached gas chromatography syringe and needle (MacLeod et al., 2014; Lane et al., 2014), have enabled geochemical characterization of smaller and scarcer glass shards than before. These developments contribute to extending tephra search into even more distal areas and allow for trace amounts of ultra-distal cryptotephra to be analysed. For example, the 12.1 ka Vedde Ash was recently handpicked and analysed from lake sediment in the Ural Mountains in Russia, > 4000 km away from its Icelandic source volcano, Katla (Hafliðason et al., 2019). This new finding extends the known dispersal area of the Vedde Ash further east by 1700 km (Wastegård et al., 2000; Hafliðason et al., 2019). In Svalbard, cryptotephra shards from lacustrine sediment were concentrated with a micromanipulator and identified as ultra-distal occurrence of tephra from the KS_2 eruption of the Kamchatkan Ksudach volcano, and the authors suggest that the tephra transport route may have been nearly circumarctic (van der Bilt et al., 2017).

The increased research efforts in tephrochronology are reflected both in new cryptotephra frameworks emerging from previously understudied regions, like Poland (Tylmann et al., 2016; Wulf et al., 2013, 2016; Watson et al., 2017a; Kinder et al., 2020) and southern UK (Watson et al., 2017b; Jones et al., 2019) as well as in new tephra findings and improved correlations that refine the (crypto)tephrochronologies of the well-investigated areas. For example, the wide-spread and well-established Glen Garry (e.g. Dugmore & Newton, 1992; Dugmore et al., 1995; Pilcher & Hall, 1996; van den Bogaard & Schmincke, 2002; Barber et al., 2008; Watson et al., 2016; Ratcliffe et al., 2018) and AD 860 B (e.g. Pilcher et al., 1995; van den Bogaard & Schmincke, 2002; Hall & Pilcher, 2002) tephra marker horizons have both been only recently correlated to the Icelandic Askja ~2000 (10 CE) (Óladóttir et al., 2011; Guðmundsdóttir et al., 2016) and Alaskan Mt. Churchill (Jensen et al., 2014) eruptions, respectively. The northern European tephra framework is constantly developing, and even if its core has traditionally been formed by tephras from Icelandic volcanic eruptions, the role of cryptotephras originating from other volcanic regions can be expected to increase in the future (e.g. Plunkett & Pilcher, 2018; Jones et al., 2019).

1.4 Icelandic tephrochronology

Iceland is the source region for most of the cryptotephra deposits identified thus far in northern Europe. Iceland is part of the North Atlantic Igneous Province and volcanically highly active due to its location on the Mid-Atlantic Ridge and above a mantle hot spot (e.g. Wolfe et al., 1997; Thordarson & Höskuldsson, 2008). Volcanic activity in Iceland is confined to the volcanic zones and belts (Jakobsson, 1979; Sæmundsson, 1979), and takes place within the volcanic systems (Figure 1) that consist of a basalt-producing fissure swarm located above a deep magma reservoir, and often of a central volcano, that may erupt also intermediate and silicic magmas from a crustal magma chamber (Figure 1, Jakobsson, 1979; Sæmundsson 1979). The geochemical differences between the Icelandic volcanic systems (Figure 2) provide the basis for tracing eruption products back to their source volcanoes and correlating the tephra layers over large distances (Imsland, 1978; Jakobsson, 1972, 1979).

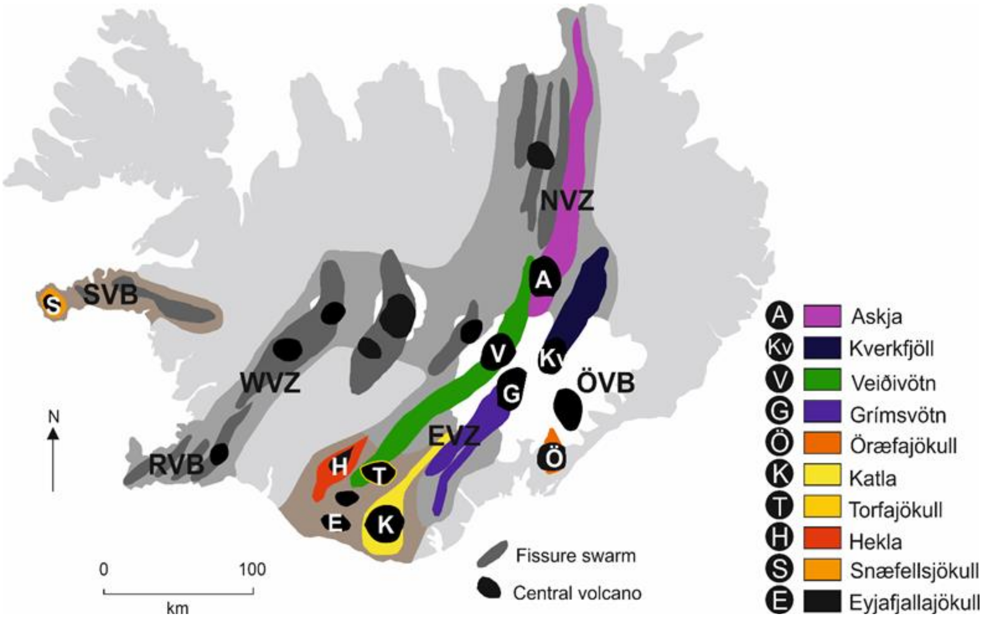

Figure 1. Location of the volcanic zones, belts and relevant volcanic systems. SVB=Snæfellsnes Volcanic Belt, RVB=Reykjanes Volcanic Belt, WVZ=West Volcanic Zone, EVZ=East Volcanic Zone, ÖVB=Öræfi Volcanic Belt, NVZ=North Volcanic Zone. Map modified from Jakobsson 1979 and Thordarson & Höskuldsson 2008. Colour coding of the volcanic systems as in Guðmundsdóttir et al., 2016.

Volcanism in Iceland is dominated by mafic magmatism, and it has been calculated that volcanic eruptions have taken place at least once in every five years during the historical time (Thordarson & Larsen, 2007). Despite the predominantly mafic nature of the magmatism, nearly 80 % of the Icelandic volcanic eruptions are explosive, due to frequent phreatomagmatic eruptions from subglacial volcanic systems (e.g. Larsen, 2002; Óladóttir et al., 2011; Thordarson & Höskuldsson, 2008). The exact number of Holocene tephra layers in Iceland is not known, but it has been estimated that potential tephra-producing Holocene eruptions could have been around 1900 (e.g. Thordarson & Höskuldsson, 2008), if the eruption frequency would have remained the same throughout the Holocene as during the historical period. However, changes in eruption frequency are known to have occurred during the Holocene (e.g. Larsen & Eiríksson, 2008; Óladóttir et al., 2011). Additionally, the preservation potential of many tephra layers is low due to dynamic proximal environment with poor vegetation cover and high erosion rates. The smallest eruptions may also have produced only local tephra fall-out. For example, some of the historical tephra layers originating from the subglacial volcanoes have been recorded only from the glacier ice and are difficult to trace further away from the volcano (Larsen, 2002; Óladóttir et al., 2011). There is no site in Iceland that would comprise a complete tephra stratigraphy of all the major marker layers, and the regional tephrochronologies are built by combining tephra records from various sites (e.g. Óladóttir et al., 2011; Guðmundsdóttir et al., 2016; Harning et al., 2018). Because the extent (of the dispersal area) of a tephra layer is determined both by the power of the eruption and the prevailing wind directions during the eruption, most of the marker layers are visible only within a certain sector extending away from the volcano (Larsen & Thorarinsson, 1977). Also, the tephra preservation potential may vary through time at any one site due to changing environmental conditions, which contributes to gaps in the tephra stratigraphy of a single site (Boygle, 1999; Janebo et al., 2016).

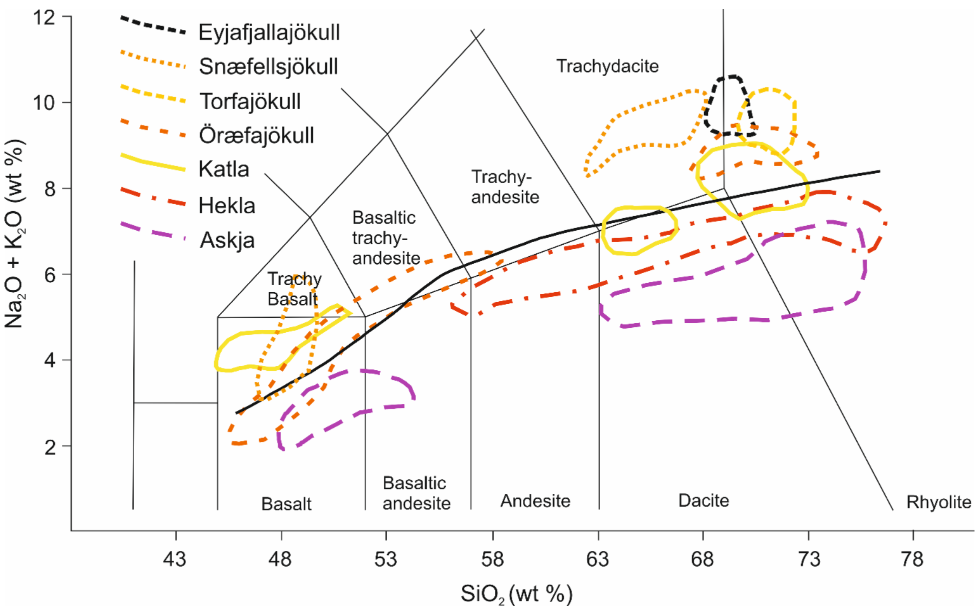

Figure 2. Geochemical differences of Icelandic volcanic systems that have produced silicic tephra during the Holocene. Colour codes are as in Figure 1. Nomenclature of volcanic rocks from Le Bas et al. (1986). The Kuno line (drawn in black) separates the high and low alkali products (Kuno 1966). Geochemical composition of Icelandic volcanic systems is mainly from Larsen et al., 1999, and additionally from Sigvaldason, 1979; Prestvik, 1985; Steinthorsson et al., 1985; Larsen et al., 2001; Larsen et al., 2002; Eiríksson et al., 2004; Sverrisdóttir, 2007; Guðmundsdóttir et al., 2011b; Óladóttir et al., 2011; Publication I in this dissertation).

Majority of the tephra layers forming the Icelandic tephrostratigraphy are basaltic and they originate mainly from the Grímsvötn, Veiðivötn-Bárðarbunga, Kverkfjöll

(Óladóttir et al., 2011) and Katla (Óladóttir et al., 2005, 2008) volcanic systems. In contrast, most of the marker horizons that form the foundation of the Icelandic tephrochronology are intermediate to silicic (Larsen & Eiríksson, 2008). The basaltic tephras can be traced to their source volcanoes based on their major element geochemistry (e.g. Óladóttir et al., 2011; Guðmundsdóttir et al., 2016), but assigning them to a source eruption is generally difficult due to limited geochemical variation in the composition of volcanic glass from the same volcanic system between consequent eruptions (e.g. Óladóttir et al., 2008, 2011). Because of this, between-site correlations of the basaltic tephras and their status as isochrons are difficult to establish. Consequently, basaltic marker layers older than 1250 years are very rare in Iceland (Table 1), the most notable exception being the extensive Grímsvötn 10 ka series: (Óladóttir et al., 2020). On the other hand, basaltic tephra pairs or a series of basaltic layers can sometimes be used as marker sequences (e.g. Guðmundsdóttir et al., 2011). The Icelandic intermediate and silicic tephra layers are better suited as marker layers, because they originate from sub-Plinian to Plinian eruptions with higher eruption plumes, have larger dispersal areas and often harbour geochemical characteristics that distinguish them from other tephra layers. The silicic products of the Icelandic volcanoes can be traced to their source volcanoes based on their major element geochemistry (e.g. Imsland 1978; Larsen, 1981) and it has been shown that even the products of separate eruptions of the same volcano can often be told apart by using bivariate plots of selected major element ratios (Larsen et al., 1999). Volcanic eruptions that produce intermediate and silicic tephras are also less frequent, which aids in tracing them across the landscape and separating them from other tephra layers on stratigraphic grounds. About half of the ca. 100 Holocene silicic tephra layers in Iceland originate from the Hekla central volcano (Larsen & Eiríksson, 2008) but also Katla, Askja, Öræfajökull, Torfajökull, Snæfellsjökull and Eyjafjallajökull have produced several important silicic tephra isochrons (Table 1).

Table 1. Main marker layers of the Icelandic tephrochronology. Modified from Óladóttir et al., 2011; Guðmundsdóttir et al., 2012, 2016; Larsen et al., 2001, 2020; Hafliðason 2000, Thorarinsson 1981. Codes for geochemical composition: B=Basaltic, I=Intermediate, A=Andesitic, S=Silicic, D=Dacitic, R=Rhyolitic.

Marker layer	Source volcano	Age (cal yr)	Age (cal yr BP)	Compo-sition	Reference
H-1947	Hekla	1947 CE	3	I (A-D)	Larsen et al. 1999
G-1922	Grímsvötn	1922 CE	28	B	Thorarinsson 1974
K-1918	Katla	1918 CE	32	B	Thorarinsson 1958
A-1875	Askja	1875 CE	75	S (R)	Thorarinsson 1963
H-1845	Hekla	1845 CE	105	I (A)	Thorarinsson 1967
Ey-1821	Eyjafjallajökull	1821 CE	129	S (R)	Larsen et al. 1999
H-1766	Hekla	1766 CE	184	I (A)	Thorarinsson 1967
K-1755	Katla	1755 CE	195	B	Thorarinsson 1981
Ö-1727	Öræfajökull	1727 CE	223	I (A)	Thorarinsson 1958

V-1717	Bárðarbunga	1717 CE	233	B	Eiríksson et al. 2004
H-1693	Hekla	1693 CE	257	I (A)	Thorarinsson, 1967
H-1636	Hekla	1636 CE	314	I (A)	Larsen 1982
K-1625	Katla	1625 CE	325	B	Thorarinsson, 1981
G-1619	Grímsvötn	1619 CE	331	B	Thorarinsson, 1981
H-1510	Hekla	1510 CE	440	I (A-D)	Larsen et al. 1999
K-1500	Katla	1500 CE	450	B	Larsen 2010
V-1477	Bárðarbunga	1477 CE	473	B	Larsen et al. 2002
V-1410	Bárðarbunga	1410 CE	544	B	Larsen 1982
Ö-1362	Öræfajökull	1362 CE	588	S (R)	Thorarinsson 1958
G-1354	Grímsvötn	1354 CE	596	B	Larsen, 1982
H-1300	Hekla	1300 CE	650	I (D-A)	Larsen et al. 2002
K-1262	Katla	1262 CE	688	B	Larsen 2010
H-1206	Hekla	1206 CE	744	A	Thorarinsson 1967
H-1158	Hekla	1158 CE	792	S (D)	Larsen 1982
H-1104	Hekla	1104 CE	846	S (R)	Thorarinsson 1967
Eldgjá	Katla	934 CE	1016	B	Hammer et al. 1980
V-871	Bárðarbunga	871 CE	1079	B	Grönvold et al. 1995
T-871	Torfajökull	871 CE	1079	S (R)	Larsen et al. 1999
Hrafnkatla	Katla	760 CE	1195	B	Óladóttir et al. 2011
SILK-YN	Katla	380 CE	1570	I(D)	Larsen et al. 2020
Sn-1	Snæfellsjökull	130 CE	1820	S (D)	Larsen et al., 2002
Grákolla	Torfajökull	10 CE	1940	S (R)	Óladóttir et al., 2011
Askja ~ 2000	Askja	10 CE	1940	S (R-D)	Guðmundsdóttir et al., 2016
H-X	Hekla	260 BCE	2210	I (A)	Larsen et al., 2020
H-A	Hekla			I (A-D)	Larsen et al., 2020
H-Y	Hekla	680 BCE	2630	I (A-D)	Larsen et al., 2020
H-Z	Hekla	760 BCE	2710	I (A)	Larsen et al., 2020
H-B	Hekla	800 BCE	2750	I (A-D)	Larsen et al., 2020
SILK-UN	Katla	830 BCE	2780	I (D)	Larsen et al., 2020
H-C	Hekla	840 BCE	2790	I (A-D)	Larsen et al. 2020
H-M	Hekla	890 BCE	2840	I (A-D)	Larsen et al. 2020
H-N	Hekla	920 BCE	2870	I (A-D)	Larsen et al. 2020
H-D	Hekla	940 BCE	2890	I (A)	Larsen et al. 2020
H-O	Hekla	1000 BCE	2950	I (A)	Larsen et al. 2020
H-3	Hekla	1050 BCE	3000	R-D-A	Dugmore et al., 1995
SILK-MN	Katla	1194 BCE	3144	I (D)	Larsen et al. 2001
SILK-LN	Katla	1430 BCE	3380	I (D)	Larsen et al. 2001
H-S	Hekla	1855 BCE	3805	R-D-A	Larsen et al. 2001
SILK-N4	Katla	1940 BCE	3890	I (D)	Larsen et al. 2001
H-4	Hekla	2250 BCE	4200	R-D-A	Dugmore et al. 1995
Sn-2	Snæfellsjökull	2450 BCE	4400	-	Jóhannesson 1981
SILK-N2	Katla	2780 BCE	4730	I (D)	Larsen et al. 2001
SILK-N1	Katla	3200 BCE	5150	I (D)	Larsen et al. 2001
SILK-A1	Katla	3750 BCE	5700	I (D)	Larsen et al. 2001
H-Ö	Hekla	4110 BCE	6060	R-D-A	Guðmundsdóttir et al. 2011
H-DH	Hekla	4700 BCE	6650	I (A)	Guðmundsdóttir et al. 2011
SILK-A7	Katla	5100 BCE	7050	I (D)	Larsen et al. 2001
H-5	Hekla	5120 BCE	7070	S (R)	Thorarinsson 1971
SILK-A8	Katla	5350 BCE	7300	I (D)	Larsen et al. 2001
SILK-A9	Katla	5540 BCE	7490	I (D)	Larsen et al. 2001
Suðuroy	Katla	6050 BCE	8000	S (R)	Wastegård 2002
LL1755	Bárðarbunga	8040 BCE	9990	B	Guðmundsdóttir et al. 2016

Fosen/ Reitsvík	Unknown	8250 BCE	10200	S (R)	Lind et al. 2013, Guðmundsdóttir et al. 2016
G10ka series	Grímsvötn	8350 BCE	10 300	B	Óladóttir et al. 2020
Askja-S	Askja	8450 BCE	10 800	S (R)	Guðmundsdóttir et al. 2016
Vedde Ash	Katla	10150 BCE	12 100	S (R), B	Norðdahl & Hafliðason 1992

1.5 Objectives of this study

The aim of this study is to assess the potential of cryptotephra studies in Finland by testing the commonly used cryptotephra research methods. No cryptotephra studies have been conducted in Finland thus far, despite the benefits of tephrochronology as a dating method and the favourable location of Finland regarding the prevailing westerly winds that are known to transport Icelandic tephra towards Fennoscandia (e.g. Wastegård, 2005). Possibilities for using tephrochronology in environmental research in the region are investigated by searching for cryptotephra from the most important environmental archives in Finland: peat sequences, homogenic lake sediments and varved lacustrine sediments. Special attention is given to the Hekla 1947 tephra, that was reported to have formed a visible fall-out on snowpack surface in southern and central Finland (Salmi, 1948), and a possible effect of precipitation on tephra fall-out and shard concentration is investigated. Also, a sample collection of Hekla 1947 tephra that was collected from Finland immediately after the eruption (Salmi, 1948) is revisited for obtaining geochemical data with modern methods. Ultimately, the objective of this study is to fill a gap in knowledge on the dispersal patterns of Icelandic tephras in northern Europe and to produce a first outline of a Holocene cryptotephra framework for Finland by dating and geochemical fingerprinting of cryptotephra deposits from geological records. An important aspect of this project is also to enhance dialogue between distal and proximal tephra studies by combining research from Iceland and Finland. This is done by geochemically characterizing selected Icelandic tephras from proximal records with the aim to improve the proximal geochemistry datasets and establish more robust tephra correlations between Iceland and distal areas.

2 Materials and Methods

2.1 Field work

The main research area in this study covers the southern and central Finland, from the Åland archipelago in the west until the Russian border in the east (Figure 3). Additionally, one lake site in the northernmost part of Finland was included in the study. Altogether, 30 research sites, 24 peatlands and six lakes in Finland, were selected for investigation (Table 2). Field work at the peatland sites was carried out during the summer field seasons of 2014, 2015 and 2018, when a Russian peat corer was used for collecting the full peat stratigraphy of each site and at least one additional peat monolith was cut from the surface peat at every site. Surface sediment cores from the lake sites were collected with a Limnos sediment sampler either from aboard a rubber boat during summer field season or through a hole in the lake ice cover during winter. Long lacustrine sediment cores were collected using a piston corer during spring season, when lake ice could be used as a coring platform. A list of the collected cores and co-ordinates of all the research sites are given in Table 2.

Proximal samples of Icelandic tephra were collected from soil sections near Hekla central volcano in the autumn 2018. The tephra layers of interest (Hekla 1845, Hekla X, Hekla Y and Hekla Z) were identified based both on their physical properties (colour, grain size, layer thickness) as well as their stratigraphic position in relation to known marker layers in the area. Each layer was sampled throughout its thickness and in the case of the two-coloured Hekla layers X, Y and Z, the dark and the light-coloured parts of the layers were sampled into separate plastic bags.

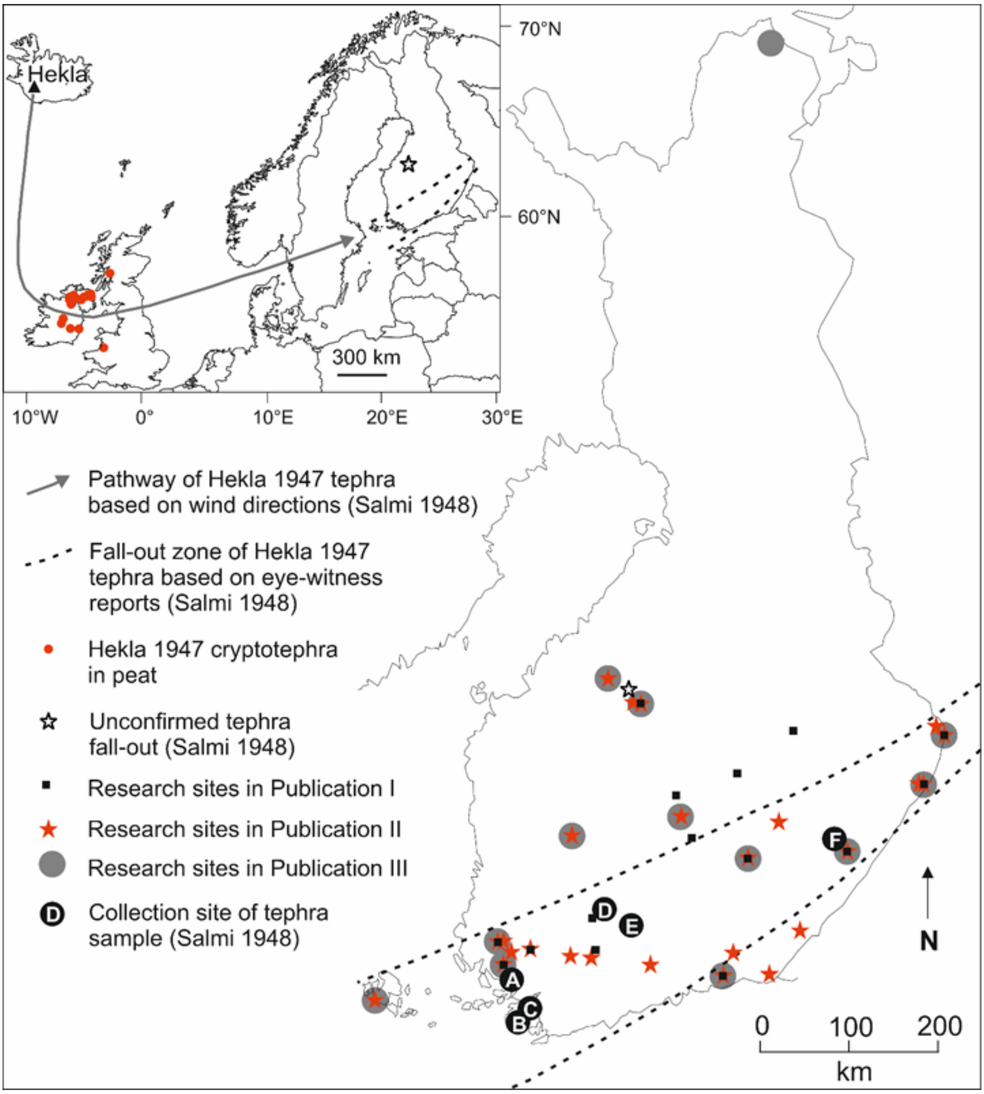

Figure 3. Research sites in this study. The observed fall-out zone and inferred transport pathway of Hekla 1947 tephra are given for reference.

Table 2. Investigated peatland and lake sites in Finland.

Research site	Material type	Investigated core length/ Total core length (cm)	Lat. (N)	Long. (E)
Stormossen	*Carex* peat	90/90	60.12	19.75
Kolkansuo	*Sphagnum* peat	500/500	60.82	22.11
Kaukosuo	*Sphagnum* and *Carex* peat	90/650	60.83	22.23
Rehtsuo	*Sphagnum* peat	455/455	60.60	22.25
Kurjenrahka	*Sphagnum* peat	36/36	60.72	22.40
Kontolanrahka	*Sphagnum* peat	410/410	60.77	22.78

Suovanalanen	*Sphagnum* and *Carex* peat	569/569	61.92	23.50
Torronsuo	*Sphagnum* peat	50/900	60.72	23.61
Ahvenuslammi	Homogeneous gyttja	30/30	61.06	23.98
Purinsuo	*Sphagnum* peat	50/425	60.71	24.03
Kalattomanlammit	Homogeneous gyttja	30/30	60.76	24.08
Kivihypönneva	*Carex* and *Sphagnum* peat	247/247	63.50	24.12
Pakosuo	*Carex* peat	50/267	63.27	24.69
Pervarvikonneva	*Sphagnum* and *Carex* peat	275/275	63.26	24.87
Isosuo	*Sphagnum* and *Carex* peat	50/540	60.66	25.23
Korttajärvi	Varved clastic-organic lacustrine sediment	Only selected varve intervals were investigated	62.32	25.67
Haapasuo	*Carex* and *Sphagnum* peat	319/319	61.91	26.05
Kananiemensuo	*Sphagnum* and *Carex* peat	545/545	60.57	26.71
Hangassuo	*Sphagnum* and *Carex* peat	50/320	60.79	26.91
Kallio-Kourujärvi	Varved organic lacustrine sediment	266.5/266.5	62.55	27.00
Tarilampi	*Carex* and *Sphagnum* peat	238/238	61.74	27.22
Hallinsuo	*Sphagnum* and *Carex* peat	50/340	60.58	27.64
Vuotsinsuo	*Sphagnum* and *Carex* peat	50/500	62.10	27.88
Kuninkaisenlampi	Varved clastic-organic lacustrine sediment	Only selected varve intervals were investigated	62.97	28.23
Hämmäauteensuo	*Carex* and *Sphagnum* peat	50/185	61.01	28.29
Punkaharju	*Carex* peat	660/660	61.79	29.31
Parkusuo	*Carex* and *Sphagnum* peat	415/415	62.42	30.99
Koivusuo	*Sphagnum* and *Carex* peat	50/513	62.99	31.35
Hanhisuo	*Sphagnum* and *Carex* peat	312/312	62.89	31.51
Sirrajärvi	Homogeneous gyttja	206/206	68.53	22.24

2.2 Hekla 1947 tephra samples (Salmi 1948)

In 1947, tephra fall-out was observed in southern and central Finland during three days following the March 29th Hekla eruption (Figure 3). Finnish citizens collected tephra from snow cover and various other surfaces shortly after the fall-out on request of Salmi (1948). The volcanic origin of all the collected samples was verified by microscope inspection, and composition of one of the tephra samples was analysed (Salmi, 1948). In this study, six samples (A–F in Figure 3) from the collection were reinvestigated for defining the physical properties of the Hekla 1947 tephra in Finland and for obtaining new geochemical data on the tephra composition by electron microprobe, a technique that had been unavailable for Salmi in 1947.

2.3 Laboratory work

The most suitable laboratory and analytical methods for finding and defining cryptotephra layers in Finnish geological records were tested and determined. Cryptotephra detection and extraction from environmental archives is based on differences in physical and chemical properties of tephra shards and their host matrix, and the nature of the host matrix guides the selection of laboratory methods at each instance. Commonly used laboratory methods of cryptotephra detection and extraction in the distal area include ashing (Pilcher & Hall, 1992) or acid digestion (Dugmore, 1989) of organic matter, sieving, heavy liquid density separation of volcanic glass from minerogenic matrix (Turney, 1998), as well as XRF core scanning (Kylander et al., 2011).

Collected peat and lake sediment cores in this study were first subsampled in 5–10 cm-long increments and dried overnight at 105°C. Next, they were combusted at 550°C for 4 h for burning away organic matter and treated with 10 % HCl for removing carbonates and breaking aggregates. All the lake sediment samples and the peat samples that contained plenty of minerogenic grains and/or diatoms were then sieved with 80 µm and either 25 or 10 µm meshes. The fraction retained on the finer sieve was subjected to heavy liquid separation for concentrating the volcanic glass. Commonly, heavy liquid densities of 2.3 and 2.5 g/cm^3 are used for floating off the light (< 2.3 g/cm^3) organic remains and separating the vesicular volcanic glass from the denser (> 2.5 g/cm^3) minerogenic matrix. The separation technique has been observed to work well for rhyolitic volcanic glass that often has a density in the range of 2.3–2.5 g/cm^3 (Turney, 1998). However, basaltic glass is heavier and has a density > 2.5 g/cm3 and separates poorly from the minerogenic matrix. In this study the Hekla andesite-dacite was observed to most commonly have a density of 2.5–2.6 g/cm^3 (Publication II), and therefore heavy liquid densities 2.3 and 2.6 g/cm^3 were used. After density separation, the samples were mounted on microscope slides with Canada Balsam for inspection under a polarizing microscope. Volcanic glass was identified based on its distinct morphological features, such as vesicularity and fluted surfaces (Fig. 4 A–C), and optical isotropy (e.g. Lowe, 2011). Where volcanic glass was identified, new high-resolution 1–2-cm-thick subsamples of known volume (1–10 cm^3, depending on the sample) were prepared and investigated under a microscope. This time, cryptotephra shards were counted, measured, described, and photographed for documentation and for determining the average grain size and depth of peak shard concentrations.

Cryptotephra samples for electron microprobe analysis were prepared by using acid digestion method instead of ashing to avoid geochemical alteration of volcanic glass in high temperatures (e.g. Pilcher & Hall, 1992, Dugmore et al., 1995). The volcanic glass in the residue was concentrated by sieving, heavy liquid separation, and hand-picking the shards by using a micromanipulator with a micro-syringe and a needle where necessary. The glass shards were fixed on microscope slides with epoxy and the samples were sanded and polished down to a thickness of around 15 µm for bringing the shards to the sample surface. Because identification of volcanic glass is often difficult during EMPA work when no polarizer is available, measures were taken to ensure that the shards would be easy to find during microprobe sessions. Each polished sample was inspected under a petrographic microscope before carbon coating and drawings of the shapes and locations of the cryptotephra shards in the samples were made. That way EMPA time could be used efficiently, and only volcanic glass was analysed instead of accidental analysis of e.g. quartz or biogenic silica.

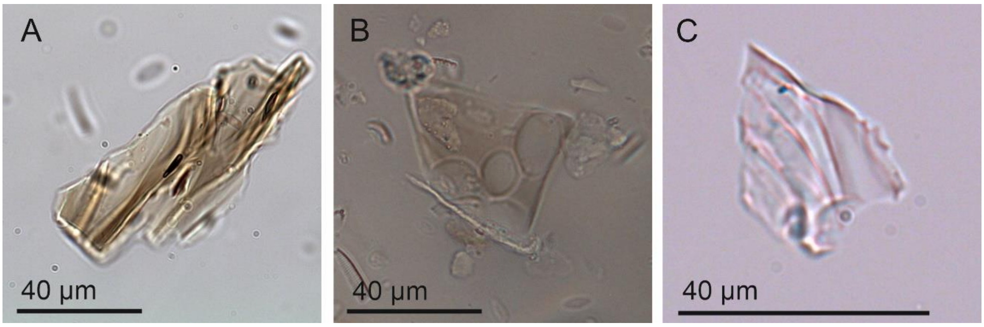

Figure 4. Cryptotephra shards from Finnish peatlands. A: Askja 1875 from Kananiemensuo, B: SN-1 from Kivihypönneva, C: Hekla 5 from Kivihypönneva.

Tephra samples from proximal sites in Iceland were processed using the routine laboratory methods of the tephrochronology group at IES: organic matter was removed from the samples with tweezers and by wet sieving through a stack of standard mesh sizes (1mm, 0.5 mm, 250 µm, 125 µm and 63 µm). Afterwards, the separate size fractions were inspected under a stereo microscope and described. In this study, both the 63–125 µm and 125–250 µm fractions were prepared for EMPA at the thin section laboratory of IES, where they were mounted in epoxy stubs, sanded, polished and carbon coated.

2.4 Electron microprobe analysis

The volcanic glass was analysed with either the JEOL JXA-8230 SuperProbe at the Institute of Earth Science (IES), University of Iceland or the Cameca SX100 microprobe at the Tephra Analysis Unit (TAU) of the University of Edinburgh. On both instruments, standard wavelength dispersive technique was used for obtaining point analyses of ten major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and P) on as many individual glass shards within each sample as available. At TAU, beam size of 3–5 µm, accelerating voltage 15 kV and beam current range from 0.5 to 80 nA was used. Lipari obsidian and BCR2g secondary glass standards were analysed together with the samples. More information on the analysis order of the elements and microprobe configuration at TAU is available in Hayward (2012). At IES, accelerating voltage 15 kV, beam current 10 nA and a beam diameter of 5-10 µm was used. Secondary standards Lipari obsidian and ATHO rhyolitic glass were analysed in the beginning and end of each batch of 50 point analysis. In this study, the JEOL JXA-8230 SuperProbe at IES was used for the first time in analysing cryptotephra particles, and therefore part of the samples were analysed both at TAU and IES to confirm that the instruments produce comparable results.

2.5 Radiocarbon dating

Radiocarbon dating was used for obtaining an independent age estimation for selected cryptotephra deposits at the Finnish sites. ^{14}C dating of peat produces more reliable dates if identified macrofossils are dated instead of the bulk peat that may contain remnants of roots that are much younger than the peat surrounding them. Therefore, *Sphagnum* sp stems and leaves were picked under a stereomicroscope from the depth of the cryptotephra layer if core material was left. If no material was left, the peat either immediately above or below the cryptotephra horizon was targeted. Majority (5) of the samples for ^{14}C dating were taken from the Kivihypönneva peat core, that contains the highest number or cryptotephra horizons. Additionally, one cryptotephra deposit from Parkusuo was dated. The samples were analysed at the Aarhus AMS Centre and an online version of OxCal 4.3 (Bronk Ramsey, 2009) with the IntCal-13 calibration curve (Reimer et al., 2013) was used for calibrating the obtained radiocarbon ages.

3 Results

3.1 Improved geochemical datasets for proximal tephras

This study resulted in an improved dataset of the geochemical compositions of the Hekla 1845, Hekla X, Hekla Y and Hekla Z tephra layers from proximal records in Iceland. EMPA results from 15 volcanic glass grains of the Hekla 1845 tephra, 41 grains of Hekla X, 35 grains of Hekla Y and 36 grains of Hekla Z are presented here (Publications II and III). The geochemical composition of the Hekla 1845 tephra from proximal sites has not been published before, and previous correlations of distal deposits of the Hekla 1845 cryptotephra in Faroe Islands and Ireland had been established mainly on stratigraphic grounds (Wastegård, 2002; Watson et al., 2015). The new EMPA results enable future correlations of the Hekla 1845 tephra to be made based on geochemical composition. EMPA dataset of the glass geochemical composition of the Hekla alphabet layers (Hekla A, B, C, M, N, X, Y and Z) has been recently published (Meara et al., 2020). Additionally, results of XRF analysis of bulk geochemistry of the same layers were published at the same time (Larsen et al., 2020). Interestingly, the EMPA results were reported to reveal no differences between the geochemical signature of these layers, whereas the XRF data indicate slight differences in geochemical composition (Larsen et al., 2020). The new EMPA results presented in this study support the findings of the XRF study for the Hekla X, Y and Z tephras and indicate that slight geochemical differences between the compositions of these tephras do exist and may help in separating them from each other (Publication III).

3.2 Hekla 1947 tephra in Finland

In this project, new data on the Hekla 1947 tephra in Finland was produced. Reinvestigation of the Hekla 1947 tephra sample collection revealed that the physical properties of the shards differ from what had been reported earlier (Salmi, 1948). The average grain size of the tephra in Finland is ~ 80 µm instead of the previously reported 3–15 µm (Publication II). Density measurements of the tephra show that majority of the shards fall in the density range 2.5–2.6 g/cm^3, which appears to be a common density for Hekla andesite-dacite. Electron microprobe analysis of the Hekla 1947 tephra resulted in a dataset of 115 point analysis of single shards. Since these samples represent pristine tephra that has been stored in sealed glass vials since the eruption and has thus not been subjected to geochemical alteration in the natural environment or during laboratory processing, the EMPA data can be used as a reference point when assessing the degree of alteration in future findings of Hekla 1947 tephra (Publication II).

3.3 Cryptotephra framework for Finland

This study resulted in detection of 16 geochemically unique cryptotephras in Finnish peatlands and lake sediments (Publication III). In addition to geochemical characterization of the cryptotephra deposits and correlations to the proximal tephra records, selected cryptotephra horizons were radiocarbon dated to confirm their ages. A schematic tephra framework, where all the identified cryptotephra deposits from the investigated sites are brought together, is presented in Figure 5. Robust correlations to proximal tephra records have been established for most cryptotephra layers in this framework. However, only tentative correlations are suggested for the ca. 2.1 ka Askja (Stömyren) tephra, Aniakchak, Hekla-S and ca. 3.5 ka Öræfajökull tephra (Publication III). The Askja Stömyren tephra in Sweden (Wastegård, 2005) has not yet been correlated to any proximal deposits in Iceland, and the Aniakchak, Hekla-S and Öræfajökull 3.5 ka tephra have not yet been radiocarbon dated in Finland.

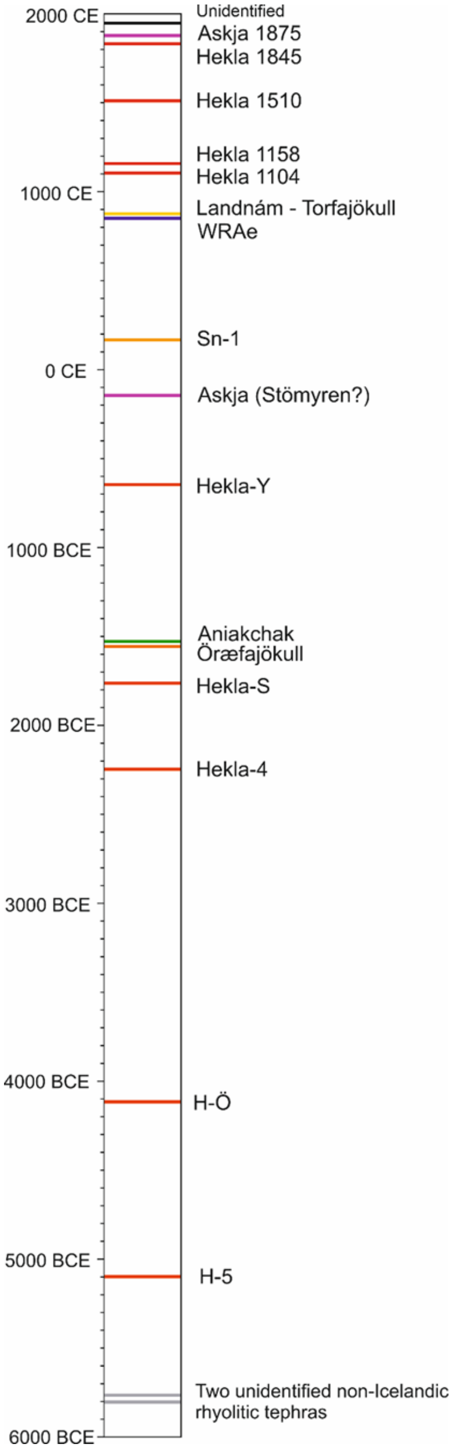

Figure 5. A schematic tephrochronological framework for Finland, colour codes are as in Figure 1.

3.4 Review of the original publications I–III

3.4.1 Publication I

This publication presents the first cryptotephra study in Finland. Cryptotephra research methods were tested and cryptotephra was searched from five lakes and ten peatland sites to assess the potential for using tephrochronology in Finland. Study sites were selected to represent a range of geological records commonly used in Finnish environmental research: peat archives, homogeneous organic lake sediment, varved organic lake sediment and varved clastic-organic lake sediment. One cryptotephra horizon was detected at eight of the fifteen sites. Geochemical characterization of the volcanic glass revealed that the deposits consist predominantly of rhyolite from the Icelandic Askja central volcano. Additionally, a dacitic minor component was analysed alongside the rhyolitic glass. This dacitic tephra population is not well known from the proximal tephra records in Iceland. However, careful comparisons of the new results with petrographic studies of proximal Askja 1875 products and previously published cryptotephra analysis from Swedish sites show that both components originate from the Askja 1875 eruption. These first cryptotephra findings from Finland refine and extend the known dispersal area of the Askja 1875 tephra further east. Additionally, the common presence of the Askja 1875 cryptotephra in Finnish environmental records indicates that it has great potential to become an important marker layer in the region. The main conclusion of this paper is that Icelandic tephra can be transported to Finland and deposited in the geological records in detectable amounts, which confirms that there is potential for further cryptotephrochronological research in Finland.

3.4.2 Publication II

In this publication, a detailed investigation of the occurrence of the Hekla 1947 tephra in Finland is disseminated. Cryptotephra was searched from 25 peatlands, of which 18 are located within the previously inferred fall-out zone of the Hekla 1947 tephra in southern and central Finland. Precipitation maps for the days following the Hekla 1947 eruption were produced from Finnish Meteorological Office weather data to test for a possible correlation between precipitation, cryptotephra occurrence and tephra shard concentration. Six tephra samples that were collected from Finland after the tephra fall-out and investigated by Salmi in 1947, were reinvestigated in this study with modern methods for a better understanding of the properties of the Hekla 1947 tephra in Finland. Altogether, 47 surface peat cores and monoliths from the research sites were investigated using both routine and modified laboratory methods. Despite rigorous laboratory work, no deposits of Hekla 1947 tephra were detected at the Finnish sites. Instead, cryptotephra from three other historical Icelandic volcanic eruptions, Hekla 1845, Hekla 1510, and Hekla 1158, was identified for the first time in Finland. These findings represent the first reported occurrence of Hekla 1845 and Hekla 1510 cryptotephras outside of Ireland, Faroe Islands and the UK and extend the known dispersal area of each tephra significantly further east. All the Hekla cryptotephras detected in Finland in this study originate from moderate-sized eruptions with Volcanic Explosivity Index ≤ 4 and erupted tephra volumes ≤ 0.6 km^3. This result highlights that Icelandic smaller scale eruptions produce tephra isochrones with much wider dispersal areas than previously realized. One of the most important findings of this study is that Icelandic moderate eruptions can form interregional tephra marker layers in the distal field and the geochronological value of smaller scale tephras is higher than hitherto known. Identification of four historical Icelandic tephras in Finland confirms that volcanic ash from Iceland is transported to Finland frequently and it may travel along complex southerly and northerly transport routes in addition to a direct eastward dispersal.

3.4.3 Publication III

This manuscript presents a study of the Holocene tephrochronology of Finland. The full peat stratigraphy of 12 peatland sites and the sediments of one lake site were investigated for occurrence of cryptotephra. The peatland sites cover southern and central Finland and the lake site is located in the northernmost part of Finland. Additionally, three Hekla layers (Hekla X, Hekla Y and Hekla Z) from a proximal site in Iceland were geochemically characterized for improving the geochemical dataset. Laboratory and EMPA work resulted in identification of 14 cryptotephras from Icelandic volcanic eruptions and two cryptotephras that originate from volcanic eruptions in Alaska. Several cryptotephra deposits could not be correlated to source eruptions because of difficulties in obtaining robust EMPA results from very small and vesicular shards. The geochemical compositions of the cryptotephra deposits in the Finnish sites were compared with datasets of proximal tephra geochemistry for establishing correlations. Additionally, selected tephra deposits were ^{14}C dated for an independent age determination. The most important outcome of this study is an outline for a Finnish Holocene tephra framework that can be used as a basis for future cryptotephra work in the region. The oldest geochemically identified cryptotephra horizon in Finland is the 7 ka Hekla 5 tephra. However, at least two older cryptotephra deposits that bear a geochemical signature of non-Icelandic volcanism are present at one of the sites. The results of this study reveal an excellent potential for future cryptotephra studies in Finland and a complete list of the properties of the detected cryptotephra deposits together with several photographs is published as part of this manuscript to be used as an aid in further investigations in Finland.

4 Discussion

4.1 Potential of tephrochronology in Finland

The results of this study reveal that silicic tephra has been dispersed to Finland from at least 14 Icelandic and two Alaskan volcanic eruptions during the Holocene (Figure 5). Oldest cryptotephra identified at the Finnish sites is the ca. 7 ka Hekla 5 tephra, whereas the youngest one is the Askja 1875 tephra (Publications I, II, III). At one of the research sites also basaltic tephra from Grímsvötn, Veiðivötn and Kverkfjöll volcanic systems is present (Publication III). In addition to these cryptotephra findings, volcanic ash from three Icelandic eruptions – Hekla 1947 (Salmi, 1948), Eyjafjallajökull 2010 (Davies et al., 2010) and Grímsvötn 2011 (Kerminen et al., 2011) – has been reported in the Finnish airspace during the past 100 years but no cryptotephra deposits from these eruptions have been found from the environmental archives in the region. These results indicate that dispersal of tephra to Finland has been a relatively frequent event during the Holocene and there is an excellent potential for using tephrochronology as a dating method in environmental studies in Finland. Altogether, volcanic ash has been transported to Finland at least 22 times during the past 7000 years which gives a return time of ~320 years for volcanic ash events in the Finnish airspace. However, the events are not temporally evenly spaced; 11 of them have occurred within the past two millennia, whereas for example only two cryptotephra deposits from the period 5000–3000 BCE were detected (Publication III). The higher frequency of volcanic ash events during the past 2000 years partly reflects availability of tephra observation records, but that alone does not fully explain the differences in frequency. It is possible, that older cryptotephra deposits in the Finnish peatland sites are poorly preserved and more difficult to detect, which would place constraints on using tephrochronology as a dating method for the early Holocene. Alteration and even total dissolution of volcanic glass has been suggested to take place in acidic environments such as ombrotrophic peat bogs over longer timescales (e.g. Pollard et al., 2003; Cooper et al., 2019a). Cryptotephra deposits in the Finnish peatland sites often consist of very small and thin glass grains and some of the shards show signs of leaching, such as pitted surfaces (Figure 4 B). However, the alteration of volcanic glass in Finnish peatlands does not seem to increase with age of the deposits, but is perhaps more dependent on the geochemical composition of the tephra, as has been suggested in earlier studies on geochemical stability of different tephras (Pollard et al., 2003). For example, based on the appearance of the glass shards, the trachydacitic Sn-1 tephra (ca. 170 CE) shows higher degree of leaching than the 5000 years older rhyolitic Hekla 5 (ca. 5120 BCE) at the same peatland site in central Finland (Fig 4 B and C).

Since majority of the cryptotephra layers (9 out of 16 tephras) in the Finnish tephrochronology originates from the Hekla central volcano (Figure 5), it is likely that the differences in number of cryptotephra horizons through time reflect the changes in the eruption history of Hekla itself rather than varying preservation potential. Three separate stages in the eruption history of Hekla have been recognized based on eruption style and composition of the eruptives (Larsen & Thorarinsson, 1977). During the first eruption stage (> 7.0 ka) the Hekla volcanic system produced basaltic lavas from fissure eruptions and no silicic tephras of this age are known from Iceland (Larsen & Thorarinsson, 1977). The five silicic major Hekla layers (Hekla 5, Hekla Ö, Hekla 4, Hekla S and Hekla 3) all represent the second eruption stage (from ca. 7.0 ka to 3.0 ka) that is characterized by a few large (> 1 km^3) Plinian eruptions and a long repose time between eruptions (Larsen & Thorarinsson, 1977). On the contrary, the historical Hekla eruptions belong to the third eruption stage (ca. 3.0 ka and onwards), that comprises frequent, moderate-sized subplinian to Plinian eruptions with tephra volumes < 1 km^3 (Larsen & Thorarinsson, 1977; Larsen et al., 2020). The tephra plume heights (12 – 36 km) of all the historical Hekla eruptions are sufficient for tephra dispersal to Northern Europe (Thorarinsson, 1967; Janebo et al., 2016), and therefore the environmental archives of the region are likely to contain several Hekla cryptotephra deposits of third eruption stage.

Askja 1875 tephra is the most common cryptotephra horizon detected in Finland. It forms deposits with high shard concentration (up to 559 shards/ cm^2) and the average grain-size of the volcanic glass is > 75 µm, higher than for any other cryptotephra identified in Finland (Publication III). The distinct physical properties of the Askja 1875 tephra together with its unique geochemical signature, make its identification relatively straightforward in Finland. The Askja 1875 tephra is widely dispersed in Scandinavia (Carey et al., 2010; Wastegård, 2005) and it has great potential to become an important marker horizon in the region. The geochronological value of the Askja 1875 tephra in Finland is increased by its deposition time at the onset of extensive forest clearance and drainage of peatlands in areas that had previously been relatively unaffected by anthropogenic activities (Publication III). Environmental research focusing on this large-scale land use change and its ecological impact could thus greatly benefit from using the Askja 1875 tephra as a dating horizon.

The Finnish tephrochronology differs significantly from the well-established Swedish tephra framework (e.g. Wastegård, 2005; Watson et al., 2016). The most important Holocene tephra marker layers in Sweden are the Hekla 4, Hekla 3, Hekla S and Askja 1875 tephras (Wastegård, 2005). Of these, only Askja 1875 tephra forms a significant isochron in Finland. Hekla 4 has been found from two sites, and a tentative correlation to Hekla-S has been suggested at one site, whereas Hekla 3 has not yet been identified with certainty from Finnish environmental records (Publication III). In Sweden, these mid-Holocene Hekla marker layers have been reported mainly from southern and central parts of the country (Wastegård, 2005), from an area southwest from Finland. Thus far they have been identified at just one site closer to Finland, on the east coast of northern Sweden (Watson et al., 2016). The shard concentrations for Hekla 3, Hekla S and Hekla 4 tephras at that site are fairly low (≤ 50 shards/cm^2: Watson et al., 2016), which indicates that they may all be close to detection limit further east in central Finland. However, many cryptotephra deposits in the peatland sites in southern Finland remain unanalysed (Publication III) and based on their occurrence depths, it is likely that some of them represent the mid-Holocene Hekla tephras. The results of this study therefore suggest that future research may improve the knowledge on dispersal of these tephras within Finland and further increase their geochronological value in the region.

Half of the 16 tephras identified in this study have not been found from Sweden thus far, which points at either complex tephra dispersal routes instead of a direct eastward transport, patchy fall-out controlled by local weather conditions, or both. For example, the historical Hekla 1845 and Hekla 1510 tephras that were identified in southern and central Finland (Publication II) had previously been found only from Ireland (Pilcher et al., 1996; Watson et al., 2015), the UK (Dugmore et al., 1995, 1996: Watson et al., 2017) and Faroe Islands (Wastegård, 2002). They therefore most likely travelled to Finland along similar transport pathways as the Hekla 1947 tephra that formed a visible fall-out in Finland (Salmi, 1948) and has been found as a cryptotephra horizon in Ireland (Rea et al., 2012; Watson et al., 2015). Other tephras, such as the Hekla 1158 and Hekla Y tephra, are present only at some of the northernmost investigated peatland sites in Finland and have not yet been identified in southern Finland. Hekla 1158 tephra has been reported from northern Sweden (Watson et al., 2016; Cooper et al., 2019b) and Norway (Pilcher et al., 2005; Balascio et al., 2011), whereas correlations to Hekla Y eruption have not been established for cryptotephra deposits in northern Scandinavia. However, based on comparisons of geochemical composition of cryptotephras in this study (Publication III), Hekla Y is likely present in Lake Svartkälsjärn on the east coast of northern Sweden (SV-L2 tephra in Watson et al., 2016). Hekla 1158 and Hekla Y seem to have reached Finland via a northerly transport route. The differences between the Swedish and Finnish tephrochronologies may partly be due to different laboratory techniques. At the

Finnish sites, the recently developed technique of concentrating scarce glass shards with a micromanipulator (MacLeod et al., 2014; Lane et al., 2014) was applied and great effort was made to analyse even the cryptotephra deposits with very low shard concentrations. In Sweden, the earlier research focused on the most prominent cryptotephra layers, and some of the deposits with lower shard concentrations are possibly still unidentified.

In addition to Icelandic tephra, two Alaskan cryptotephras were identified in this study, the WRAe (White River Ash eastern lobe: Jensen et al., 2014) and Aniakchak tephra (Kaufman et al., 2012). The detection of these tephras in Finland extends their known dispersal further east and provides opportunities for precise correlations between environmental records in Northern America and Northern Europe. In addition, two rhyolitic cryptotephra deposits (> 7.0 ka) that bear geochemical signature of non-Icelandic volcanism were detected at one site (Figure 5). However, no robust correlations could be established for these deposits based on only a couple of point analysis by electron microprobe. These results indicate that further cryptotephra research in Finland would be worthwhile and is likely to greatly improve the first outline for Finnish tephra framework presented in this study.

4.2 Challenges of distal tephra studies

Analytical advances of the recent years have enabled geochemical fingerprinting of smaller and scarcer volcanic glass shards than before (Hayward et al., 2012). The shard concentrations in the cryptotephra deposits in the Finnish sites are often low (Figure 6) and the average length of the longest axis of the shards is mostly 30–60 µm (Publication III). Concentrating the volcanic glass by hand-picking the shards using a micromanipulator with an attached syringe and a needle is necessary for majority of the cryptotephra deposits in Finland. Due to the fine grain-size of the shards, several cryptotephra deposits at the Finnish sites remain still unanalysed, despite multiple attempts at preparing EMPA samples (Publication II and III). Even if great care is taken during the EMPA sample preparation, and location of the volcanic glass in the samples is monitored by microscope inspection throughout the sanding and polishing process, specially the smallest shards with platy morphologies are in a high risk of getting sanded or polished away when attempts are made at bringing them to the sample surface.

The EMPA of small shards poses its own challenges. If the average grain size of vesicular volcanic glass is < 40 µm, fitting the electron beam on the shard surface is difficult, especially if a possible alteration rim on the shard is to be avoided. Additionally, analysing the Hekla andesite can be challenging due to the common occurrence of micron-sized microlites (Hunt & Hill, 2001). These problems in EMPA may result in low totals or a large range of values for some elements. When the number of successful analyses per cryptotephra deposit is low, it may become impossible to assess which of the point analyses represent the true geochemical composition of the tephra and which show signs of alteration or microlite contamination.

Additionally, when only a few good analyses are obtained from a cryptotephra deposit, the full geochemical range present at that site is unlikely to be captured. Sometimes the full compositional range of a tephra is an important diagnostic feature that may aid in its identification. The mid-Holocene Hekla marker layers typically have a wide range of geochemical compositions (Larsen & Thorarinsson, 1977; Sverrisdóttir, 2007). For example, the Hekla 5 can often be separated from the otherwise similar Hekla-Ö based on the absence of volcanic glass < 70 % wt SiO_2 in Hekla 5 deposits (Eiríksson et al., 2004), whereas Hekla Ö has a SiO_2 range of 60–77 % wt (Óladóttir, 2009; Guðmundsdóttir et al., 2011). In Finland, the Hekla 5 and the Hekla Ö cryptotephra deposits do not contain any glass with SiO_2 < 70 % wt. These tephras at the Finnish site can, however, be separated from each other based on stratigraphic position, ^{14}C dating and presence of a geochemically distinct cryptotephra population in the Finnish Hekla Ö deposit, that is known to be present in Iceland only in the Hekla Ö tephra layer east-northeast of Hekla (Publication III).

Correlating the distal cryptotephras to the proximal tephra record presents another set of challenges in distal tephrochronology. Even if the Icelandic tephrochronology is relatively well studied and consists of geochemically well-characterized tephra layers, many tephras may still be missing from it. For example, the geochemistry and eruption histories of Snæfellsjökull, Öræfajökull and Torfajökull (and Þórðarhyrna) volcanic systems have not yet been investigated sufficiently well (e.g. Hafliðason et al., 2000). Tephra from Snæfellsjökull, Öræfajökull and Þórðarhyrna may also have a low preservation potential in the Icelandic terrestrial records, due to the location of these subglacial volcanoes near the seashore. A further complication in establishing correlations between the distal cryptotephra findings and the proximal tephrochronology are the syn-eruptive changes in the geochemical composition of the eruption products, which take place for example at Hekla central volcano. Hekla is known to erupt tephra with a wide range of geochemical compositions (Larsen and Thorarinsson, 1977; Sverrisdóttir 2007), from a zoned magma chamber (Sigmarsson et al., 1992). Tephra with highest silica content is erupted during the opening phase and the less evolved eruptives are released as the eruption proceeds. Shifting wind direction during an eruption from the zoned magma chamber of Hekla may manifest itself as presence of several tephra sectors extending away from the volcano, each with a slightly different tephra composition (Larsen and Thorarinsson, 1977; Jónsson et al., 2020). In Iceland, correlations between different tephra sectors are supported by the stratigraphic position of the tephra between other tephra layers as well as comparisons with the more complete proximal tephra stack that represents several eruption phases (Jónsson et al., 2020). However, in the distal area the difficulties in correlating deposits that represent different phases of the same eruption become accentuated. The full range of erupted products is less likely to be present or analysed from a scarce cryptotephra deposit, and complex tephra dispersal patterns may deposit cryptotephra from different eruption phases in unexpected directions from the source volcano and the wind direction data from Iceland may thus be of little help.

The precision of tephrochronology as a dating method relies on accurate determination of isochron position in the environmental records. Most of the cryptotephra deposits in the Finnish sites form clear horizons that are confined to 1–3 cm of peat (Figure 6), whereas other deposits are diffuse. Post-depositional movement of tephra shards due to taphonomic processed in the peat has been verified experimentally (Payne & Gehrels, 2010). However, the diffuse deposits at the Finnish sites do not appear to represent just vertical post-depositional movement of tephra, but rather presence of cryptotephra from several temporally closely spaced volcanic eruptions. This may create difficulties in defining the exact isochron position for each tephra by simple shard counts, since it is generally not possible to determine which glass shards belong to each layer without EMPA. In some cases, determining the isochron position might be possible only by analysing the volcanic glass in each centimetre of the diffuse deposit and counting the ratios of separate tephra populations in each sample.

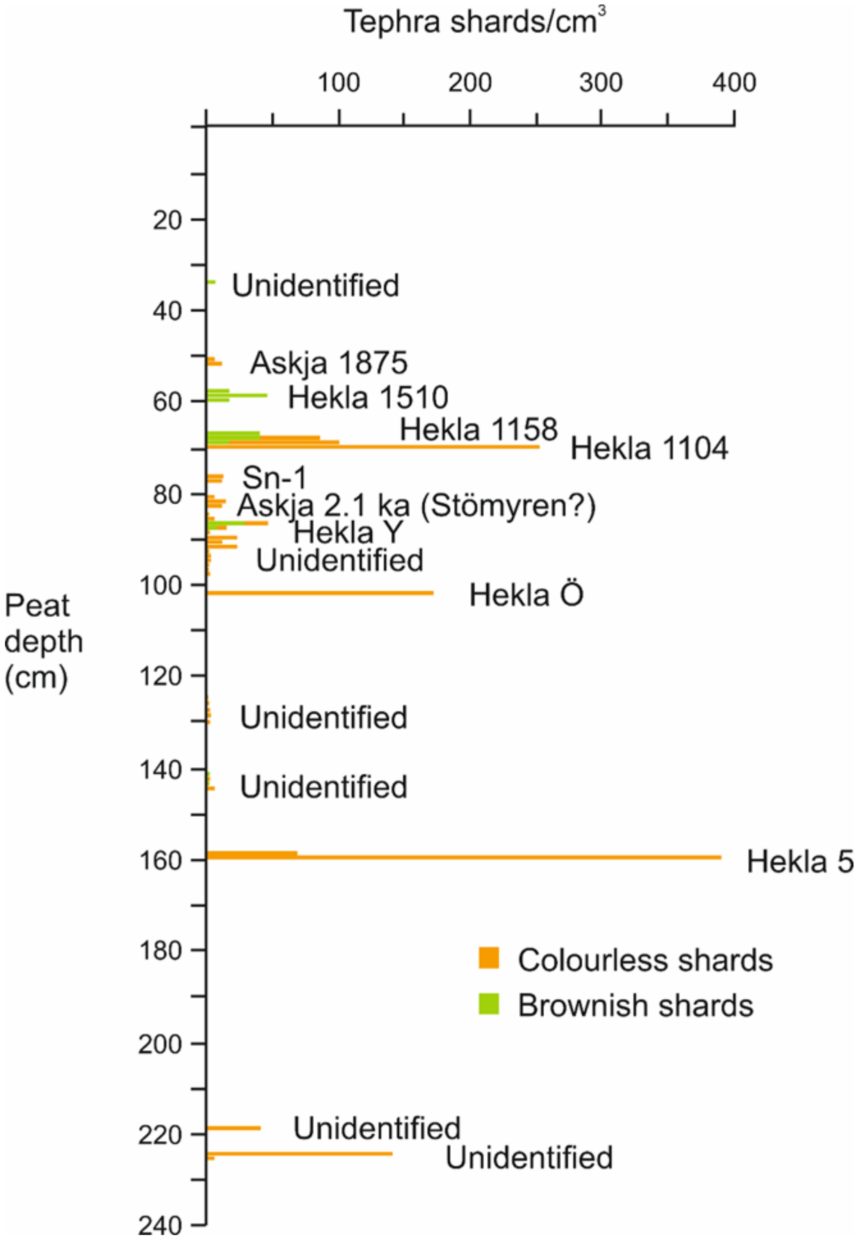

Figure 6. An example of tephra shard concentration profile from Kivihypönneva, west-central Finland.

4.3 Dialogue between proximal and distal tephra studies

Tephrochronological research in Iceland and cryptotephra studies in Northern Europe have advanced mostly along separate paths during the past decades. Important developments in the recent past include constructing new, regional tephrochronologies in Iceland (e.g. Óladóttir et al., 2011; Guðmundsdóttir et al., 2016, 2018; Harning et al., 2018) and extending the cryptotephra research in Northern Europe to previously understudied areas (Watson et al., 2016, 2017b; Cooper et al., 2019b; Kinder et al., 2020; Vakhrameeva et al., 2020). In this project, first steps for strengthening the dialogue between tephra research in Iceland and cryptotephra research in Northern Europe were taken with the aim of improving the Icelandic proximal geochemistry dataset and the Northern European cryptotephra framework simultaneously (Publication II and III). As a result, new proximal geochemistry datasets for Hekla 1845, Hekla X, Hekla Y and Hekla Z tephras were published and used for establishing robust correlations between cryptotephra findings in Finland and the proximal tephra records in Iceland.

Cryptotephra deposits in Northern Europe point at many silicic layers missing from both the LGIT and the Holocene tephra stratigraphy of Iceland (e.g. Lind et al., 2013; Jones et al., 2019). On the other hand, the chronological significance of sporadic distal cryptotephra findings remains low without a robust correlation to a proximal, well-constrained tephrochronology. An example of such cryptotephra deposit is the ca. 2.1 ka Askja tephra that was identified at one Finnish site (Publication III) and possibly correlated to Askja Stömyren tephra that has been geochemically characterized at one Swedish site (Wastegård, 2005). No correlation to proximal tephrochronology has been established for this tephra yet. One of the greatest challenges in constructing the Icelandic tephrochronology is the low preservation potential of tephra in the dynamic proximal environment (e.g. Boygle, 1999; Janebo et al., 2016). Lack of vegetation and high erosion rates work against stabilization of tephra deposits at some sites, whereas accumulation of remobilized tephra at others may result in secondary tephra deposits that could be mistaken for primary fall-out without careful assessment of the layer and tephra grain properties and methodical analysis of tephra geochemistry (e.g. Guðmundsdóttir et al., 2011b). Additionally, the sheer number of Holocene volcanic eruptions makes establishing the geochemical composition of every eruption a slow task. Consequently, published geochemical data may be lacking even for some of the well-known eruptions. One way to address these shortcomings and to facilitate better correlations between the distal and proximal tephrochronologies is to use the Northern European tephrochronological framework as an instrument to target specific sections of the proximal tephrostratigraphy for locating and geochemically characterizing the tephra layers that are known only from distal records overseas. In Iceland, the distal areas that are located well away from the active volcanic zones are likely to have more stable environmental conditions with continuous and calmer sedimentation and thus provide an opportunity to test also high-resolution cryptotephra research methods within Iceland. First cryptotephra studies in the distal areas in Iceland indicate that the methods can be modified for Icelandic conditions and used for refining the tephrochronology of single sites (Kalliokoski et al., in preparation). Therefore, further cryptotephra work at Icelandic sites is recommended for enhancing the dialogue between proximal and distal tephra studies and for improving both the Icelandic and Northern European tephra framework simultaneously.

5 Summary/Conclusions

In this dissertation Finnish environmental records were investigated for presence of cryptotephra. The commonly used cryptotephra research methods were tested for the first time in Finland with good results. The main outcome of this study is an outline for a Finnish Holocene tephrochronology that consists of 16 geochemically characterized cryptotephras. Cryptotephras identified in Finland originate both from Icelandic and Alaskan volcanic eruptions and offer opportunities for precise dating and intercontinental correlations of environmental archives. Robust correlations to proximal tephra records and source eruptions have not yet been established for all the deposits that were detected in the investigated sites. Geochemical fingerprinting of the small and scarce cyptotephra shards in Finnish environmental records is a challenging task in itself, and gaps in knowledge on the eruption history and lack of proximal geochemistry data from some of the Icelandic volcanoes further complicates tracing the cryptotephras back to their source eruptions. To overcome these difficulties, geochemical data for four tephras from Icelandic proximal records were produced in this study. Simultaneous investigation of several sites in central and southern Finland allowed comparisons to be made between the tephrostratigraphies of individual sites and enabled establishing a first outline for a Finnish tephrochronology, which serves as an initial framework that can be expanded and refined by future cryptotephra research in Finland and nearby regions. This study has revealed a great potential for using tephrochronology as a dating method in Finland and demonstrates the benefits of enhancing the dialogue between proximal and distal tephra work with the aim of improving tephra frameworks of both areas simultaneously.

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