A Late Holocene tephra record of the last ±4000 years from Sundneset, Barentsøya, E-Svalbard.

S.J. Schouten

Student nr: 5699266

Abstract

With an increase in public interest towards climate science and the high demand for chronological markers correlating palaeoclimatological data from proxies, an accurate timescale is imperative. In this thesis, attention is drawn to tephrochronology: the use of volcanic ashes from known eruptions that act as time equivalent stratigraphic markers. Here, a tephrochronological research on lacustrine sediments from the Svalbard archipelago is outlined. A careful collection was made based on expected tephra horizons. Floating sediments were prepared into microscope slides, in which they were counted. To make use of a secondary independent proxy, diatom fragments were counted with respect to the particle density. An age depth model was constructed on which a loss of ignition profile was plotted. Shard count was plotted relative to this age model, reconstructed from C14 dates. Several tephra and corresponding diatom peaks were found and interpreted: The Hekla-1104, Öraefajökull-1362, Hekla-3 and other not yet interpreted tephra peaks around 850-900 AD and 1400-1500 AD. The resulting LOI-curve reflects the arctic climate of the past 2000 years quite good, indicating that the interpreted ages of tephra peaks are likely to be correct. Possible suggestions were given on the relative abundance of tephra in Higher LOI sections, likely related to warmer climate. The weather pattern footprint on tephra distribution was used to connect periods in time when tephra deposition on Svalbard would be more likely (due to change of average wind direction). More tephrochronological research in Svalbard will be needed, before this region becomes an important trans-arctic correlating region. This implies that the Svalbard could connect cryptotephra from different source areas (Asia, Europe and North-America).

Content

1.0 Introduction

Visualizing the course of the more recent past is of great relevance. A look at the daily CO2 charts visualizes that climate is changing. The question remains why is it changing, and has it always been changing? In fact, the climate of the earth consists of change upon change upon change… it is simply not stable. Solar cycles, for example, show a distinct climatic signal found all over the world. However, in the arctic this signal can be interpreted differently. Climate signals are amplified here into abrupt and clearly visible, sometimes critical, changes. The reconstruction of Svalbard's Holocene climate is heavily dependent on dating methods, which can be provided by different methods such as; annual laminations, C14-dating, Optically Stimulated Luminescence or Tephrochronology. In this study one of these dating methods, C-14 dating, is used to reconstruct the other, tephrochronology, a chronological record of microscopic ash particles deposited by fallout and washout from the sky after being emitted by a volcano elsewhere.

1.1 A brief introduction to tephrochronology

Tephrochronology is a method, relying on the occurrence of volcanic glass particles in sedimentary records. Glass particles which are emitted during relatively short volcanic events create regional to continental, time equivalent markers. By using several of these markers a chronology can be set-up, this method of constructing a chronology is called Tephrochronology and it is becoming increasingly popular. It proves (Gale, 2009; Lowe et al., 2007) to be a promising dating method, especially when used in late quaternary ice cores (due to clearly visible annual laminae) and limnic cores. This popularity may be related to the societal call for climate data but most probably originates from the scientific interest to correlate and understand the interaction between different climatic archives especially, ice core, marine and terrestrial records and the supporting chronological methods. Tephrochronology supports an age framework that, in many cases, supports another climate related data set. Using tephrochronology to reconstruct a stratigraphical framework relies on two rather basic assumptions: "the law of superposition" and age or date transferring by mineralogical matching of certain tephras. This study however will only focus on the first of the latter, pinpoint at tephra layers and match them in accordance to "the law of superposition". Tephras are perfect candidates to produce isochronous marker beds within age reconstructions (Lowe, 2011) because they are erupted and deposited during a, sometimes given or known, short period rarely lasting beyond two years. Note, the time scale matters, using distal (crypto) tephras with a multiple month margin for studies regarding ENSO or NAO cycles can be criticized, however, on the timescale discussed here a maximal error of two years, with respect to other dating methods, can be considered rather low. Additionally, fallout rates for tephra are relatively quick (Mills, 2000; Rose & Durant, 2009); their settling time is proven to be rapid (Manville and Wilson, 2004; Wiesner et al., 1995), which reduces the marine or lacustrine residence time, meaning there is less time to possibly modify the tephra particles (Carey, 1997). Besides, tephras are widespread and can travel over vast distances, especially cryptotephras (Blockley et al., 2007a; van der Bilt et al., 2017; Zielinski et al., 1997). Possible difficulties regarding this tephronological method are outlined in the next section.

1. Reworking and external input is proposed as one of the main contributors to errors in the tephrochronological method (Boygle 1999; Dugmore et al. 2004; Gehrels et al. 2006; Payne and Gehrels 2010). If tephrochronological layers are reworked by secondary processes, they would create diachronous instead of isochronous surfaces. Fluvial, rain flushing, aeolian reworking as well as slumping and redeposition can cause faulty age reconstructions (Manville and Wilson 2004; Shane et al. 2006). Cryoturbation, soil formation and bioturbation can cause the lacustrine layer cake to be disturbed or tephra to be concentrated into lenses (Froese et al., 2009; Sanborn et al., 2006). This can be due to Snow cover inclusion effects, especially when cold summers with little melt occur (Bergman et al., 2004; Davies et al., 2007). Indicators of reworking can be: roundness, blurry crystals or other stratigraphically cooccurring proxies, such as pollen, that do not fit with the reconstructed time from the tephra.
2. Wrong age interpretation, caused by "multiple or non-unique fingerprints" due to magma variability during eruptive events (Brendryen et al., 2010; Shane et al., 2008). This mostly applied on difficulties regarding correlating events geochemically.
3. Wrong existing frame work correlation can occur due to the lack of other stratigraphic indicators or the incompleteness of the tephronological record (Davies et al., 2004; Fiske et al., 2009; Newton et al., 2007).
4. If secondary effects related to volcanic eruptions and the tephra deposition, such as diatom blooms, acidic events or sulphate peaks, are used as a tephra indicator instead. If these proxies are connected to the tephra, regardless the lag such events might have on the actual depositional event, the age reconstruction could be considered off-date (Lowe and Higham, 1998; de Silva and Zielinski, 1998; Traufetter et al., 2004).

5. Changes in tephra thickness and distribution inside the catchment can differ laterally, also in lacustrine environments, due to climate changes. In a detailed study from Pyne-O'donnell (2011) glacial ashes were found closer to the inlets than Holocene ashes, indicating a tephra sorting effect within the lake morphology. Secondary tephra deposits from inlets can be separated by measuring the abundance of another catchment dependent mineral, indicating external sediment influx. External sedimentary input also possibly contains tephra from older stratigraphic horizons.

Besides reconstructing an age framework, tephras can also be investigated to produce an explosive volcanism record, which might allow for time-space relations which can be used to prevent natural hazard danger in the future. Distal studies on cryptotephras will contribute significantly, constructing this interhemispheric to global tephra record, since multiple eruptive sources can be aligned if found in the same core (Lowe et al., 1999; Molloy et al., 2009; Shane et al., 2006). Due to the rise in attention for cryptotephras, the geographical distributions had to be revised in many cases (Blockley et al., 2007; Coulter et al., 2009; Davies et al., 2008; Lowe et al., 2007; Payne et al., 2008), Broad distribution of tephras can be underlined by studies of modern eruptions ranging as far as ~8000 km from the source (Davies et al., 2010; Walker, 1981). Note that 1982 El Chichón spread out ~10,000 km from source (Zielinski et al., 1997), whereas 1883 Krakatau spread ~12,000 km (De Silva & Zielinski, 1998). However, weather conditions in the weeks/months after the eruption may significantly effect distribution patterns of cryptotephras (Davies et al., 2010). Furthermore, Pyne-O'donnell (2011) supported the theory that rainfall events and sea ice cover also effects the distribution of tephras, as was observed in Finland after the Hekla 1947 eruption. That ice rafting can influence the distribution of marine tephras has been proven by Austin et al. (2004) and Shane and Froggatt (1992). Tephras have been reported that fell on the sea ice and were deposited with a decadal to millennial scale lag.

Knowing the extent of volcanic ash clouds can be of basal implication for further studies regarding evolutionary patterns, as has been shown to be the case with the Laacher See tephra (Riede & Bazely, 2009), but also for studies regarding respiratory health. From studies on modern eruptions, like the Eyjafjöll eruption in 2010, an increasing amount of knowledge arises on the distal effects of volcanic eruption on the respiratory health of the affected people (Davies et al., 2010; Newnham et al., 2010).

With all of this being said it can be questioned why there is not more knowledge on tephrochronology of the arctic? This report tries to contribute to these questions by asking the following research questions:

- Which ash clouds did reach Svalbard within the last 4000 years, and are there observable trends within the frequency of ash clouds over Svalbard?
- Which mechanisms are responsible for these trends? Additionally this thesis aim to explore the value and validity of the method of simple tephra counting?

2.0 Geographical setting

2.1 Svalbard archipelago

The archipelago of Svalbard consists of many islands, of which Spitsbergen, Edgeøya, Barentsøya and Nordaustlandet are the largest. This thesis is focused on the same coring site as used by Woelders et al. (2018) in Andsjøen Sundneset on Barentsøya. Other limnological studies of importance which have been used for comparison are done on the Spitsbergen island at Kongessvatnet (D'Andrea et al., 2012) and lake Hajeren (van der Bilt et al., 2017, 2018), and the Lomonosovfonna ice cap (figure 1). The Sundneset lake is situated on the southern tip of Barentsøya, and is relatively isolated from stream runoff inlets. Although sheet like surface runoff is probably still a main contributor to the sedimentary influx into the lake, the lack of main channelized inlets makes this lake unique. Aeolian transported sediments are likely one of the main contributors to the sedimentary influx into the lake. Furthermore, the lake is surrounded by small *"Salix polaris"* plants, which allow for the construction of an independent time scale construction by C-14 dating. The scarcity of data (especially limnological data) from eastern Svalbard can be explained by its inaccessibly and its geology (Woelders et al., 2018). The geology of eastern Svalbard consists of easily erodible sedimentary rock in which small catchment basins are rare. However, the bedrock of the catchment around the Sundneset lake is different and consist of intrusive dolerite material of the Diabasodden suite (Dallmann et al., 2015). The formation of this intrusive suite is dating back to the late cretaceous high arctic large igneous activity (Senger et al., 2014). Important to notice is that the dolerite is of basaltic origin and will not contaminate the collected float, containing the volcanic glasses.

Climatically, the Svalbard archipelago, being located where the little oceanic heat left from the gulf stream meets cold arctic waters, can be considered as an important study area for climate scientist. Consequently, during the summer, Svalbard marks a boundary of the major conduits of atmospheric heat and is, during warmer periods, (also in winter) more exposed to the distinct, jet stream related, airmass boundary (Francis & Vavrus, 2012, 2015). The connection to the Atlantic regime is illustrated by the agreement between the precipitation patterns in Svalbard and the trend of fluctuations in the mode of the North Atlantic oscillation (NAO) (Dickson et al., 2000). Svalbard is an unique area to arctic climate science, because relatively much is known of its climate due to its easy accessibility within the arctic region. A record of the past 100 year exists for Longyearbyen (Nordli et al., 2014), which shows important warming trend in climate as can be expected, given the course of the last decadal carbon dioxide concentrations. Furthermore, the influence of solar activity might be recognised on a decadal scale. An hypothesis is that this pattern is aligning with the long term NAO changes. Several climatic studies done on ice caps (Divine et al., 2011; Grinsted et al., 2005) were presented as the demand for climatic understanding raised by the day. To understand how natural climatic rhythms function and shed their light upon Svalbard and its environmental conditions, one should try to get a grasp of climatic fluctuations, including a (multiple) millennial time span. In this study this is accomplished by working with two independent timescales based on C-14 and tephrochronology, lasting up to ±4000 cal. BP, which can ideally create a time frame with a decadal resolution on which climate indicators can be plotted. Major climatic events following volcanic events may then also be recognised, as they effect the high arctic climate.

As suggested by D'Andrea et al. (2012), temperature reconstructions from Svalbard do not line up with reconstructions from the rest of the arctic. This might be due to the slower/less significant response of the arctic region to changes in meridional heat flux from the gulf stream, compared to Svalbard. The same miscorrelation was found for "the little ice age"(LIA) period. To reflect on the disagreement between the trends indicating a rather warm LIA (D'Andrea et al., 2012; Spielhagen et al., 2011) and a rather cold arctic LIA (Humlum et al., 2005; Kaufman et al., 2009), a longer term LOI curve can be expected from the Andsjøen lake.

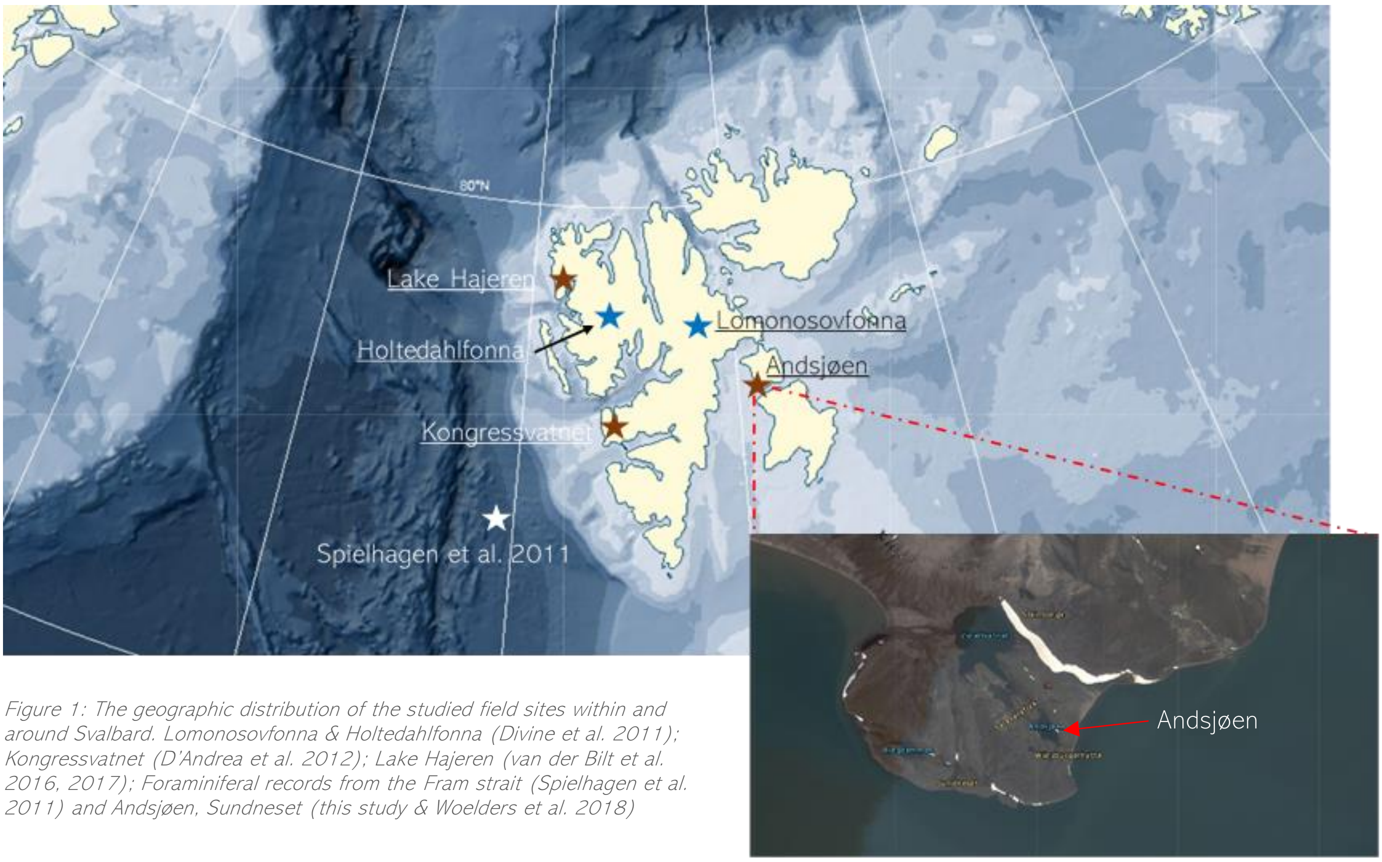


Figure 1: The geographic distribution of the studied field sites within and around Svalbard. Lomonosovfonna & Holtedahlfonna (Divine et al. 2011); Kongressvatnet (D'Andrea et al. 2012); Lake Hajeren (van der Bilt et al. 2016, 2017); Foraminiferal records from the Fram strait (Spielhagen et al. 2011) and Andsjøen, Sundneset (this study & Woelders et al. 2018)

2.2 Hypothesised tephra peaks on Svalbard (0-4000 years ago)

For the construction of a tephrochronological framework, it is important what tephra fall-out, from which volcanic source area, can be expected on Svalbard. The closest tephronological sources recorded are from Iceland, which is already quite far away. However, one closer volcano exists of which tephras have been found in Ireland, where they linked the MOR-T2 tephra to a Jan Mayen eruption. This tephra has, however, not yet been found elsewhere. Table 1 (and the connected figure 3) shows some estimations of distances from Sundneset. Note also that direction matters because of wind patterns transporting the tephra, especially when the distance to the source is higher than 1000 km (Davies et al., 2010).

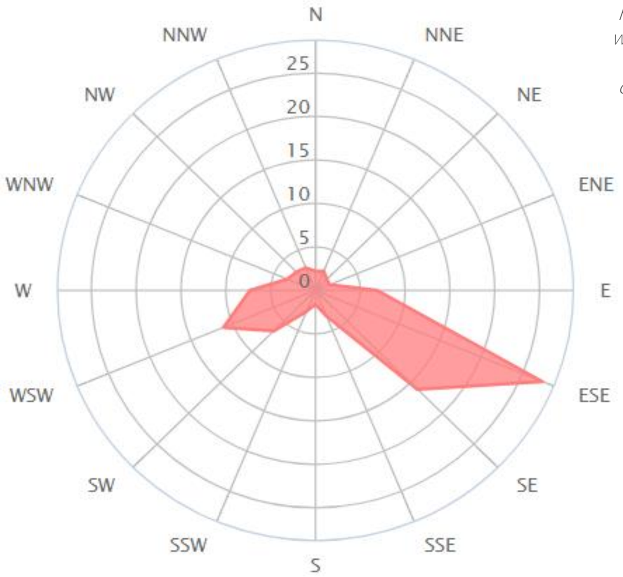


Figure 2: A windrose, reflecting the bidirectional wind distribution around Longyearbyen, Svalbard. Note there is influence of valley induced wind direction but in general it reflects wind direction distribution over Svalbard

When combining the tephrostatigraphy from Europe and Greenland, since they are closest to Svalbard, an idea of which eruptions can be expected in the lacustrine sediments of Barentsøya can be formed. However it is noteworthy that the main wind direction on Svalbard can be characterised as easterly, with minor phases (related to jet fluctuations) of wind from the south-west (figure 2). This limits the reliability of correlating tephras based on timing without doing any further geochemical characterization, especially regarding tephra horizons that have yet not been correlated to a volcanic event. Since Icelandic volcanoes alone already produced close to 150 tephra layers in one millennium (Larsen & Eiríksson, 2008) a selection was made among tephra layers that were assumed as relevant. The following tephras can be expected based on their distribution and known literature.

Area's	Distance from Sundneset (km)
Lofoten	1100 S
Jan Mayen	1160 SW
NGRIP, NEEM	1500 W
Iceland	2000 SSW
GRIP, GISP2	2000 WSW
Swedish lakes	2000 S
UK, NL, Ireland	3000 S
S-Alaska	4800 N
Kamchatka	5000 NE

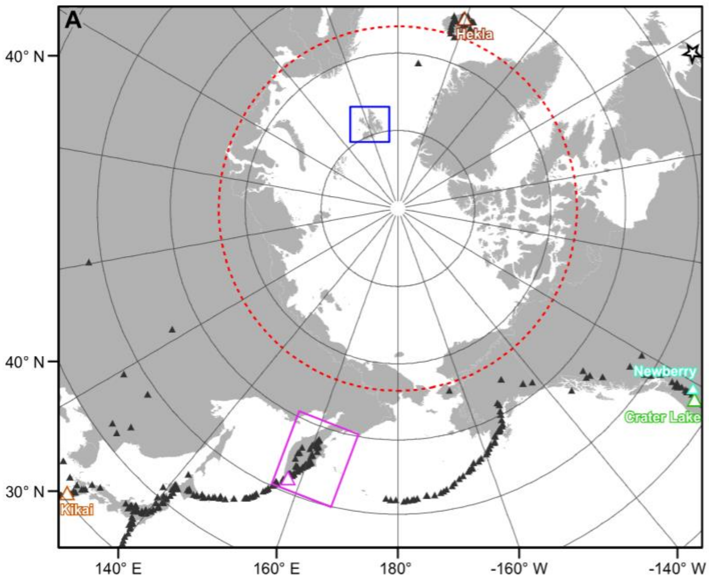


Figure 3 & Table 1: The location of volcanic sources around the arctic; figure was modified from van der Bilt et al. 2017. Table 1 outlines source areas (blue & black) and catchment areas where tephra was found (red & pink) and gives an indication of the distances

Hekla-1947

This tephra has been reported to the south of Iceland on ships and has mainly been observed in the Baltic states and Finland (Thorarinsson, 1954). Another southerly lobe existed (figure 10), based on records from three bogs in Ireland (Kirkbride & Dugmore, 2003; Swindles, 2006). The identification of shards from this eruption event in North-Western Canada, however, raises extra awareness to this study. The finding of this tephra in Yukon suggests a transpolar pathway possibly passing over Svalbard (Yalcin et al. 2003).

Grímsvötn-1903

10 Tephra particles from this eruption have been documented in Svalbard in a study of the Lomonosovfonna ice cap (figure 10) (Isaksson et al. 2001). TiO_2 concentrations are described between 2.8-3.2% with a FeO_{tot} around 13%. Kekonen et al. (2005) based an age model on two other reference layers in the Svalbard ice: the Laki 1783 tephra and a radioactive layer, constructed with the (Nye, 1963) relation, based on the radio- activity peaks (connected to nuclear tests) that were found in that core, which appear in 1962-63 and 1954 (Pinglot et al., 1999). The Grímsvötn and laki tephras were stratigraphically aligned to these peaks, to construct an age depth model. Additionally, a north-easterly dispersal has been always been assumed for the tephra from this eruption as an ash cloud was also observed from a ship to the north-east of Iceland.

Askja-1875

Although the Askja 1875 eruption is not the largest tephra emitting event of Icelandic origin, it is unique, since it has mainly been described on northern locations like the Lofoten Norway and Sweden (Persson 1966, 1967; Pilcher et al., 2005; Wastegård and Davies, 2009). This tephra was emitted relatively fast in a matter of a few hours (Sigvaldason, 2002) making its proximal impact on north-eastern Icelandic communities very significant and documented (Pilcher et al., 2005). This tephra has a relatively high MgO and TIO_2 content (Davies et al., 2007; Larsen et al., 1999).

Laki-Grímsvötn eruptions-1783:

Tephra from this eruption has been retrieved from the Lomonosovfonna ice cap, where the tephra was used to add proof on the sulphuric event that occurred in the aftermath of this eruption (Kekonen et al., 2005). The Laki-Grímsvötn eruption is known to have produced mayor amounts of aerosols and has therefore always been studied because of its continental/hemispheric climatic impact, causing large scale crop failures in Europe and health effects on Europe (Durand & Grattan, 1999; Grattan & Charman, 1994). So-called dry fogs and a significant cooling event, as well as a sulphuric event, are associated with this eruption across north western Europe including the Netherlands (Gastron, 1997), where it also occurred as a visible tephra horizon (Cremer et al., 2010).

Veidivötn-1477

The Veidivötn-1477 eruption can be considered as one of the most explosive events in Icelandic history. Tephra from this eruption has been found on the north Icelandic shelf (Larsen et al. 2002), central Sweden (Davies et al., 2007) and western Ireland (Chambers et al. 2004). Tephra from this eruption has a tholeiitic composition and originates from the Veidivötn fissure swarm. It is possible that this tephra reached Svalbard, since it has a relatively large north-easterly dispersal (Larsen et al. 2002; Davies et al. 2007).

Jan Mayen-ca.1400 (MOR-T2 & PMG-5)

Eruptions from mt. Beerenberg have been reported in 1732, 1818 and 1970 (Sylvester, 1975). Jan Mayen eruptions are proposed as a potential source for the mysterious tephra layers MOR-T2 and PMG-5 in Irish lakes (Chambers et al., 2004; Hall & Pilcher, 2002). Since the location of Jan Mayen is favourably close to Svalbard one should keep a close eye on possibilities of tephra correlation with the geochemical composition of mt. Beerenberg. (Na_2O & K_2O is high). The tephra could easily have reached Svalbard under the influence of summertime south-westerly winds.

Öræfajökull-1362: Svalbard

The Öræfajökull 1362 eruption was the most voluminous Icelandic eruption of the Icelandic volcanic record (Palais et al., 1991; Thorarinsson, 1958). Cryptotephra from this eruption has been identified at many places across Europe and was also found on the GRIP coring site in Greenland (Coulter et al., 2012; Pilcher et al., 1996). This makes the Öræfajökull 1362 tephra a useful isochronous marker across Europe. The tephra can be geochemically identified by its high Na_2O and very low MgO composition (Larsen et al., 1999). Its dispersal was northerly with a small southerly lobe as depicted in figure 10.

Hekla-1158

This VEI 4 eruption occurred just decades after the large VEI 5 Hekla-1104 eruption. Nonetheless, its composition differs significantly enough to be distinguished from its older twin. TiO_2 concentrations are lower than the Hekla-1 and FeO_{tot} concentrations are higher (Larsen et al., 1999). The Hekla 1158 eruption has a north-easterly dispersal (Thorarinsson, 1967) which is confirmed by the findings of this tephra in Lofoten lakes (Pilcher et al., 2005). Tephra from a similar composition has also been found in Ireland (Hall and Pilcher, 2002).

Hekla-1104

The Hekla-1104 eruption (or Hekla-1) can be considered as a very important isochronous marker in the European tephrochronology (Boygle, 1999; Chambers et al., 2004; Vorren et al., 2007). The main dispersion is northly (figure 10) which can be concluded from the many north Icelandic marine studies (Eiríksson et al., 2000; Kristjánsdóttir et al., 2007); findings in Scandinavia, Faroe islands and Svalbard (D'Andrea et al., 2012; Pilcher et al., 2005; Vorren et al., 2007; Wastegård et al., 2001). A southerly lobe must also have existed as suggested by findings in from Irish lakes (Chambers et al., 2004; Hall, 2003; Pilcher et al., 1996) The occurrence of the Hekla-1 tephra coincides with wet environments, such as western Norway and Ireland, suggesting a distributional relation with precipitation patterns by the time of eruption (Langdon et al., 2003).

Landnám tephra-875:

The Landnám tephra is thus far recognised in the Lofoten, Swedish lakes and GRIP ice cores (Pilcher et al., 2005; Wastegård et al., 2003 Grönvold et al., 1995). All these areas surround the Svalbard archipelago and suggest a northerly distribution of this tephra. The tephra is the result of a double eruption of the Veidivötn volcanic system. Two different magma chambers erupted, which resulted in the production of basaltic and rhyolitic tephra components. On the Greenland ice sheet this tephra has been dated and correlated to sulphuric horizons (Grönvold et al., 1995; Zielinski et al., 1997)

White river ash-AD860

This tephra has first been described in the Sluggan Bog in Northern Ireland, where its data was defined by wiggle matching to AD-860 (Pilcher et al., 1995). Nowadays, the tephra is known from Northern Germany and Ireland and has been proposed to be found on Svalbard (Plunkett and Pilcher, 2018), where its source was proposed to be the Alaskan Churchill mountain. The White river ash had a northern lobe, which might be represented in Kongressvatnet, Svalbard, (D'Andrea et al., 2012). It seems to be likely that this ash also made it into Europe, with new insights suggesting an easterly lobe extending all the way into Poland and Scandinavia (Watson et al., 2017). Besides, tephra from an older mt. Churchill eruption, named the Hall tephra, has been found in Northern Ireland, interfingering with the Hekla-4 Tephra.

Kamchatkan tephras: SH3 (650 AD) & KS1-200 AD

Since the first finding of Kamchatkan tephra on the Svalbard archipelago dates back to approximately 7000 cal. yr. BP (van der Bilt et al., 2017), a new option for interhemispheric/transarctic tephra correlation opens up. Earlier ashes have been correlated to Kamchatkan sources in Ireland, where a small number of tephras correlated positively with geochemistry of the Shiveluch produced tephra, as described by Ponomareva et al. (2015, 2017). Tephra from eruptions that can be expected in Svalbards record are the Ksudach 1, Shiveluch 2 and 3 as defined by Braitseva et al. (1997).

Hekla-3 (1087-1006 BC)

The Hekla 3 tephra is much discussed, because its hypothesized climatic impact in the 1100's BC (Baillie & Munro, 1988). The tephra is not much studied yet, since its known distribution is limited to Northern Germany, Scandinavia and Northern Icelandic shelf (Van Bogaard and Schmincke, 2002; Dugmore et al., 1995; Plunkett, 2006). This may indicate a two lobe distribution of ash clouds: a northern lobe and a south-eastern lobe. This northern lobe may have reached Svalbard, but since no tephra from this period of time has yet been found in the arctic region (Pilcher et al., 2005), no conclusions were made. Typical about this tephra is that its magnitude is not well known and it is one of the few tephras that is virtually absent in the Faroe and British isles.

3.0 Methods

Samples were taken in the Andsjøen lake on the island of Barentsøya, Svalbard (figure 1) during the 2015 SEES.NL expedition. The sedimentary record is a composite which consist of 5 different core segments. Two of the cores were gravity cores (SN-I, SN-II) which were taken at two locations some 5 meter apart, in the lake. At the location of Gravity Core SN-I, two subsequent piston cores (SN-III and SN-IV) and one gauge SN-V have been obtained. The gravity cores and gauge core were described and sampled in the field. Every centimeter was sampled and taken to the lab for geo/eco(chemical) analysis. The piston cores remained closed in the field and were only opened in the laboratory. The lake was chosen because of its accessibility - given that the SEES.NL expedition went alongside Sundneset - and depth, as a 3+ meter water depth was expected to be sufficient for liquid water to remain at the bottom of the lake during winter and for the sediment not to be cryoturbated. Another criteria was elevation, meaning that the lake is not connected to the sea and is slowly being elevated due to glacio-isostatic rebound, but on the other hand is not too high to be directly influenced by a glaciers or a glacial rivers. The occurrence of the *Salix polaris* around the lake, appeared to be of crucial importance to obtain a good chronology for the cores. Salix leaves were abundantly present in the cores and sampled for C-14 dating to construct an age depth model. In this study one main dating method was consciously used (C-14) to construct and check the reliability of another dating method. However because the age estimations used for tephra preparation were based on C-14 dates the two cannot be considered as independent proxies. In this way tephrochronological ages may visibly confirm or contrast with the retrieved C-14 dates. If age reconstructions turn out to align well then one might be more confident on the composite LOI graph, which shows the first results of this research project, as presented on the "EGU general assembly" (Hoek et al., 2016). This results in the possibility of aligning trends between LOI and tephra layers, as was also done by Gehrels et al. (2006, 2008) and Payne and Gehrels (2010)

To identify tephra layers within the Sundneset sediments, a certain interval of sediments must be captured and analyzed in the laboratory. Known methods to differentiate between silicic fractions: diatomic, phytolithic, volcanic (crypto, micro and macro tephra) and quarzitic are described by Blockley et al. (2005), Lowe (2011), Plunkett and Pilcher (2018).

The Sampled sediments were handled and prepared according to the following procedure:

1. Small *Salix polaris* leaves were taken for AMS C-14 analysis
2. Samples of 1cc were dried at 150 and ashed on 550 degrees to produce a LOI & moisture profile
3. From the C-14 dates, a sedimentation rate could be determined and a continuous estimation of age depth correlation was constructed (figure 4).
4. Known eruptions were correlated to depth, after which the ashed samples were taken for further analysis
5. Samples were washed with HCL to dissolve the $CaCO_3$ components and remove some of the iron coating on the grains.
6. Sodium dithionite was added to dissolve the remains of the iron coating that was still on the samples after the oxidation of iron during ashing
7. Samples were sieved through a 30 μm mesh. The residue was kept, since it is reported that the size of tephra shards mostly ranges between 10-100 μm (Wastegård, 2004)
8. The residue was further sieved through a 8 μm sieve to still have access to the 8 – 30 μm fractions. Smaller (<8 μm) siliceous fractions were washed away.
9. Sodium poly-tungstate SPT liquid was used to separate the quartzic and rhyolitic & felsic components at a density of. 2.5 kg/l
10. The samples were centrifuged for 10 min on 2500 rpm to separate the floating fraction from the sinking fraction properly. This step was done 3 times over to make sure all the float was captured.
11. The SPT fluid was recycled by adding distilled water, reducing the concentration of the heavy liquid and centrifuging on 2500 rpm for 10 m three times.
12. Samples were prepared for microscopic analysis on glass slides (with glycerine and parafine).

Simple counting using a a Leitz polarizing microscope with a 500x magnification was used as a method to quantify the tephra inside every centimeter of sample (see below).

To identify and characterize tephra particles in the given sample, glass shard morphology and isotropy was analyzed. Assuming that the glass composition has a direct relation with the magma composition, one could expect tephra particles to have a nearly unique fingerprint. However, for some Icelandic tephras this is disproven, since the corresponding volcanic events have near similar fingerprints (Larsen & Eiríksson, 2008). Typical characteristics are:

1. Disappear under microscopic cross-polarizing light (Lowe, 2011)
2. Tephras may look stretched and are most often glassy.
3. Particles may contain a bubble wall
4. Particles can be vesicular
5. The angularity of the shards can, if not modified by secondary processes, give an indication of the eruption characteristic (Hamann et al., 2010)

Quantifying the amount of tephra inside a 1 cm sample was rather difficult since there was a lot of floating target fraction captured. Therefore, a fractional estimation was made that one slide contains a representative pallet of particles. Since the goal of this pilot study is restricted to roughly locate tephra horizons, for some sampled cm where tephra was expected, a microscope slide was made which was scanned through for tephra particles. The total amount of tephra must give an indication whether certain peaks might be present in the record, accordingly to the aim of this research. This would help further research to be done on this core more directly. Tephra can be picked at the approximate horizons from the untreated core material and used for XRF or laser-ablation geochemical analysis. Besides rational counting, a sense of the tephra particle density was made by counting in representing circular area's on the thin section. At these area's diatoms were also counted by assuming that a diatom bloom will arise from the silicic input of a tephra peak (Hamme et al., 2010; Harper & Mc Leod, 1986; Merkt et al., 1993). A more or less random selection of 2 to 4 representative areas per thin-section were scanned on diatom (fragments). This allows us to use a secondary indirect proxy on finding the stratigraphic position of tephra peaks.

4.0 Results

4.1 Constructing an age depth model

The age depth model for the Sundneset composite core log was made via an extrapolation of the C-14 dates that were retained from *Salix polaris* leaves in the core. Deposition rate was determined by:

$$Sedimentation\ rate\left(\frac{cm}{yr}\right) = {dz}/{dt} = {d_2 - d_1}/{C^{14}{}_{d2} - C^{14}{}_{d1}}$$

Following up on this is the time captured in one cm of deposited sediment which is accordingly; $(\boldsymbol{Sedimentation\ rate})^{-1}$. An age depth correlation was constructed (Figure 4). The graph shows a three stage model of the sedimentation in the lake. The constructed composite is not linear, indicating differences over time within depositional rate. Therefore, the core was subdivided into 3 depositional stages. Stage I represents rather slow and continuous deposition, stage II has a more variable and faster deposition rate and stage III has a high deposition rate. Furthermore, the age depth model visualizes that within a taken cored section the depth correlation is not linear, except SN-V, which seems to be linear. The other cores, however, visualise that the depositional stages are not related to the cored sections, which underlines the quality of the composite. A similar age depth relation (Figure 4, orange) was made for the core taken at Kongressvatnet (West-Spitsbergen) (D'Andrea et al., 2012).

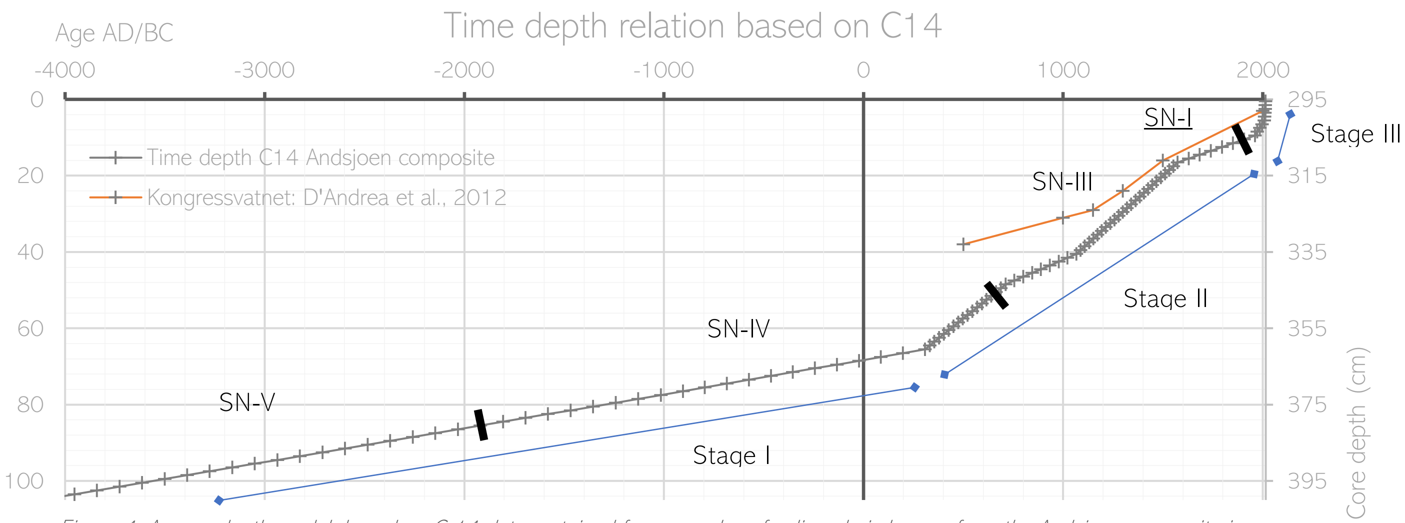


Figure 4: An age depth model, based on C-14 dates retained from samples of salix polaris leaves, from the Andsjoen composite is presented in grey. The age depth model from Kongressvatnet (figure 1) is presented in organe. Furthermore the cores are assigned with SN-I, III, IV and V and the stage model is outlined by three blue lines reflecting the general trend.

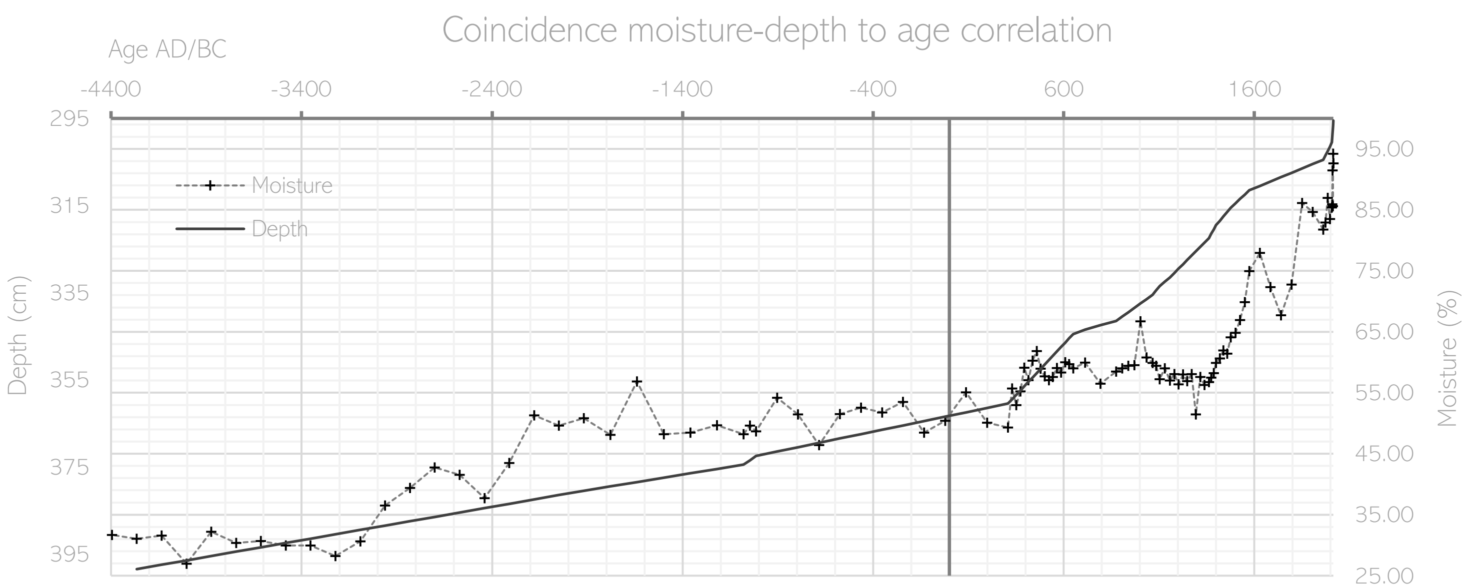


Figure 5: The combined, tephrochonological and C-14 date, age depth model is plotted with the grey line. The moisture content of the composite is plotted with the dotted line, data points are given with the + signs.

A two stage linear diagram was constructed. Although the time depth correlation at Kongressvatnet is a bit younger and was cored less deep, the trend visualises the same as found in Andsjøen. The top 15 cm of the Andsjøen composite is made up by sediment obtained with a gravity corer, which was fairly saturated with water.

To get a sense of the correspondence between moisture and sedimentation rate, the two are plotted in figure 5. Even though the moisture content and the depth to age model show the similar trends over time, It is important to keep in mind that moisture content is also dependent on sediment type and organic content. The start of the distinct rise in moisture around the 1400 AD does not coincide with the lowering of the sedimentation rate, which already starts around 400 AD. Another deficit between the two parameters occurs around 2000 BC where the moisture content remains relatively high and the sedimentation rate is also already quite high. Note the inverse relation between sedimentation rate and time captured in a unit of depth. The overall trend, however, outlines the same level of decline. The latter is supported by the data presented in figure 6 where the moisture content is plotted against the invert of the sedimentation rate. The general trend in decline of moisture is visualized by a trendline with the apparent formulae denoted in the graph. Even though the linear relation between these parameters is not fitting perfectly, it displays that they are closely related.

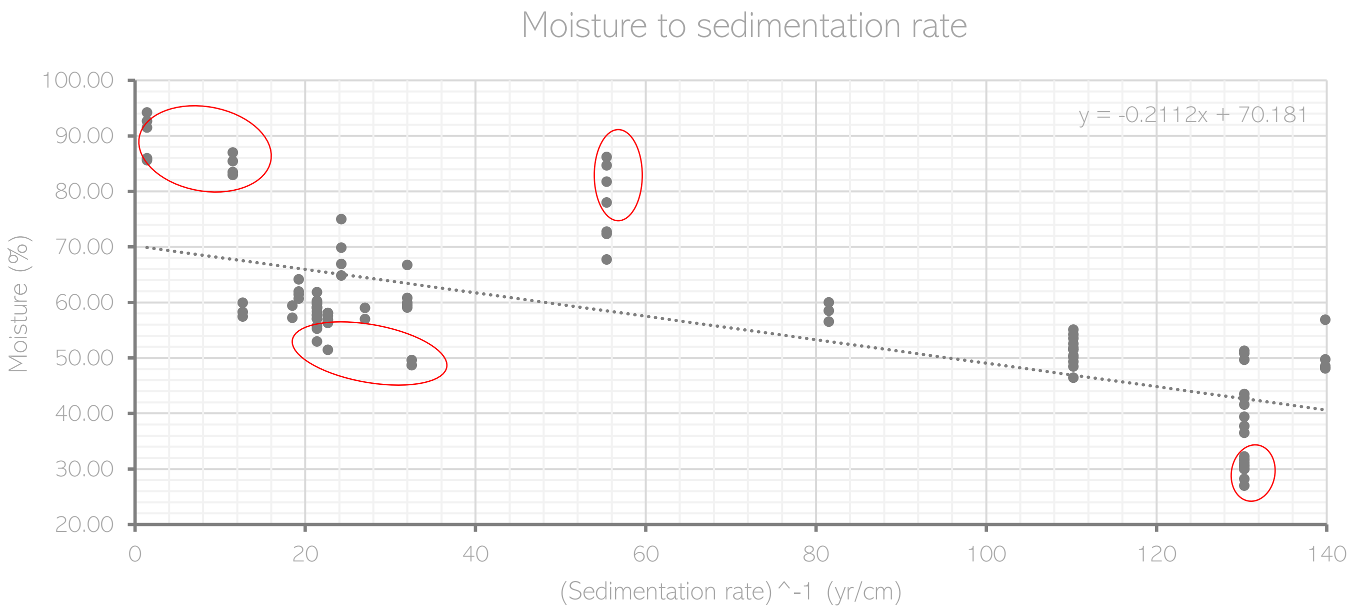


Figure 6: Moisture content is plotted to the inverse of the sedimentation rate; Altought the scatter is high there is a linear correlation extractable meaning that the two parameters are closely related and so moisture content is responsible for certain trends in the age depth model. Scattered points that are out of line, highlighted in red, may represent failure/uncertain areas within the age depth model.

4.2 Quantifying: a tephra count & tephra layers

Throughout this thesis an introduction based on literature was given, after which a methodology was described. The same structural set up helped finding tephra peaks. Most of the core was not prepared into microscope slides, since there was a limitation of time and thus a careful selection of sample depths was made, based on the C-14 dated age model. The likelihood of tephra peaks existing in cored sections was taken into account when selecting samples for further analysis in thin-sections. Subsequently, these thin sections were scanned for tephra particles, as was also done in the first written-section of Pilcher et al. (2005). Multiple tephra horizons were found. Shards of different sizes, but always larger than 30 µm, were recorded. The tephra was qualified as tephra solely by looking at typical tephra characteristics, the relief, brightness, sharpness and fading with cross-directional light. A shard graph was constructed (figure 8a) to visualize the tephra peaks. Visible tephra was found throughout almost all of the scanned sections.

An indication of diatom/diatom fragment density was produced by counting the amount of diatoms respectively to the shard concentration. The results of the found diatom peaks support the earlier suggested link with effective silicic production and verify the existence of certain tephra peaks. (in blue, figure 8a)

Correlating tephras to the known tephrochronology

Between, 314-324 cm, expected to be late medieval times: Tephra was found throughout all of the sampled section, although not always in large quantities. The expected peaks were the Hekla-1510, Veidivotn-1477, MOR-T2 Jan Mayen related tephra and at the very bottom the 1362 Öræfajökull tephra (revised dispersal maps, figure 10). The distribution of three peaks was found with two peaks near the top and bottom being the most pronounced in tephra count. Both peaks are as well linked to distinct diatom assemblage peaks. The most likely eruptions related are suggested to be the Veidivotn-1477, MOR-T2 (uncertain) and 1362 Öræfajökull.

Between, 330-334 cm, around 1100 AD: There were two main tephra horizons visible in this section although the existence of the second peak is not certain and there might have been some external influence on the thin-section, devaluating the count result. The main peak is expected to represent tephra from the VEI 5 Hekla-1104 eruption, since this was found in the Arctic and north Atlantic region before (D'Andrea et al., 2012; Pilcher et al., 2005; Wastegård et al., 2001; Vorren et al., 2007) (dispersal map, figure 10). The possible second peak may correspond with the smaller VEI 4 Hekla-1158 eruption.

Between, 335-349 cm, expected to be around 1000-500 AD: No distinct tephra horizons were encountered. However, clear evidence of tephra particles was found throughout all sections with the main peaks at depths 340-341 and 344-345. These peaks may represent tephra from the same unknown horizons found at Borge (Lofoten, Norway). Tephra from these depths was, in Svalbard, suggested to correlate to the Sn-1 tephra (D'Andrea et al., 2012). other options might be the Landnám tephra (Wastegård et al., 2003; Grönvold et al., 1995) or the White river ash (Plunkett and Pilcher, 2018). Geochemical microprobe analysis is needed to correlate tephras to eruptions and get clarity on this discussion.

Between, 371-376 cm, expected to be around 1000-1200 BC: one distinct tephra peak was found with other thin sections containing significantly less tephra as the peak. The peak is hypothesised to represent the Hekla-3 tephra. This tephra was not found in the Lofoten but a northerly dispersal is suggested by findings in Scandinavia and the northern Iceland shelf (Dugmore et al., 1995; Plunkett, 2006). The connection to climate forcing may be observable in figure 15 where a decline in LOI follows up on the Hekla-3 tephra peak.

The main peaks were thus found at certain depths. A judgement of value was added based on tephra peak quality:

1. SN-III, 315-316: 21 shards, *Veidivotn 1477* *having a relatively high chance of finding a tephra peak*
2. SN-III, 319-320: 9 shards, *MOR-T2* *having a relatively low chance of finding a tephra peak*
3. SN-III, 322-323: 14 shards, *Öræfajökull 1362* *having a relatively high chance of finding a tephra peak*
4. SN-III, 330-331: 27 shards, *Hekla-1158* *having a relatively low chance of finding a tephra peak*
5. SN-III, 332-333: 77 shards, *Hekla-1104* *having a relatively high chance of finding a tephra peak*
6. SN-III, 340-341: 14 shards, *Landnam/White river/Sn-1* *having a relatively low chance of finding a tephra peak*
7. SN-III, 344-345: 20+ shards, *650 AD unknown* *having a relatively high chance of finding a tephra peak*
8. SN-IV, 374-375: 47 shards, *Hekla-3 tephra* *having a relatively high chance of finding a tephra peak*

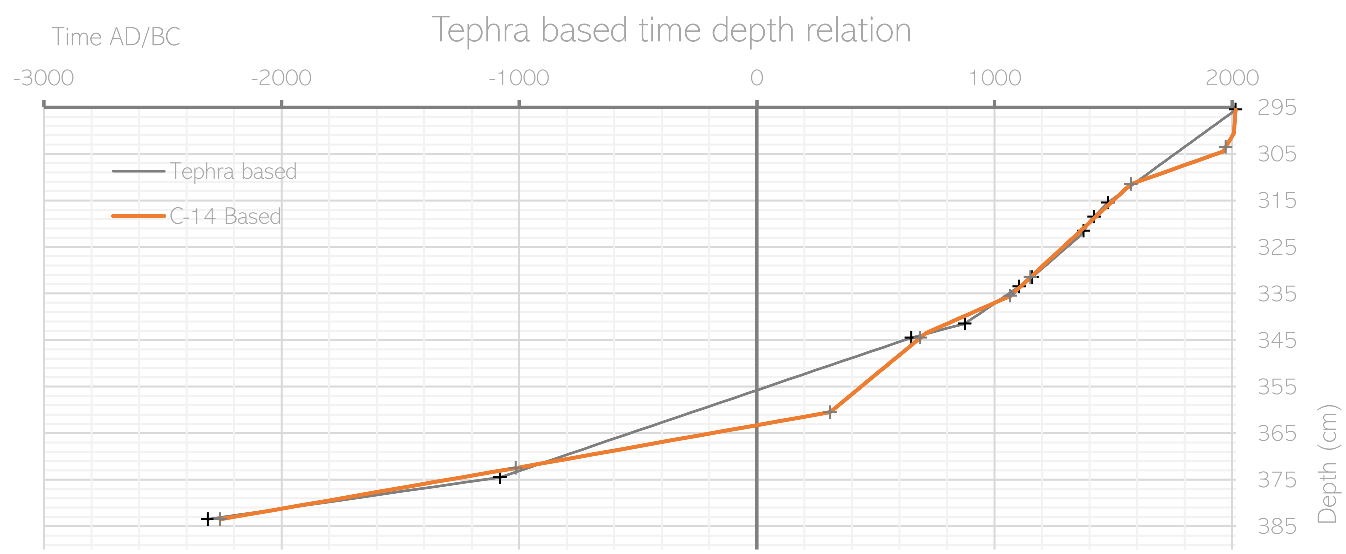
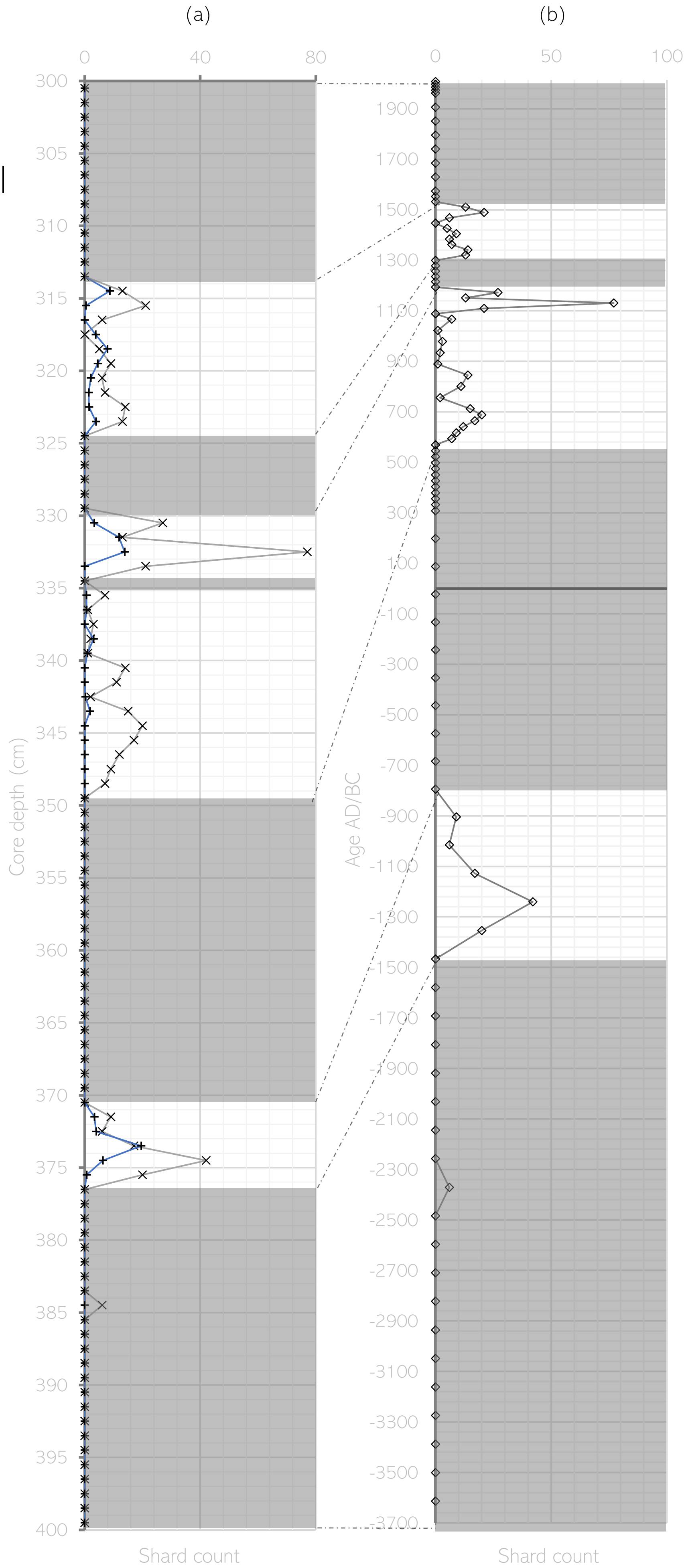


Figure 7: The two age depth models are plotted with the actual data point being showed with the + sign. Orange line represents the C-14 based model whereas the grey line shows the tephra based model. They do not differ to much which supports the suggested peak interpretation, however the C-14 model seems to be more accurate at depths where no tephra search was done



The amount of tephra shards was also plotted against the C-14 reconstructed age (figure 8b). This visualizes the proposed position in time of certain tephra peak horizons. The most likely correlation to certain tephras was made, based on these proposed ages. After correlation a tephra related time-depth model was setup (figure 7). The peaks that seemed to be coinciding with key events in the European tephrochronological record such as, the Hekla-1 and Hekla-3 eruptions and the 875AD Landnám tephra which might also be the AD860 tephra (Plunkett and Pilcher, 2018), were used for this age-depth model. However, since the correlation is only based on shard counts, there are large uncertainties in the constructed age model, Nonetheless, the age-depth model can be used to test on the reliability of the suggested tephra peaks. Future research and particularly geochemical microprobe analysis must prove the existence of these exact tephra horizons at these depths, but is seems likely based on their expected isochronous position. Moisture and loss of ignition were measured visualizing a trend from marine to lacustrine to contaminated within the sediment (figures 5 and 15). The loss of ignition profile serves as an ecological record representing the length of the growth season and therefore climate. The three stage loss of ignition model that was found for this core, does coincide with the timing of the three stages of the age-depth model described above.

Figure 8 a and b (left): Tephra peak distribution with depth (left) and with C-14 based time (right). Diatom concentration is given in blue in the left figure, Note that at depths 340-350 this diatom density was not accurately sampled. The peak correlation depth to time is given with the dotted lines.

5.0 Discussion

In the previous section a suggested tephrochronology for the Svalbard archipelago of the last 4000 years has been outlined. Here a comparison will be made to previous literature and an reflection will be made on the obtained results. The contribution of this study to current discussions regarding arctic tephras and climate reconstruction will be addressed. The combined age depth model will be introduced. The amount of time captured in a centimetre is shown to be dependent on the moisture content of the sampled centimetre (figure 5). A lower moisture content may have caused a small depth deficit between the results from Kongressvatnet and Andsjøen.

5.1 Matching E-Svalbard tephras to mainland relatives

With the suggested higher ash cloud frequency over north western Europe (Watson et al. 2017) and almost all the tephra reported and linked to events (Plunkett and Pilcher, 2018) it is likely that, also in Svalbards sediments, a diversity of tephra has been recorded. Its geographical position may not be as perfect as Ireland, which collects the most of the volcanic cryptotephra (Lawson et al., 2012) but, its position as being downwind of Iceland during the summer months allows for at least a seasonal deposition. A seasonal exposure to Icelandic sources is also the case for Scandinavian catchments, where mainly the autumn and winter months are dominated by steady westerlies (Lacasse, 2001). Additionally, Svalbard has a closer position to trans-arctic sources like Kamchatka and Alaska range. The distance (table 1) is however still very considerable and thus dependent on the altitude of the ash clouds and wind patterns across the arctic. The fact that trans-hemispheric tephra can be found in Europe enlightens new opportunities for constructing a more detailed tephra record. Tephra count results from Pilcher et al. (2005) were modified into graphs, with depth and time, which are supplied in figure 13a and 14a.

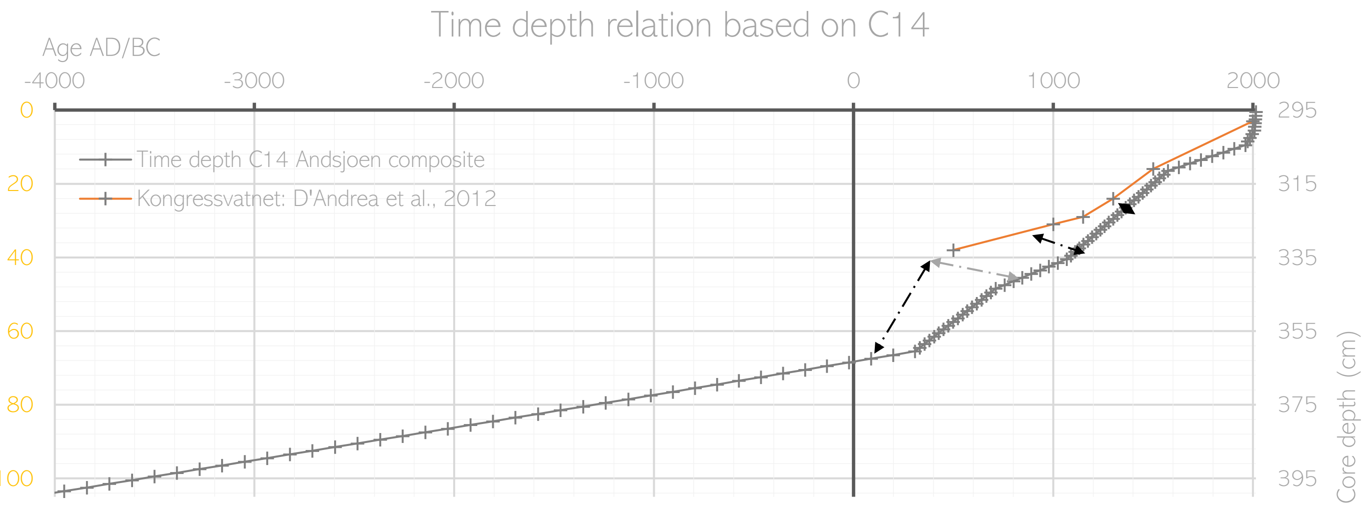


Figure 8: The age depth models of Kongressvatnet and Andsjøen, the black lines show the translation of the findings of D'Andrea et al. 2012 to the results from Andsjøen with the intrepetation of Öræfajökull-1362, Hekla-1 and Snæfellsjökull-1. The grey line shows the intrepreation of Plunkett and Pilcher, 2018 where the last tephra horizon was claimed to be part of the AD860 tephra and thus the White river ash (Watson et al. 2017)

Peaks that were found in lake Andsjøen around 1500-1400 AD seem not to be corresponding with the Norwegian findings. The peaks of the Hekla-1158 and Hekla-1104 are coinciding (in time and depth) with the Borge tephra record. Other tephra peaks that are coinciding are the AD-875 and AD-650 tephra peak layers. The correlation of the Öræfajökull, however, is not straightforward since it is not clearly and separately identified within the Borge section. In the Andsjøen core the Öræfajökull tephra horizon is suggested to be located around the 322-323 depth (see results section). This interpretation may be wrong because underlying the suggested peak an uninvestigated section starts. The peak thus may lie deeper then suggested. Translating the tephras found by D'Andrea et al. (2012) to the Sundneset age model as is done in figure 9(black arrows) puts question marks to the suggested correlation to the Sn-1 tephra. The proposed correlation to the AD-860 tephra and white river ash, as marked by a light grey arrow in figure 9, makes more sense (Plunkett and Pilcher, 2018; Watson et al. 2016). New dispersal patterns of certain eruptions that have been suggested based on this study, are depicted in figure 10.

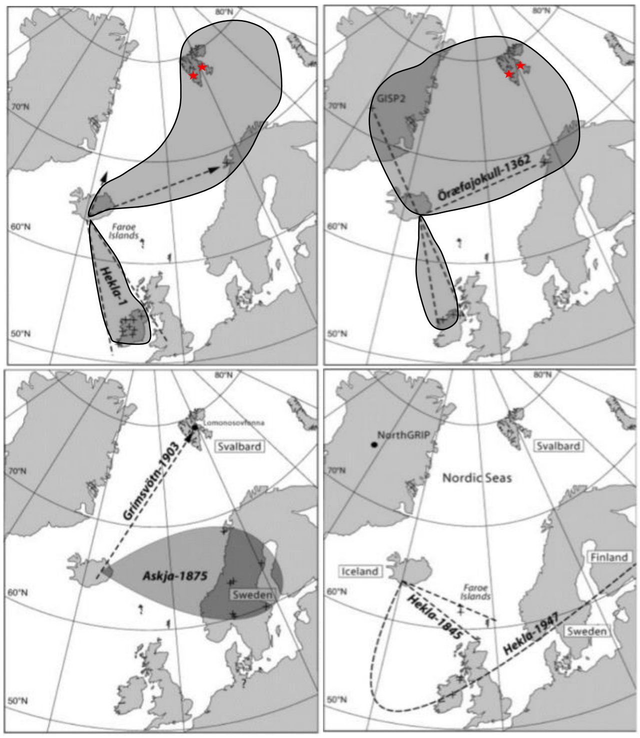


Figure 10: Tephra distribution implications of the new findings on Svalbard. This figure was modified from Wastegård and Davies, 2009. New tephra findings on Svalbard with suggested dispersal patterns are given in figures a and b.

5.2 Analysis of single tephra shards

Most of the tephra was found within a certain elevated layer in the thin sections since it has (in general) a high relief. (figure 11) Most of the tephra was subsequently found on the outer ring of the thin sections (figure 11). However it did not appear to be the very edge of the thin section that hosted the most of the tephra either. Tephra was most depleted in the middle and on the edge. All different sizes of tephra were counted, if noticed, while scanning through the slides. The size differed a lot, some tephra was larger than other tephra as is clear from comparison of figure 12a and b. Some tephra contained clearly formed air pockets. However, not all tephra particles contained air pockets as is visible from figure 12 and in SEM-pictures of tephra captured from the more recent eruption of the Eyjafjöll in 2010 (Davies et al., 2010).

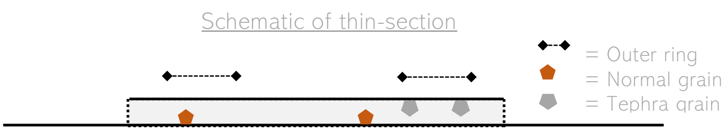
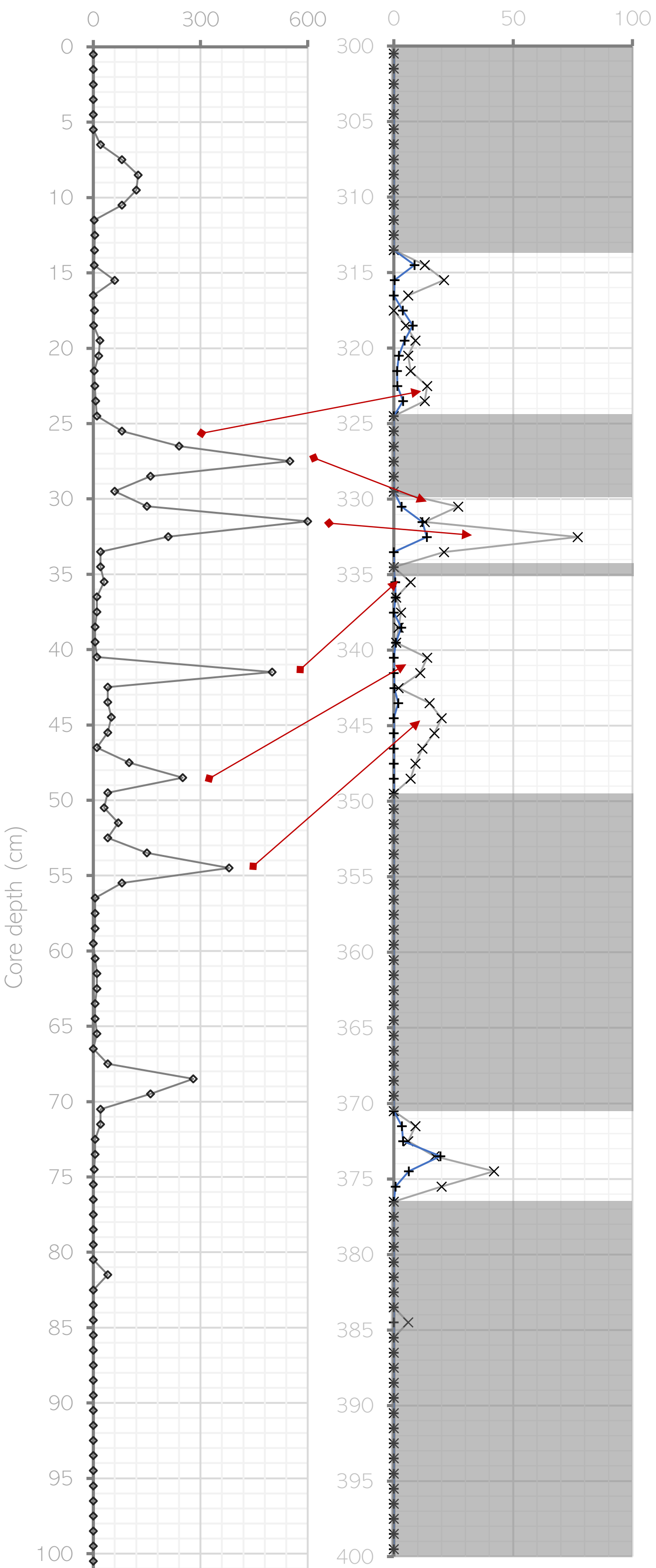


Figure 11: A schematic thin-section, representing the most commonly observed position of tephra respecively to other particles.

Figure 12: Pictures taken from samples of tephra retrieved from the Andsjøen sediments, Svalbard. Pictures are taken through a 500x Leitz lens on a mineralogical microscope

Borge (left) vs. Andsjøen (right) with depth



Borge (left) vs. Andsjøen (right) with time

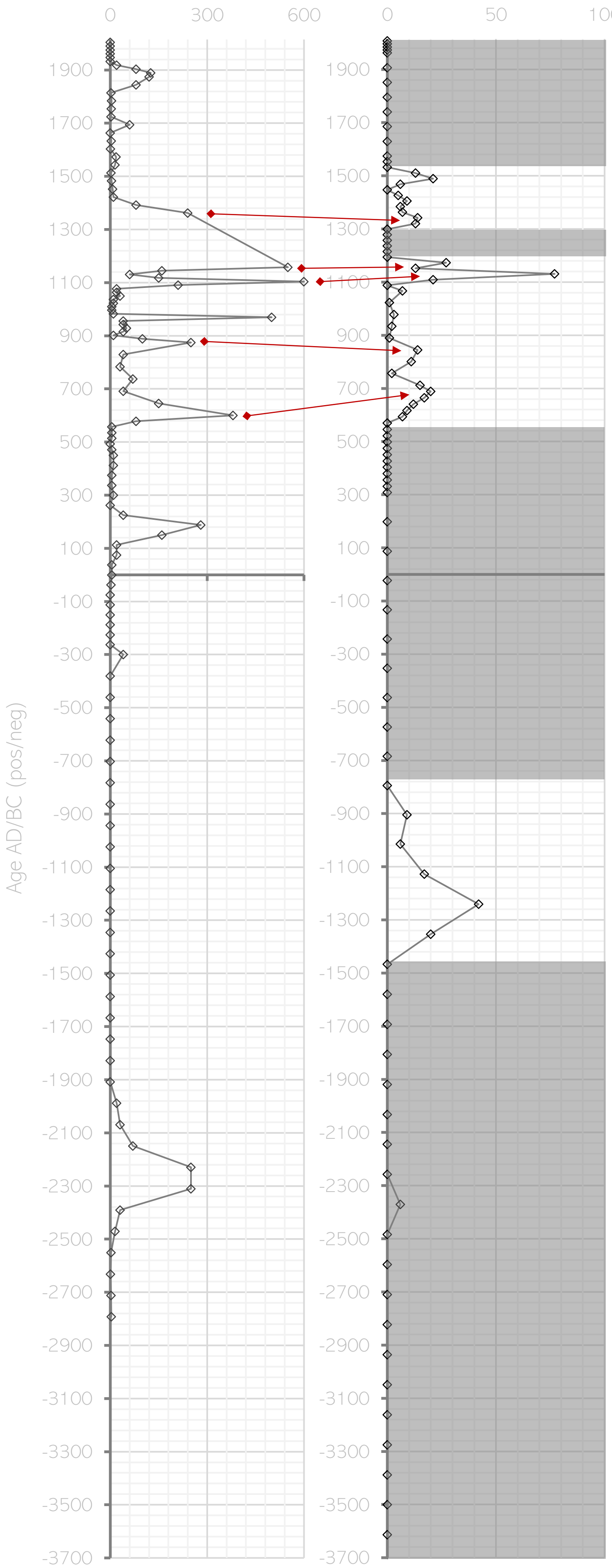


Figure 13 (left) & Figure 14 (right): The comparison, based on core depth (13) and time(14), of the results found at Borge, Lofoten (Pilcher et al. 2005) and the findings of Andsjøen. The C-14 time-model was used for Andsjøen Red arrows indicate the corelated peaks. Figure 14 (right):

5.3 Reliability of the use of tephra for a chronological framework

As is the case for most of temporal records, dating is uncertain. The amount of time captured in a sampled centimeter of Andsjøen lake sediment contains multiple years, ranging from 2 years at the top to 130 years at the bottom. As a result the resolution of the record diminishes with depth. However, this is a problem that occurs to all dating methods relying on sampled core material, and is still one of the main problems within quaternary climate reconstruction (Pilcher et al., 2005). Other encountered problems are reworking of the sediment and the meteorological control on the dispersal patterns of tephra. The exact dating of certain tephras from specific eruptions is sometimes considered uncertain. The resolution of the defined dates of most tephras, however, are/is in the sense of months or maximum +/- 1 year. The resolution deficit of the core does exceed the resolution deficit of the dated tephra which makes the latter uncertainty inappropriate.

Site specific processes may have been of large influence on the timing of the tephra peaks in the Andsjøen sediments. Studies (Pyne-O'Donnell et al., 2008) have shown that tephra deposition in lacustrine environments is highly sensitive to reworking, bioturbation or downward migration (Beierle & Bond, 2002; Davies et al., 2007). Another uncertainty in the implication of lacustrine arctic tephra might be the effect of snow and ice, favouring aeolian redeposition before ending up in the lake. Tephra may end up being scatted around in wind determined patches (Davies et al. 2007).

Distal cryptotephrochronolgy is limited to certain, only of the largest category, eruptions (Larsen & Eiríksson, 2008). Whereas other erupted tephras, from less energetic eruptions, may be more limited to weather conditions (Dugmore et al., 1996; Thorarinsson, 1981). Tephra horizons were suggested for the Andsjøen lake that favour a basaltic composition, like the candidate Veidivötn-1477 tephra at depth 315-316. If this was proven to be truly a tephra from the Veidivötn-1477 eruption it would be extra unique. That is, tephra has a strong bias to rhyolitic composition with respect to basaltic. Possible explanations for the scarcity of basaltic tephra at more distal sites may be (Larsen and Eiríksson, 2008):

1. The difference in specific weight
2. The most commonly known preparation method favours rhyolitic extraction
3. The degradation rate within certain high organic environments like peat bogs
4. The difference in eruption type between basaltic eruptions and rhyolitic eruptions. Rhyolitic eruptions can be considered more violent and explosive, correlating to a fast eruptive events. Basaltic eruptions on the other hand are lasting longer and therefore have a lower intensity.

Visual inspection has proven not to be a good method to record tephra. An example from the north Icelandic shelf (Eiríksson et al., 2004; Søndergaard, 2005) shows that 27 layers out of 34 have yet not been identified. In proximal areas however micro- and macroscopic tephra characteristics, such as sharpness and brightness, are more valid and can be used to distinguish tephras (Larsen and Eiríksson, 2008). In this study the careful results retrieved from the tephra counting match quite well with the constructed age depth model from C-14 dates, (figure 7). Furthermore, it seems to be possible to correlate the tephra peaks to peaks found in other areas. The LOI curve, based on a combined C-14 and tephrochronological age model, seems to be portraying logical and correct trends in climate related biological production. Additionally, although Icelandic eruptions provide a good maker framework for the northwest European tephra record, not all eruptions have characteristic geochemical fingerprints on which they can be distinguished from others (Larsen et al., 1999). Magma composition is sometimes constant over time, as is the case for the Veidivötn, Grímsvötn, Hekla, Öræfajökull, Askja Snaefellsjökull. However, it can occur that older tephra is re-ejected into the atmosphere during the most violent first phase of the eruption. Indicating that geochemical analysis may even add in extra uncertainty with regard to linking tephra deposits to certain eruptions.

5.4 Climate and tephra

The similarity within peak distribution, according to age, between the Lofoten (Pilcher et al., 2005) and Svalbard (this research; van der Bilt et al., 2016; D'Andrea et al., 2012) reflects the climatic affinity between the two regions. As has been described before, the climatic control on tephra distribution is high, which immediately raises the question whether tephra distribution can be used as a climate indicator. The likelihood of certain wind patterns changes when climate changes. Since warmer hemispheric periods favour an enhanced warming of the arctic, hence with sea ice albedo feedback, seems to favour a wavier lower stratospheric jet (Cohen et al., 2014; Francis and Vavrus, 2012, 2015; Jaiser et al., 2012; Tang et al., 2013, 2014). With a decreasing meridional gradient so-called 'Rossby waves' in the jet stream can advect more warmth towards the arctic (Liu et al., 2012). Exactly these high atmospheric variations cause a more diverse wind direction in Svalbard. It is highly likely that more south-westerly winds come with warmer periods and more easterly winds come with colder periods. It can thus be expected that Icelandic tephra preservation rate is highest during warmer periods.

When looking at figure 15, where the loss of ignition profile of the Andsjøen lake is outlined, two warmer phases can be

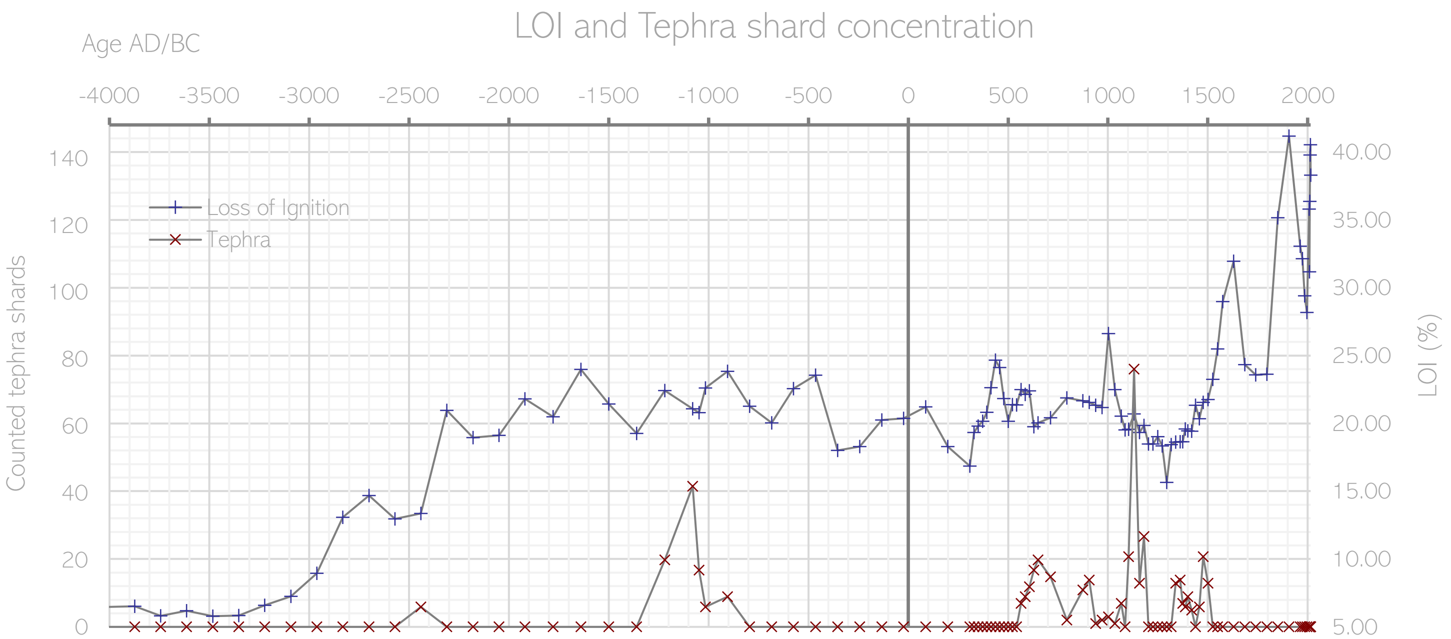


Figure 15: The Loss of ignition values (given in blue) were plotted over the combined age model. The tephra record (red) was also plotted over the combined age model. An indication is given of the coincidence of longer growth season (LOI) and tephra counts. Note that the three stage model that the LOI graph outlines is not the same as the three stage model, from the age depth model discussed before. The three stage model of the LOI represent an isolation / marine phase; a lacustrine phase and a phase of suggested external organic contamination.

recognized, based on high organic contents. The first, before and around the 1000 AD warm period (Kaufman et al., 2009), corresponding with the increased summer temperatures on Svalbard in Kongressvatnet (D'Andrea et al., 2012) and offshore Svalbard (Spielhagen et al., 2011). The second warm period is the recent historical industrial times. Winter temperatures on the Lomonovsfonna ice cap do not show such trends (Divine et al., 2011), a gradual decline until the 19th century can here be observed. LOI values were found to be relatively high between 500-1000 AD followed by a period of lower LOI that was associated with glaciation and low temperatures around 1250 AD (Baranowski & Karlén, 1976; Werner, 1993). The drop within LOI around the 18th century can be associated with the little ice age (figure 15). Whether the temperature is the leading parameter in this drop remains a question. It has been suggested that winter precipitation caused the glacial advance associated with the little ice age period on Svalbard (D'Andrea et al., 2012; Spielhagen et al., 2011). Since a correlation was proved between NAO and winter precipitation over Svalbard and Scandinavia (Dickson et al., 2000; Nesje et al., 2008). The high summer temperatures may correlate with the high amount of tephra found within the 500-1100 AD period. The winds may have been longer blowing from the southwest causing a longer growth season (LOI) and more ash depositional potential. Furthermore, high ash preservation on Svalbard can be expected 1550-1700 and 1900-recent, as these periods also mark high LOI periods.

5.5 Future research

The tephras found and discussed in this study show an example on the difficulty of correlating arctic tephras. Yet, constructing a tephrochronology of the arctic is of great importance especially when one would like to deal with the underutilization of tephrochronology over large areas (Machida, 2002). Especially in the organic depleted arctic, where radiocarbon dating is not always possible, tephrochronology can provide a valuable age-depth model. From Kekonen et al. (2005) it is clear that sulphate horizons may lag tephra layers by several months. Similar connections to other proxies have been proven with diatoms (Hamme et al., 2010; Harper & Mc Leod, 1986; Merkt et al., 1993) and *Lycopodium* spores (Gehrels et al., 2006). Gehrels et al. 2006 added *Lycopodium* spores to tephra samples, it turned out that the number of shards that occurred per 100 spores was representative, so the relation between spores and tephra was defined as: $shards\ per\ miligram\ dry\ weight = \frac{added\ lycopodium \cdot shard\ count}{lycopodium\ count \cdot dry\ weight}$ (Gehrels et al., 2006). In this study a diatom bloom was used as an independent record, indicating tephra peak horizons. It will be such secondary indicators that can contribute to the quality of determinations of tephra peaks in the future. Since the arctic is a crucial geographical region for climate research where climate changes are always amplified (arctic amplification, Cohen et al. 2014 and references therein), it is no surprise that current demand for isochronous markers contributing to a regional chronology is high. Therefore, an aim should be to reconstruct a circum-arctic tephrochronological records using systematic name coding for eruptive events that does sufficient justice to existing nomenclatures of tephra in Europe, Asia and North America. Furthermore, a full gechemically supported analysis from tephra layers on multiple locations in Svalbard should give a boost to constructing this tephrochronological record.

6.0 Conclusions

In this research a possible tephrochronology, of the last 4000 years, for the Svalbard archipelago is outlined, opening up the construction of a trans-arctic tephrochronology. Certain tephra peaks were implied, based on shard counts and diatom bloom peaks. The Hekla 1104 tephra peak has most certainly been found. Other tephras like: Öraefajökull-1362, Landnám tephra, Veidivötn-1477 have been suggested as possible candidates. Tephra origin from Icelandic systems have been assumed based on the similarities between the produced data and findings from the Lofoten area (figure 13 and 14). Based on the age depth model it is likely that the third tephra found at Kongressvatnet is part of the AD 860 tephra and, therefore, can be correlated to the white river ash (Watson et al., 2017). The presented data should, however, be used with caution. Tephra characterization is not certain due to the lack of geochemical analysis and arctic lacustrine uncertainties, such as: reworking, aeolian redistribution on ice and snow and downward migration. However, when comparing the two constructed age depth models, only a slight difference is recognized. It can be concluded that, even without employing an expensive and time consuming tephra characterization, there is still a lot that can be learned from volcanic glass occurrences in sediment layers. Counting of tephra shards can thus be considered as a valid implication to get a sense of the broad distribution of tephra within a cored section. Implications have been suggested regarding the effects of weather patterns on tephra distribution. It is likely that tephra dispersal patterns are influenced by large scale climate variations. Clear evidence is however not yet provided, also within the Andsjøen composite there is little evidence for such relations. With further implication of trans-arctic tephrochronology the Svalbard archipelago will become an important linking region bridging the information from Asia, Europe and North-America. A first pillar to start building on this tephrostratigraphy may be dispensed from the three lakes that are already cored. If one aims to construct a proper foundation for further use of tephrochronology, close cooperation and data sharing would be necessary. A complete arctic tephrostratigraphy is still missing and logically more data would be needed, also, to start using the tephrochronology as a primary Holocene dating method in Svalbard.

References

Austin, W. E. N., Wilson, L. J., & Hunt, J. B. (2004). The age and chronostratigraphical significance of North Atlantic Ash Zone II. *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.821

Baillie, M. G. L., & Munro, M. A. R. (1988). Irish tree rings, Santorini and volcanic dust veils. *Nature*. https://doi.org/10.1038/332344a0

Baranowski, S., & Karlén, W. (1976). Remnants of Viking Age Tundra in Spitsbergen and Northern Scandinavia. *Geografiska Annaler: Series A, Physical Geography*, *58*(1–2), 35–40. https://doi.org/10.1080/04353676.1976.11879922

Beierle, B., & Bond, J. (2002). Density-induced settling of tephra through organic lake sediments. *Journal of Paleolimnology*. https://doi.org/10.1023/A:1021675501346

Bergman, J., Wasteg??rd, S., Hammarlund, D., Wohlfarth, B., & Roberts, S. J. (2004). Holocene tephra horizons at Klocka Bog, west-central Sweden: Aspects of reproducibility in subarctic peat deposits. *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.833

Blockley, S. P. E., Lane, C. S., Lotter, A. F., & Pollard, A. M. (2007). Evidence for the presence of the Vedde Ash in Central Europe. *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2007.09.010

Blockley, S. P. E., Pyne-O'Donnell, S. D. F., Lowe, J. J., Matthews, I. P., Stone, A., Pollard, A. M., … Molyneux, E. G. (2005). A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. *Quaternary Science Reviews*, *24*(16–17), 1952–1960. https://doi.org/10.1016/J.QUASCIREV.2004.12.008

Boygle, J. (1999). Variability of tephra in lake and catchment sediments, Svinavatn, Iceland. *Global and Planetary Change*. https://doi.org/10.1016/S0921-8181(99)00011-9

Braitseva, O. A., Ponomareva, V. V., Sulerzhitsky, L. D., Melekestsev, I. V., & Bailey, J. (1997). Holocene Key-Marker Tephra Layers in Kamchatka, Russia. *Quaternary Research*. https://doi.org/10.1006/qres.1996.1876

Brendryen, J., Haflidason, H., & Sejrup, H. P. (2010). Norwegian Sea tephrostratigraphy of marine isotope stages 4 and 5: Prospects and problems for tephrochronology in the North Atlantic region. *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2009.12.004

Carey, S. (1997). Influence of convective sedimentation on the formation of widespread tephra fall layers in the deep sea. *Geology*. https://doi.org/10.1130/0091-7613(1997)025<0839:IOCSOT>2.3.CO;2

Chambers, F. M., Daniell, J. R. G., Hunt, J. B., Molloy, K., & O'Connell, M. (2004). Tephrostratigraphy of An Loch Mór, Inis Oírr, western Ireland: Implications for Holocene tephrochronology in the northeastern Atlantic region. *Holocene*. https://doi.org/10.1191/0959683604hl749rp

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., … Jones, J. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, *7*(9), 627–637. https://doi.org/10.1038/ngeo2234

Coulter, S. E., Pilcher, J. R., Plunkett, G., Baillie, M., Hall, V. A., Steffensen, J. P., … Johnsen, S. J. (2012). Holocene tephras highlight complexity of volcanic signals in Greenland ice cores. *Journal of Geophysical Research Atmospheres*. https://doi.org/10.1029/2012JD017698

Coulter, S. E., Turney, C. S. M., Kershaw, P., & Rule, S. (2009). The characterization and significance of a MIS 5a distal tephra on mainland Australia. *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2009.04.018

Cremer, H., Bunnik, F. P. M., Donders, T. H., Hoek, W. Z., Koolen-Eekhout, M., Koolmees, H. H., & Lavooi, E. (2010). River flooding and landscape changes impact ecological conditions of a scour hole lake in the Rhine-Meuse delta, The Netherlands. *Journal of Paleolimnology*. https://doi.org/10.1007/s10933-010-9452-2

D'Andrea, W. J., Vaillencourt, D. A., Balascio, N. L., Werner, A., Roof, S. R., Retelle, M., & Bradley, R. S. (2012). Mild Little Ice Age and unprecedented recent warmth in an 1800 year lake sediment record from Svalbard. *Geology*, *40*(11), 1007–1010. https://doi.org/10.1130/G33365.1

Dallmann, W. K., Kuvvet, A., Blomeier, D., Bond, D., Christiansen, H., Elevold, S., … Hormes, A. (2015). *Geoscience atlas of Svalbard*.

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

Davies, S. M., Larsen, G., Wastegård, S., Turney, C. S. M., Hall, V. A., Coyle, L., & Thordarson, T. (2010). Widespread dispersal of Icelandic tephra: How does the Eyjafjöll eruption of 2010 compare to past Icelandic events? *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.1421

Davies, S. M., Wastegård, S., Rasmussen, T. L., Svensson, A., Johnsen, S. J., Steffensen, J. P., & Andersen, K. K. (2008). Identification of the Fugloyarbanki tephra in the NGRIP ice core: A key tie-point for marine and ice-core sequences during the last glacial period. *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.1182

Davies, S. M., Wohlfarth, B., Wastegård, S., Andersson, M., Blockley, S., & Possnert, G. (2004). Were there two Borrobol Tephras during the early Lateglacial period: Implications for tephrochronology? *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2003.11.006

De Silva, S. L., & Zielinski, G. A. (1998). Global influence of the

AD 1600 eruption of Huaynaputina, Peru. *Nature*. https://doi.org/10.1038/30948

Dickson, R. R., Osborn, T. J., Hurrell, J. W., Meinke, J., Blindheim, J., Adlandsvik, B., … Maslowski, W. (2000). The Arctic Ocean response to the North Atlantic Oscillation. *Journal of Climate*. https://doi.org/10.1175/1520-0442(2000)013<2671:TAORTT>2.0.CO;2

Divine, D., Isaksson, E., Martma, T., Meijer, H. A. J., Moore, J., Pohjola, V., … Godtliebsen, F. (2011). Thousand years of winter surface air temperature variations in Svalbard and northern norway reconstructed from ice-core data. *Polar Research*. https://doi.org/10.3402/polar.v30i0.7379

Dugmore, A. J., Larsen, G., & Newton, A. J. (1995). Seven tephra isochrones in Scotland. *Holocene*. https://doi.org/10.1177/095968369500500301

Dugmore, A. J., Larsen, G., & Newton, A. J. (2004). Tephrochronology and its Application to Late Quaternary Environmental Reconstruction, with Special Reference to the North Atlantic Islands. In C. E. Buck & A. R. Millard (Eds.), *Tools for constructing chronologies: Crossing Disciplinary Boundaries.* (vol. 177, pp. 173–188). Springer, London. https://doi.org/10.1007/978-1-4471-0231-1_8

Dugmore, A. J., Newton, A. J., Edwards, K. J., Larsen, G., Blackford, J. J., & Cook, G. T. (1996). Long-distance marker horizons from smallscale eruptions: British tephra deposits from the AD 1510 eruption of Hekla, Iceland. *Journal of Quaternary Science*. https://doi.org/10.1002/(SICI)1099-1417(199611/12)11:6<511::AID-JQS284>3.0.CO;2-C

Durand, M., & Grattan, J. (1999). Extensive respiratory health effects of volcanogenic dry fog in 1783 inferred from European documentary sources. *Environmental Geochemistry and Health*. https://doi.org/10.1023/A:1006700921208

Eiríksson, J., Knudsen, K. L., Haflidason, H., & Heinemeier, J. (2000). Chronology of late Holocene climatic events in the northern North Atlantic based on AMS 14C dates and tephra markers from the volcano Hekla, Iceland. *Journal of Quaternary Science*. https://doi.org/10.1002/1099-1417(200009)15:6<573::AID-JQS554>3.0.CO;2-A

Eiríksson, J., Larsen, G., Knudsen, K. L., Heinemeier, J., & Símonarson, L. A. (2004). Marine reservoir age variability and water mass distribution in the Iceland Sea. In *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2004.08.002

Fiske, R. S., Rose, T. R., Swanson, D. A., Champion, D. E., & McGeehin, J. P. (2009). Kulanaokuaiki Tephra (ca, A.D. 400-1000): Newly recognized evidence for highly explosive eruptions at Kilauea Volcano, Hawai'i. *Bulletin of the Geological Society of America*. https://doi.org/10.1130/B26327.1

Francis, J. A., & Vavrus, S. J. (2012). Evidence linking Arctic Amplification to Extreme Weather. *Geophysical Research Letters*. https://doi.org/10.1029/2012GL051000

Francis, J. A., & Vavrus, S. J. (2015). Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/10/1/014005

Froese, D. G., Zazula, G. D., Westgate, J. A., Preece, S. J., Sanborn, P. T., Reyes, A. V., & Pearce, N. J. G. (2009). The Klondike goldfields and Pleistocene environments of Beringia. *GSA Today*. https://doi.org/10.1130/GSATG54A.1

Gale, S. J. (2009). Event chronostratigraphy: A high-resolution tool for dating the recent past. *Quaternary Geochronology*. https://doi.org/10.1016/j.quageo.2008.12.003

Gastron R.D. (1997). "De grote droge nevel" van 1783 in de zuidelijke nederlanden een historisch klimatologische studie. *Tijdschrift Voor Ecologische Geschiedenis*.

Gehrels, M. J., Lowe, D. J., Hazell, Z. J., & Newnham, R. M. (2006). A continuous 5300-yr Holocene cryptotephrostratigraphic record from northern New Zealand and implications for tephrochronology and volcanic hazard assessment. *Holocene*. https://doi.org/10.1191/0959683606hl918rp

Gehrels, M. J., Newnham, R. M., Lowe, D. J., Wynne, S., Hazell, Z. J., & Caseldine, C. (2008). Towards rapid assay of cryptotephra in peat cores: Review and evaluation of various methods. *Quaternary International*. https://doi.org/10.1016/j.quaint.2006.10.014

Grattan, J., & Charman, D. J. (1994). Non-climatic factors and the environmental impact of volcanic volatiles: Implications of the Laki fissure eruption of AD 1783. *Holocene*. https://doi.org/10.1177/095968369400400113

Grinsted, A., Moore, J. C., Pohjola, V., Martma, T., & Isaksson, E. (2006). Svalbard summer melting, continentality, and sea ice extent from the Lomonosovfonna ice core. *Journal of Geophysical Research Atmospheres*. https://doi.org/10.1029/2005JD006494

Grönvold, K., Óskarsson, N., Johnsen, S. J., Clausen, H. B., Hammer, C. U., Bond, G., & Bard, E. (1995). Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. *Earth and Planetary Science Letters*. https://doi.org/10.1016/0012-821X(95)00145-3

Hall, V. A. (2003). Assessing the impact of Icelandic volcanism on vegetation systems in the north of Ireland in the fifth and sixth millennia BC. *Holocene*. https://doi.org/10.1191/0959683603hl574rr

Hall, V. A., & Pilcher, J. R. (2002). Late-Quaternary Icelandic tephras in Ireland and Great Britain: Detection, characterization and usefulness. *Holocene*. https://doi.org/10.1191/0959683602h1538rr

Hamann, Y., Wulf, S., Ersoy, O., Ehrmann, W., Aydar, E., & Schmiedl, G. (2010). First evidence of a distal early Holocene ash layer in Eastern Mediterranean deep-sea sediments derived from the Anatolian volcanic province. *Quaternary Research*. https://doi.org/10.1016/j.yqres.2009.12.004

Hamme, R. C., Webley, P. W., Crawford, W. R., Whitney, F. A., Degrandpre, M. D., Emerson, S. R., … Lockwood, D. (2010). Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific. *Geophysical Research Letters*. https://doi.org/10.1029/2010GL044629

Harper, M. A., & Mc Leod, M. (1986). Late holocene diatoms in lake poukawa: Effects of airfall tephra and changes in depth. *New Zealand Journal of Marine and Freshwater Research*. https://doi.org/10.1080/00288330.1986.9516135

Hoek, W., Woelders, L., Akkerman, K., van Hoof, T., Moller Just, R., & Wagner-Cremer, F. (2016). Climate and environmental changes during the last 2000 years on Barentsøya and Edgeøya (E-Svalbard). *EGU General Assembly 2016, Held 17-22 April, 2016 in Vienna Austria, Id. EPSC2016-18392*, *18*. Retrieved from http://adsabs.harvard.edu/abs/2016EGUGA..1818392H

Humlum, O., Elberling, B., Hormes, A., Fjordheim, K., Hansen, O. H., & Heinemeier, J. (2005). Late-Holocene glacier growth in Svalbard, documented by subglacial relict vegetation and living soil microbes. *Holocene*. https://doi.org/10.1191/0959683605hl817rp

Isaksson, E., Divine, D., Kohler, J., Martma, T., Pohjola, V., Motoyama, H., & Watanabe, O. (2005). Climate oscillations as recorded in Svalbard ice core δ18O records between AD 1200 and 1997. *Geografiska Annaler, Series A: Physical Geography*. https://doi.org/10.1111/j.0435-3676.2005.00253.x

Isaksson, E., Pohjola, V., Jauhiainen, T., Moore, J., Pinglot, J. F., Vaikmäe, R., … Van Den Broeke, M. (2001). A new ice-core record from Lomonosovfonna, Svalbard: Viewing the 1920-97 data in relation to present climate and environmental conditions. *Journal of Glaciology*. https://doi.org/10.3189/172756501781832313

Jaiser, R., Dethloff, K., Handorf, D., Rinke, A., & Cohen, J. (2012). Impact of sea ice cover changes on the northern hemisphere atmospheric winter circulation. *Tellus, Series A: Dynamic Meteorology and Oceanography*. https://doi.org/10.3402/tellusa.v64i0.11595

Kaufman, D. S., Schneider, D. P., McKay, N. P., Ammann, C. M., Bradley, R. S., Briffa, K. R., … Thomas, E. (2009). Recent warming reverses long-term arctic cooling. *Science*. https://doi.org/10.1126/science.1173983

Kekonen, T., Moore, J., Perämäki, P., & Martma, T. (2005). The Icelandic Laki volcanic tephra layer in the Lomonosovfonna ice core, Svalbard. *Polar Research*, *24*(1–2), 33–40. https://doi.org/10.3402/polar.v24i1.6251

Kirkbride, M. P., & Dugmore, A. J. (2003). Glaciological response to distal tephra fallout from the 1947 eruption of Hekla, south Iceland. *Journal of Glaciology*. https://doi.org/10.3189/172756503781830575

Kristjánsdóttir, G. B., Stoner, J. S., Jennings, A. E., Andrews, J. T., & Grönvold, K. (2007). Geochemistry of Holocene cryptotephras from the North Iceland Shelf (MD99-2269): Intercalibration with radiocarbon and palaeomagnetic chronostratigraphies. *Holocene*. https://doi.org/10.1177/0959683607075829

Lacasse, C. (2001). Influence of climate variability on the atmospheric transport of Icelandic tephra in the subpolar North Atlantic. *Global and Planetary Change*. https://doi.org/10.1016/S0921-8181(01)00099-6

Langdon, P. G., Barber, K. E., & Hughes, P. D. M. (2003). A 7500-year peat-based palaeoclimatic reconstruction and evidence for an 1100-year cyclicity in bog surface wetness from Temple Hill Moss, Pentland Hills, southeast Scotland. *Quaternary Science Reviews*. https://doi.org/10.1016/S0277-3791(02)00093-8

Larsen, G., Dugmore, A., & Newton, A. (1999). Geochemistry of historical-age silicic tephras in Iceland. *Holocene*. https://doi.org/10.1191/095968399669624108

Larsen, G., & Eiríksson, J. (2008). Late Quaternary terrestrial tephrochronology of Iceland - Frequency of explosive eruptions type and volume of tephra deposits. *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.1129

Larsen, G., Eiríksson, J., Knudsen, K. L., & Heinemeier, J. (2002). Correlation of late Holocene terrestrial and marine tephra markers, north Iceland: Implications for reservoir age changes. *Polar Research*. https://doi.org/10.1111/j.1751-8369.2002.tb00082.x

Lawson, I. T., Swindles, G. T., Plunkett, G., & Greenberg, D. (2012). The spatial distribution of Holocene cryptotephras in north-west Europe since 7 ka: Implications for understanding ash fall events from Icelandic eruptions. *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2012.02.018

Liu, J., Curry, J., Wang, H., & … M. S. (2012). Impact of declining Arctic sea ice on winter snowfall. *National Acad Sciences*. Retrieved from http://www.pnas.org/content/109/11/4074.short

Lowe, D., & Higham, T. (1998). Hit-or-myth? Linking a 1259 AD acid spike with an Okataina eruption. *Antiquity 72*, 427–431. Retrieved from https://www.cambridge.org/core/journals/antiquity/article/hitormyth-linking-a-1259-ad-acid-spike-with-an-okataina-eruption/EB119282E602A6FB42764ACD416F5404

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., Newnham, R. M., & Ward, C. M. (1999). Stratigraphy and chronology of a 15 ka sequence of multi-sourced silicic tephras in a montane peat bog, eastern North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*. https://doi.org/10.1080/00288306.1999.9514863

Lowe, J. J., Blockley, S., Trincardi, F., Asioli, A., Cattaneo, A., Matthews, I. P., … Wulf, S. (2007). Age modelling of late Quaternary marine sequences in the Adriatic: Towards improved precision and accuracy using volcanic event stratigraphy. *Continental Shelf Research*. https://doi.org/10.1016/j.csr.2005.12.017

Manville, V., & Wilson, C. J. N. (2004). Vertical density currents: a review of their potential role in the deposition and interpretation of deep-sea ash layers. *Journal of the Geological Society*. https://doi.org/10.1144/0016-764903-067

Merkt, J., Müller, H., Knabe, W., Müller, P., & Weiser, T. (1993). The early Holocene Saksunarvatn tephra found in lake sediments in NW Germany. *Boreas*. https://doi.org/10.1111/j.1502-3885.1993.tb00168.x

Mills, M. J. (2000). Volcanic aerosol and global atmospheric effects. Encyclopaedia of Volcanoes. *Academic Press, San Diego*, 931–943.

Molloy, C., Shane, P., & Augustinus, P. (2009). Eruption recurrence rates in a basaltic volcanic field based on tephralayers in maar sediments: Implications for hazards in the Auckland volcanic field. *Bulletin of the Geological Society of America*. https://doi.org/10.1130/B26447.1

Nesje, A., Dahl, S. O., Thun, T., & Nordli. (2008). The "Little Ice Age" glacial expansion in western Scandinavia: Summer temperature or winter precipitation? *Climate Dynamics*. https://doi.org/10.1007/s00382-007-0324-z

Newnham, R. M., Dirks, K. N., & Samaranayake, D. (2010). An investigation into long-distance health impacts of the 1996 eruption of Mt Ruapehu, New Zealand. *Atmospheric Environment*. https://doi.org/10.1016/j.atmosenv.2009.12.040

Newton, A. J., Dugmore, A. J., & Gittings, B. M. (2007). Tephrabase: Tephrochronology and the development of a centralised European database. *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.1094

Nordli, Ø., Przybylak, R., Ogilvie, A. E. J., & Isaksen, K. (2014). Long-term temperature trends and variability on spitsbergen: The extended svalbard airport temperature series, 1898-2012. *Polar Research*. https://doi.org/10.3402/polar.v33.21349

Nye, J. F. (1963). Correction factor for accumulation measured by the thickness of the annual layers in an ice sheet. *Journal of Glaciology*. https://doi.org/10.1017/S0022143000028367

Palais, J. M., Taylor, K., Mayewski, P. A., & Grootes, P. (1991). Volcanic ash from the 1362 A.D. Öræfajökull Eruption (Iceland) in the Greenland Ice Sheet. *Geophysical Research Letters*. https://doi.org/10.1029/91GL01557

Payne, R., Blackford, J., & van der Plicht, J. (2008). Using cryptotephras to extend regional tephrochronologies: An example from southeast Alaska and implications for hazard assessment. *Quaternary Research*. https://doi.org/10.1016/j.yqres.2007.10.007

Payne, R., & Gehrels, M. (2010). The formation of tephra layers in peatlands: An experimental approach. *Catena*. https://doi.org/10.1016/j.catena.2009.12.001

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

Persson, C. (1967). Försök Till Tefrokronologisk Datering I Tre Norska Myrar. *Geologiska Föreningen i Stockholm Förhandlingar*, *89*(2), 181–197. https://doi.org/10.1080/11035896709448363

Pilcher, J., Bradley, R. S., Francus, P., Pilcher, L. A., & Anderson, L. (2005). A Holocene tephra record from the Lofoten Islands, Arctic Norway. *Arctic Norway. Boreas*, *34*, 136–156. https://doi.org/10.1080/03009480510012935

Pilcher, J. R., Hall, V. A., & McCormac, F. G. (1995). Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats. *Holocene*. https://doi.org/10.1177/095968369500500111

Pilcher, J. R., Hall, V. A., & McCormac, F. G. (1996). An outline tephrochronology for the Holocene of the north of Ireland. *Journal of Quaternary Science*, *11*(6), 485–494. https://doi.org/10.1002/(SICI)1099-1417(199611/12)11:6<485::AID-JQS266>3.0.CO;2-T

Pinglot, J. F., Pourchet, M., Lefauconnier, B., Hagen, J. O., Isaksson, E., Vaikmäe, R., & Kamiyama, K. (1999). Accumulation in Svalbard glaciers deduced from ice cores with nuclear tests and Chernobyl reference layers. In *Polar Research*. https://doi.org/10.3402/polar.v18i2.6590

Plunkett, G. (2006). Hekla 3, environmental downturn and Irish Late Bronze Age hillfort connections revisited. *Emania*, *20*, 55–60. Retrieved from https://scholar.google.nl/scholar?hl=en&as_sdt=0%2C5&q=Plunkett+2006%2C+Hekla+3+Environmental+downturn+and+irish+late+bronze+age+&btnG=

Plunkett, G., & Pilcher, J. R. (2018). Defining the potential source region of volcanic ash in northwest Europe during the Mid- to Late Holocene. *Earth-Science Reviews*, *179*, 20–37. https://doi.org/10.1016/J.EARSCIREV.2018.02.006

Ponomareva, V., Portnyagin, M., Pendea, I. F., Zelenin, E., Bourgeois, J., Pinegina, T., & Kozhurin, A. (2017). A full holocene tephrochronology for the Kamchatsky Peninsula region: Applications from Kamchatka to North America. *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2017.04.031

Ponomareva, V., Portnyagin, M., Pevzner, M., Blaauw, M., Kyle, P., & Derkachev, A. (2015). Tephra from andesitic Shiveluch volcano, Kamchatka, NW Pacific: chronology of explosive eruptions and geochemical fingerprinting of volcanic glass. *International Journal of Earth Sciences*. https://doi.org/10.1007/s00531-015-1156-4

Pyne-O'donnell, S. (2011). The taphonomy of Last Glacial-Interglacial Transition (LGIT) distal volcanic ash in small Scottish lakes. *Boreas*. https://doi.org/10.1111/j.1502-3885.2010.00154.x

Pyne-O'Donnell, S. D. F., Blockley, S. P. E., Turney, C. S. M., & Lowe, J. J. (2008). Distal volcanic ash layers in the Lateglacial Interstadial (GI-1): problems of stratigraphic discrimination. *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2007.02.019

Riede, F., & Bazely, O. (2009). Testing the "Laacher See hypothesis": a health hazard perspective. *Journal of Archaeological Science*. https://doi.org/10.1016/j.jas.2008.10.013

Rose, W. I., & Durant, A. J. (2009). Fine ash content of explosive eruptions. *Journal of Volcanology and Geothermal Research*. https://doi.org/10.1016/j.jvolgeores.2009.01.010

Sanborn, P. T., Smith, C. A. S., Froese, D. G., Zazula, G. D., &

Westgate, J. A. (2006). Full-glacial paleosols in perennially frozen loess sequences, Klondike goldfields, Yukon Territory, Canada. *Quaternary Research*. https://doi.org/10.1016/j.yqres.2006.02.008

Senger, K., Tveranger, J., Ogata, K., Braathen, A., & Planke, S. (2014). Late Mesozoic magmatism in Svalbard: A review. *Earth-Science Reviews*. https://doi.org/10.1016/j.earscirev.2014.09.002

Shane, P. A., & Froggatt, P. C. (1992). Composition of widespread volcanic glass in deep-sea sediments of the Southern Pacific Ocean: an Antarctic source inferred. *Bulletin of Volcanology*. https://doi.org/10.1007/BF00569943

Shane, P., Nairn, I. A., Martin, S. B., & Smith, V. C. (2008). Compositional heterogeneity in tephra deposits resulting from the eruption of multiple magma bodies: Implications for tephrochronology. *Quaternary International*. https://doi.org/10.1016/j.quaint.2006.11.014

Shane, P., Sikes, E. L., & Guilderson, T. P. (2006). Tephra beds in deep-sea cores off northern New Zealand: implications for the history of Taupo Volcanic Zone, Mayor Island and White Island volcanoes. *Journal of Volcanology and Geothermal Research*. https://doi.org/10.1016/j.jvolgeores.2006.03.021

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*. https://doi.org/10.1007/s00445-002-0204-7

Sondergaard, M. K. B. (2005). Lateglacial and holocene palaeoclimatic fluctuations on the north icelandic shelf - foraminiferal analysis sedimentology and tephrochronology of core MD992275. *Aarhus Geoscience - PhD Thesis*, *26*.

Spielhagen, R. F., Werner, K., Sørensen, S. A., Zamelczyk, K., Kandiano, E., Budeus, G., … Hald, M. (2011). Enhanced modern heat transfer to the arctic by warm atlantic water. *Science*. https://doi.org/10.1126/science.1197397

Swindles, G. T. (2006). Reconstructions of Holocene climate change from peatland in the north of Ireland. PhD thesis. *Queen's University Belfast*.

Sylvester, A. G. (1975). History and surveillance of volcanic activity on Jan Mayen island. *Bulletin Volcanologique*. https://doi.org/10.1007/BF02597834

Tang, Q., Zhang, X., & Francis, J. A. (2014). Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere. *Nature Climate Change*. https://doi.org/10.1038/nclimate2065

Tang, Q., Zhang, X., Yang, X., & Francis, J. A. (2013). Cold winter extremes in northern continents linked to Arctic sea ice loss. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/8/1/014036

Thorarinsson, S. (1958). The Öraefajökull eruption of 1362. *Acta Naturalia Islandica*, *2*, 1–99.

Thorarinsson, S. (1967). The eruptions of Hekla in historical times. The eruption of Hekla 1947-1948. *Societas Scientarium Islandica*, *1*, 1–183.

Thorarinsson, S. (1981). Greetings from Iceland. Ash-Falls and Volcanic Aerosols in Scandinavia. *Geografiska Annaler. Series A, Physical Geography*. https://doi.org/10.2307/520822

Thorarinsson, S., Einarsson, T., & Kjartansson, G. (1954). The eruption of Hekla, 1947-48, Part II 3. The tephra-fall from Hekla on March 29 th, 1947. *Societas Scientarum Islandica: Reykjavik*, 1–68. Retrieved from https://ci.nii.ac.jp/naid/10003670195/

Traufetter, F., Oerter, H., Fischer, H., Weller, R., & Miller, H. (2004). Spatio-temporal variability in volcanic sulphate deposition over the past 2 kyr in snow pits and firn cores from Amundsenisen, Antarctica. *Journal of Glaciology*. https://doi.org/10.3189/172756504781830222

Van Bogaard, C. Den, & Schmincke, H. U. (2002). Linking the North Atlantic to central Europe: A high-resolution Holocene tephrochronological record from northern Germany. *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.636

van der Bilt, W. G. M., D'Andrea, W. J., Bakke, J., Balascio, N. L., Werner, J. P., Gjerde, M., & Bradley, R. S. (2018). Alkenone-based reconstructions reveal four-phase Holocene temperature evolution for High Arctic Svalbard. *Quaternary Science Reviews*. https://doi.org/10.1016/j.quascirev.2016.10.006

van der Bilt, W. G. M., Lane, C. S., & Bakke, J. (2017). Ultra-distal Kamchatkan ash on Arctic Svalbard: Towards hemispheric cryptotephra correlation. *Quaternary Science Reviews*, *164*, 230–235. https://doi.org/10.1016/j.quascirev.2017.04.007

Vorren, K. D., Blaauw, M., Wastegård, S., Van Der Plicht, J., & Jensen, C. (2007). High-resolution stratigraphy of the northernmost concentric raised bog in Europe: Sellevollmyra, Andøya, northern Norway. *Boreas*. https://doi.org/10.1111/j.1502-3885.2007.tb01249.x

Walker, G. P. L. (1981). Generation and dispersal of fine ash and dust by volcanic eruptions. *Journal of Volcanology and Geothermal Research*. https://doi.org/10.1016/0377-0273(81)90077-9

Wastegård, S. (2004). Late Quaternary tephrochronology of Sweden: A review. *Quaternary International*. https://doi.org/10.1016/j.quaint.2004.04.030

Wastegård, S., Björck, S., Grauert, M., & Hannon, G. E. (2001). The Mjáuvøtn tephra and other Holocene tephra horizons from the Faroe Islands: A link between the Icelandic source region, the Nordic Seas, and the European continent. *Holocene*. https://doi.org/10.1191/095968301668079904

Wastegård, S., & Davies SM. (2009). An overview of distal tephrochronology in northern Europe during the last 1000 years. *Journal of Quaternary Science*. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/jqs.1269/full

Wastegård, S., Hall, V. A., Hannon, G. E., Van Den Bogaard, C., Pilcher, J. R., Sigurgeirsson, M. Á., & Hermanns-Auoardóttir, M. (2003). Rhyolitic tephra horizons in northwestern Europe and Iceland from the AD 700s-800s: A potential alternative for dating first human impact. *Holocene*. https://doi.org/10.1191/0959683603hl617rr

Watson, E. J., Swindles, G. T., Savov, I. P., Lawson, I. T., Connor, C. B., & Wilson, J. A. (2017). Estimating the frequency of volcanic ash clouds over northern Europe. *Earth and Planetary Science Letters*. https://doi.org/10.1016/j.epsl.2016.11.054

Werner, A. (1993). Holocene moraine chronology, Spitsbergen, Svalbard: lichenometric evidence for multiple Neoglacial advances in the Arctic. *Holocene*. https://doi.org/10.1177/095968369300300204

Wiesner, M. G., Yubo Wang, & Lianfu Zheng. (1995). Fallout of volcanic ash to the deep South China Sea induced by the 1991 eruption of Mount Pinatubo (Philippines). *Geology*. https://doi.org/10.1130/0091-7613(1995)023<0885:FOVATT>2.3.CO;2

Woelders, L., Lenaerts, J. T. M., Hagemans, K., Akkerman, K., van Hoof, T. B., & Hoek, W. Z. (2018). Recent climate warming drives ecological change in a remote high-Arctic lake. *Scientific Reports*, *8*(1), 6858. https://doi.org/10.1038/s41598-018-25148-7

Yalcin, K. (2003). A 100-year record of North Pacific volcanism in an ice core from Eclipse Icefield, Yukon Territory, Canada. *Journal of Geophysical Research*. https://doi.org/10.1029/2002JD002449

Zielinski, G. A., Mayewski, P. A., Meeker, L. D., Grönvold, K., Germani, M. S., Whitlow, S., … Taylor, K. (1997). Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores. *Journal of Geophysical Research: Oceans*. https://doi.org/10.1029/96JC03547

Acknowledgements

I would like to thank all the members of the SEES.NL expedition, of whom also my supervisor dr. W.Z.Hoek. without whom there would be no samples to analyze, and no data to work on and no laboratory instructions to rely on. Laboratory facilities were made available by the Physical Geography Department of Utrecht University. Furthermore I would like to thank Annabel Schouten for helping me with the counting of tephras within the thin-sections.