Lateglacial cryptotephra detected within clay varves in Östergötland, SE Sweden

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Abstract

Here we present a 710 year-long floating varve record from south east Sweden. Tephra analyses confirm the presence of the rhyolitic Vedde Ash preserved within two consecutive varve years, confirming the Younger Dryas age of the varve series. This permits, for the first time, direct correlation of Swedish varved clay with other records of equivalent resolution which also preserve the Vedde Ash and demonstrates that the potential exists to independently date the Swedish Timescale. This discovery will allow direct comparison of rates, timing and duration of key climatic events across Europe and the North Atlantic region in records of equivalent resolution.

Key words: Varves, Sweden, Tephra, Vedde Ash, Younger Dryas

Introduction

Varved sediment records have the potential to allow the assessment of climatic data at annual and potentially sub-annual scales. They are one of very few archives of environmental change which have the ability to provide data at a resolution comparable to tree ring series (Friedrich *et al.,* 2004) and ice-core records (Rasmussen *et al.,* 2006; Svensson *et al.,* 2008). Thus varved records are critical for assessing the spatial and temporal differences in environmental responses to changing climates. Throughout Europe, there have been notable successes in extracting detailed climate-proxy data from varved records from the Last Glacial to Interglacial transition (LGIT: c. 16-8ka BP; De Geer, 1940; Brunnberg, 1995; Lotter, 1991; Andrén *et al.,* 1999; Brauer *et al.,* 1999; Litt *et al.,* 2001; Lundqvist and Wohlfarth, 2001; Hang, 2003; Ringberg *et al.,* 2003; Johnson *et al.,* 2013; Lane *et al.,* 2013). However, many of these records are not varved to the present day and often those that are have substantial counting uncertainties associated with them, or potential problems of 'missing years'. One of the most widely-recognised varve chronologies is the internationally acclaimed Swedish glacial varve chronology (“The Swedish Timescale (STS)). The STS is based on cross-correlation of numerous clastic varve series and provides an unprecedented annually-resolved climate record (e.g. Strömberg, 1985). Although considered a ‘count down from the top’ continuous chronology comprising 13,257 varve years from present (considered as 1986: Cato, 1987; Wohlfarth *et al.,* 1994; 1995), the total number of years represented in the STS is controversial. Several authors have contested that there may be between 700 and 900 years missing from the STS around the Younger Dryas-Preboreal climatic transition or in the Holocene part of the chronology (Wohlfarth *et al.,* 1996, 1997). Current approaches applied to deal with this assume that Greenland and Northern Europe are responding synchronously to a common climate forcing mechanism and consequently this restricts the potential to make independent comparisons between each lake record. To avoid this circularity, independent means of correlation are required in order that rates, durations and synchroneity of response to climatic change can be more precisely assessed.

Much of the research linking varve series between sites in the STS relies on the principle that common varve thickness patterns or distinct sedimentological features are considered to reflect regional processes that demonstrate the varve series are temporally related (i.e. colour changes, marine incursion, ice-rafted limestone debris, lake drainage). It is this technique that permits the construction of a continuous, overlapping record which tracked ice recession from South to North of Sweden following the last glacial maximum. This approach taken by De Geer and others (e.g. Andrén *et al.,* 1999) has been successful in allowing construction (but not testing) of the timescale, however where local, rather than regional, factors influence deposition, distinctive and secure matches cannot always be located and this precludes long (c. 1000 year) varve series from extending and/or reinforcing the current STS. Consequently, independent correlation methods must be sought if these long series are to be fully utilised. Detailed sedimentology (thin-section analysis) may assist with these correlation challenges by identifying features not visible at the macro-scale, while attempts have also been made using radiocarbon dating of macrofossils to both temporally anchor and link varve series (Wohlfarth *et al.,* 1993). However, chronological precision is often not sufficient due to small sample sizes, large error margins and prevalent radiocarbon plateaux during the Lateglacial and early Holocene. The use of time-synchronous marker horizons such as tephra layers could help unlock the hitherto unrealised potential of some of these sites.

Tephra analysis has previously been conducted on mid-Holocene varves from sites in West central Sweden (Zillén *et al.,* 2002) and tephra is preserved throughout the lateglacial period in non-varved contexts (Wastegård *et al.,* 1998, 2000; Björck and Wastegård, 1999; Davies *et al.,* 2003, 2004; Wohlfarth *et al.,* 2006; Lilja *et al.,* 2013). Björck and Wastegård (1999) reported occurrences of Icelandic ash of lateglacial age from the sites of Fågelmossen and Högstorpsmossen. These sites are close to the current study area and this increases the likelihood that it may also be possible to detect it in the lateglacial portion of Swedish clay varves in this region. The lateglacial Vedde Ash (12,121 ±114 GICC05 a BP; Rasmussen *et al.,* 2006 with the according age from the type-site of 12,064 ±99 cal a BP; Lohne et al., 2013; 2014) in particular has proven to be extremely useful for palaeoclimate studies and has recently been used to synchronise climate records from Greenland, Norway and Germany. This suggests that the climate amelioration which took place midway through Younger Dryas (YD) was time-transgressive across Europe (Lane *et al.,* 2013) and not synchronous as previously assumed (Bakke *et al.,* 2009). Identification of this tephra in Sweden also allows spatial variability to be assessed on an east-west gradient.

Site details

The site investigated in this study is Gropviken which is located directly South of the mapped YD ice margin in eastern part of the province of Östergötland (58°21'21"N 16°37'45"E) and was a part of the Baltic Ice Lake during deglaciation (Figure 1). Sites directly south of the YD ice-margin often show long continuous series of several hundred varves (Brunnberg, 1995) and this suggests that ice-recession in this region was relatively slow. This observation is supported by data from the Mount Billingen area to the west of Gropviken, which indicates that for the first c.700 years of the YD ice retreated at an average rate of c.10m a^{-1} and then increased to c.50-70m a^{-1} (Strömberg, 1994). Gropviken is today a narrow inlet of the Baltic Sea and the core was taken close to the shoreline at approximately current sea level. The core is 5.5m in length and is varved throughout. The varves were deposited in water depths exceeding 100m throughout the YD (Brunnberg, 1995).This region formed part of a larger study by Brunnberg, (1995) which connected this region to the STS; however it is also one of the most problematic sectors of the timescale and would benefit from independent chronological control.

Methods

Varve analysis

Visual and physical properties of the sediments were assessed at the macro-scale with clear and rhythmic variations evident in both colour and grain-size. These variations can be observed to correspond to a pattern of alternating silt and clay couplets, the latter being consistently characterised by a sharp upper contact with the succeeding silt layer. Based on this, and the palaeogeographic glaciolacustrine setting at the margins of the retreating Scandinavian ice sheet, it is considered that the sediments record annual accumulation throughout their length akin to the processes outlined by Ringberg and Erlström (1999). Annual layer counting and thickness measurements were obtained at the macro-scale using visible variation in sediment grain-size, colour and structure to delimit boundaries and results are presented as varve thickness graphs.

Tephra analysis

The entire core was scanned contiguously for tephra content by taking approximately 5cm-long samples. However, sample length was increased or decreased in order that a known number of whole varve years could be incorporated within each sample. Scan samples were processed using the method outlined by Turney (1998) and Blockley *et al.,* (2005) with the following minor modifications: samples were not combusted prior to processing, 10% H_2O_2 was used to disaggregate the samples and due to the low amount of organic matter only a single cleaning float of heavy liquid (2.0g cm^{-3}) was needed. Where tephra was detected samples were refined to varve-scale and processed as before. Samples for Wavelength Dispersive Electron Probe Micro Analysis (WDS-EPMA) chemical analysis were also prepared at varve-scale but were not subjected to either HCl or H_2O_2 treatment. Individual tephra grains were handpicked using a micromanipulator and gas chromatography syringe, mounted on a Specifix-40 resin stub and sectioned to create a polished surface (Matthews *et al.,* in prep). Analyses were carried out using the Cameca SX-100 Electron microprobe at the University of Edinburgh and probe conditions can be found in Supporting Table S1. A 5 µm beam diameter was used (Hayward, 2012).

Results

Here we present the first geochemically characterised occurrence of a tephra within YD Swedish clay varves. The site of Gropviken contains 710 varve years (Figure 2) and tephra was detected in the younger part of this sequence. At the scan stage, 10 shards g^{-1} of dry sediment tephra shards were identified across two 5cm samples. When this was refined to varve scale, 16-17 shards g^{-1} of dry sediment were constrained within only two varve years (Figure 2), the first occurrence being in varve number 91 (count down from the top). This therefore provides a well-constrained marker horizon for this core. In total, 18 EPMA analyses were obtained from individual volcanic glass shards (see Supporting Table S2). Their chemical profile (Figure 3) is consistent in that all analyses are of rhyolitic composition, likely being sourced from Iceland and more specifically the Katla volcanic centre. Eruptions which have been reported in the literature and which have similar or identical chemical signatures include Dimna Ash (15,400-14,850 cal a BP; Koren *et al.,* 2008), Vedde Ash (Mangerud *et al.,* 1984), AF555 (11,790-11,200 cal a BP; Matthews *et al.,* 2011) and the Suđuroy tephra (8310-7868 cal a BP; Wastegård, 2002). Given what is known about the position and timing of ice extent and recession in the region around Gropviken, it is considered unlikely that this tephra could represent the Dimna Ash, AF555 or the Suđuroy tephra layers. Consequently, we consider that this represents an occurrence of the Vedde Ash (12,121 ± 114 GICC05 a BP;

Rasmusssen *et al.,* 2006) which has been detected within sediments of YD age across northern Europe and in the Greenland ice cores. The Vedde Ash is also known to have a basaltic component (Mangerud *et al.,* 1984, Davies *et al.,* 2001), however no shards of this composition were detected in this study.

Discussion

The Swedish varves provide a direct proxy of the melting of the Scandinavian ice-sheet (Andrén *et al.,* 1999) and an exact tephra-based synchronisation between this annual climate archive and other annually resolved records has never been accomplished. Detection of the Vedde Ash within the Swedish clay varves unlocks the potential to be able to build an independently-dated chronology which can be directly equated to other records of equivalent resolution in order to assess for leads and lags in the climate system and to analyse the rates and durations of key climatic shifts across broad regions. With further work focussing on securely connecting Gropviken to the STS, it is also considered that it will be possible to quantify any chronological offset between the STS and other high-resolution climate archives in the North Atlantic region.

The fact that the tephra is constrained to 2 years suggests that in this case reworking of tephra from ice, snow beds, or the surrounding catchment over decadal-centennial timescales as proposed for some sites (Davies et al. 2005; Matthews et al. 2011) does not apply and that this tephra represents a true isochronous layer of the Vedde Ash. This suggests that clay-varve records while providing an excellent way of testing for these effects are viable archives for constructing precise tephrostratigraphies.

Our tephra-based correlation using the Vedde Ash is one example where tephrochronology can make significant contributions to the climate modelling community, especially as models now need to capture very abrupt changes on short time-scales (Lane *et al.,* 2013). The Vedde Ash is, however, not the only tephra found in the Baltic region that has a potential to test hypotheses regarding synchronous or non-synchronous responses to climate forcing. Also the lateglacial Laacher See Tephra (c 12,880 cal a BP) has been reported (but not confirmed) to be present in a Baltic Sea core (Påhlsson, and Bergh Alm, 1985) and the early Holocene Hässeldalen and Askja-S tephras (11,360-11,300 cal a BP and 10,350-10,500 cal a BP respectively; Davies *et al.,* 2003; Lind and Wastegård, 2011; Lilja *et al.,* 2013) are known to occur across the southern Baltic area and might also be used to synchronise varved records with other palaeoclimate records.

Conclusions

This study has confirmed for the first time that volcanic ash correlating to the mid-YD Vedde Ash has been preserved and chemically characterised within the Swedish glacial clay varves. This layer is detected as a well-constrained marker horizon within two varve years and, when combined with the associated varve series, demonstrates that this part of Östergötland was ice-free by at least (but likely prior to) 12,740 ± 114 GICC05 a BP. Results from Gropviken represent the first very positive steps in developing an absolute chronological link between the record of ice recession and climate preserved within the terrestrial Swedish clay varves and other records of equivalent temporal resolution. Further work will be directed to attain a secure connection to the STS.

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Supporting Table captions

Supporting Table S1: Edinburgh University operating conditions for the CAMECA SX-100 Electron Microprobe. Elemental analyses corresponding to a beam current of 2nA are listed in bold text and those relating to 80nA in regular text (Hayward, 2012).

Supporting Table S2: Major element data measured as oxide concentrations (weight %) via WDS-EPMA. Analyses were obtained from individual glass shards extracted from varves 91 and 90 in Gropviken (see Supporting Table S1 for operating conditions).

Figure captions

Figure 1: A. Location of the study site in South East Sweden and other locations mentioned in the text; B. Location of Gropviken in Östergötland relative to De Geer's clay varve chronology illustrating that the site records sediment accumulation prior to 11,800 clay varve years BP (adapted from Brunnberg, 1995).

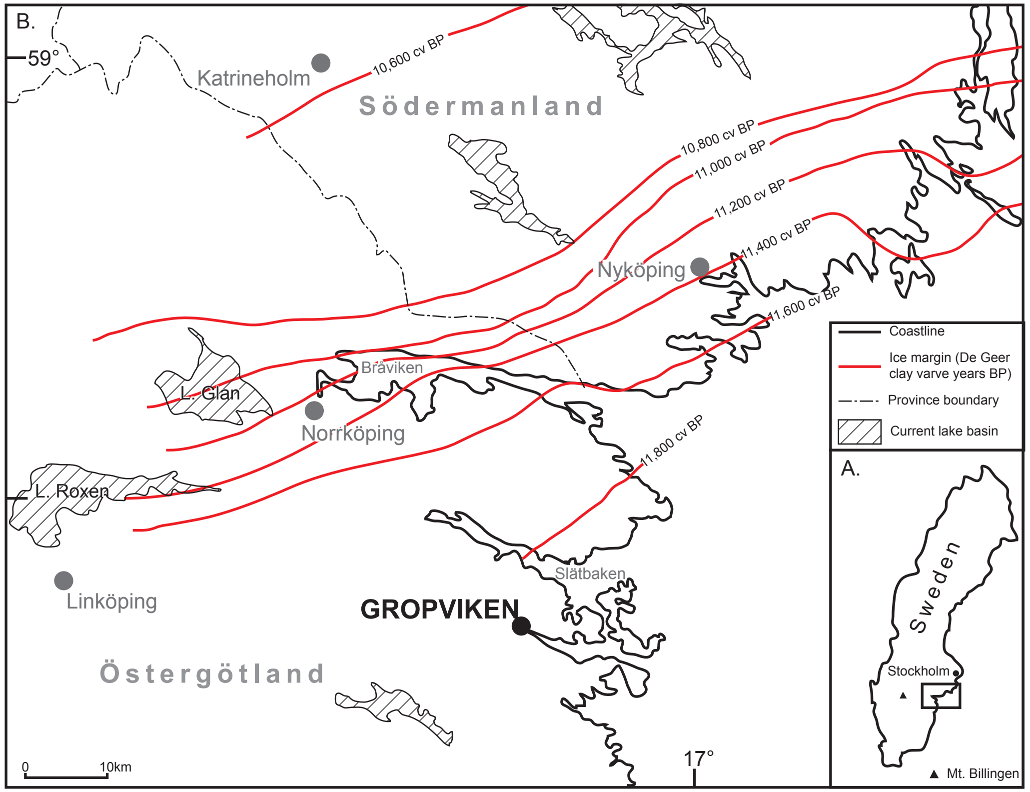
Figure 2: Gropviken varve thickness record with the position of the tephra layer highlighted in red shading towards the top of the sequence within varve numbers 91 and 90. This well constrained layer and clear first appearance of ash provides a well-constrained chronostratigraphic marker.

Figure 3: Biplots of Gropviken WDS-EPMA data compared with adjacent non-varved sites from Östergötland (Björck and Wastegård, 1999) and Kråkenes in Norway (Lane *et al.,* 2012), illustrating the coherence of the data generated in this study with that of published data for the Vedde Ash. It should also be noted that these data lie comfortably within the range of data presented for the type-site of the Vedde Ash (Kvamme et al., 1989; Supplementary Figure S1).

Supporting Figure caption

Supporting Figure S1: Biplots of Gropviken WDS-EPMA data compared with adjacent non-varved sites from Östergötland (Björck and Wastegård, 1999), Kråkenes in Norway (Lane *et al.,* 2012) and the Vedde Ash type-site from Kvamme et al., (1989) and Mangerud et al. (1984). These plots illustrate the coherence of the data generated in this study with that of published data for the Vedde Ash. The data is included here for completeness as it reflects the analyses obtained from the type locality, however it was not used in the main figure as more recently obtained data from sites in Norway provide a more tightly clustered dataset of rhyolitic glass shard analyses. It is not known why this is the case, however it can be postulated to relate to improved precision of the WDS-EPMA technique in recent years.

Figure 1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Norrköping
L. Roxen
Linköping
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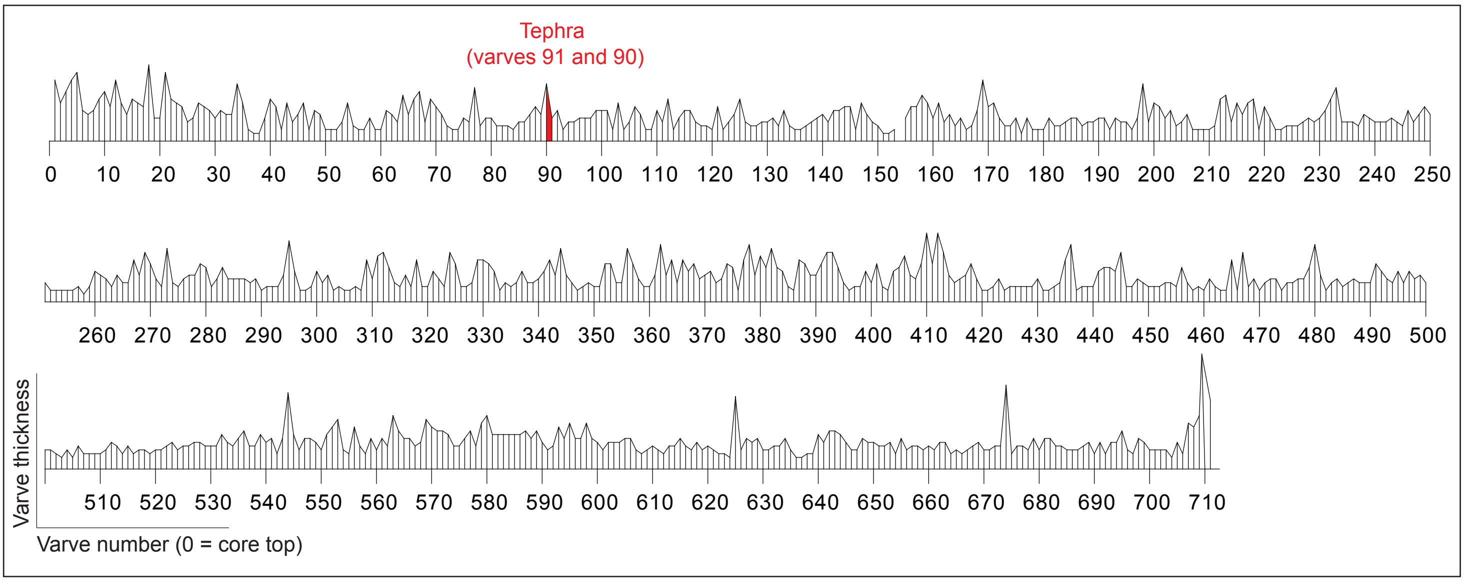
▲ Mt. Billingen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(varves 91 and 90)
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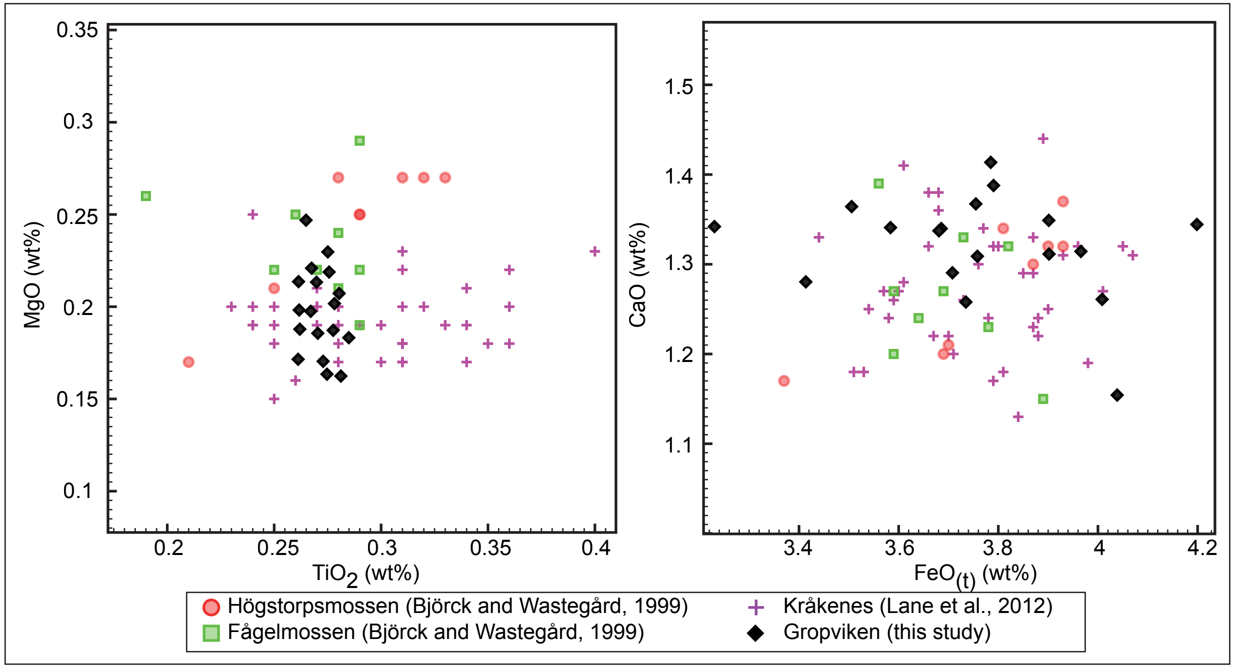
Varve thickness
Varve number (0 = core top)

Figure 3



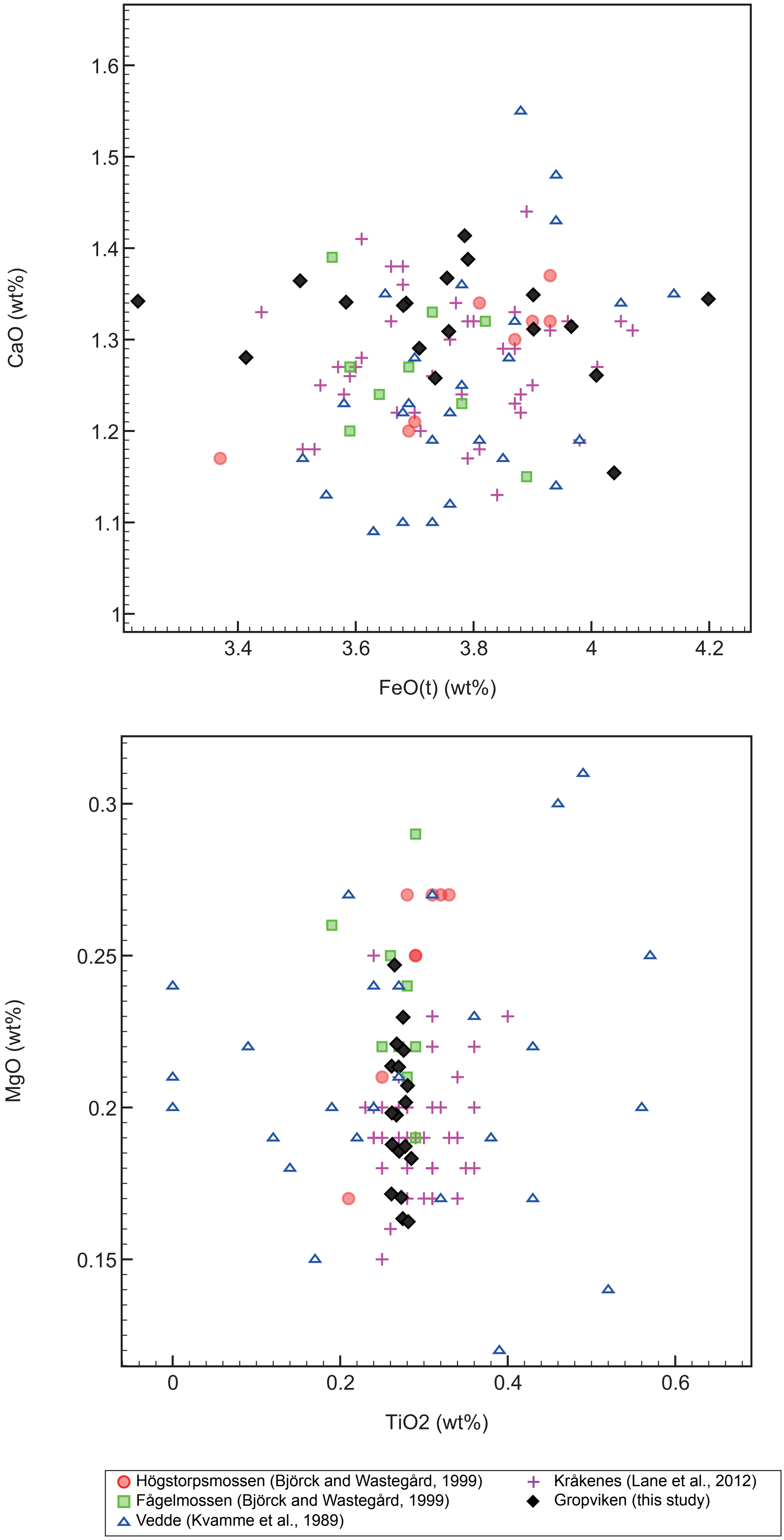
0.35
0.3
0.25
0.2
0.15
0.1
MgO (wt%)
0.2
0.25
0.3
0.35
0.4
TiO_2 (wt%)
1.5
1.4
1.3
1.2
1.1
CaO (wt%)
3.4
3.6
3.8
4
4.2
$FeO_{(t)}$ (wt%)
Högstorpsmossen (Björck and Wastegård, 1999)
Fågelmossen (Björck and Wastegård, 1999)
Kråkenes (Lane et al., 2012)
Gropviken (this study)

Supporting Table S1

Electron Microprobe	Cameca Sx-100, 5 Spectrometers
Elements analysed	**Na**, **Al**, **Si**, **Fe**, **K**, **Ca**, **Mg**, Mn and Ti
Accelerating volatage	15keV
Beam current	**2nA**/80 nA
Beam diameter	5 µm
Primary/Secondary calibration	Standard calibration blocks/Lipari obsidian

Supporting Table S2

Gropviken	***Weight % oxides***									
	SiO_2	TiO_2	Al_2O_3	$FeO_{(t)}$	***MnO***	***MgO***	***CaO***	Na_2O	K_2O	***Total***
n										
#1	69.57	0.27	13.23	3.51	0.15	0.19	1.36	5.27	3.32	96.90
#2	69.62	0.28	13.31	3.90	0.15	0.16	1.31	5.29	3.40	97.47
#3	69.79	0.27	13.26	3.90	0.16	0.22	1.35	5.12	3.52	97.63
#4	69.89	0.27	13.53	3.71	0.14	0.17	1.29	5.58	3.41	98.04
#5	70.14	0.28	12.94	3.23	0.15	0.19	1.34	4.85	3.23	96.38
#6	70.71	0.26	14.18	3.73	0.15	0.20	1.26	5.35	3.44	99.31
#7	70.89	0.26	14.14	3.69	0.11	0.19	1.34	5.39	3.38	99.43
#8	70.99	0.28	13.81	3.97	0.15	0.22	1.31	5.03	3.56	99.35
#9	71.00	0.27	13.31	3.78	0.14	0.20	1.41	5.13	3.63	98.89
#10	71.39	0.28	13.58	3.76	0.15	0.21	1.31	5.37	3.63	99.73
#11	71.40	0.27	13.71	4.04	0.15	0.16	1.15	5.21	3.60	99.74
#12	71.57	0.28	13.56	3.41	0.13	0.20	1.28	5.42	3.34	99.22
#13	72.04	0.27	13.91	3.75	0.12	0.21	1.37	5.28	3.51	100.50
#14	72.15	0.28	13.39	3.68	0.16	0.23	1.34	5.49	3.76	100.53
#15	72.23	0.26	13.62	3.79	0.13	0.21	1.39	5.11	3.52	100.31
#16	72.47	0.26	13.66	4.01	0.15	0.17	1.26	5.36	3.57	100.94
#17	72.66	0.28	14.24	4.20	0.14	0.18	1.34	5.38	3.70	102.17
#18	72.94	0.26	13.34	3.58	0.17	0.25	1.34	5.30	3.52	100.76
Mean	71.14	0.27	13.61	3.76	0.14	0.20	1.32	5.26	3.49	99.22
Std Dev	1.09	0.01	0.36	0.23	0.01	0.02	0.06	0.18	0.14	1.53


CaO (wt%)
1.6
1.5
1.4
1.3
1.2
1.1
1
3.4
3.6
3.8
4
4.2
FeO(t) (wt%)
MgO (wt%)
0.3
0.25
0.2
0.15
0
0.2
0.4
0.6
TiO2 (wt%)
Högstorpsmossen (Björck and Wastegård, 1999)
Fågelmossen (Björck and Wastegård, 1999)
Vedde (Kvamme et al., 1989)
Kråkenes (Lane et al., 2012)
Gropviken (this study)