A second tephra isochron for the Younger Dryas period in Northern Europe: the Abernethy Tephra

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Abstract

Visible and non-visible (cryptotephra) volcanic ash layers are increasingly being used to underpin the chronology and high-precision correlation of sequences dating to the last glacial-interglacial transition (LGIT). As the number of sediment records analysed for tephra content rises, and methodological developments permit the detection, extraction and chemical analysis of increasingly scantily represented glass shard concentrations, greater complexity in shard count profiles is elucidated. Here we present new evidence from sites in Scotland, and review published evidence from sites elsewhere in NW Europe, that indicate complexity in the eruptive history of Katla volcano during the mid-Younger Dryas and Early Holocene. We propose evidence for a previously-overlooked tephra isochron, here named the Abernethy Tephra, which is consistently found to lie close to the Younger Dryas/Holocene transition. It has a major-element chemical profile indistinguishable from that of the Vedde Ash, which was erupted from the Katla volcano at 12,121 ±114 cal a BP. The new data suggest that Katla may have erupted again between 11,720-11,230 cal a BP and the subsequent ash fall increases the potential to assess environmental response to Holocene warming across north and west Europe.

Key words: Tephra; Katla; Younger Dryas; Northern Europe; Abernethy Tephra; Vedde Ash; varve

1. ***Introduction***

Volcanic ash layers deposited in the North Atlantic region during the last glacial-interglacial transition (LGIT: 16-8 ka) have attracted heightened interest in recent decades, due to their potential for constraining the chronology of events reflected in high-resolution proxy records (e.g. Davies et al., 2012; Lane et al., 2013). Early interest in tephra-based correlations focussed on the study of visible ash layers preserved in terrestrial archives (Mangerud et al., 1984). This approach initially led to the detection of only a small numbers of tephra layers, but more recent discoveries of non-visible ash layers (cryptotephra) in marine, lake, bog and ice archives, has greatly increased the number and geographical range of these important isochronous markers (e.g. Wastegård, 2002; Swindles et al., 2011; Davies, 2014). This was an important development, because tephrostratigraphical correlation offers the potential not only to refine inter-regional correlations, but also to significantly reduce the chronological uncertainties that can compromise age models derived using other methods, such as radiocarbon dating. This includes the prospect of calibrating radiocarbon-based chronologies derived from marine contexts, which are frequently distorted by marine reservoir errors (Lowe et al., 2007; Austin and Hibbert, 2012).

The tephrostratigraphical framework established for NW Europe during the LGIT currently comprises more than 20 discrete volcanic ash layers (i.e. layers that are chemically well-characterised, within published ranges, and stratigraphically constrained), the majority of which are found only in cryptotephra form, attributed mostly to Icelandic volcanic eruptions (Blockley et al., 2014). Early tephrostratigraphic frameworks were comparatively simplistic, comprising only the most frequently encountered tephra layers. However, as cryptotephra investigations have become more routinely applied and protocols for standardisation of analytical techniques evolved, further complexity has emerged. For instance, not all reported layers are widely distributed, a number do not have unique chemical signatures, and taphonomic studies have revealed how individual layers may be discontinuously preserved within a site or possibly derived by secondary re-deposition (Davies et al., 2007; Pyne-O'Donnell, 2007, 2011; Griggs et al., 2014). Much, therefore, remains to be done to refine the record by more robust testing of the chemical composition, age and regional footprints of individual layers.

Here we focus on the tephrostratigraphical record of the Younger Dryas (YD) interval in NW Europe, and on new evidence from sites in Scotland that suggests it to have been more complex than recognised hitherto. This article includes records from sites that are widely dispersed across the North Atlantic region and focuses more on the sequence and relative age of the ash layers than on their precise age estimates. Because of this, we employ the long-established Scandinavian stratigraphic terminology (rather than local stratigraphic terms – see discussion by Lowe et al., 2008c and supporting table S1), to signify stratigraphic units that are broadly equivalent in age, but not necessarily synchronous. Unless otherwise stated we use the lithostratigraphic boundaries to define these units.

2. Background

The majority of tephra layers in NW Europe are frequently present in trace amounts only and require particular care in analysis and interpretation. The concentration of shards preserved within a site located distally from the source volcano is dependent on a combination of factors that include eruption characteristics, distance from source, local or regional weather patterns during ash dispersal and site or catchment-specific taphonomic processes (Mangerud et al., 1984; Davies et al., 2007; Pyne-O'Donnell, 2011; Leadbetter and Hort, 2011; Stevenson et al., 2011). The Vedde Ash (Figure 1a) is the most widespread (on current evidence) and most frequently recorded of the Icelandic distal tephras, and is generally considered to represent a single isochronous marker of mid-YD age (12,171 ± 114 yr b2k Rasmussen et al., 2006; 12,064 ± 99 cal a BP; Lohne et al., 2013; 2014). Originating from Katla volcano in Iceland, this ash has been reported from sites more than 3000 km from source, in Russia, Switzerland, Northern Italy and Slovenia (Wastegård et al., 2000; Blockley et al., 2007; Lane et al., 2011a, 2011b), as well as in numerous localities closer to source (Table 1). However, it is not chemically unique, as three additional layers deposited during the LGIT exhibit statistically indistinguishable major element spectra: the Dimna Ash (15,400-14,850 cal a BP; Koren et al., 2008), the AF555 tephra (11,720-11,230 cal a BP; Matthews et al., 2011; Bronk Ramsey et al., in press) and the Suđurøy tephra (8310-7868 cal a BP; Wastegård, 2002). Lane et al. (2012c) have also shown that it is not possible to discriminate between the Vedde and Dimna ash layers using minor and trace element ratios. Care needs to be exercised, therefore, when assigning a distal ash with Katla-type chemistry to a particular eruption.

Fortunately, in the majority of cases, the Suđurøy tephra, Vedde Ash and Dimna Ash can be readily distinguished if all three occur in the same stratigraphic sequence, because they are consistently found in three superposed, distinctive lithostratigraphic units, dating to the early Holocene, YD and 'Oldest Dryas' (OD) respectively (Wastegård, 2002; Koren et al., 2008). Problems arise, however, if the full lithostratigraphic or tephrostratigraphic suite is not represented and the stratigraphic context is not clear, especially in sites where the tephra record is complex (see e.g. Housley et al., 2013), as chemical fingerprinting of glass, via major or trace element spectra, alone will not discriminate which of the layers are represented.

In its visible form, distal Vedde Ash is considered to comprise two parts, a lower basaltic and upper rhyolitic end member (Mangerud et al., 1984). When chemical data are plotted (Le Maitre and Streckeisen, 2002) there is a characteristic linear trend between end members also including shards of basaltic-andesite composition. At the type site of Lake Gjølvatn in Norway, Mangerud et al. (1984) described the ash layer as being visible, up to 5cm in thickness and composed of 80-90% colourless shards with the other 10-20% being pale to dark brown in colour. This bimodal composition is replicated at the only visible deposit of the Vedde Ash in the UK, at Loch Ashik on the Isle of Skye, where Davies et al. (2001) report the basal part of the layer to be dominated by basaltic glass (99% of the total peak value of glass shard concentration). Elsewhere in Europe, the Vedde Ash is predominantly characterised by the colourless rhyolitic glass component only, and is reported as a single event within the YD chronozone (e.g. Lane et al., 2012a; 2011a Blockley et al., 2007). An exception to this is Meerfelder Maar where Lane et al. (2013) also detect shards with lower SiO_2 and Total alkali contents.

A further factor to consider, however, is the temporal and stratigraphic resolution with which LGIT sediment sequences have been analysed, and any contained tephra layers can be resolved. Detailed analysis of sediments deposited during the Bølling-Allerød interstadial interval has shown how low sedimentation rates can lead to the conflation of tephras of different age, for example, the distal, presumed Icelandic Borrobol and Penifiler tephras (Pyne-O'Donnell et al., 2008; Matthews et al., 2011) which are detected across northern Europe. This can be difficult to discriminate, however, and only comes to light in sequences which have sufficiently robust stratigraphic control, where the sequences can be examined in high temporal resolution, and where the additional volcanic activity can be demonstrated to be consistently represented in multiple sequences. Here we review the evidence of distal ash layers recorded for the YD interval, and present new data from three sites in the central Scottish Highlands (Figure 1b), Loch Etteridge, Loch Laggan East and the Glen Turret Fan (Glen Roy), that together suggest more than one volcanic event to be represented in the YD sediment records.

3. Laboratory methods

3.1 *Analysis of previously unpublished records*

Cryptotephra were located in the new sediment records using the procedures of Turney (1998) and Blockley et al. (2005), with some minor modifications. Samples were processed using density flotation procedures to extract material of 15-80 μm grain-size, and the fraction with a density range of between 1.95 and 2.55 g cm^{-3} was mounted in Canada Balsam and examined at 100x and 400x magnification. Due to the low number of glass shards recovered from one or more of the sites, the samples were isolated from other sources rich in tephra by conducting all procedures within a purpose-built tephra laboratory designed to eliminate the potential of contamination of samples with very low concentrations of ash. Improvements in the methods used to extract small cryptotephra particles and to determine their chemical composition (Matthews et al., in prep), combined with technical advances that allow Wavelength Dispersive Electron Probe Micro Analysis (WDS-EPMA) to be conducted using smaller beam diameters (Hayward, 2012), were crucial developments that enabled the detection and chemical characterisation of trace amounts of cryptotephra from two of the sequences reported below.

Sampling for tephra analysis was carried out in three phases: (i) a scan phase conducted at 5cm vertical resolution tested for presence or absence of glass shards; (ii) for those intervals in which scanning indicated the presence of glass shards, sampling was refined to 1cm resolution; (iii) the horizons containing peak levels of volcanic glass were re-sampled to select suitable shards for WDS-EPMA using a modification of the procedure described by Pyne-O'Donnell (2004). Chemical analyses were conducted using electron microprobes at the Tephra Analytical Unit, University of Edinburgh and the Research Laboratory for Archaeology and the History of Art, Oxford University; the analytical operating conditions and the full set of raw data and standard analyses obtained are provided in Supporting Table S2 and S3. Where published and unpublished data are compared in later sections of this paper, care has been taken to ensure that the chemical preparation and analytical procedures adopted have been consistent. Any modifications to procedures (such as reduced sieve sizes and shard concentration techniques) were adopted for the purpose of improving the detection potential only.

3.2 The Loch Etteridge record

Loch Etteridge, located c.10 km north-east of Dalwhinnie, is a partially in-filled lake basin that occupies Glen Fernisdale, a tributary valley of the River Spey. Initial work at this site was conducted by Walker (1975), who reported pollen-stratigraphic and radiocarbon evidence that demonstrated a full Lateglacial sequence is preserved in the basin. A basal radiocarbon age estimate suggested the sediments started to accumulate before 13,150 ±350 ^{14}C yr BP (c.15,763 ±1173 cal a BP), subsequently corroborated by a more recent basal date of 12,930 ±40 ^{14}C yr BP (15,455 ±200 cal a BP) obtained by Everest and Golledge (2004). Further investigations by the present authors recovered an almost identical lithostratigraphic sequence to that reported by Walker (1975) and Everest and Golledge (2004), but from a deeper part of the basin (Figure 2). Using the methods summarised above, five discrete tephra layers were identified within the lateglacial sediment sequence, three within the Bølling-Allerød (B-A) interval (LET-1 to LET-3) and two within the YD (LET-4 and LET-5). This shard profile has been replicated across several core sequences from this site. Chemical analytical investigations reported in Lowe et al. (2008a) and Albert (2007) indicated that LET-1 and LET-2 could be assigned to the Borrobol and Penifiler tephras respectively, while LET-4 was assigned to the Vedde Ash (Figure 3). Here we present new data for the LET-5 tephra layer, which lies within a clay-rich gyttja deposit, although on pollen-stratigraphic evidence this lithostratigraphic unit has been ascribed to the YD period (Albert, 2007). This layer is stratigraphically isolated from, and has a lower shard concentration than, LET-4. Hence in this sequence two discrete ash layers fall within the YD interval. Major element chemical analysis (Supporting Table S3) of the LET-5 layers reveals that it comprises rhyolitic glass with a major element composition that is indistinguishable from that of LET-4, previously ascribed to the Vedde Ash (Figure 3).

3.3. The Loch Laggan East and Glen Turret Fan records

Loch Laggan and Glen Turret are valleys adjacent to Glen Roy that were occupied by the ice-dammed lakes that formed pronounced shorelines (the 'Parallel Roads') during the YD (Figures 1 and 4; Sissons, 1978; Lowe et al., 2008b). Close to the eastern shore of the present-day Loch Laggan, and on the surface of a large fan at the mouth of Glen Turret, glaciolacustrine varves have accumulated, and the records from these localities have contributed to the construction of a local varve chronology reported by Palmer et al. (2010) and MacLeod (2010). At both the Loch Laggan East (LLE) and Glen Turret fan (GTF) sites, multiple cores and sediment sections were analysed to construct a 515-yr-long master varve chronology, the Lochaber Master Varve Chronology (LMVC). This provides an estimate of the period of time that the ice-dammed lakes were in existence during the YD, and hence when the glaciers were sufficiently large to form effective dams. The lakes drained catastrophically at the onset of Holocene warming (Sissons, 1979). Varve thickness and micro-sedimentology (examined by thin section) display a high-degree of coherence between the LLE and GTF records (Figure 4), probably as a result of sediment input controlled by the advancing ice front that blocked the lakes (Palmer et al., 2010). The longest record of sediment accumulation is to be found at LLE, which started to accumulate from the time when the ice-dammed lakes were initially formed. A shorter record, starting later in the YD, is to be found at GTF, because, due to its higher altitude, glaciolacustrine varved sediments did not begin to accumulate until lake levels rose to 325 m, after the ice-front had encroached into the lower part of Glen Roy (Figure 4; see Palmer et al., 2010 for details). It is the tephrostratigraphical records from these sequences that are the main focus here.

Both the LLE and GTF sequences were systematically scanned for the presence of tephra shards. The mineral-rich sediments were found to be devoid of glass shards, except in low numbers in two horizons. In the LLE sequence, a low concentration of 12 colourless tephra shards per gram of dry sediment were detected, with the first appearance dated to varve year 120 in the LMVC (i.e. 120 years after the start of varve sedimentation in Loch Laggan). At this time the GTF was not yet fully submerged, and glaciolacustrine varved sediment began to accumulate here c. 190 years after the start of varve sediment accumulation at LLE. In the GTF varve sequence, a discrete layer consisting of 13 colourless tephra shards per gram of dry sediment was detected within a 5-cm-thick interval characterised by varves disturbed by post-depositional deformation. The shards are very small, with a maximum a-axis of c. 60 µm and b-axis c. 10-30 µm. As a consequence, the surface areas suitable for WDS-EPMA were restricted. This interval consists of c.30 deformed varves, deposited during LMVC years 425-455, the subsequent deformation being attributed to seismic activity in the region (Ringrose, 1989). Because the lake at GTF did not exist when the Vedde Ash was deposited at LLE this precludes reworking as the source of the GTF ash layer. The evidence therefore suggests that two eruptive events may be represented in the Lochaber varved sequence and that these are separated by c. 320 ±15 varve years.

Chemical analysis of shards extracted from the layer in the GTF sequence indicates a rhyolitic composition (Supporting Table S3) that is indistinguishable from published data for the Vedde Ash; they also correlate well with the data obtained from Loch Etteridge layers LET-4 and -5 (Figure 3). However, no chemical data could be obtained from the LLE layer (LMVC yr 120) due to the small size and low concentration of shards available, and hence the identity of this layer can only be conjectured at this stage, though we return to this in the discussion section below.

4. *Previously-published records of tephra layers assigned to the YD*

Previously-published reports of the Vedde Ash detected in terrestrial deposits tend to focus on its representation as a single event within the YD. However, there are numerous published records that display more complex shard concentration variations (Table 1), and in this section we review the evidence that suggests that the Vedde Ash was not the only tephra deposited over NW Europe during the YD. We summarise first the relevant evidence from the distal type sites for the Vedde Ash, and then examine the shard deposition profiles of other tephra records from NW Europe that fall into three categories: those sites that contain a single peak of visible or cryptotephra; those which preserve a double peak in shard concentrations, but with no hiatus in shard deposition between the peaks; and those with two peaks in shard concentrations that are clearly separated by sediments containing no detectable glass shards. Figure 1c shows the distribution of the sites considered.

4.1 *The Vedde Ash in NW Norway*

The distal type sites for the Vedde Ash are Lake Gjølvatn, Torvlømyra and Saudedalsmyra, in the Ålesund region of NW Norway (Mangerud et al., 1984). Within these three basins and the site of Lerstadvatn (an extant lake), the ash layer is reported as comprising a single concentration of shards between 1 and 24 cm in thickness, though this varies considerably depending on location in each basin and also the size of the basin catchments. Torvlømyra, for example, has a catchment 65 times the size of the former lake basin, and the ash layer is up to 24 cm thick, whereas Lerstadvatn is smaller with a catchment only 5 times bigger than its current lake surface area, and here the Vedde Ash is only around 1 cm thick, and consists of much more fine-grained glass shards (Mangerud et al., 1984). Also at the latter site a second tephra layer, with a chemical signature identical to the Vedde Ash, was detected at the base of the overlying Early Holocene (EH) deposits, which was attributed to reworking from the older Vedde Ash layer (Mangerud et al., 1984). An alternative possibility, however, is that this could represent a younger eruption and a fresh dispersal of ash from Katla. In the data presented by Mangerud et al. (1984) from Gjølvatn, Torvlømyra and

Saudedalsmyra, it is not currently possible to assess whether a second layer is present. This is due to a difference in sample processing method to that of Lerstadvatn and it is possible that more further analyses of these other records may elucidate greater detail. Single peaks of visible or non-visible Vedde Ash are also reported from a number of other sites in Norway and across Europe; the key layers are discussed below and a comprehensive list of sites and shard peak structure is provided in Table 1.

4.2 *Sites with a single peak in shard concentration*

Outside Norway, Loch Ashik on the Isle of Skye, Scotland, is the only other distal terrestrial site containing a visible Vedde Ash layer. Davies et al. (2001) describe a single layer, 1cm in thickness, comprised predominantly of basaltic volcanic glass shards but with a component of colourless shards. Subsequent work by Pyne-O'Donnell et al. (2008) showed that the non-visible component of this layer also has a single peak but is spread through an interval of c. 10 cm, which represents a considerable part of the YD stratigraphic unit. Pyne-O'Donnell (2010) also found evidence of significant re-working of the visible ash particles, which, as in the case of sites in NW Norway discussed above, may have resulted in the masking of any later ash layer with lower shard concentrations.

To the south of Norway and excluding Loch Ashik on Skye, the Vedde Ash is more commonly detected and presented as a single peak of non-visible, cryptotephra in terrestrial archives (Table 1). Reasons for this relative paucity of visible occurrences is not fully understood but is considered to reflect a combination of site-specific processes (Davies et al., 2007) and aeolian transport pathways and precipitation patterns that favoured the concentration and deposition of larger quantities of ash in specific localities.

Evidence for greater complexity in Vedde Ash shard profiles may also be masked where the ash layer is indicated schematically, using a single arrow or line on a stratigraphic log (e.g. Wastegård et al., 2000; Davies et al., 2003). In such cases, quantified estimates of the distribution of shard numbers are usually not provided, thus precluding the possibility of resolving the pattern of shard deposition. In other cases, shard counts may only be presented for the horizon in which chemical data for the Vedde Ash has been obtained and not for any subsidiary peaks which may have been present in the upper part of the YD interval.

4.3 *Sites with two linked peaks in shard concentration*

A number of records do not show a single peak in shard concentrations in the ash layer assigned to the Vedde Ash. In this first type of example (see 4.4 for second), two clear peaks are separated by an interval in which shards are present throughout, but in lower quantities. Records displaying this characteristic include Borrobol in Scotland (Lowe and Turney, 1997) and Lake Madtjärn, Sweden (Wastegård et al., 1998). At Borrobol, the upper peak is in the order of 1500 shards cm^{-3} of sediment, which equates to approximately a fifth of the concentration of the lower peak (Figure 5). In Lake Madtjärn however, the upper peak represents the larger of the two (c. 3100 shards cm^{-3} in the upper peak and c. 2100 shards g^{-1} in the lower peak). In the case of Borrobol, chemical data are available for the lower peak only, while at Lake Madtjärn, chemical data are presented for the upper peak. In both cases the data match well to the Vedde Ash chemistry and the upper peaks are interpreted in the published accounts as likely to be the result of reworking.

4.4. *Sites with two discrete peaks in shard concentration*

A final group of sites with ash layers assigned to the Vedde Ash show evidence of two peaks in shard concentrations within the YD stratigraphic unit, which are separated by sediment found to be devoid of volcanic glass shards. Records displaying this characteristic (Figure 5) include Muir Park Reservoir, Loch Etteridge, Abernethy Forest and Lochan an Druim in Scotland (Lowe and Roberts, 2003; Lowe et al., 2008a; Matthews et al., 2011; Ranner et al., 2005) and the Loch Laggan-Glen Turret Fan varved sequence discussed above. In all cases, the upper peak contains a lower concentration of glass shards than the lower. Chemical analyses are available for the upper and lower peaks in the Loch Etteridge (this study) and Abernethy Forest records, for the lower peak only in the Muir Park Reservoir and Lochan An Druim records, and the upper peak only for the Loch Laggan-Glen Turret Fan varved sequence (this study).

5. ***Discussion***

Until recently (Matthews et al., 2011, Lane et al., 2012), it has generally been assumed that distal ash records for the North-East Atlantic and Europe include only one tephra layer of Icelandic origin that dates to the YD chronozone. As a result, any ash layers found within the YD interval that have Katla-type chemistry are presumed to represent the Vedde Ash, and are assigned the GICC05 age for the Vedde Ash (12,171 ± 114 b2k). In the preceding sections, however, we have shown that the Icelandic tephrostratigraphical record for the YD is frequently more complex, commonly displaying two distinct peaks in glass shard concentrations, sometimes separated by non-tephra-bearing sediment. In some cases, this pattern may reflect the effects of reworking. An alternative possibility, however, is that at least two separate eruptions of Katla occurred during the YD, with the upper of the two peaks alluded to above representing an eruption that post-dated the Vedde Ash. We have proposed that this second ash layer is generally less pronounced than the Vedde Ash, and that it could become obscured by reworking of the Vedde Ash in catchments or basins that collected particularly high concentrations of Vedde Ash.

We concede that correlation remains tentative in those cases discussed above that lack the support of chemical measurements, and that these therefore require further investigation. Nevertheless we consider the case for a second ash fall of Katla origin within the YD to be strong, for the following reasons. First, in those sequences where the YD tephrostratigraphical record is well resolved, such as Loch Etteridge (presented here), Abernethy Forest (Matthews et al., 2011), Muir Park Reservoir (Lowe and Roberts, 2003) and Lochan an Druim (Ranner et al., 2005), the upper layer is a discrete, single layer, with a well-defined peak, similar to other distal ash layers that are considered primary deposits. It might be expected that if these occurrences reflected reworking, then a less structured pattern would be evident, involving sporadic influx of low concentrations of reworked material between the first and second peaks. Second, all of the upper tephra layers consistently lie very close to the YD/Holocene boundary, suggesting isochronous development. Thirdly, as previously stated, the interval between the likely Vedde Ash in LLE and the ash layer in GTF is a minimum of 320 years with no evidence of tephra shards in the intervening period. Throughout this period, sediment thin sections confirm that sedimentation is rhythmic, undisturbed and continuous apart from two discrete points (sand layer and deformation zone; Figure 4). The first of these event layers (sand layer) contains no tephra, indicating that during this basin-wide event tephra is not being introduced from the catchment. This therefore provides additional strength to the proposal that the GTF ash layer represents a separate eruptive event.

Other independent evidence points to the possibility of an eruption of Katla close to the YD/Holocene boundary. From their studies of eruptives in central Iceland, van Vliet-Lanoë et al. (2007) conclude that silicic material was erupted by Katla several times during the YD, and they present evidence for the Mykjunes Tephra, which has a chemical signature identical to the Vedde Ash, but was erupted later in the YD. Björck et al. (1992) also identified two tephra-rich horizons within clay-rich sediments of YD-age above the Vedde Ash at Lake Torfaldsvatn, northern Iceland, though no chemical data was presented for these layers. Within the NorthGRIP ice core, Mortensen et al. (2005) detected evidence for two ash layers which occur stratigraphically above the Vedde Ash. Again, no chemical information is available for these layers, but they are considered to be rhyolitic on the basis of morphological analysis. Although some of these YD sites currently lack the defining chemical data, Larsen et al. (2001) demonstrate that the mid- to late-Holocene silicic eruptions from Katla produce ash layers with very similar major element chemical profiles. This is echoed from other Icelandic volcanoes with Jóhannsdóttir et al. (2005) showing that ash layers with identical major element chemical signatures are also produced from eruptions of Grímsvotn volcano with repose times an order of magnitude lower than those seen at Katla (10’s to 100’s of years).

A number of lines of evidence therefore point to the possibility of a Katla eruption event late in the YD or at the YD/Holocene boundary. The best radiocarbon-based age estimate currently available for the layers which we assign to this event is that of the

AF555 tephra layer in the Abernethy Forest sequence, where it is dated to between 11,720 and 11,230 cal a BP, with a 2σ error range (Bronk Ramsey, in press). This would make the mean age around 300 years younger than the mean age for the Vedde Ash. It is therefore interesting to note that the difference in age between the LLE tephra layer that is tentatively assigned to the Vedde Ash, and the GTF ash layer which is considered the correlative of AF555, is also around 300 varve years (Figure 2). The two ash layers detected in the NGRIP ice core, alluded to above, date to around 11,926 yrs b2k (maximum counting error (m.c.e) ±106) and 11,681 yrs b2k (m.c.e ±106; Mortensen et al., 2005), making them around 245 and 490 years younger than the Vedde Ash, respectively.

6. ***Conclusions***

It is contended that sufficient evidence exists to indicate the strong possibility of a Katla eruption event dating close to the YD/Holocene boundary, and that eruptive products from this event can be found at several sites in Scotland and perhaps at other sites in NW Europe. If correct, then this would add a further important tephra isochron to the developing tephrostratigraphical scheme for NW Europe during the LGIT, one that coincides with a key palaeoclimatic transition (see Brooks et al., 2012). The proximity of this layer to the onset of Holocene climatic conditions also means that, as evidenced from sites in Scotland and Norway, this tephra may not always be found in the unit that is assigned to the YD interval on lithostratigraphic criteria. Given its potential importance, we suggest this tephra be named the Abernethy Tephra, after the site in which it was first chemically characterised and dated in a terrestrial context, but where it was provisionally labelled the AF555 tephra (Matthews et al., 2011). Further research is under way to test for the presence of this tephra at other sites in Scotland, and we would encourage others to make closer scrutiny of YD and Early Holocene records from other regions, to test the conclusions presented here.

It is recommended that in sites where only one of these ash layers is detected, such as is exemplified by Lane et al. (2013), Brauer et al. (2008) and Bakke et al. (2009), it is vital to strengthen correlations and interpretations with robust chronologies and high-resolution proxy data. In the above cases, miscorrelation to the Vedde Ash is unlikely because of the rigorous approaches taken and these should be used as 'model' examples of best practice if both YD ash layers are not present. This is perhaps especially important when the tephra is being used to assess and quantify leads, lags and rates of terrestrial environmental response to changes in ocean and atmospheric circulation patterns. In sequences where both ash layers are present, the generation of associated high-resolution palaeoclimatic data, as achieved at Abernethy Forest, will provide a more consistent basis for establishing spatial variations in the local timing of environmental responses to climatic warming.

Acknowledgements

Thanks are extended to Christopher Hayward (Tephra Analytical Unit, Edinburgh University) and Norman Charnley (Earth Sciences, Oxford University) for their assistance with WDS-EPMA analysis. Aspects of this work was undertaken while AM was in receipt of a NERC studentship as part of the NERC RAPID Climate Change thematic programme (NE/C509158/1), and latterly while in receipt of a Leverhulme Trust Early Career Fellowship. We also thank Christine Lane for a thorough review which improved an earlier version of this article. This is RHOXTOR publication number 0042.

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Table Captions

Table 1: Summary of terrestrial sites across Europe which are been reported in the literature to contain the Vedde Ash. These have been sub-divided to distinguish the different styles of peak structure observed within the record. In many cases, the significance of this peak structure is not considered in the original publication but in light of the data presented here is now considered to represent previously unrecognised complexity in the eruptive history of Katla volcano, Iceland, during the YD.

Figure Captions

Figure 1: A) Sites where Vedde Ash has been identified across Europe. B) Sites known to preserve Vedde Ash within the UK and the location of the new sites presented here. C) Shard profile categorisation of sites containing Vedde Ash across Europe highlighting that those furthest from source are reported to preserve only a single non-visible peak in glass shards and highlighting the location of sites where two YD peaks in glass shards can be identified. These are currently restricted to Scotland, Norway and Sweden. Plots were produced using the Plot function within the RESET database (Bronk Ramsey, 2014; http://c14.arch.ox.ac.uk/reset/)

Figure 2: Loch Etteridge lithostratigraphy and tephra record highlighting the position of the late-YD peak in tephra shards (LET-5). Adapted from Lowe et al. (2008a) and Albert, 2007.

Figure 3: A) Total Alkali Silica classification (Le Maitre and Streckeisen, 2002) of chemical analyses from the upper and lower YD ash layers in Loch Etteridge (LET-4 and LET-5), Glen Turret Fan (GTF) and the type site of Abernethy Forest (AF555 and AF591; Matthews et al., 2011). Comparative data for the Vedde Ash has been obtained from the RESET database (http://c14.arch.ox.ac.uk/reset/). B) Inset of figure A. C+D) TiO_2 versus MgO and $FeO_{(t)}$ versus CaO biplots indicating that the upper and lower ash layers investigated within this study have a strong chemical affinity with the Vedde Ash despite being stratigraphically separate.

Figure 4: A-B Illustrates the context of Loch Laggan East and Glen Turret Fan in relation to ice advance from the south and glacial lake development which is sustained by a common ice margin. A) Reflects initiation of the 260m lake level during which varve accumulation begins at LLE. As the sediment surface at GTF is at an altitude of 251-267m, water levels would likely have been too shallow to allow varve development at this time. As the YD developed (B), ice advanced into Glen Roy allowing lake levels to rise to 325m (controlled by the Roy/Laggan col). Lake levels at LLE remained at 260m controlled by the Pattack/Mashie col. It is during this time that varve accumulation was initiated at GTF. Full details of Lochaber lake development can be found in Palmer et al. (2010) C) Varve thickness records from both LLE (left) and GTF (right) demonstrating the coherence in total varve thickness patterns across the two records. This correlation is reinforced by the presence of two key marker layers (sand layer and section of deformed varves) and by varve microfacies (see Palmer et al., 2010). The position of tephra has been highlighted and demonstrates the presence of two discrete layers within the varved deposits.

Figure 5: Selected published sites from across the North Atlantic region exhibiting evidence for a double peak in tephra at or near the YD Holocene boundary. Sites included illustrate the different forms of tephra peaks, based on shard concentration data (note variable x-axis scales), discussed within this article and identify sequences where further analyses may elucidate additional correlations, such as the rhyolitic

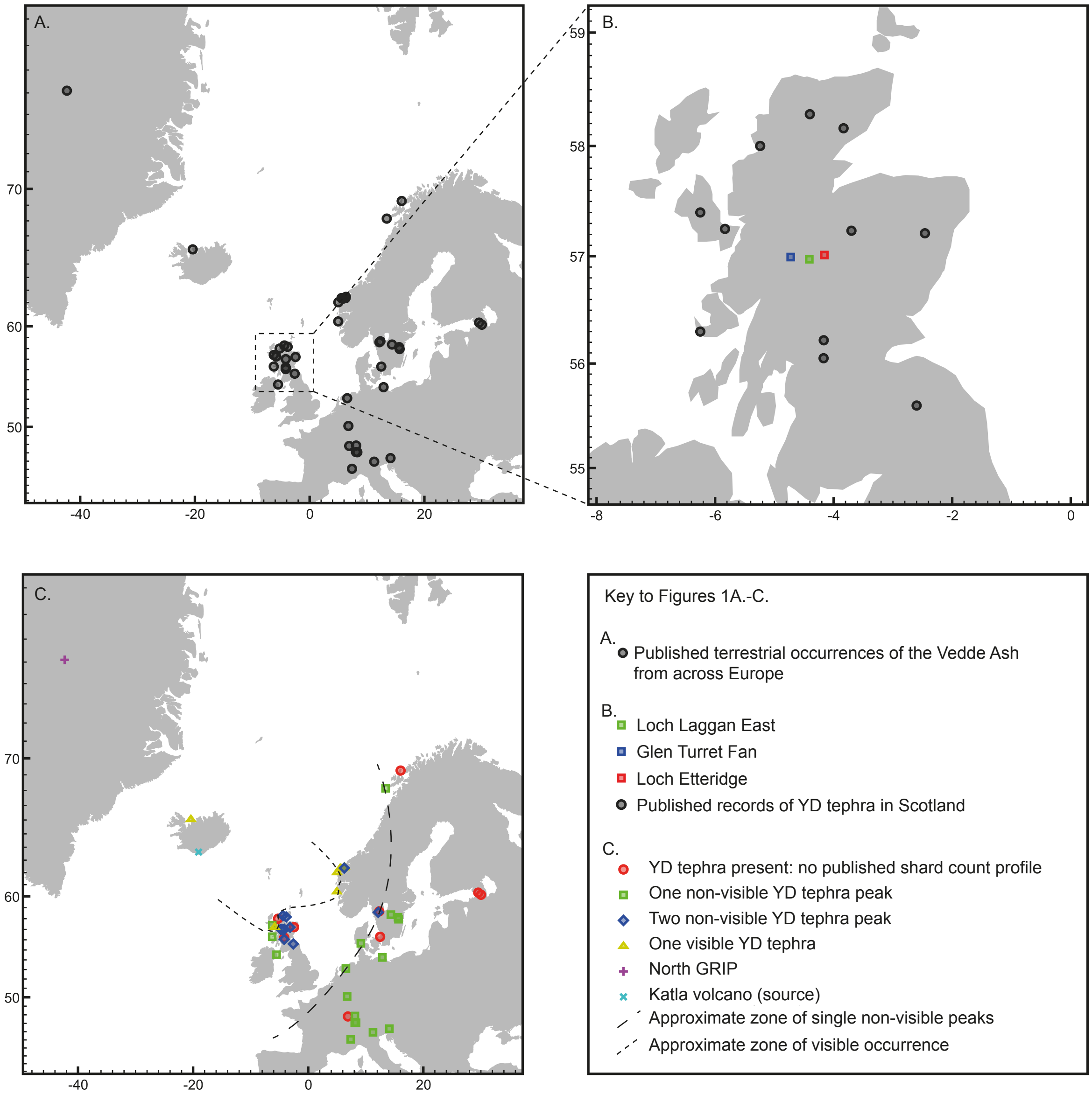
layers above the Vedde Ash within the ice core record (ash layers at 1499.14 and 1491.48m depth). The shaded region marks the transition from the sediments of Lateglacial Interstadial, YD and Holocene age and reflects those defined on climatic and/or stratigraphic grounds by each associated publication. This also demonstrates that the upper ash layer can be contained within mineral or organic-rich lithostratigraphic contexts possibly reflecting asynchrony in landscape response to climate forcing (Pyne-O'Donnell et al., 2008, Matthews et al., 2011).

Supporting Table Captions

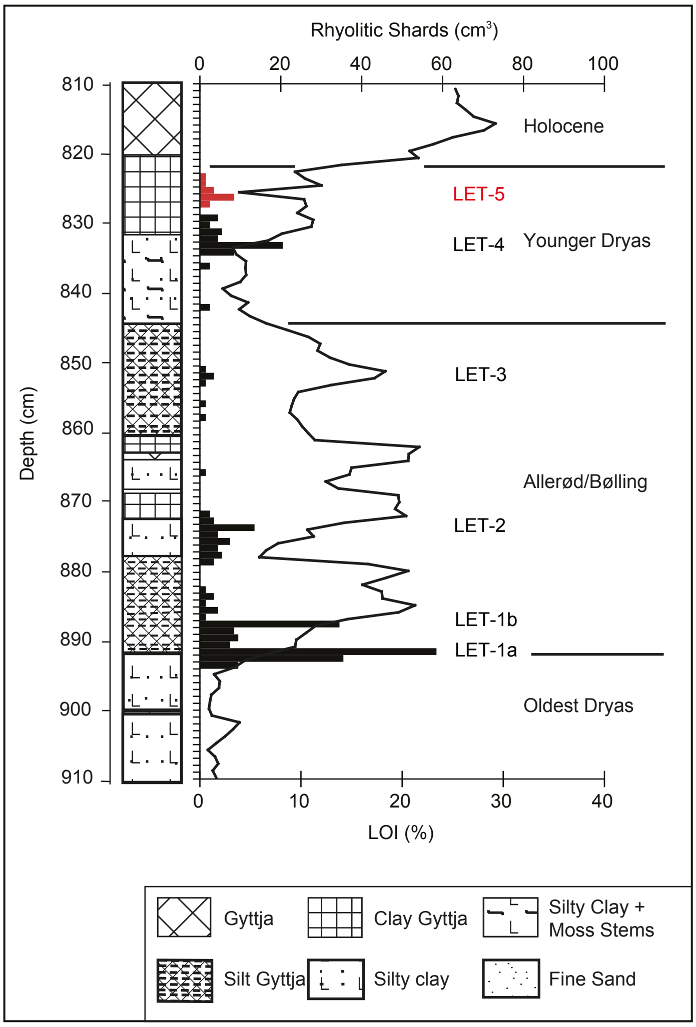
S1: Summary table highlighting the various terminologies applied to climatostratigraphic chronozones across Europe. This table is adapted from van Raden et al. (2013) by adding British terminology to demonstrate approximate equivalence of terms. The scheme applied in this study is that of Scandinavia/Swiss Plateau/S. Germany but this is used to simplify descriptions in the text rather than to imply equivalence across regions.

S2: WDS-EPMA Operating conditions for the CAMECA SX-100 (Tephra Analytical Unit, University of Edinburgh) and the Jeol JXA-8800R (Oxford University) Electron Microprobes used.

S3: Major element and secondary standard data measured as oxide concentrations (weight %) via WDS-EPMA for Loch Etteridge (LET-4 and LET-5) and Glen Turret Fan (LMVC-T424). The data from LET-4 highlighted in bold text was obtained from the Electron Microprobe Unit at Oxford University whilst the remaining data from both LET-4, LET-5 and GTF was obtained at the Tephra Analytical Unit, University of Edinburgh.



A.
B.
C.
70
60
50
59
58
57
56
55
-40
-20
0
20
-8
-6
-4
-2
0
Key to Figures 1A.-C.
A.
Published terrestrial occurrences of the Vedde Ash from across Europe
B.
Loch Laggan East
Glen Turret Fan
Loch Etteridge
Published records of YD tephra in Scotland
C.
YD tephra present: no published shard count profile
One non-visible YD tephra peak
Two non-visible YD tephra peak
One visible YD tephra
North GRIP
Katla volcano (source)
Approximate zone of single non-visible peaks
Approximate zone of visible occurrence



Rhyolitic Shards (cm3)
0
20
40
60
80
100
Depth (cm)
810
820
830
840
850
860
870
880
890
900
910
Holocene
LET-5
LET-4
Younger Dryas
LET-3
Allerød/Bølling
LET-2
LET-1b
LET-1a
Oldest Dryas
0
10
20
30
40
LOI (%)
Gyttja
Clay Gyttja
Silty Clay + Moss Stems
Silt Gyttja
Silty clay
Fine Sand

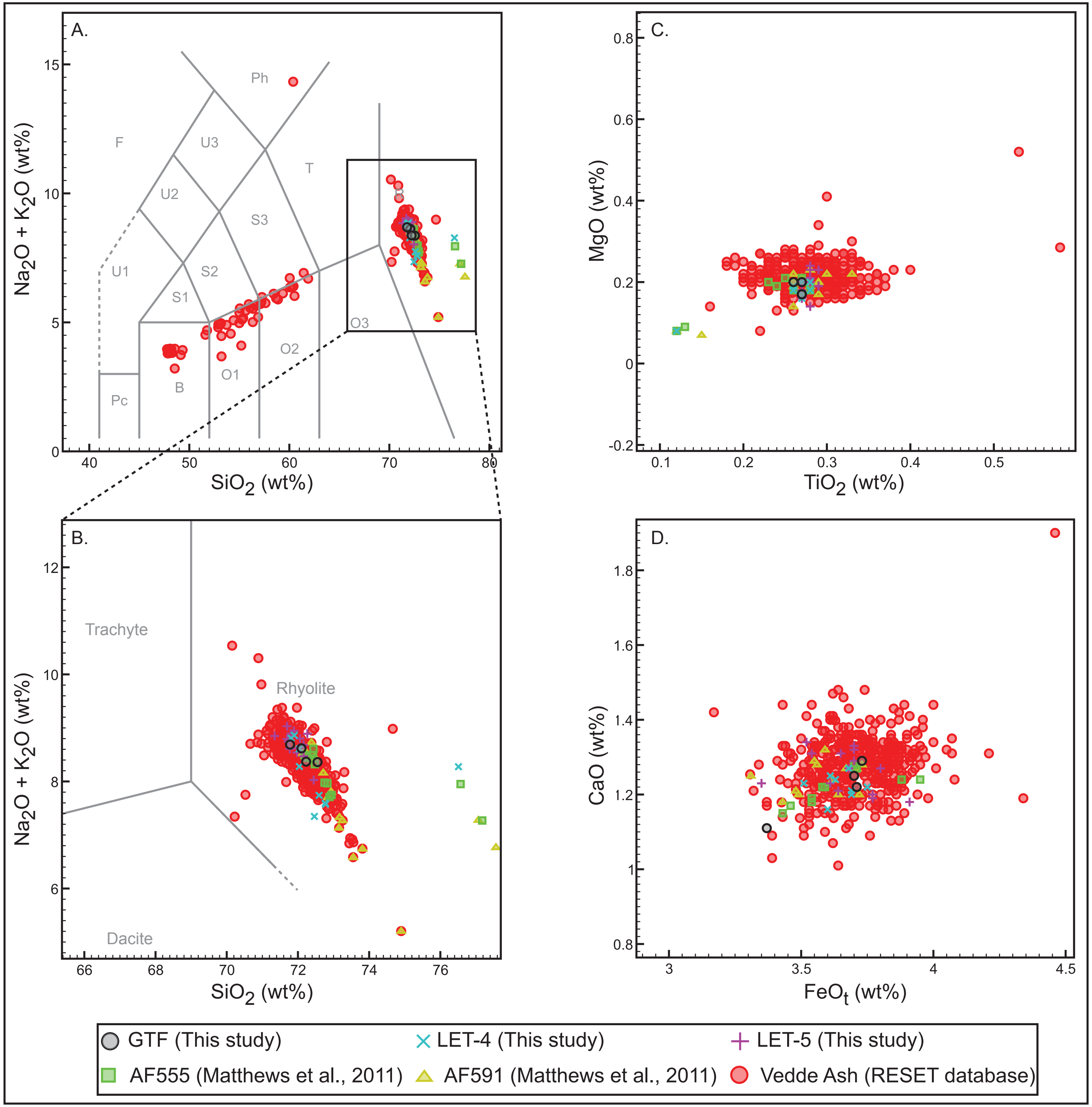
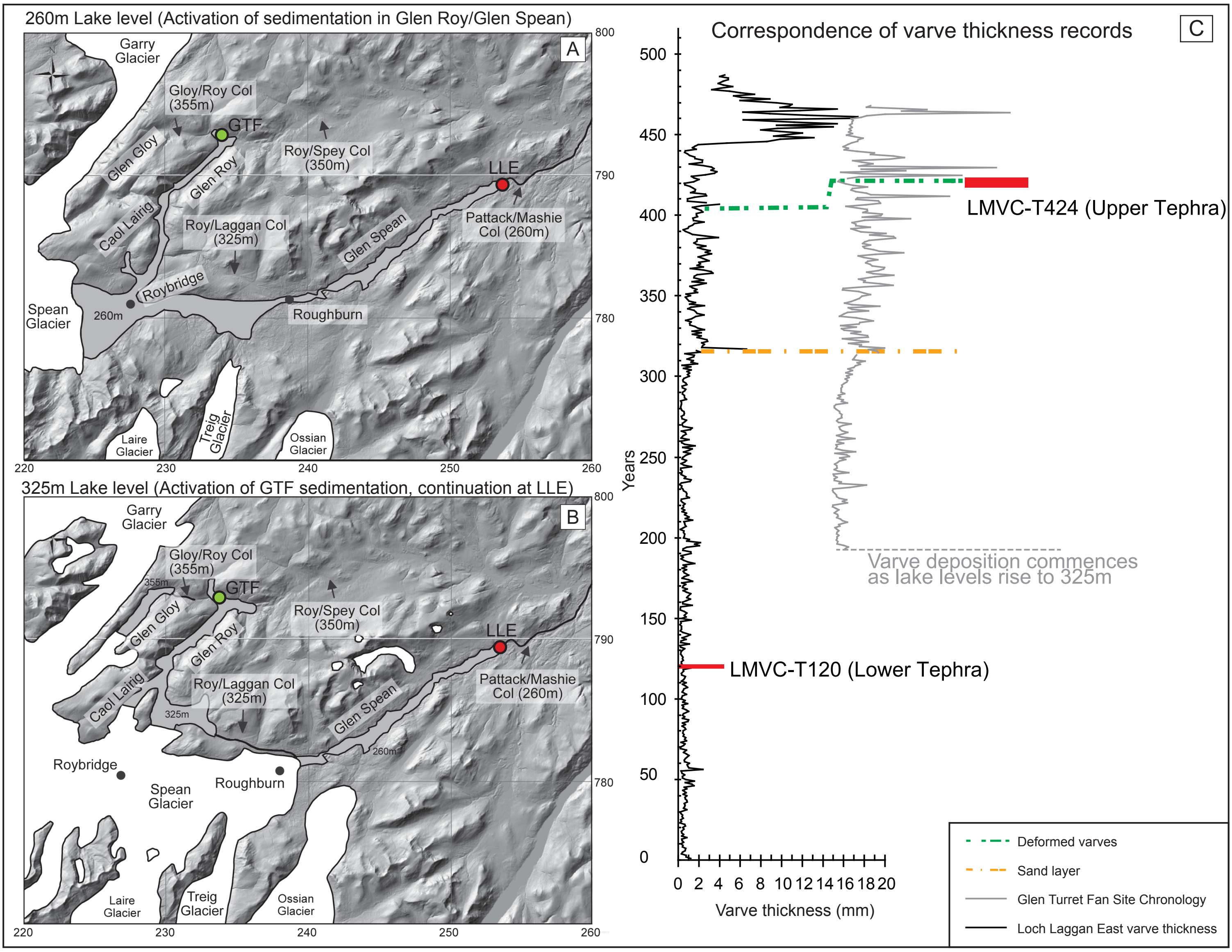
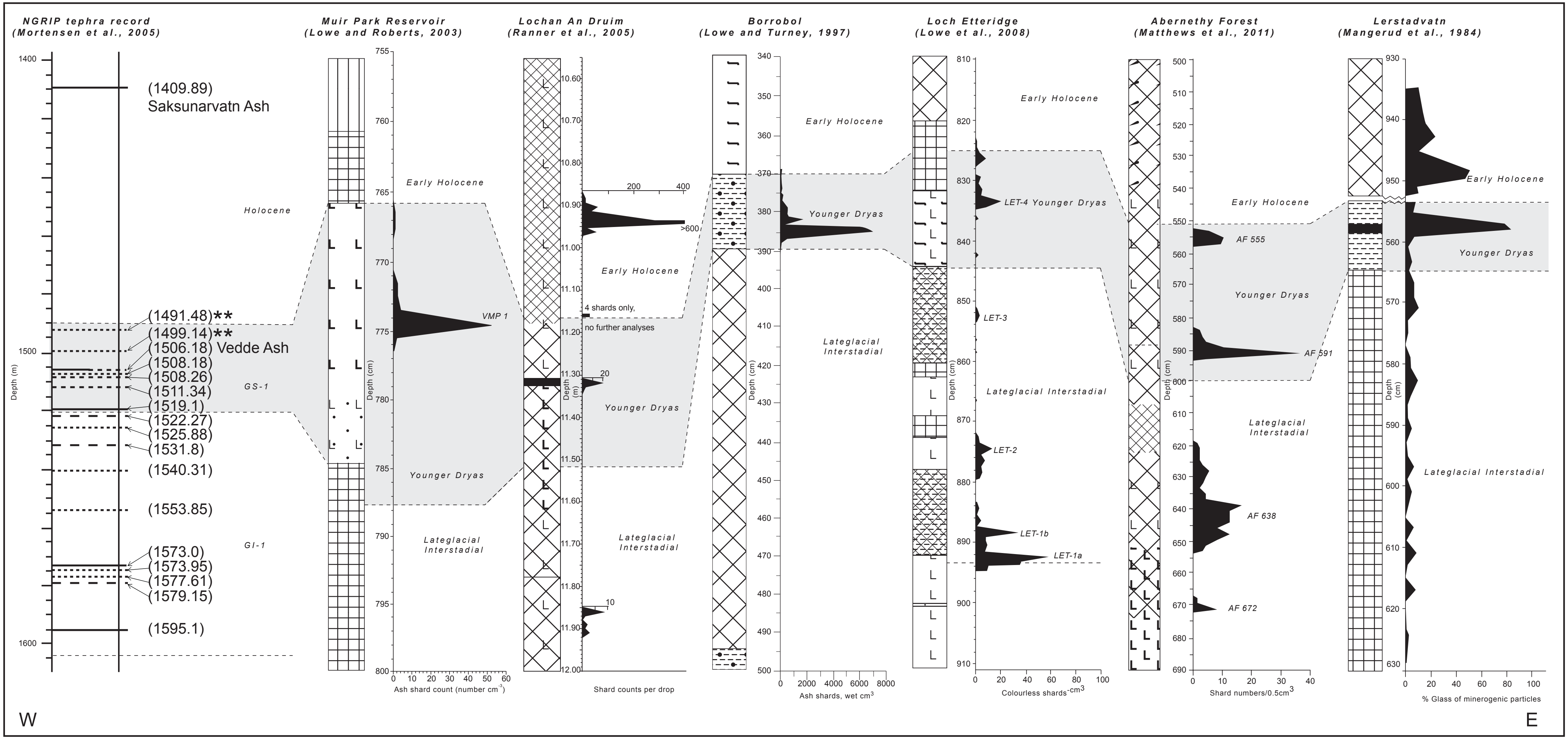

A.
B.
C.
D.
$Na_2O + K_2O$ (wt%)
SiO_2 (wt%)
MgO (wt%)
TiO_2 (wt%)
CaO (wt%)
FeO_t (wt%)
Ph
F
U3
U2
U1
T
S3
S2
S1
O3
O2
O1
B
Pc
R
Trachyte
Rhyolite
Dacite
GTF (This study)
LET-4 (This study)
LET-5 (This study)
AF555 (Matthews et al., 2011)
AF591 (Matthews et al., 2011)
Vedde Ash (RESET database)

Figure 4


260m Lake level (Activation of sedimentation in Glen Roy/Glen Spean)
A
Garry Glacier
Gloy/Roy Col (355m)
GTF
Roy/Spey Col (350m)
Glen Gloy
Glen Roy
Caol Lairig
LLE
Roy/Laggan Col (325m)
Pattack/Mashie Col (260m)
Glen Spean
Roybridge
Spean Glacier
260m
Roughburn
Laire Glacier
Treig Glacier
Ossian Glacier
325m Lake level (Activation of GTF sedimentation, continuation at LLE)
B
355m
325m
260m
Correspondence of varve thickness records
C
LMVC-T424 (Upper Tephra)
Varve deposition commences as lake levels rise to 325m
LMVC-T120 (Lower Tephra)
Years
Varve thickness (mm)
Deformed varves
Sand layer
Glen Turret Fan Site Chronology
Loch Laggan East varve thickness



NGRIP tephra record (Mortensen et al., 2005)
Muir Park Reservoir (Lowe and Roberts, 2003)
Lochan An Druim (Ranner et al., 2005)
Borrobol (Lowe and Turney, 1997)
Loch Etteridge (Lowe et al., 2008)
Abernethy Forest (Matthews et al., 2011)
Lerstadvatn (Mangerud et al., 1984)
(1409.89) Saksunarvatn Ash
(1491.48)**
(1499.14)**
(1506.18) Vedde Ash
(1508.18)
(1508.26)
(1511.34)
(1519.1)
(1522.27)
(1525.88)
(1531.8)
(1540.31)
(1553.85)
(1573.0)
(1573.95)
(1577.61)
(1579.15)
(1595.1)
Holocene
GS-1
GI-1
Depth (m)
Early Holocene
Younger Dryas
Lateglacial Interstadial
VMP 1
4 shards only, no further analyses
>600
LET-4
LET-3
LET-2
LET-1b
LET-1a
AF 555
AF 591
AF 638
AF 672
Depth (cm)
Ash shard count (number cm^{-3})
Shard counts per drop
Ash shards, wet cm^3
Colourless shards^{-}cm^3
Shard numbers/0.5cm^3
% Glass of minerogenic particles
W
E

Table 1

Sites containing a single visible layer of tephra			
Site no.	***Site***	***Location***	***Reference***
1	Gjølvatn	Norway	Mangerud et al., 1984
2	Kloppamyra	Norway	Mangerud et al., 1984
3	Kråkenes	Norway	Mangerud et al., 1984
4	Kvaltjern	Norway	Mangerud et al., 1984
5	Lerstadvatn	Norway	Mangerud et al., 1984
6	Saudedalsmyra	Norway	Mangerud et al., 1984
7	Torvlømyra	Norway	Mangerud et al., 1984
Sites containing a single non-visible layer of tephra			
	Site	***Location***	***Reference***
8	Store Slotseng	Denmark	Larsen et al., 2013
9	Endinger Bruch	Germany	Lane et al., 2012b
10	Meerfelder Maar	Germany	Lane et al., 2013
11	Rotmeer	Germany	Blockley et al., 2007
12	Lago di Lavarone	Italy	Lane et al., 2011a
13	Lago Piccolo di Avigliana	Italy	Lane et al., 2011a
14	Roddans Port	Northern Ireland	Turney et al., 2006
15	Kostverloren Veen	Netherlands	Davies et al., 2005
16	Andøya	Norway	Bondevik and Mangerud, 2002
17	Borge Bog	Norway	Bondevik and Mangerud, 2002
18	Irgenstjørn	Norway	Bondevik and Mangerud, 2002
19	Nedre Ærasvatn	Norway	Bondevik and Mangerud, 2002
20	Stølsmyra	Norway	Bondevik and Mangerud, 2002
21	Medvedeskoye	Russia	Wastegård et al., 2000
22	Pastorskoye	Russia	Wastegård et al., 2000
23	Druim Loch	Scotland	Pyne-O’Donnell, 2007
24	Loch An t’Suidhe	Scotland	Pyne-O’Donnell, 2007
25	Tanera Mor	Scotland	Roberts, 1997
26	Tynaspirit West	Scotland	Turney et al., 1997
27	Whitrig Bog	Scotland	Turney et al., 1997
28	Lake Bled	Slovenia	Lane et al., 2011b
29	Fågelmossen	Sweden	Björck and Wastegård, 1999
30	Götesjön	Sweden	Schoning, 2001
31	Högstorpsmossen	Sweden	Björck and Wastegård, 1999
32	Kullatorpssjön	Sweden	Grönvold et al., 1995
33	Rotsee	Switzerland	Lane et al., 2012a
34	Soppensee	Switzerland	Blockley et al., 2007
Sites containing a double non-visible peak in tephra (no gap between peaks)			
	Site	***Location***	***Reference***
35	Borrobol	Scotland	Lowe and Turney, 1997
36	Madtjärn	Sweden	Wastegård et al., 1998

Sites containing a double non-visible peak in tephra (gap between peaks)			
	Site	***Location***	***Reference***
37	Abernethy Forest	Scotland	Matthews et al., 2011
38	Loch Etteridge	Scotland	Lowe et al., 2008a; This study
39	Loch Laggan-Glen Turret Fan	Scotland	This study
40	Lochan an Druim	Scotland	Ranner et al., 2005
41	Muir Park Reservoir	Scotland	Lowe and Roberts, 2003

Supporting Table S1

Broadly equivalent chronozones			
Scandinavia/Swiss Plateau/S. Germany	**N. Germany**	**British Isles**	**Greenland**
Holocene	Holocene	Holocene	Holocene
Younger Dryas	Younger Dryas	Loch Lomond Stadial	GS-1
Allerød/Bølling	Allerød/Bølling/ Meindorf	Windermere Interstadial	GI-1(a-d)
Oldest Dryas	Pleniglacial	Dimlington Stadial	GS-2

Supporting Table S2

Tephra Analyitical Unit, Edinburgh University	
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
Research Laboratory for Archaeology and the History of Art, Oxford University	
Electron Microprobe	Jeol JXA-8800R, 4 Spectrometers
Elements analysed	Na, Al, Si, Fe, K, Ca, Mg, Mn and Ti
Accelerating volatage	15keV
Beam current	10 nA
Beam diameter	10 µm
Primary/Secondary calibration	Standard calibration blocks/ StHs6/80-G

Supporting Table S3

n=9	***Weight % oxides***									
	SiO₂	***TiO₂***	***Al₂O₃***	***FeO(t)***	***MnO***	***MgO***	***CaO***	***Na₂O***	***K₂O***	***Total***
Loch Etteridge LET-4	70.10	0.28	13.04	3.51	0.14	0.18	1.23	5.10	3.54	97.52
	70.20	0.27	13.12	3.69	0.14	0.16	1.20	4.99	3.62	97.77
	71.12	0.28	13.19	3.68	0.15	0.20	1.27	4.90	3.60	98.75
	72.76	0.12	12.04	1.26	0.06	0.08	0.70	4.01	3.86	95.10
	69.40	**0.27**	**13.32**	**3.69**	**0.14**	**0.17**	**1.21**	**3.89**	**3.51**	**95.60**
	69.87	**0.26**	**13.52**	**3.75**	**0.16**	**0.18**	**1.22**	**4.43**	**3.60**	**96.99**
	70.33	**0.27**	**13.62**	**3.60**	**0.14**	**0.20**	**1.16**	**3.82**	**3.50**	**96.64**
	70.52	**0.27**	**14.21**	**3.63**	**0.13**	**0.17**	**1.24**	**3.74**	**3.41**	**97.32**
	70.81	**0.26**	**13.66**	**3.61**	**0.14**	**0.19**	**1.25**	**3.80**	**3.59**	**97.31**
Mean	*70.57*	*0.25*	*13.30*	*3.38*	*0.13*	*0.17*	*1.16*	*4.30*	*3.58*	*97.00*
Std Dev	*0.96*	*0.05*	*0.59*	*0.80*	*0.03*	*0.04*	*0.18*	*0.56*	*0.12*	*1.11*

n=20	***Weight % oxides***									
	SiO₂	***TiO₂***	***Al₂O₃***	***FeO(t)***	***MnO***	***MgO***	***CaO***	***Na₂O***	***K₂O***	***Total***
Loch Etteridge LET-5	68.74	0.28	12.68	3.70	0.16	0.21	1.32	4.94	3.49	95.51
	68.86	0.28	12.59	3.52	0.14	0.23	1.34	5.11	3.42	95.48
	68.95	0.27	12.96	3.68	0.16	0.16	1.27	4.74	3.53	95.71
	69.17	0.27	12.44	3.35	0.15	0.18	1.23	5.06	3.45	95.31
	69.19	0.27	12.62	3.61	0.15	0.20	1.23	5.07	3.54	95.86
	70.05	0.28	13.00	3.70	0.15	0.21	1.33	5.13	3.41	97.25
	70.54	0.29	13.21	3.54	0.15	0.19	1.31	4.99	3.38	97.60
	70.66	0.27	13.14	3.64	0.16	0.20	1.21	4.42	3.41	97.10
	70.81	0.29	12.78	3.65	0.15	0.19	1.31	5.17	3.35	97.70
	70.87	0.29	12.99	3.77	0.15	0.23	1.20	4.98	3.34	97.80
	71.19	0.28	13.68	3.91	0.13	0.14	1.18	5.25	3.58	99.35
	71.60	0.27	13.21	3.77	0.14	0.20	1.19	5.11	3.46	98.96
	71.97	0.28	13.03	3.80	0.15	0.20	1.27	5.24	3.55	99.50
	71.99	0.28	13.28	3.70	0.16	0.24	1.29	5.44	3.63	100.01
	73.03	0.08	12.61	1.47	0.06	0.04	0.77	4.03	5.26	97.35
	73.91	0.08	13.25	1.54	0.08	0.04	0.77	3.98	5.14	98.78
	73.97	0.08	12.68	1.49	0.06	0.03	0.76	3.96	5.03	98.06
	74.08	0.08	12.48	1.38	0.07	0.03	0.69	3.97	5.28	98.05
	74.21	0.08	13.24	1.59	0.07	0.03	0.77	4.03	5.12	99.15
	74.68	0.08	12.82	1.72	0.06	0.08	0.79	4.17	5.22	99.62
Mean	*71.42*	*0.22*	*12.93*	*3.03*	*0.12*	*0.15*	*1.11*	*4.74*	*3.98*	*97.71*
Std Dev	*1.99*	*0.09*	*0.33*	*1.01*	*0.04*	*0.08*	*0.24*	*0.52*	*0.81*	*1.51*

n=4	***Weight % oxides***									
	SiO₂	***TiO₂***	***Al₂O₃***	***FeO(t)***	***MnO***	***MgO***	***CaO***	***Na₂O***	***K₂O***	***Total***
Glen Turret Fan LMVC-T424	71.15	0.26	13.18	3.37	0.14	0.20	1.11	4.87	3.33	97.60
	71.95	0.27	13.62	3.71	0.16	0.17	1.22	5.04	3.67	99.81
	71.97	0.27	13.33	3.73	0.14	0.17	1.29	4.70	3.64	99.23
	73.03	0.27	13.56	3.70	0.13	0.20	1.25	5.16	3.57	100.86

Mean	*72.02*	*0.27*	*13.42*	*3.63*	*0.14*	*0.18*	*1.22*	*4.94*	*3.55*	*99.37*
Std Dev	*0.77*	*0.01*	*0.20*	*0.17*	*0.01*	*0.01*	*0.08*	*0.20*	*0.16*	*1.36*
n=8	***Secondary Standard data : weight % oxides***									
	SiO_2	***TiO_2***	***Al_2O_3***	***$FeO_{(t)}$***	***MnO***	***MgO***	***CaO***	***Na_2O***	***K_2O***	***Total***
Lipari Obsidian - Edinburgh	73.03	0.08	12.61	1.47	0.06	0.04	0.77	4.03	5.26	97.35
	73.03	0.08	12.61	1.47	0.06	0.04	0.77	4.03	5.26	97.35
	73.91	0.08	13.25	1.54	0.08	0.04	0.77	3.98	5.14	98.78
	73.91	0.08	13.25	1.54	0.08	0.04	0.77	3.98	5.14	98.78
	73.97	0.08	12.68	1.49	0.06	0.03	0.76	3.96	5.03	98.06
	74.08	0.08	12.48	1.38	0.07	0.03	0.69	3.97	5.28	98.05
	74.21	0.08	13.24	1.59	0.07	0.03	0.77	4.03	5.12	99.15
	74.68	0.08	12.82	1.72	0.06	0.08	0.79	4.17	5.22	99.62
Mean	*73.85*	*0.08*	*12.87*	*1.52*	*0.07*	*0.04*	*0.76*	*4.02*	*5.18*	*98.39*
Std Dev	*0.57*	*0.01*	*0.33*	*0.10*	*0.01*	*0.02*	*0.03*	*0.07*	*0.09*	*0.83*
n=6	***Secondary Standard data : weight % oxides***									
	SiO_2	***TiO_2***	***Al_2O_3***	***$FeO_{(t)}$***	***MnO***	***MgO***	***CaO***	***Na_2O***	***K_2O***	***Total***
StHs6/80-G - Oxford	64.89	0.68	18.29	4.31	0.11	2.02	5.26	3.96	1.34	100.86
	65.09	0.76	18.16	4.37	0.05	2.00	5.22	4.18	1.33	101.15
	64.98	0.69	18.25	4.30	0.06	1.94	5.19	4.08	1.31	100.79
	64.71	0.72	18.31	4.30	0.07	1.99	5.21	4.48	1.31	101.10
	64.98	0.71	18.18	4.28	0.05	2.02	5.19	4.51	1.28	101.20
	64.59	0.71	18.35	4.39	0.09	2.04	5.27	4.84	1.35	101.61
Mean	*64.87*	*0.71*	*18.26*	*4.32*	*0.07*	*2.00*	*5.22*	*4.34*	*1.32*	*101.12*
Std Dev	*0.37*	*0.03*	*0.07*	*0.05*	*0.02*	*0.04*	*0.04*	*0.33*	*0.03*	*0.30*