

1 *Identification of the Askja-S Tephra in a rare turlough record from Pant-y-Llyn, south Wales*

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10 Key words: cryptotephra, Askja-S Tephra, turlough, tephra dispersal, radiocarbon dating,
11 carbonates

12

13 **Abstract**

14 Tephrochronology and especially crypto-tephrochronology is an established chronological
15 technique employed in a range of depositional environments in Europe and beyond. During
16 the late Quaternary, Icelandic cryptotephra deposits are widely found in palaeorecords
17 across northern latitudes of Europe e.g. Scotland, Ireland, Norway, Sweden and the Faroe
18 Islands but are sporadic in southerly latitudes as distance from Iceland increases. As yet,
19 very few Icelandic cryptotephra have been identified in Wales or southern England which
20 may well reflect the geographical limit of Icelandic tephra distribution. Here, however, we
21 report the discovery of an Icelandic cryptotephra deposit within a sediment sequence
22 retrieved from the Pant-y-Llyn turlough (Carmarthenshire, south Wales), the only known
23 turlough in Britain. Turloughs are groundwater-fed ephemeral lakes associated with
24 limestone bedrock and can accumulate sediments that may yield records suitable for
25 palaeoreconstructions. A discrete peak of glass shards originating from the Askja-S eruption
26 is identified in the sediment record. This discovery extends the distribution of this early
27 Holocene eruption giving new insight into its dispersal patterns and also indicates that
28 sedimentary sequences from sites in these more southerly latitudes are valuable repositories
29 for ash preservation. Furthermore, its discovery within a carbonate-rich sequence provides a
30 minimum age constraint on the timing of sediment accumulation and provides an alternative
31 tool for what is typically a problematic dating environment.

32

33 **1. Introduction**

1 Tephrochronology is a powerful dating technique whereby geochemically distinct and well-
2 constrained ash deposits can underpin a chronological framework as well as allow precise
3 and direct synchronisation of geological records (Lowe, 2011). In recent years, this
4 technique has significantly progressed beyond the realms of visible or macro-ash deposits to
5 focus on cryptotephra deposits preserved in distal areas relative to the volcanic source
6 (Davies, 2015). Cryptotephra deposits are invisible to the naked eye and contain a low
7 concentration of volcanic glass shards that can only be detected by microscopy following a
8 series of extraction steps to isolate the shards from the host sediment. Discrete horizons
9 were identified in distal peat bog deposits as early as the 1960s, where stratigraphic
10 information was employed to suggest the preservation of the Hekla 3, Hekla 4, Askja 1875
11 and Öraefajökull 1362 cryptotephra in Swedish, Norwegian and Faroes peat bogs
12 (Persson, 1966, 1971). It was the discovery of cryptotephra in Scottish peat (Dugmore,
13 1989), however, that instigated the recent advances in the search for ash deposits far
14 removed from volcanic centres.

15 Extensive employment of extraction techniques such as ashing (for organic rich deposits;
16 Dugmore, 1989) and density separation (for minerogenic sediments; Turney, 1998) together
17 with robust chemical characterisation of glass shards (Hayward, 2012) have given rise to an
18 abundant European network of cryptotephra discoveries (Fig. 1). Traces of Icelandic
19 eruptions spanning the last 15,000 years have been identified in depositional records across
20 Europe (e.g. Wastegård and Davies, 2009; Lawson et al., 2012; Davies et al., 2012; Timms
21 et al., 2016; Wulf et al., 2016). However, there are very few reported findings of distal ash
22 deposits south of 53° latitude and east of 6° longitude and noticeable gaps in Wales,
23 southern England and large parts of France are evident on spatial distribution maps (Fig. 1).
24 The density of cryptotephra discoveries is also skewed towards the sites located in northerly
25 latitudes with only the largest known eruptions such as the Vedde Ash and the Askja-S
26 Tephra found in more southerly latitudes (e.g. Lane et al., 2011, 2012b). This apparent
27 absence may be an indicator of the geographical limit of most Icelandic ash plumes but most
28 likely reflects a sampling bias with very few studies conducted in lowland areas of Wales and
29 southern England. With the exception of a recent study by Watson et al., (2017), there have
30 been traces of potential cryptotephra deposits identified in sites in the Brecon Beacons and
31 mid-Wales but these findings have not been supported by geochemical characterisation of
32 the shards themselves (Williams, 2001; Williams et al., 2007; Buckley and Walker, 2002).

33 Here we explore tephra preservation in a sediment sequence extracted from the Pant-y-Llyn
34 turlough in south Wales (Fig. 2). Turloughs are ephemeral water bodies associated with
35 topographic depressions in karst and are periodically inundated mainly by groundwater.
36 Turloughs are common in the Republic of Ireland (Skeffington et al., 2006; Naughton et al.,

1 2012), however, this is the only known turlough in Britain (Campbell et al., 1992; Hardwick
2 and Gunn, 1995) and as such is a designated Annex I priority habitat under the EU Habitats
3 Directive 92/43/EC (McLeod et al., 2005). Turloughs do not have a true inflow or outflow
4 stream, and fill and empty either diffusely across their base or via estavelles, a karst feature
5 that can act as both a spring and a sink (Tynan et al., 2007). Sediments from turloughs are
6 rich in calcium carbonate (Coxon and Coxon, 1994) and an investigation of their infill can
7 provide insight into the development and formation of these rare features. Dating such
8 sedimentary sequences using the conventional radiocarbon method, however, is problematic
9 due to the erroneous effects of hard-water and contamination by old carbon (Lowe and
10 Walker, 2000). Tephra deposits have huge potential as an alternative dating technique for
11 such sequences (e.g. Candy et al., 2016; Timms et al., 2016) and we present the first
12 positive findings in Wales to date a carbonate-rich record retrieved from a turlough.

13

14 **2. Site Description and Methods**

15 The Pant-y-Llyn turlough is located in south Wales, UK (Lat: 51° 49' 51" N, Long: 4° 1' 26"
16 W) at an altitude of 150 m OD. The lake is small, just 160 m long and 60 m wide, and lies in
17 a depression formed in the underlying Carboniferous Dowlais Limestone Formation (Fig. 2).

18 Sediment cores were obtained on 28th August 2013 when water levels were sufficiently low
19 to allow access into the turlough basin. A basin survey was conducted using a peat probe
20 and hand auger at 10 locations to determine the area with the thickest sequence of soft
21 sediment. Using a Russian corer (5 cm diameter, 50 cm length) a 550 cm core was obtained
22 from the eastern part of the turlough basin, but the bedrock was not reached (Fig. 2). The
23 core (British Geological Survey borehole reference SN61NW12) is comprised of a sequence
24 of unconsolidated lake muds, silts and peat. Cores were wrapped in cling film and stored in a
25 cold room at <4 °C until sub-sampling was undertaken. Four 100 g bulk sediment samples
26 from 200, 245, 395, 510 cm depth below ground level were sent to the ¹⁴CHRONO Centre at
27 Queens University Belfast for dating (Table. 1).

28 Loss on ignition (LOI) was conducted on the core between 550-300 cm. LOI was performed
29 at a 4-cm resolution between 550-530 cm and 490-300 cm and at a 2-cm resolution between
30 530-490 cm spanning the transition from the basal unit of reddish silty clay and organic lake
31 mud unit. The standard protocol of Heiri et al., (2001) was followed with samples placed in a
32 furnace at 550 °C for 2 hours to determine the organic matter loss by weight percent and a
33 further 2 h at 1000 °C to determine the calcium carbonate (CaCO₃) loss by weight percent.

1 Tephra investigations focused on the 350-550 cm portion of the sequence with initial
2 searches conducted on 5-cm contiguous samples and followed the methodology outlined in
3 Turney, (1998). The samples were ashed at 550 °C for 2 hours and the remaining particulate
4 material was sieved at 80 and 25 µm. Due to the minerogenic nature of the sediment a
5 density separation was performed using sodium polytungstate and the 2.3-2.5 gcm⁻³ density
6 fraction was mounted onto microscope slides using Canada Balsam. A light-powered,
7 polarizing microscope was used at x100 and x200 magnification to identify and count the
8 glass shard concentrations. Where a distinct peak in tephra shard concentration was
9 present, 1-cm segments were sub-sampled from the core to pinpoint the position of the
10 tephra isochron to the nearest cm. For geochemical analysis, samples were processed
11 following the same methodology as outlined above, with the exception of the ashing step.
12 Due to the low shard concentrations a micro-manipulator was used to extract individual
13 shards for geochemical analysis. Shards were placed on a microprobe slide and embedded
14 in epoxy resin. Glass shards were sectioned using decreasing grades of silicon carbide
15 paper and polished using 9, 6 and 1 µm diamond suspension and 0.3 µm micro-polish.

16 Geochemical analysis was undertaken at the Tephra Analytical Unit at the University of
17 Edinburgh using a Cameca SX100 wavelength dispersive spectrometer electron-probe micro
18 analysis (WDS EPMA). Operating conditions are noted in the supporting information. A 3 µm
19 beam set-up was used for some shards due to the small particle size (Hayward, 2012). No
20 analytical offsets were observed between the 3 and 5 µm set-ups (see supporting
21 information). Lipari and BCR2g secondary standards were analysed at regular intervals to
22 examine the accuracy of the instrument and the precision of the analysed tephra shards (see
23 supporting information).

24

25 **3. Results**

26 *3.1. Lithostratigraphy, LOI and radiocarbon dates*

27 The lithostratigraphy is shown in Fig. 3, and consists of a basal unit of reddish silty clay (550-
28 522 cm) overlain by grey silty clay (522-511 cm). An organic lake mud is present between
29 511 and 450 cm and is overlain by brown, carbonate-rich mud that shows some evidence of
30 fine laminations (450-362 cm). These are not thought to be annually resolved. Organic fen
31 peat is found in the uppermost part of the sequence (362-0 cm). LOI values are low (~12 %)
32 within the basal clay unit indicating a high minerogenic input which we suggest has been
33 deposited during the Loch Lomond Stadial. Calcium carbonate values also remain low (~5
34 %) within this unit. A sudden increase in LOI values is observed at 511 cm, reaching values

1 of 50 % by 508 cm. We suggest that this may represent the early Holocene transition. The
2 highest LOI values (55-70 %) are observed between 500 and 466 cm with a shift towards
3 slightly lower values of around 50 % between 466 and 430 cm. Calcium carbonate values
4 begin to increase at around 480 cm but show marked fluctuations between 10 and 40 %
5 between 480 and 430 cm. A short-lived peak of 70 % in calcium carbonate content is
6 observed at 422 cm and is accompanied by a dip in LOI at the same depth. Between 410
7 and 360 cm, low LOI values (10-25 %) are accompanied by higher calcium carbonate values
8 (60-76 %). The increase in LOI values and corresponding decrease in calcium carbonate
9 values observed 360 cm (47 % and 10 % respectively) coincides with a shift from lake mud
10 to fen peat. In the uppermost part of the record, LOI increases to ~60 % at 335 cm and
11 calcium carbonate content falls to ~10 % (Fig. 3). The overall calcium carbonate variations in
12 this sequence may reflect periods of stronger groundwater influence in this turlough.

13 Radiocarbon ages obtained from four bulk samples are summarised in Table 1. The
14 lowermost radiocarbon date lies stratigraphically at the base of the lake mud unit, which is
15 assumed to represent the early Holocene. However, the radiocarbon age estimate reveals a
16 much older age of 12958-12713 cal BP which is closer to the onset of the Loch Lomond
17 Stadial. Similarly, an age range of 12589-12105 cal BP is obtained for the sample at 395 cm,
18 which lies 115 cm above the lowermost radiocarbon age, implying a relatively high
19 sedimentation rate (7 yrs/cm) compared with other similar sediment deposits of this age (e.g.
20 Quoyloo Meadow - ~46 yrs/cm: Timms et al., 2016). The uppermost ages at 200 and 245 cm
21 are also close in age (~8.7 cal BP and ~8.6 cal BP, respectively) and indicate a slight
22 inversion with the former yielding an older age than the latter (Table. 1).

23

24 3.2. *Tephra discoveries*

25 Low-resolution investigation of the tephra content revealed the presence of one distinct peak
26 in shard concentration at 495-500 cm whilst the rest of the sequence revealed a low
27 background of ~ 2-3 glass shards per 0.5 gram dry weight (g dw) at intermittent intervals.
28 Due to the low shard concentrations, no geochemical results were attempted and without
29 this information, the significance of the apparent background in glass shards is uncertain.
30 The distinct peak in shard concentration between 495-500 cm was refined to 1 cm where a
31 concentration of 72 shards per 0.5 gram dry weight (g dw) was established at 499-500 cm
32 (labelled PLL_500 in Fig 3 and 4). The shards were colourless and typically platy and fluted
33 in morphology. Microprobe analyses confirm their homogenous rhyolitic composition with
34 SiO₂ values ranging between 72.24 - 76.4 wt%, K₂O values of 2.39 – 2.65 wt% and CaO
35 values of 1.5 – 1.75 wt% (Table 2). Major oxide biplots reveal a strong correlation with the

1 Askja-S Tephra (Fig. 4) which can easily be distinguished from other early Holocene age
2 tephtras such as the Hässeldalen Tephra on the basis of higher FeO and CaO values (Fig.
3 4). The tephra at Pant-y-Llyn is also geochemically distinct relative to other early Holocene
4 tephtras including the Suðuroy, An Druim, Breakish, Hovsdalur, Høvdarhagi, L274, Skopun,
5 Fosen, Ashik and Abernethy tephra (Fig. 4) (Wastegård, 2002; Ranner et al., 2005; Pyne
6 O'Donnell, 2007; Lind and Wastegård, 2011; Matthews et al., 2011; Lind et al., 2013). The
7 Askja-S geochemical signature can also be discriminated from older widespread tephtras
8 such as the Vedde Ash based on higher SiO₂ and CaO values.

9 Whilst chemical similarity is shown between the Askja-S Tephra and the 499-500 cm
10 deposit, the radiocarbon dates would suggest an older age than presently suggested for the
11 Askja-S Tephra. It is possible that PLL_500 could be a previously unknown tephtra
12 originating from the Dyngjufjöll volcanic system, given the closely timed tephtra deposits of
13 similar chemical signatures derived from Icelandic provenances, such as Katla (Lane et al.,
14 2012b) or the numerous Borrobol-type deposits discovered (Lind et al., 2016; Jones et al.,
15 2017). As yet, however, there are no reported findings of older Askja-S-type tephtras in the
16 literature. Guðmundsdóttir et al., (2016) have reported a younger tephtra – the Askja L–
17 dated to approximately 9400 cal BP (Striberger et al., 2012) and the Askja H tephtra – dated
18 to 8850 years old has been identified by Jóhannsdóttir, (2007). The former tephtra reveals an
19 identical chemical composition to Askja-S but the Al₂O₃ and FeO content for the latter differs
20 from the Askja-S (Guðmundsdóttir et al., 2016). The Askja L and H have, however, never
21 been discovered outside of Iceland making the Askja-S correlation most likely in Pant-y-Llyn.
22 The lithostratigraphic information also supports this correlation to the early Holocene Askja-S
23 Tephtra in line with other studies (e.g. Davies et al., 2003; Wulf et al., 2016; Timms et al.,
24 2016).

25

26 **4. Discussion**

27 *4.1. Askja-S Tephtra dispersal and significance*

28 The identification of the Askja-S Tephtra in the Pant-y-Llyn record, extends the geographical
29 area of Icelandic ash deposition. Until now, very few Icelandic tephtras have been found
30 south of 53° latitude and east of 6° longitude (Fig. 1) and our new findings indicate that this
31 is not a reflection of the dominance of more northerly dispersal trajectories (see also recent
32 findings outlined by Watson et al., 2017). We propose potential dispersal maps based on
33 reported Askja-S findings and, given the reported negative findings for this tephtra (Table 3
34 and Fig 5c), speculate that dispersal may have been characterised by more than one plume

1 trajectory (Fig. 5c). Proximal deposits in Iceland, however, suggest the main axis of Askja-S
2 dispersal was mainly to the NNE (Sigvaldason et al., 2002). We acknowledge that several
3 other factors may also account for the absence of the Askja-S Tephra in some records (e.g.
4 uneven ash distribution within sites, failure to pinpoint cryptotephra deposits in low-resolution
5 searches; Pyne O'Donnell, 2011; Timms et al., 2016), however, we use our maps to
6 highlight geographical areas that are most likely to result in fruitful recovery of the Askja-S
7 deposit. In particular, the relatively high shard concentrations (72 shards per 0.5 gdw)
8 highlight the tantalising possibilities of tracing the Askja-S Tephra, as well as other Icelandic
9 tephtras, further south in the British Isles and perhaps France.

10

11 *4.2. Askja-S age estimate*

12 The Askja-S Tephra is considered to be a key isochronous marker for the early Holocene
13 and its extensive distribution from Arctic Norway (Pilcher et al., 2005) to Switzerland (Lane et
14 al., 2011) and from northern Ireland (Turney et al., 2006) to north Poland (Wulf et al., 2016)
15 now allows Pant-y-Llyn to be precisely integrated within a broad palaeorecord network (Fig.
16 5). One age estimate for the Askja-S Tephra is $10,830 \pm 57$ cal BP, which was derived by
17 age-modelling a range of radiocarbon dates (Bronk Ramsey et al., 2015 and references
18 within), however, Ott et al., (2016) provide an older age of $11,228 \pm 26$ cal BP based on a
19 varve-interval from the Hässeldalen tephra in Lake Czechowskie, Poland. Based on the
20 relative stratigraphic positions of tephtras in the Lake Hämelsee record, Jones et al (2017)
21 suggests that the Ott et al., (2016) age estimate is marginally too old than the age estimate
22 outlined by Bronk Ramsey et al., (2015).

23 In the Pant-y-Llyn sequence, the radiocarbon date at 510 cm (10 cm below the Askja-S
24 Tephra) has revealed an age range of 12,958–12,713 cal BP, almost ~2000 years older than
25 the Askja-S Tephra. A further date of 12589–12105 cal BP is obtained from the sample
26 dated at 395 cm (Table 1 & Fig. 3). Given the hard-water error that affects sediments in
27 limestone terrain (Walker, 2005), we suggest that these ages cannot be used to obtain a
28 reliable age-model, especially the sample obtained from 395 cm where CaCO_3 content is 68
29 %. The discrete Askja-S peak, however, provides a well-constrained age marker for the
30 lowermost part of the sequence and constrains the brown gyttja to the early Holocene
31 interval. Although bedrock was not reached during coring, the Askja-S Tephra provides a
32 minimum age estimate for the sediment sequence and indicates that the underlying silty clay
33 unit is likely to represent the Loch Lomond Stadial. Further work will need to ascertain
34 whether a full Late-glacial sequence is preserved at the site; such records are limited in
35 number in south Wales (e.g. Walker et al., 2003, 2009).

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5. Conclusion

The identification of the Askja-S Tephra in the Pant-y-Llyn turlough sediments extends the known distribution of this tephra further south and east in the British Isles and suggests that sites south of 53° latitude and east of 6° longitude can be valuable repositories for ash preservation. We compile positive and negative findings of the Askja-S Tephra and use this distribution to propose a three plume trajectory. The independently dated age estimate for the Askja-S Tephra (10,830±57 cal BP – Bronk Ramsey et al., 2015) provides a crucial chronological marker for this record and provides a minimum age estimate for the onset of sediment accumulation at Pant-y-Llyn. This study highlights the value of using cryptotephra deposits to overcome the problems of radiocarbon dating sediment in limestone terrain. The lowermost silty clay deposit at Pant-y-Llyn is likely to have been deposited during the Loch Lomond Stadial and highlights the potential of extracting a palaeoenvironmental record from this sequence that extends back into the Late-glacial period. Further analysis of this core sequence may yield information on the evolution and formation of this rare turlough.

Acknowledgements

We would like to thank Natural Resources Wales who manage Pant-y-Llyn. Dr Chris Vane and Dr David Scofield (British Geological Survey) for supporting the collection of the core and radiocarbon dating. Gareth Farr publishes with the permission of the Executive Director of the British Geological Survey (NERC). We would like to thank Dr Chris Hayward for his assistance with the use of the electron microprobe at the Tephrochronology Analytical Unit, University of Edinburgh. Thanks also to Gareth James (Swansea University) for laboratory assistance. Two anonymous reviewers are thanked for their constructive comments.

Funding: This work was conducted as part of a PhD study, supported by the Coleg Cymraeg Cenedlaethol.

Appendix A. Supporting Information

Supplementary material related to this article can be found in the online version.

1 **Table 1.** Four radiocarbon dates measured from bulk sediment at 14CHRONO Centre at
 2 Queens University Belfast. Ages were calibrated using OxCal and the IntCal13 calibration
 3 set (Bronk Ramsey, 2009; Reimer et al., 2013). Acid-Alkali-Acid (AAA) pre-treatment was
 4 undertaken on samples. Dates supplied by the British Geological Survey.

Laboratory ID code	Depth (cm)	$\delta^{13}\text{C}$ ‰	14C age yrs BP	Calibrated age range (cal BP)(95.4%)
UBA-26393	200	-25.4	7857±41	8932–8545
UBA-26392	245	-23.4	7833±37	8748–8541
UBA-26394	395	-26.8	10479±65	12589–12105
UBA-26391	510	-29.1	10953±47	12958–12713

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10 **Table 2.** Summary geochemical data displayed as major oxide concentrations (average and
 11 standard deviation) for the tephra layer 499-500 cm (PLL_500). A complete list of analyses
 12 and full microprobe operating conditions can be found in the supplementary data.

13

	SiO₂	TiO₂	Al₂O₃	FeO	MnO	MgO	CaO	Na₂O	K₂O	P₂O₅	Total
499-500 cm	wt %										
<i>average</i> (<i>n</i> =33)	73.8	0.3	11.8	2.5			1.6		2.5		97.2
<i>st dev</i>	6	0	1	0	0.09	0.24	3	4.28	1	0.04	5
		0.0		0.0			0.0		0.0		
	0.79	1	0.30	9	0.01	0.03	6	0.17	6	0.01	1.02

14

15

16 Table 3. A compilation of positive and negative findings of the Askja-S Tephra (ordered by publication date). Absences are noted according to
 17 the sampling interval, age models and the stratigraphic position of other tephras in the original studies

Site	Latitude and Longitude	Numer in Fig 5	Reference	Askja-S Tephra present
Lake Hämelsee, Germany	52°45' N, 9°18' E	1	Jones et al., 2017	Yes
Turret Bank, Scotland	57°00' N, 4°44' E	2	Lowe et al., 2017	Yes
Inverlair, Scotland	56°52' N, 4°43' W	3	Kelly et al., 2016	Yes
Quoyloo Meadow, Scotland	59°03' N, 3°18' W	4	Timms et al., 2016	Yes
Lake Tiefer See, Germany	53°35' N, 12°31' E	5	Wulf et al., 2016	Yes
Lake Czechowskie, Poland	53°52' N, 18°14' E	6	Wulf et al., 2016	Yes
Meerfelder Maar, Germany	50°06' N, 6°45' E	7	Lane et al., 2015	No
Store Slotseng basin, SW Denmark	55°19' N, 9°16' E	8	Larsen & Noe-Nygaard, 2014	No
Grønli fen, Norway	63°47' N, 10°28' E	9	Lind et al., 2013	No
Weglina, Poland	51°49' N, 14°43' E	10	Housley et al., 2013	No
Mulakullegöl, Sweden	57°12' N, 13°25' E	11	Lilja et al., 2013	Yes
Tøvelde, Denmark	54°57' N, 12°17' E	12	Larsen, 2013	Yes
Endinger Bruch, Germany	54°14' N, 12°53' E	13	Lane et al., 2012	Yes
Havnardalsmyren, Faroe Islands	62°01' N, 6°84' W	14	Kylander et al., 2012; Wastegård pers comm	Yes
Abernethy Forest, Scotland	57°14' N, 3°42' W	15	Matthews et al., 2011	No
Soppensee, Switzerland	47°05' N, 8°05' E	16	Lane et al., 2011	Yes
Høvdarhagi bog, Faroe Islands	61°54' N, 6°55' W	17	Lind & Wastegård, 2011	Yes
Loch Achik, Scotland	57°15' N, 5°50' W	18	Pyne O'Donnell, 2007	No
Lough Nadourcan, northwest Ireland	55°03' N, 7°54' W	19	Turney et al., 2006	Yes
Long Lough, Northern Ireland	54°26' N, 5°55' W	20	Turney et al., 2006	Yes
Borge Bog, Arctic Norway	68°14' N, 13°44' E	21	Pilcher et al., 2005	Yes
Hässeldala port, Sweden	56°16' N, 15°03' E	22	Davies et al., 2003	Yes

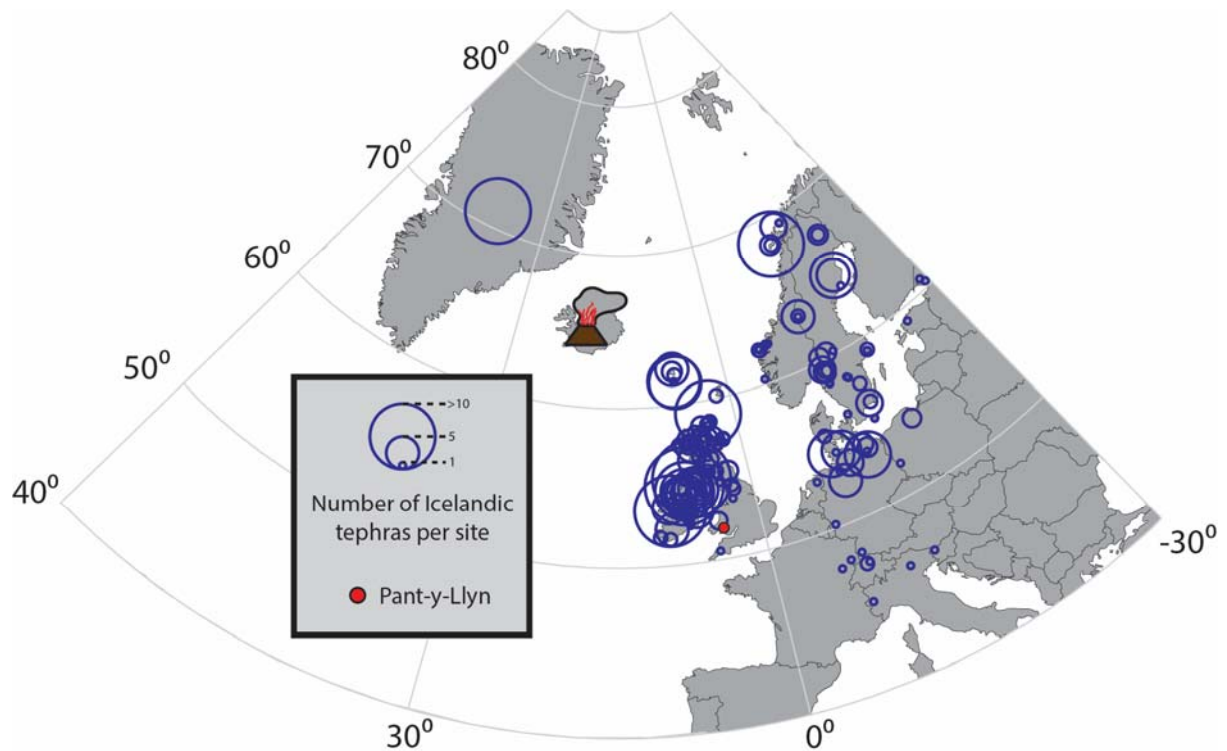


Figure 1. Spatial distribution map of Europe including distal sites (outside of Iceland) that contain Icelandic tephra layers of Holocene and Lateglacial age (~15 ka yr BP to present). Circle size relates to the number of tephra layers found in each site. Data from published sources (Davies et al., 2012; Lawson et al., 2012; Wulf et al., 2016; Watson et al., 2017; and references within). The circle on Greenland corresponds to the SUMMIT cores and NGRIP (Grönvold et al., 1995; Mortensen et al., 2005). Only one record in Wales has reported geochemical results to support tephra findings (Watson et al., 2017).

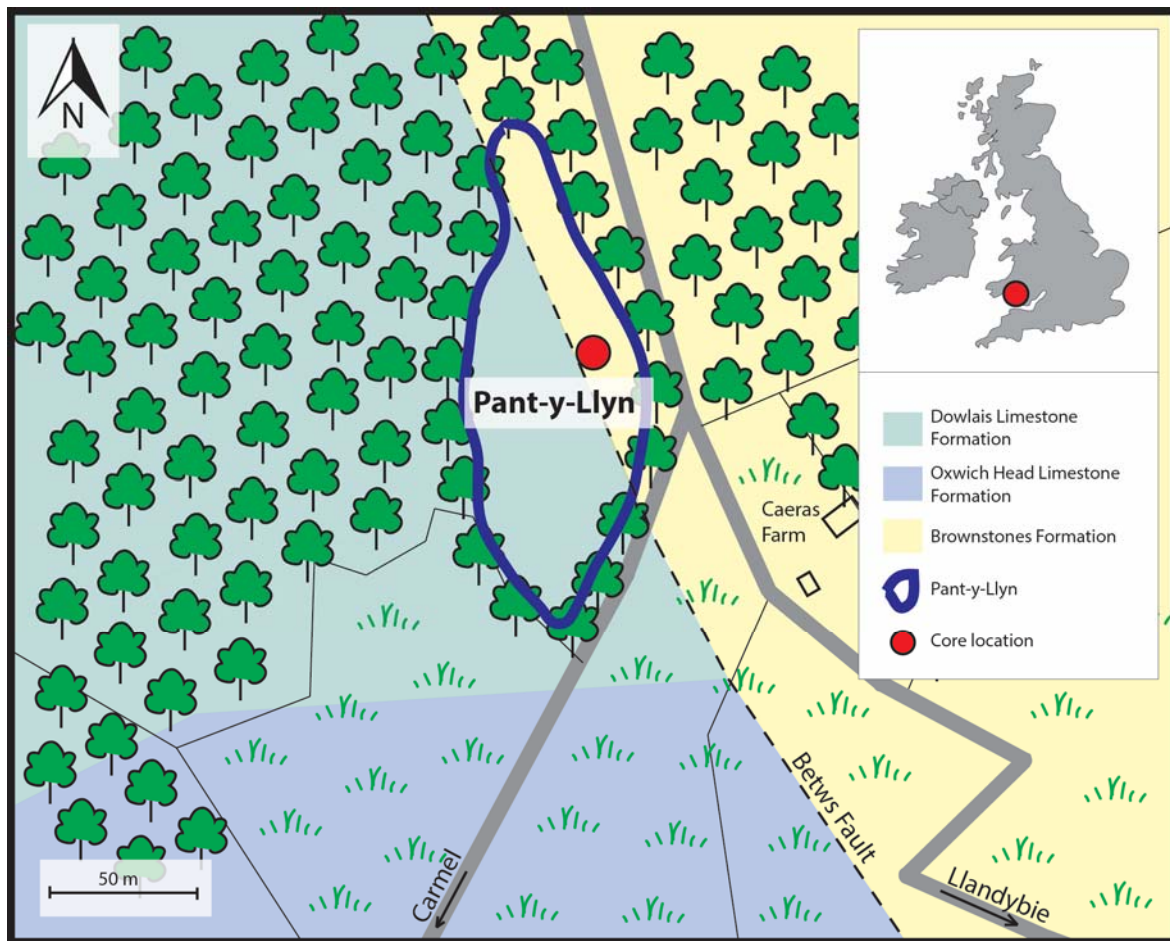


Figure 2. Location map of the Pant-y-Llyn turlough (Lat: $51^{\circ} 49' 51''$, Long: $-4^{\circ} 1' 26''$), coring location and local bedrock geology. 'Contains British Geological Survey Digi Map 1:50,000 Bedrock Geological Map and Ordnance Survey data © Crown Copyright and database rights 2017.

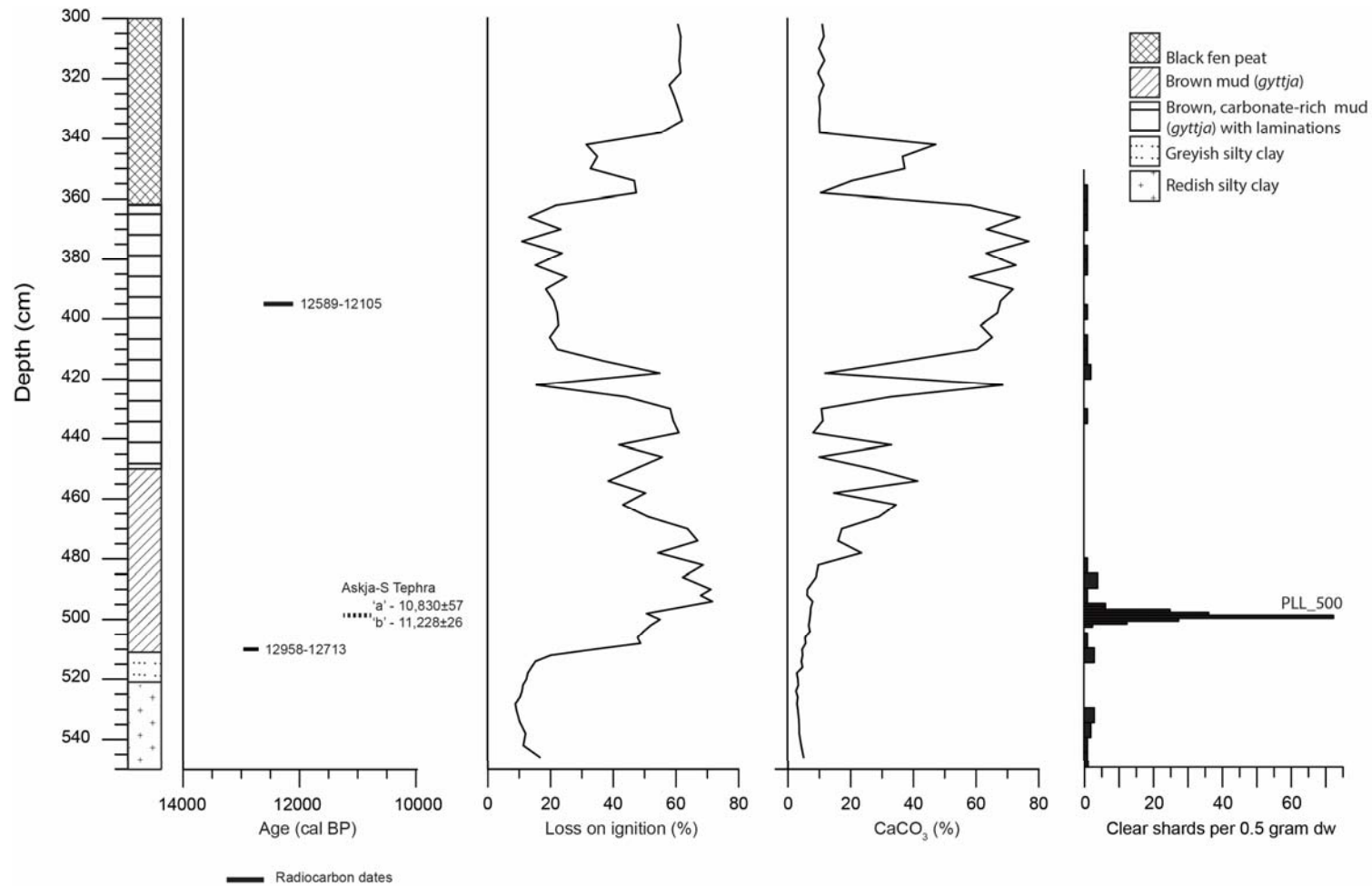
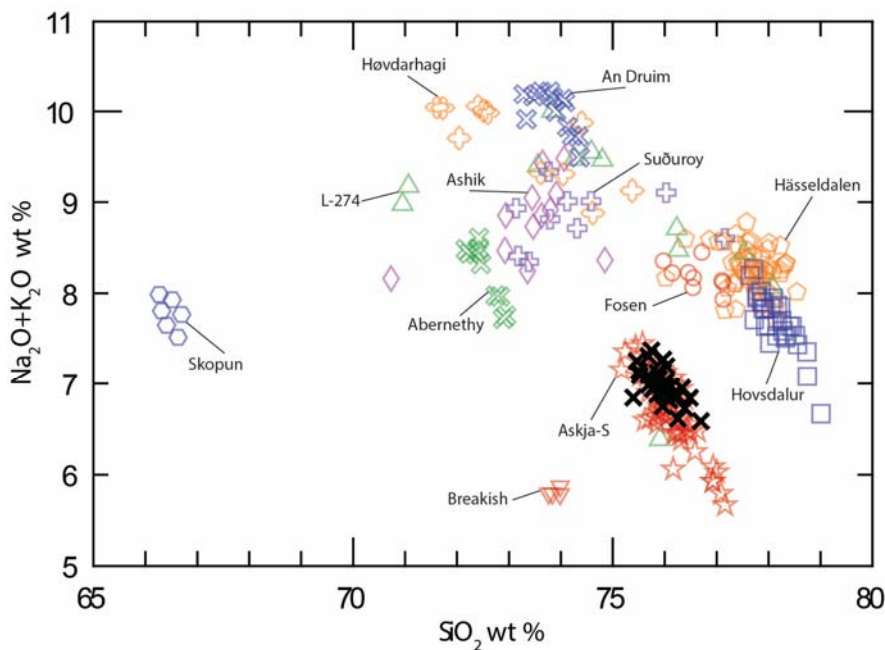
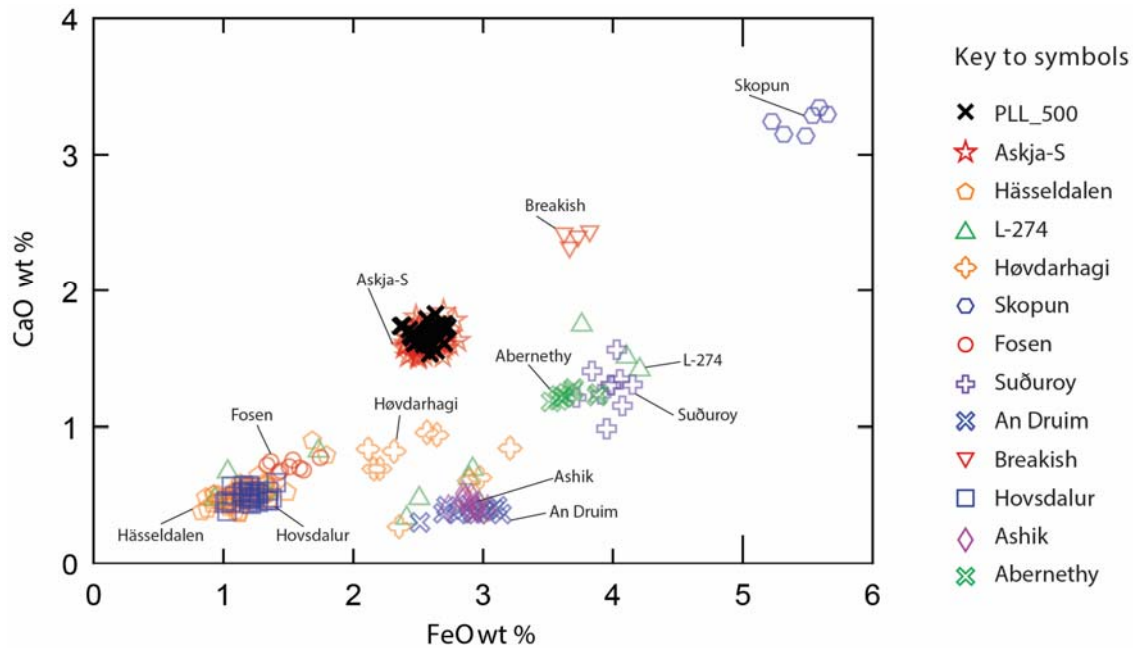


Figure 3. Lithostratigraphy, radiocarbon dates, loss on ignition, CaCO₃ content and total shard concentrations for the Pant-y-Llyn core (BGS Borehole reference SN61NW12). Radiocarbon dates are derived from bulk sediment samples. Calibrated age ranges are shown here and outlined in table 1. Askja-S Tephra age estimates are from Bronk Ramsey et al., 2015 (a) and Ott et al., 2016 (b).

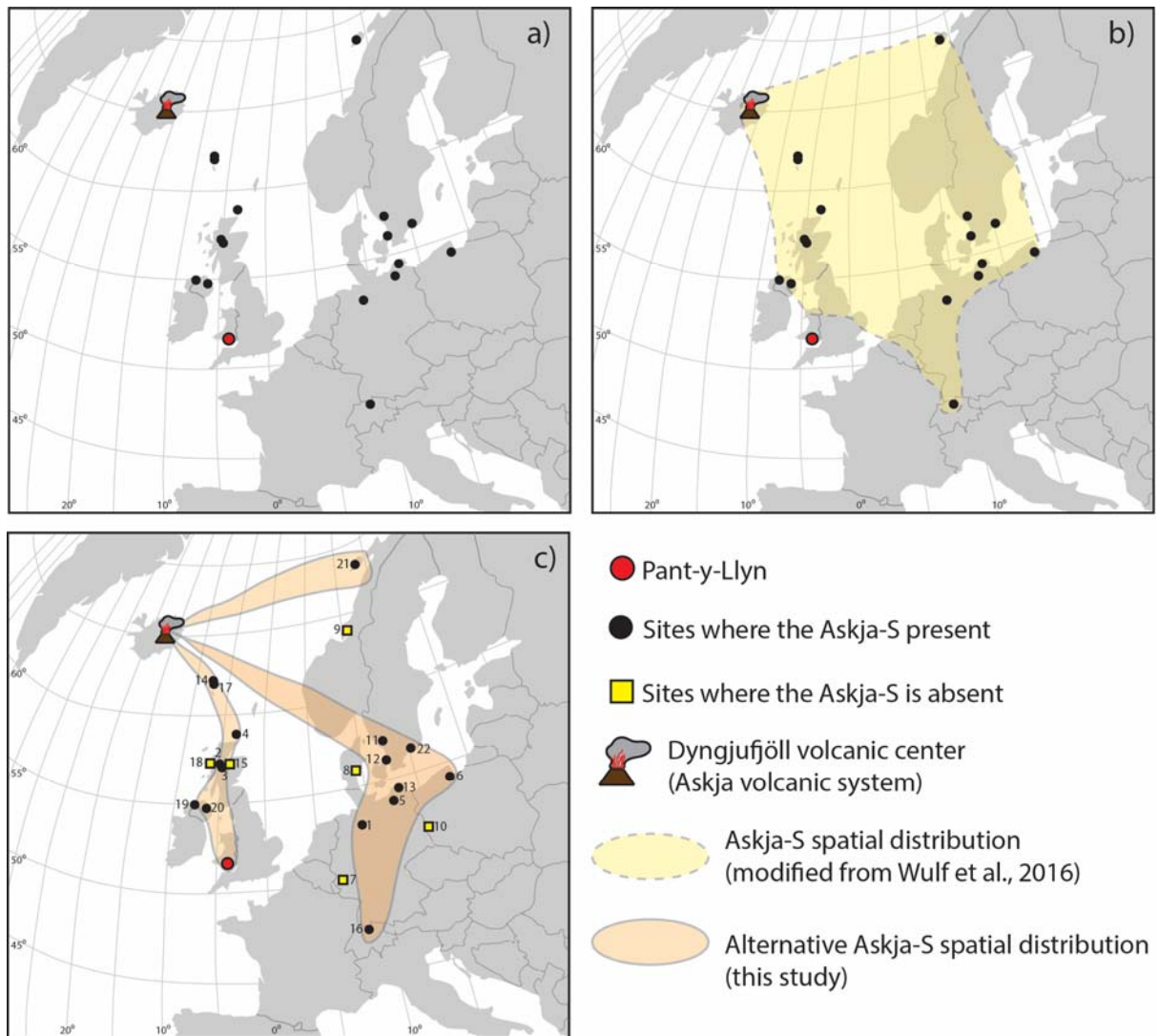
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4 **Figure 4.** Selected bi-plots showing tephra PLL_500 glass shard major element composition
 5 correlating to the Askja-S Tephra. Hässeldalen, L-274 ,Høvdarhagi, Skopun, Fosen,
 6 Suðuroy, An Druim, Breakish, Hovsdalur, Ashik and Abernethy Tephra data also shown for
 7 discrimination. Data have been normalised. Data from: (Wastegård, 2002; Ranner et al.,
 8 2005; Pyne O'Donnell, 2007; Lind & Wastegård, 2011; Matthews et al., 2011; Lane et al.,
 9 2011, 2012a; Lind et al., 2013; Lilja et al., 2013; Wulf et al., 2016; Timms et al., 2016 and
 10 Jones et al., 2017).



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3 **Figure 5.** Spatial distribution maps for the Askja-S Tephra. a) Sites where the Askja-S
 4 Tephra is present. b) Current spatial distribution envelope for the Askja-S Tephra (modified
 5 from Wulf et al., 2016). c) Suggested plume trajectory, given the location of sites where the
 6 Askja-S is present and absent. Site numbers and details are provided in full in Table 3.

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