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Swindles, GT, Watson, EJ, Galloway, J et al. (11 more authors) (2013) Re-deposited cryptotephra layers in Holocene peats linked to anthropogenic activity. *Holocene*, 23 (10). 1493 - 1501. ISSN 0959-6836

<https://doi.org/10.1177/0959683613489586>

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Paper:

Swindles, GT, Watson, EJ, Galloway, J, Outram, Z, Batt, C, Bond, J, Bashford, D, Turner, K, Schofield, JE, Edwards, KJ, Newton, AJ, Dugmore, AJ, Church, MJ and Turner, V (2013) *Re-deposited cryptotephra layers in Holocene peats linked to anthropogenic activity*. *Holocene*, 23 (10). 1493 - 1501. ISSN 0959-6836

<http://http://dx.doi.org/10.1177/0959683613489586>

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Re-deposited cryptotephra layers in Holocene peats linked to anthropogenic activity

MANUSCRIPT FOR THE HOLOCENE

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Abstract

Tephra layers can form useful age-equivalent stratigraphic markers for correlating palaeoenvironmental sequences and they provide information about the spatio-temporal nature of past volcanic ash fall events. The use of microscopic 'cryptotephra' layers has both increased the stratigraphic resolution of tephra sequences in proximal areas and extended the distal application of tephrochronology to regions of the world situated far from volcanoes. Effective tephrochronology requires the discrimination between in-situ tephra deposited directly from volcanic plumes and tephras that have been remobilised since their initial deposition. We present tephrostratigraphic and glass chemistry data from two proximal peat profiles (one lowland, one upland) from the Shetland Islands, UK. Both profiles contain the Hekla-Selsund tephra (deposited ca. 1800–1750 cal. BC), whilst the Hekla 4 ash (ca. 2395-2279 cal. BC) is present in the upland record. Overlying the Hekla-Selsund tephra are a number of distinct peaks in tephra shard abundance. The geochemistry of these layers shows that they represent re-working of the Hekla 4 and Hekla-Selsund layers rather than primary air-fall deposits. Pollen analysis of the peat sequences illustrates that these re-deposited tephra layers are coincident with a rise in heather-dominated vegetation communities (heath and/or moorland) and a subsequent intensification of burning in the landscape. We suggest that burning caused increased erosion of peats resulting in the remobilisation of tephra shards. The study demonstrates both the need for caution, and the opportunities created when applying tephrochronologies in regions heavily affected by past human activity that contain both reworked tephra layers and in-situ fallout.

Introduction

Tephra layers can form stratigraphically-distinctive and spatially-extensive isochronous horizons, and offer outstanding potential for the dating and correlation of sedimentary sequences and palaeoclimatic records (a technique referred to as tephrochronology; e.g. Thórarinnsson, 1944; Lowe, 2011). Depending on location, the weather at the time of the eruption, the explosivity and volume of ejecta produced, tephras can form extensive layers visible in the stratigraphy (e.g. Larsen et al., 1999; Lowe et al., 2000). In addition, a combination of low deposition volume and very small grain sizes can lead to the formation of tephra deposits that are hidden from view (e.g., Dugmore, 1989; Dugmore et al., 1995; Hall and Pilcher, 2002; Wastegård, 2005; Gehrels et al., 2006; Hang et al., 2006; Payne et al., 2008). These 'cryptotephras' (*sensu* Lowe and Hunt, 2001) are important for two reasons. They can be used to increase the numbers of discrete tephra horizons in proximal areas of fallout - adding details to the stratigraphy between the visible layers of tephra, and can also be identified across continental scales, greatly increasing the potential applications of the technique and creating opportunities for correlations of fundamental importance, such as those between ice core, marine and terrestrial proxy records.

Tephras are also important for understanding the spatio-temporal nature of volcanic ash hazards. For example, Swindles et al. (2011) and Lawson et al. (2012) carried out comprehensive spatio-temporal analysis of European cryptotephras in peats and lake sediments and provide a probability estimate of how frequently volcanic ash clouds affected Northern Europe during the Holocene. One pre-requisite for studies using tephra layers for volcanic hazard research, or for dating and correlating sedimentary sequences, is that the primary air-fall deposit is identified through appropriate stratigraphic, petrographic and geochemical methods (Westgate and Gordon, 1981; Swindles et al., 2010; Dugmore and Newton, 2012). However, several studies have suggested that tephra records can be confounded by taphonomic problems including the re-working of primary air-fall deposits (Dugmore et al., 1995; Edwards and Craigie, 1998; Boyle, 1999; Payne and Gehrels, 2010; Gudmundsdóttir et al., 2011). In this paper we present unambiguous evidence of redeposited cryptotephra layers in Holocene peats from the Shetland Islands, UK (Figure 1) that are a result of the re-working of primary ash-fall deposits. We use pollen analysis to provide landscape context and to

examine the factors leading to the re-working of tephtras.

Methods

An 80-cm peat sequence from Underhoull in Unst, Shetland Islands, (Figure 1) was sampled in 2008 (the 'lowland site'). A monolith tin was used to extract a column of peat from the open face of a trench (following de Vleeschouwer et al., 2010). This peat formed in a small (~13 × 8 m) topographic hollow adjacent to a Norse longhouse, referred to as the 'Upper House' (Bond et al., 2013) to distinguish it from the 'Lower House' investigated downslope by Small (1966). The site is immediately south of the Iron Age 'Broch of Underhoull' (DD: 60.71878, -0.9475). A 160-cm core was extracted from an upland peat bog (the 'upland site') using a Russian corer and the parallel hole method (following de Vleeschouwer et al., 2010). The upland site is at the crest of a hill directly to the northeast of the Norse longhouse and thus the two sites are only separated by a distance of ~820m (DD: 60.7225, -0.9344) (Figures 1 and 2).

All the peat samples were stored at 4°C prior to sub-sampling. Tephra layers in each profile were determined using an ashing and extraction technique on contiguous 1-cm samples (Hall and Pilcher, 2002; Swindles et al., 2010). Loss-on-ignition was carried out using standard methods (Dean, 1974). As the samples contained some minerogenic material, LST Fastfloat (2.3-2.5 g cm⁻³) was used to concentrate the shards. The total number of tephra shards within a 1 cm³ sample was counted under light microscopy at 100-200x magnification. Peat samples from depths of peak shard concentration were selected for subsequent geochemical analysis (Payne and Gehrels, 2010). Approximately 5 cm³ of peat was acid-digested (using H₂SO₄ and HNO₃) following standard procedures (Pilcher and Hall, 1992) and density separation was undertaken as before. The samples were sieved through a 10 µm mesh and washed with deionised water before being centrifuged to concentrate the tephra shards. The tephtras were mounted on glass slides and epoxy disks and were polished to a 0.25 µm diamond finish before being carbon coated (e.g. Hall and Pilcher, 2002; Swindles et al., 2010).

The majority of the geochemical analysis was carried out at the UK Natural Environment Research Council

(NERC) Tephra Analytical Unit at Edinburgh University. A CAMECA SX100 electron microprobe with an accelerating voltage of 15kV, a beam current of 2nA and diameter of 5 μm was used for the wavelength-dispersive spectroscopy (WDS) analyses. The microprobe was calibrated using a mixture of natural and synthetic standards and instrument stability was monitored using both a Lipari obsidian and BCRsg glass standard. X-PHI corrections for counter deadtime, atomic number effects, fluorescence and absorption were undertaken on the instrument's PeakSight version 4.0 software. Energy-dispersive spectroscopy (EDS) using the Princeton Gamma Tech Spirit EDS system was used to aid in the initial detection of tephra shards. Once a shard was located, the beam was moved to a flat section of the shard (avoiding vesicles) for wavelength-dispersive spectroscopy. Further analyses were carried out on the University of Leeds Jeol 8230 electron microprobe. Comparison of tephra and standard analyses showed the results to be equivalent. It has been suggested that acid digestion can alter the chemistry of tephra shards (Blockley et al., 2005; cf. Dugmore et al., 1992). However, the use of the acid digestion method allows us to carry out 'like-with-like' comparisons with type data which have been prepared in this way. Our results were compared to those on TephraBase (Newton et al., 2007).

Samples were submitted for AMS ^{14}C dating at the NERC radiocarbon laboratory at East Kilbride, Scotland. In the upland sequence, macrofossils (>125 μm) were sieved from the peat and dated. At the lowland site the peat did not contain easily identifiable macrofossils so measurements were carried out on a combination of the humin and humic acid fractions. Dates were calibrated using Calib 6.0.2 (Stuiver and Reimer, 1993) and the Intcal09 calibration curve (Reimer et al., 2009).

Samples from the upland site were prepared for palynological analysis following the standard techniques described by Fægri and Iversen (1989) excluding hydrofluoric acid (HF) treatment. Pollen samples from the lowland site were treated with HF due to their high minerogenic content (Moore et al., 1991). *Lycopodium* tablets (Stockmarr, 1971) were added prior to processing to allow the determination of pollen concentrations. Pollen and spores were identified using a light microscope (x400 magnification). Selected non-pollen palynomorphs (NPPs) and microscopic charcoal particles were also counted. The relative

abundances of pollen, spores, freshwater algae and microscopic charcoal were calculated in TILIA v 2.0 (Grimm 1993) using a pollen sum that included pollen from obligately terrestrial plants. Pollen diagrams were drawn using TGView. Stratigraphically constrained incremental sum of squares (CONISS) cluster analysis was performed following square-root transformation of relative abundance data to aid the identification of palynological assemblage zones (Grimm 1987).

Results and Discussion

At the lowland site a sequence of well-humified peat with high minerogenic content (including some rock clasts) was encountered in a hollow adjacent to the Norse longhouse (Figure 3). At the upland site an ombrogenous *Sphagnum* and *Eriophorum* peat with varying levels of humification was identified. Several algal pool mud (gyttja) layers were also observed in the upland profile (Figure 3). All the tephras encountered in this study were silicic in composition; no basaltic tephras were found (Figure 4). In the lowland peat profile the Hekla-Selsund/Kebister tephra (Dugmore et al., 1995; dated ca. 1800–1750 cal. BC by Wastegård et al., 2008) was identified. Above this, a tephra exhibiting a mixed geochemistry (and matching Hekla 4 and Hekla-Selsund) is present (Figures 3 and 5; Supporting Table S1). In the upland profile a tephra clearly matching Hekla 4 is present (ca. 2395-2279 cal. BC; Pilcher et al., 1995, 2300-2204 cal. BC; Dugmore et al., 1995). This is overlain by the Hekla-Selsund tephra, followed by further peaks with similar geochemistry. Overlying these are several more peaks of tephra that have a geochemistry matching a combination of Hekla-Selsund and Hekla 4. It is apparent that the tephrostratigraphy of these profiles is anomalous and does not match the tephra event stratigraphy of Iceland, or NW Europe (cf. Larsen and Thórarinnsson, 1977; Larsen and Eiríksson, 2008; Swindles et al., 2011). Four main modes of tephra reworking are identified:

1. A blurred peak (Hekla 4 – upland profile). The Plinian eruption responsible for Hekla 4 tephra probably lasted less than two days (24-30 hours has been estimated by Larsen and Thórarinnsson (1977)) and yet tephra grains are spread over ~10 cm representing several centuries of peat accumulation.
2. A split peak (Hekla-Selsund – lowland profile). The Hekla-Selsund tephra was also formed by a

Plinian eruption, whose duration would have been similar to that which produced Hekla 4, and would have delivered to the site as discrete (sub-annual) event. The peaks in the lowland profile are separated by ~2 cm of stratigraphy representing at least several decades. This double-peak distribution is similar to that observed for the historical age tephra horizon at Loch Portain, North Uist (Dugmore et al., 1996).

3. Multiple peaks (Hekla-Selsund – upland profile). The multi peak distribution covers 20 cm of the stratigraphy, similar to the pattern inferred by x-ray imagery of Hekla 4 at in Profile 2 at Altnabreac, northern Scotland by Dugmore and Newton (1992). There is still no other tephra layers involved in the redistribution. This implies a shallow/near surface set of processes following the initial deposition of the Hekla-Selsund tephra.
4. Mixed tephra peaks (Hekla-Selsund and Hekla 4 in both upland and lowland profiles). Tephra from different deposits originally separated by centuries/decimetres of stratigraphy have been remobilised and combined to create discrete peaks.

Radiocarbon dating of the peat profiles was also highly problematic. In the lowland site the ^{14}C dates do not represent a coherent chronosequence and the development of a statistical age-depth model was not possible. There are major differences between the dates on humic acids and those on humin; the latter was typically older by ~200-300 calendar years that may be due to mobility of the humic acid fraction (e.g. Shore et al., 1995). There is a very slow rate of peat accumulation in this profile and hiatuses or addition of carbon of different ages, through human activities such as burning of peat or old wood, is potentially present due to the Iron Age and Norse phases of activity recorded nearby. The ^{14}C dates on humin and humic acid at the Hekla-Selsund tephra layer are approximately 1200-900 cal. yr younger than the tephra horizon suggests. However, there is a possibility that the Hekla-Selsund tephra in the lowland site may also represent inwash to the peat hollow, rather than the primary airfall deposit. The ^{14}C date at the Hekla 4 layer in the upland site is also ~500 years younger than the accepted data of Hekla 4 (ca. 2395-2279 cal. BC; Pilcher et al., 1995), which may be due to the presence of intrusive *Eriophorum* rootlets or fungal contamination of the sample. Despite these problems, the ^{14}C dates and tephra layers suggest that the peat horizon containing

the major reworked tephra layers spans the Middle-Late Bronze Age and the Iron Age (including the first few centuries AD) in the upland profile. The reworked tephtras that have been geochemically analysed in the lowland profile date to the first few centuries AD. However, mixed tephra populations are found lower in the peat profile that date to the Iron Age and possibly into the Bronze Age (Figure 3).

Pollen analysis from both the upland and lowland sites shows that the anomalous tephra layers occur during a phase of major landscape change, indicated by a rise in *Calluna vulgaris* pollen and a major increase in the abundance of microscopic charcoal (assemblage zones U2 and L3; Figure 6). A number of palaeoecological records from lakes in Shetland contain a marked rise in charcoal in association with the expansion of *Calluna*-dominated heathlands and moorlands (Bennett et al., 1992; Bennett and Sharp, 1993a,b; Bennett et al., 1993; Edwards and Whittington, 1998; Edwards et al., 2005, 2009). The presence of charcoal may be due to deliberate burning of the landscape by humans to extend rough grazing areas (Edwards et al., 1995; Schofield et al., 2013), or it may reflect increased wildfire across heather-dominated plant communities as these are environments susceptible to natural fires (Gimingham, 1972). In addition, where grazing pressure is absent, *Calluna* will re-establish as the dominant vegetation type after burning (Rawes and Hobbs, 1979).

There are widespread archaeological remains dating to the Iron Age in this area of Unst; the Broch of Underhoull and several smaller Iron Age structures are found within 200m of the lowland site (Small, 1966; Figure 1). The expansion of heathland and/or moorland may reflect abandonment of this area in the first few centuries AD (Schofield et al., 2013). Landscape instability following the abandonment of the Iron Age structures may also be suggested by a soil layer between the upper Iron Age and Norse horizons in the archaeological stratigraphy at Underhoull (Small, 1966). It has been suggested that this soil layer represents in-wash from the surrounding slopes when Underhoull was deserted for a considerable time before the arrival of the Norse (Small, 1966). Alternatively, the soil layer may represent material brought in to build up the platform for the Norse house.

Extensive erosion is a known outcome of fire in blanket peatlands (Tallis, 1998; Yeloff et al., 2006). Reworked tephra layers in both profiles at Underhoull may therefore be the product of the disturbance of peatlands triggered by either anthropogenic or natural burning. Fire in the peatlands led to the removal of vegetation and greater exposure of soils and other peatland surfaces, making these more susceptible to erosion (on the slopes and high ground above the lowland profile, and in the high bedrock ridge around the upland site). This could have promoted the concentration of tephra at the surface, followed by subsequent exposure and re-mobilisation by wind and water, and finally, re-deposition. We found no statistically significant difference between the percentage potassium or total alkali data in the primary and re-worked Hekla-Selsund tephras, suggesting that the temperatures of fires were not high enough to change shard chemistry (Figures 4 and 7). There is also no obvious morphological difference between the primary and reworked tephra grains. It is highly probable that the problems encountered when ^{14}C dating these peats are also the product of the re-deposition of organic components of different ages. There is also a possibility of the re-working we identify here being a regional phenomenon, as re-working of both Hekla 4 and Hekla-Selsund has been observed in later Holocene peat and lake sequences in the Faroes (cf. Edwards et al., 2005; Lawson et al., 2007, 2008). In the case of the Faroes, climatically-driven geomorphic and pedogenic disturbance is proposed as the driver, rather than anthropogenic activity, as humans did not settle in the Faroes until the first millennium AD.

Tephrochronology is a well-established tool for dating sediments and peats. However, a number of problems have been identified including spatial 'patchiness' of tephra layers at the regional scale (e.g. Dugmore et al., 1996; Payne et al., 2013; Rea et al., 2012) and taphonomic problems of re-working and redistribution in peatlands and in lake sediments (Holmes 1998; Boyle, 1999; Payne et al., 2005, Payne and Gehrels, 2010). In addition, the tephra layer with the highest concentration of glass shards may not necessarily represent a primary ash-fall layer but instead may reflect the re-deposition of eroded tephra from exposures or surfaces adjacent to a peat bog or lake (Swindles et al., 2010). The thickest layers in proximal areas do not always represent primary fallout (Dugmore and Newton, 2012). In this study we have clear evidence for different modes of redistribution of tephras at the landscape scale in relation to changing human activities

and/or fire disturbance. Our results illustrate the need for high quality geochemical data before using tephra layers as isochrones and the importance of identifying the primary air fall deposit in sedimentary sequences.

Conclusions

Two proximal peatland tephra records from Unst in the Shetland Islands, contain a tephra layer with geochemistry matching that of the widespread Hekla-Selsund isochron. In both profiles, distinct tephra peaks overlie this layer. These represent re-working of the Hekla-Selsund and older Hekla 4 layers rather than primary air-fall tephra deposits. Pollen analysis of the peat sequences shows that these reworked tephra layers occur at a time characterised by an increase in heather-dominated vegetation communities (heathland and moorland) and intensified burning in the landscape. Four modes of tephra reworking are identified, which reflect different rates of earth surface processes. We suggest that the reworked tephra layers in this study are indicators of wider landscape change, representing erosion of peat and the re-deposition of tephra shards. Tephrostratigraphies, including those composed of cryptotephra, can therefore provide important information about environmental processes within landscapes (erosion and deposition) as well as chronology (Dugmore and Newton, 2012). Our results also demonstrate the need for high quality geochemical data when using tephras as age-equivalent stratigraphic markers and highlight the use of palynology to place tephrostratigraphies in a wider landscape context.

Acknowledgements

The Viking Unst Project investigations at Underhoull were sponsored by Heritage Lottery Fund, European Agricultural Guidance and Guarantee Fund, Shetland Development Trust, Shetland Enterprise Company, Shetland Amenity Trust, Historic Scotland, Shetland Islands Council, and the University of Bradford, with additional funding from International Polar Year project 'Long Term Human Ecodynamics in the Norse North Atlantic: cases of sustainability, survival, and collapse' (NSF Award number 0732327). This research was also supported by grants from the Natural Environmental Research Council (UK) for ¹⁴C dating (allocations: 1493.0910, 1466.0410) and geochemical analysis of tephras at the School of GeoSciences, University of

Edinburgh (allocation: TAU58/1109). We thank the Shetland Amenity Trust for funding further geochemical analysis at the University of Leeds. We would like to thank Dr Chris Hayward (University of Edinburgh) and Dr Eric Condcliffe (University of Leeds) for their advice on tephra geochemical analysis. Many thanks to Gill Plunkett and Keith Bennett (Queen's University Belfast) for constructive comments on the pollen data. Many thanks to all staff and students involved in the Viking Unst project for their assistance in the field. We also thank Linda Dancey, GSC-Calgary for pollen preparation.

Figure captions

Figure 1. The study location. (a) The island of Unst (shaded black) within the Shetland Islands; (b) The position of Shetland relative to the UK mainland; (c) Underhoull in Unst; (d) Relative locations of the upland and lowland sampling sites. The Broch of Underhoull is highlighted and the viewing position from which photo b (Figure 2) was taken is shown (the arrow within a circle).

Figure 2. Photographs of; (a) the coring location in the upland peatland at Underhoull; (b) the lowland site at Underhoull (also see Figure 1); (c) the peat section at the lowland site.

Figure 3. Stratigraphic information for both Underhoull profiles. The lithostratigraphy, tephrostratigraphy, loss-on-ignition results, and calibrated ^{14}C dates (2σ range) are shown. The stippled area refers to the pollen zone indicating the increase of *Calluna* and charcoal (see Figure 6). The interpretation of the tephra layers is based on the geochemical data shown in Figure 5. Dates in italics are those based on the humin fraction of the peat (lowland profile).

Figure 4. Total alkali–silica biplot of all tephtras analysed from Underhoull.

Figure 5a. Tephra geochemistry biplots for the upland profile. The type analyses for Hekla 4, Hekla-Selsund and Glen Garry are from Tephabase (Newton et al., 2007). The Underhoull tephtras are shown as red crosses.

Figure 5b. Tephra geochemistry biplots for the lowland profile. The type analyses for Hekla 4, Hekla-Selsund and Glen Garry are from Tephabase (Newton et al., 2007). The Underhoull tephtras are shown as red crosses.

Figure 6. Percentage pollen data from the Underhoull profiles. Main taxa only are shown (taxa occurring equal to or greater than 2% in at least one sample). The pollen sum includes pollen and spores from terrestrial plants only. CONISS is based on relative abundance of pollen and spores from terrestrial plants. The depths of the tephra layers are shown.

Figure 7. Boxplots comparing the % K_2O data from the primary and re-worked Hekla-Selsund tephra layers.

Table 1. AMS radiocarbon dates. Dates were calibrated using Calib 6.0.2 (Stuiver and Reimer, 1993) and the Intcal09 calibration curve (Reimer et al., 2009).

Supporting Table S1. Tephra shard geochemistry for each site as determined by EPMA.

Supporting Figure S2. Percentage pollen data from the Underhoull profiles. '+' indicates rare types (<1%).

The pollen sum includes pollen and spores from terrestrial plants only. Shaded areas represent 2× exaggeration of selected taxa. CONISS is based on relative abundance of pollen and spores from terrestrial plants. The depths of the tephra layers are shown.

References

Bennett KD, Boreham S, Hill K, Packman S, Sharp MJ and Switsur VR (1993) Holocene environmental history at Gunnister, north Mainland, Shetland. In: Birnie JF, Gordon JE, Bennett KD and Hall A (eds) *The Quaternary of Shetland: Field Guide*. Cambridge: Quaternary Research Association, pp. 83–98.

Bennett KD, Boreham S, Sharp MJ and Switsur VR (1992) Holocene history of environment, vegetation and human settlement on Catta Ness, Lunnasting, Shetland. *Journal of Ecology* 80: 241–273.

Bennett KD and Sharp MJ (1993a) Holocene vegetation and environment. In: Birnie JF, Gordon JE, Bennett KD and Hall A (eds) *The Quaternary of Shetland: Field Guide*. Cambridge: Quaternary Research Association, pp. 18–22.

Bennett KD and Sharp MJ (1993b) Holocene environmental history at Dallican Water, northeast Mainland, Shetland. In: Birnie JF, Gordon JE, Bennett KD and Hall A (eds) *The Quaternary of Shetland: Field Guide*. Cambridge: Quaternary Research Association, pp. 77–82.

Blockley SPE, Pyne-O'Donnell SDF, Lowe JJ, Matthews IP, Stone A, Pollard AM, Turney CSM and Molyneux EG (2005) A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. *Quaternary Science Reviews* 24: 1952–1960.

Bond JM, Dockrill SJ, Outram Z, Batey CE, Summers J, Friel R, Brown LD, Cussans J, Cook G, Legg R, Marshall W, Mustchin A, Church M, Hamlet LE and Simpson IA (2013) Excavations at Hamar and Underhoull. In: Turner VE, Bond JM and Larsen AC (eds) *Viking Unst: Excavation and Survey in Northern Shetland*. Shetland Heritage Publications, pp. 123–180

Boyle JE (1999) Variability of tephra in lake sediments, Svinavatn, Iceland. *Global and Planetary Change* 435: 129–149.

Dean WE (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology* 44: 242–248.

De Vleeschouwer F, Chambers FM and Swindles GT (2010) Coring and sub-sampling of peatlands for palaeoenvironmental research. *Mires and Peat* 7 (Article 1): 1–10.

- Dugmore AJ (1989) Icelandic volcanic ash in Scotland. *Scottish Geographical Magazine* 105(3): 168-172.
- Dugmore AJ, Larsen G and Newton AJ (1995) Seven tephra isochrones in Scotland. *The Holocene* 5: 257–266.
- Dugmore AJ, Larsen G, Newton AJ and Sugden DE (1992) Geochemical stability of fine-grained silicic tephra layers in Iceland and Scotland. *Journal of Quaternary Science* 7: 173-183.
- Dugmore AJ and Newton AJ (1992) Thin tephra layers in peat revealed by X-radiography. *Journal of Archaeological Sciences* 19: 163-170.
- Dugmore AJ and Newton AJ (2012) Isochrons and beyond- maximising the use of tephrochronology. *Jökull* 62: 39-52.
- Dugmore AJ, Newton AJ, Edwards KE, Larsen G, Blackford JJ and Cook GT (1996) Long-distance marker horizons from small-scale eruptions: British tephra deposits from the AD 1510 eruption of Hekla, Iceland. *Journal of Quaternary Science* 11: 511–516.
- Dugmore AJ, Shore JS, Cook GT, Newton AJ, Edwards KJ and Larsen G (1995) The radiocarbon dating of tephra layers in Britain and Iceland. *Radiocarbon* 37(2): 286-295.
- Edwards KJ, Borthwick DM, Cook GT, Dugmore AJ, Mairs KA, Church MJ, Simpson IA and Adderley WP (2005) A hypothesis-based approach to landscape change in Suðoroy, Faroe Islands. *Human Ecology* 33: 621-650.
- Edwards KJ and Craigie R (1998) Palynological and vegetational changes associated with the deposition of Saksunarvatn ash in the Faroe Islands. *Fróðskaparrit* 48: 245-258.
- Edwards KJ, Schofield JE, Whittington G and Melton ND (2009) Palynology 'on the edge' and the archaeological vindication of a Mesolithic presence? The case of Shetland. In Finlay N, McCartan S, Milner N and Wickham-Jones CJ (eds) *From Bann Flakes to Bushmills - papers in honour of Professor Peter Woodman*. Oxford: Prehistoric Society Paper No. 1 and Oxbow Books, pp.113-123.
- Edwards KJ and Whittington G (1998) Landscape and environment in prehistoric West Mainland, Shetland. *Landscape History* 20: 5-17.
- Edwards KJ, Whittington G and Hiron KR (1995) The relationship between fire and long-term wet heath development in South Uist, Outer Hebrides, Scotland. In Thompson DBA, Hestor AJ and Usher MB (eds) *Heaths and moorlands: cultural landscapes*. Edinburgh: HMSO, pp.240-248.
- Edwards KJ, Whittington G, Robinson M and Richter D (2005) Palaeoenvironments, the archaeological record and cereal pollen detection at Clickimin, Shetland. *Journal of Archaeological Science* 32: 1741-1756.
- Fægri K, Iversen J, Kaland PE and Krzywinski K (1989) *Textbook of Pollen Analysis*. 4th edition. Chichester: John Wiley & Sons Ltd.
- Gehrels MJ, Lowe DJ, Hazell ZJ and Newnham RM (2006) A continuous 5300-yr Holocene cryptotephrostratigraphic record from northern New Zealand and implications for tephrochronology and volcanic hazard assessment. *The Holocene* 16: 173-187.
- Gimingham CH (1972) *Ecology of Heathlands*. London: Chapman & Hall.

- Grimm EC (1987) CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geoscience* 13: 13-35.
- Grimm EC (1993) "TILIA v2.0 (computer software)." Illinois State Museum, Research and Collections Center, Springfield, Illinois, USA.
- Gudmundsdóttir ER, Eiríksson J and Larsen G (2011) Identification and definition of primary and reworked tephra in Late Glacial and Holocene marine shelf sediments off North Iceland. *Journal of Quaternary Science* 26: 589-602.
- Hall VA and Pilcher JR (2002) Late-Quaternary Icelandic tephtras in Ireland and Great Britain: detection, characterization and usefulness. *The Holocene* 12: 223-230.
- Hang T, Wastegard S, Veski S and Heinsalu A (2006) First discovery of cryptotephra in Holocene peat deposits of Estonia, eastern Baltic. *Boreas* 35: 644-649.
- Holmes JA (1998) *A Tephra-dated study of Vegetation and Climate Change in the Mid- Holocene of North West Europe*. Unpublished PhD thesis, Queen's University Belfast.
- Larsen G, Dugmore A and Newton A (1999) Geochemistry of historical-age silicic tephtras in Iceland. *The Holocene* 9: 463-471.
- Larsen G and Eiríksson J (2008) Holocene tephra archives and tephrochronology in Iceland – a brief overview. *Jökull* 58: 229-250.
- Larsen G and Thórarinsson S (1977) H4 and other acidic Hekla tephra layers. *Jökull* 27: 28-46.
- Lawson IT, Church MJ, Edwards KJ, Cook GT and Dugmore AJ (2007) Peat initiation in the Faroe Islands: Climate change, pedogenesis or human impact? *Earth and Environmental Transactions of the Royal Society of Edinburgh* 98: 15-28.
- Lawson IT, Edwards KJ, Church MJ, Newton AJ, Cook GT, Gathorne-Hardy FJ and Dugmore AJ (2008) Human impact on an island ecosystem: pollen data from Sandoy, Faroe Islands. *Journal of Biogeography* 35: 1130-1152.
- Lawson IT, Swindles GT, Plunkett G and Greenberg D (2012) The spatial distribution of Holocene cryptotephtras in north-west Europe since 7 ka: implications for understanding ash fall events from Icelandic eruptions. *Quaternary Science Reviews* 41: 57-66.
- Lowe DJ (2011) Tephrochronology and its application: A review. *Quaternary Geochronology* 6: 107-153.
- Lowe DJ and Hunt JB (2001) A summary of terminology used in tephra-related studies. In: Juvigne´ E and Raynal JP (eds.) *Tephtras, Chronology and Archaeology: Les Dossiers de l'Archaeo-logis* 1. France: CDERAD, pp. 17–22.
- Lowe DJ, Newnham RM, McFadgen BG and Higham TFG (2000) Tephtras and New Zealand archaeology. *Journal of Archaeological Science* 27: 859–870.

Moore PD, Webb JA and Collinson ME (1991) *Pollen Analysis*. Second edition. Oxford: Blackwell Scientific Publications.

Newton AJ, Dugmore AJ and Gittings BM (2007) Tephrobase: tephrochronology and the development of a centralised European database. *Journal of Quaternary Science* 22: 737-743.

Payne R, Blackford J and van der Plicht J (2008) Using cryptotephra to extend regional tephrochronologies: An example from southeast Alaska and implications for hazard assessment. *Quaternary Research* 69: 42-55.

Payne RJ, Edwards KJ and Blackford JJ (2013) Volcanic impacts on the Holocene vegetation history of Britain and Ireland: a review and meta-analysis of the palynological evidence. *Vegetation History and Archaeobotany* 22: 153-164

Payne R and Gehrels MJ (2010) The formation of tephra layers in peatlands: an experimental approach. *Catena* 81: 12–23.

Payne R, Kilfeather A, van der Meer J and Blackford J (2005) Experiments on the taphonomy of tephra in peatlands. *Suo* 56: 147-156.

Pilcher JR and Hall VA (1992) Towards a tephrochronology for the Holocene of the north of Ireland. *The Holocene* 2: 255-259.

Pilcher JR, Hall VA and McCormac FG (1995) Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats. *The Holocene* 5: 103-110.

Rawes M and Hobbs R (1979) Management of semi-natural blanket bog in the Northern Pennines. *The Journal of Ecology* 67: 789-807.

Rea HA, Swindles GT and Roe HM (2012) The Hekla 1947 tephra in the North of Ireland: distribution, concentration and geochemistry. *Journal of Quaternary Science* 27: 425-431.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J and Weyhenmeyer CE (2009) IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51: 1111–1150.

Schofield JE, Edwards KJ and Swindles GT (2013) A multi-proxy palaeoenvironmental investigation of peat deposits from Underhoull, Unst, Shetland Islands. In Turner VE, Bond JM and Larsen AC (eds) *Viking Unst: Excavation and Survey in Northern Shetland*. Lerwick: Shetland Heritage Publications, pp. 75-83.

Shore JS, Bartley DD and Harkness DD (1995) Problems encountered with the ¹⁴C dating of peat. *Quaternary Science Reviews* 14: 373–383.

Small A (1966) Excavations at Underhoull, Unst, Shetland. *Proceedings of the Society of Antiquaries of Scotland* 98: 225-248.

Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13: 615-621.

Stuiver M and Reimer PJ (1993) Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon* 35: 215-230.

Swindles GT, De Vleeschouwer F and Plunkett G (2010) Dating peat profiles using tephra: stratigraphy, geochemistry and chronology. *Mires and Peat* 7 (Article 5): 1-9.

Swindles GT, Lawson IT, Savov IP, Connor CB and Plunkett G (2011) A 7000-yr perspective on volcanic ash clouds affecting Northern Europe. *Geology* 39: 887-890.

Tallis JH (1998) Growth and degradation of British and Irish blanket mires. *Environmental Review* 6: 81-122.

Thórarinnsson S (1944) Tefrokronologiska studier på Island. *Geografiska Annaler* 26: 1-217.

Wastegård S (2005) Late Quaternary tephrochronology of Sweden: a review. *Quaternary International* 130: 49–62.

Wastegård S, Rundgren M, Schoning K, Andersson S, Björck S, Borgmark A and Possnert G (2008) Age, geochemistry and distribution of the mid-Holocene Hekla-S/Kebister tephra. *The Holocene* 18: 539-549.

Westgate JA and Gordon MP (1981) Correlation techniques in tephra studies In: Self S and Sparks RS (eds) *Tephra Studies*. Dordrecht: D. Reidal, pp.73-94.

Yeloff DE, Labadz JC and Hunt CO (2006) Causes of degradation and erosion of a blanket mire in the southern Pennines, UK. *Mires and Peat* 1 (Article 4): 1-18.