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Experiments on the taphonomy of tephra in peat

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Understanding the taphonomy of tephra (volcanic ash) is crucial to the use of tephrochronology in peatlands. This study uses field experiments on a Scottish peatland to investigate the post-depositional movement of tephra in peat. Experiments were designed to investigate the temporal change in tephra profiles over a 24-month study period, the horizontal distribution of tephra and the microscopic distribution of tephra particles within the peat. Tephra concentration profiles show that the majority of tephra shards are retained within the top cm of peat with small numbers penetrating to a maximum of 6 cm depth. This distribution would be reduced as the peat is compressed with subsequent accumulation. Examination of thin sections from the plots indicates that tephra movement may be dependent on the microscopic structure of the peat, especially porosity. These results provide general support to the use of tephrochronology although further work will be required, particularly in other peat types and environments.

Keywords: tephra, taphonomy, peatland, Achnacree

Introduction

Layers of volcanic ash (tephra) are found preserved in peatlands throughout the world (Zoltai 1988, Botis et al. 1993, Dugmore et al. 1995, Lowe et al. 1999, van den Bogaard & Schmincke 2002, Bergman et al. 2004, Payne & Blackford 2004). Tephra has been used in many palaeoecological studies as it provides a time-specific marker horizon (isochrone) allowing comparison between sites and, where the age of the eruption is known, a means of dating sediments (Chambers et al. 1997, Hall 1998, Langdon et al. 2003, Lomas-Clarke & Barber 2004). The technique is particularly valuable for comparing the timing of palaeoecological change across large areas (van den Bogaard et al. 2002, Langdon & Barber 2004) and for investigating the impacts of ancient volcanic eruptions (Blackford et al. 1992, Hall 2003).

Two fundamental assumptions underlie this work: that tephra is deposited instantaneously on the time-scale under consideration, and that tephra does not undergo substantial post-depositional movement. While the first assumption seems to be correct in most cases, the second assumption has received little consideration. Lake sediment studies have observed significant movement of tephra with secondary deposition, biological mixing processes and density-related movement with redeposition at lower levels (Anderson et al. 1985, Thompson et al. 1986, Boygle 1999, Beierle & Bond 2002). These problems can impair correla-

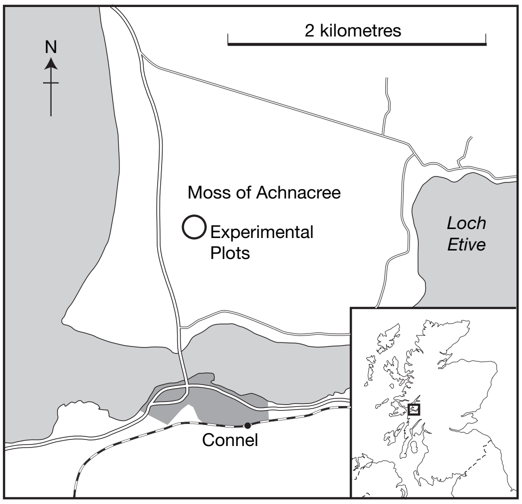

Fig. 1. Location of Moss of Achnacree and sampling area.

Kuva 1. Kokeen sijainti Achnacree -suolla Skotlannissa, jossa tutkittiin tulivuoren tuhkan käyttöä turpeen ajoittamisessa.

tions and dating based on tephras. In peat there is also evidence that depositional processes are not as straightforward as is often assumed. Bjarnasson (1991) noted the sinking of Icelandic tephra through a moss carpet. Tephra may be redeposited due to wind action, this may be a particular issue if the peat surface is frozen (Bergman et al. 2004). In the sedimentary record, some tephra profiles have been noted to have secondary and subsidiary peaks (Caseldine et al. 1998, Richard Payne, unpublished data) and some sites appear to have a background tephra concentration (Charman et al. 1995, Holmes et al. 1999).

Dugmore & Newton (1992) used X-radiography to examine the horizontal variability of a tephra layer in peat. Their study showed an uneven distribution across the palaeo-bog surface with greater quantities found in downward projecting pockets, presumably representing tephra washing into hollows. Caseldine et al. (1999) have also shown fine-scale horizontal variability in tephra concentration by examining the reflectance properties of tephra layers in peat. These studies imply the possibility of post-depositional movement of tephra and suggest that an improved knowledge of tephra taphonomy is essential to the continued use of tephrochronology. Both vertical and horizontal movement of tephra are potentially significant. If tephra moves vertically through the peat profile this could result in an erroneous age being assigned to the sediment. Horizontal movement of tephra could potentially result in concentrations being reduced below detection limits and a valuable isochrone being lost.

One possible means of investigating tephra taphonomy is to use an experimental approach. Rowley & Rowley (1956) and Clymo & Mackay (1987) investigated the taphonomy of pollen in surface peat using experimental approaches and illustrated substantial movement. These studies cannot be directly applied to tephra due to the differences in tephra morphology and size range; however similar methodologies may be applied to a study of tephra taphonomy. This study uses three field experiments to investigate the taphonomy of tephra in peat. Experiments were designed to investigate the movement of tephra through peat over time, the horizontal distribution of tephra and the microscopic distribution of tephra particles using thin sections.

Material and methods

The site chosen for this study is the Moss of Achnacree, a large raised bog in Argyll and Bute, western Scotland (Grid Reference NM9134: Fig.1). Peat deposits cover an area of almost 7Km^2 averaging around 1.9m depth; the site receives an annual rainfall of approximately 1500mm (Scottish Environmental Protection Agency, unpublished data). The peatland has been damaged and its extent reduced through a combination of grazing, drainage and peat cutting and is bordered by local roads on four sides (Fig. 1: Scottish Natural Heritage and Scottish Wildlife Trust, unpublished data). A series of 1m^2 plots was established on the site as part of a related ecological study (Payne & Blackford 2005). Tephra was applied to the plots at concentrations equivalent to Icelandic tephra found in northern British peatlands (Dugmore & Newton 1992, Dugmore et al. 1995). Results from three plots are reported here: Plot 15 (50g tephra per m^2), Plot 9 (50g tephra per m^2) and Plot 21 (300g tephra per m^2). Full details of applications and sampling are shown in Table

1. Plots 15 and 9 are hummock sites and have similar vegetation, dominated by *Calluna vulgaris* and *Eriophorum vaginatum* with an understorey of *Cladonia portentosa*, *Hypnum cupressiforme*, *Aulacomnium palustre* and *Odontoschisma sphagni.* The surface peat in these plots is compact and well humified with a defined upper surface. Plot 21 is a hollow site and has a *Sphagnum* -dominated vegetation community including *Sphagnum magellanicum, Sphagnum recurvum, Eriophorum vaginatum* and *Odontoschisma sphagni.* The surface layer in this plot consists of a *Sphagnum* carpet and is more porous than the highly humified surface peat in Plots 15 and 9.

Tephra was obtained from proximal air-fall deposits of the Öraefajökull 1362 eruption in southern Iceland (Ellershaw 2004). Tephra applied to Plots 9 and 21 passed through a 150µm sieve while that applied to Plot 15 was in the size range 150–300µm. The tephra was applied in suspension using a domestic watering can; plywood sheets were placed around the plots to keep all the tephra within the plot. Tephra was applied to Plots 9 and 15 in May 2002. To investigate tephra movement down through the peat column, Plot 15 was sampled again at five intervals over the next two years in June 2002 (1 month), September 2002 (4 months), November 2002 (6 months), June 2003 (13 months) and May 2004 (24 months). Twenty centimetre long cores were extracted using a 5cm-bore Russian corer (Aaby & Digerfeldt 1986). Coring locations were selected using a random number and grid system. In June 2003 tephra was applied to Plot 21, after three days a monolith block (10x10x20cm) was extracted from the centre of this plot and another from Plot 9. These blocks were used for the preparation of thin-sections to examine the microscopic distribution of tephra particles within the peat. At the same time, four cores were taken along a transect of Plot 9 to investigate the horizontal variability of tephra; cores 9-A, 9-B and 9-D are from lower elevation regions of the plot and core 9-C from a higher region of the plot.

The cores were sampled from the peat surface down. For the hummock sites (Plots 15 and 9) the surface was taken to be the top of the compact peat layer with the living portion of the mosses and vascular plants removed. For the hollow site there is no such defined interface between the peat and the living vegetation and the surface was taken to be the upper surface of the *Sphagnum* carpet. Sub-samples were taken at 1cm resolution from the surface to 10cm depth. Tephra samples were prepared from the nine cores following the method of Pilcher & Hall (1992). Subsamples were oven dried and then combusted at 550°C for at least 12 hours. Samples were weighed pre- and post-burning and these data used to calculate loss on ignition (LOI), which can provide an aid to locating the largest microtephra layers. The remaining inorganic residue was cleaned in 10% HCl and stored in distilled water. To allow tephra shard concentration calculations a *Lycopodium* inoculum (1 tablet, approximately 13400 spores) was added to the sample (Stockmarr 1971). Slides were made up using a small amount of sediment in glycerol and examined microscopically at 400x magnification. Tephra shards could be identified by their distinctive morphology. A minimum of 200 *Lyco-*

Table 1. Experimental treatment and sampling of plots

Taulukko 1. Tuhkakäsittelyt ja näytteenottoajankohdat ja -käytännöt koealoittain

Plot	Microform	Treatment	Time of application	Sampling
9	Low Hummock	50g tephra (< 150µm)	May 2002	Monolith and cores after 13 months
15	Low Hummock	50g tephra (150–300µm)	May 2002	Cores at 5 intervals over 24 months
21	Hollow	300g tephra (<150µm)	June 2003	Monolith after 3 days

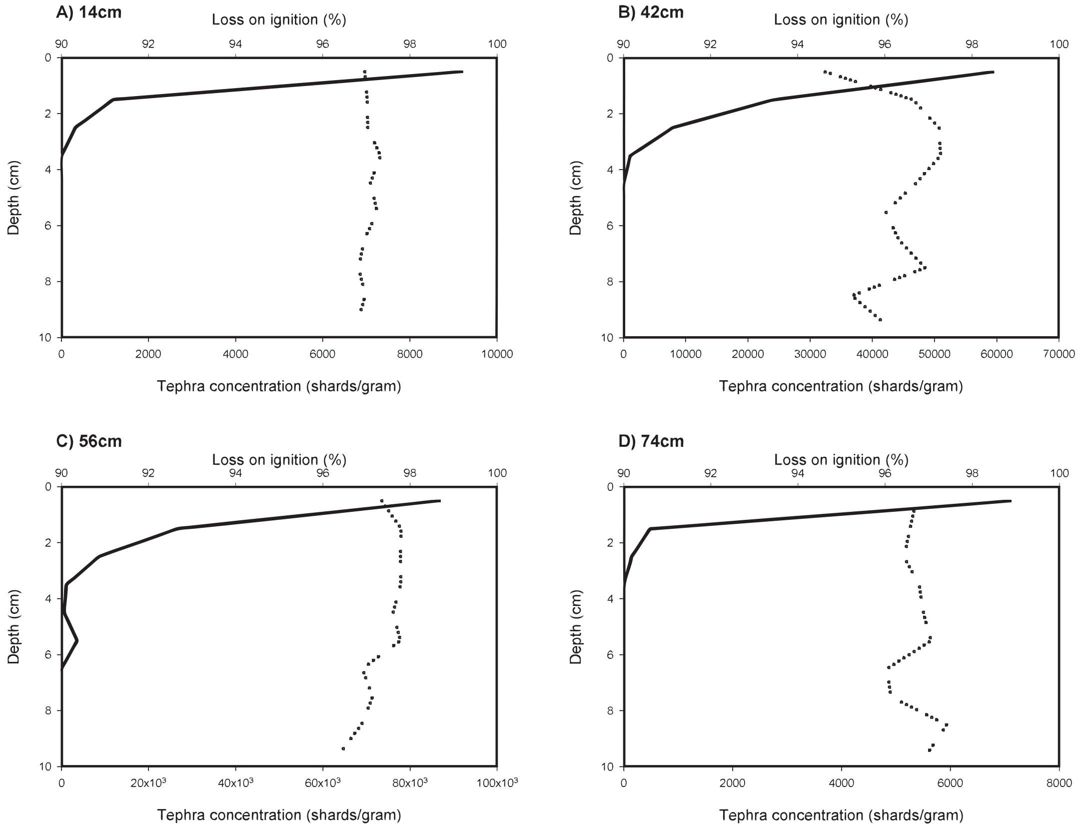

Fig. 2. Tephra concentration (solid line) and LOI profiles (dotted line) across Plot 9 on a hummock site. Sampling is 1cm contiguous blocks; points are marked at the mid-point of their depth range. Figures are labelled as distance in centimetres from the western margin of the plot. Note differences in scale between plots.

Kuva 2. Turpeen tuhkapitoisuus (partikkelia /gramma, kiinteä viiva) ja LOI profiili (hehkutushäviö, rasteriviiva) koealalla 9 mätäspinnalla. Kuvien numerointi perustuu näytteiden etäisyyteen (cm) koealan länsireunasta. Näytteet on otettu turveprofiilista 1 cm välein. Huomaa kuvien erilainen mittakaava.

podium grains were counted in the majority of samples and the number of tephra shards recorded.

To examine the microscopic distribution of tephra in two dimensions, thin sections were prepared from Plots 9 and 21. A 10 × 7cm thin-section tin was cut into a cleaned face of the extracted monolith. The samples were dried in acetone and then impregnated with crystic resin in a vacuum chamber. After impregnation, the samples were left to harden for six weeks. Samples were mounted on glass and ground to a thickness of approximately 25µm (see Murphy (1986) for full details of the laboratory procedures). The prepared thin-sections were examined at 400× magnification. Tephra shard identification is more difficult in these samples than in the ashed samples as the optical quality is somewhat poorer; shards are often partially obscured by organic material, may be shown in cross-section and cannot be moved or rotated. Due to these difficulties interpretation is based on clusters of shards. The clusters highlighted here are where two or more probable shards occur in a single field of vision. These clusters therefore show regions where tephra shards are present but provide only a semi-quantitative indication of overall tephra distribution.

Results

To investigate the horizontal distribution of tephra within the plots, a series of cores was extracted from Plot 9 and examined for tephra; tephra concentration and LOI plots are shown in Fig.2. All tephra profiles show a rapidly declining tephra concentration with depth, the majority of tephra shards remaining within the uppermost cm of peat. Core 9-C also shows a pronounced secondary tephra peak at 5–6cm. The maximum depth of tephra penetration varies from 3cm in cores 9-A and 9-D to 4cm in core 9-B and 6cm in core 9-C. Both the maximum and the overall concentrations vary greatly between cores. Much the greatest concentrations are found in core 9-B and particularly core 9-C with substantially lower concentrations in cores 9-A and 9-D. LOI plots for cores 9-A and 9-D do not show any distinct relationship to tephra concentration. However, the LOI in the uppermost cm of cores 9-B and 9-C is markedly reduced.

Fig.3 shows the results from Plot 15 investigating the vertical movement of tephra through the study period. In common with Plot 9, all tephra profiles show a rapid decline with the highest concentrations in the uppermost centimetre and tephra shards penetrating to 3cm (cores 15-B, 15-D and 15-E) or 4cm (cores 15-A, 15-C). Tephra concentrations vary greatly between the cores. There is an apparent trend of increasing tephra concentration through the study period with gradually increasing values through the first four samples and a particularly dramatic increase to the final sample. There is no apparent relationship between tephra concentration and LOI for cores 15-A to 15-D, however LOI in the uppermost cm of plot 15-E (79.6%) is much the lowest of any core examined here.

In nine investigated cores the overwhelming majority of tephra shards were contained within the uppermost centimetre of peat. The maximum depth of tephra shard penetration varied from 3 to 6cm and averaged 3.6cm. The smaller tephra shards in Plot 9 generally penetrated further than the larger shards in Plot 15. In all cores tephra concentration showed a rapid decay with depth. Secondary peaks were noted in core 15-A and 9-C. The secondary peak in core 15-A only represents a single shard and is therefore unimportant, however the secondary peak in core 9-C represents more shards and appears noteworthy. The majority of LOI profiles do not appear to show any relationship to tephra concentration presumably as the increased concentration of inorganic material was too small to be detected above the background variability. However, the reduced values in the uppermost cm of cores 15-E, 9-B and 9-C may well represent the high tephra concentrations in these samples. The LOI values of around 95–97% in most of these samples are broadly typical of ombrotrophic peatlands.

Fig. 4 shows thin-section images from Plots 21 and 9. The Plot 9 thin-section shows a relatively compact peat matrix. The peat contains fine channels (generally <5mm diameter) many of which have a roughly vertical orientation; these are most obvious in the lower half of the thin section. The centre of the slide contains a prominent root structure, which is most likely *Calluna vulgaris*. Tephra shards in this core are concentrated in the upper portions of the peat. Ten clusters were identified; these are all located on the right-hand side of the slide and reach a maximum depth of 5mm below the surface.

The thin-section from Plot 21, a *Sphagnum*-dominated hollow, shows a notably more porous structure than Plot 9. A sub-vertical band of large interconnected pores occupies the centre of the thin section. The slide bisects some roots but does not contain the large root structures of Plot 9. Tephra shards are widely distributed in this thin-section. The greatest concentration of clusters occurs on the left-hand side of the slide, approximately 5–13mm below the surface of the thin-section. A further six clusters occur towards the right-hand side of the slide between 14 and 32mm below the surface. Three clusters occur in the lower half of the slide at around 52, 68 and 74mm. It is interesting to note that all these lower clusters occur close to the channel feature in the centre of the slide.

Discussion

The results for horizontal distribution of tephra do not provide any significant evidence of tephra

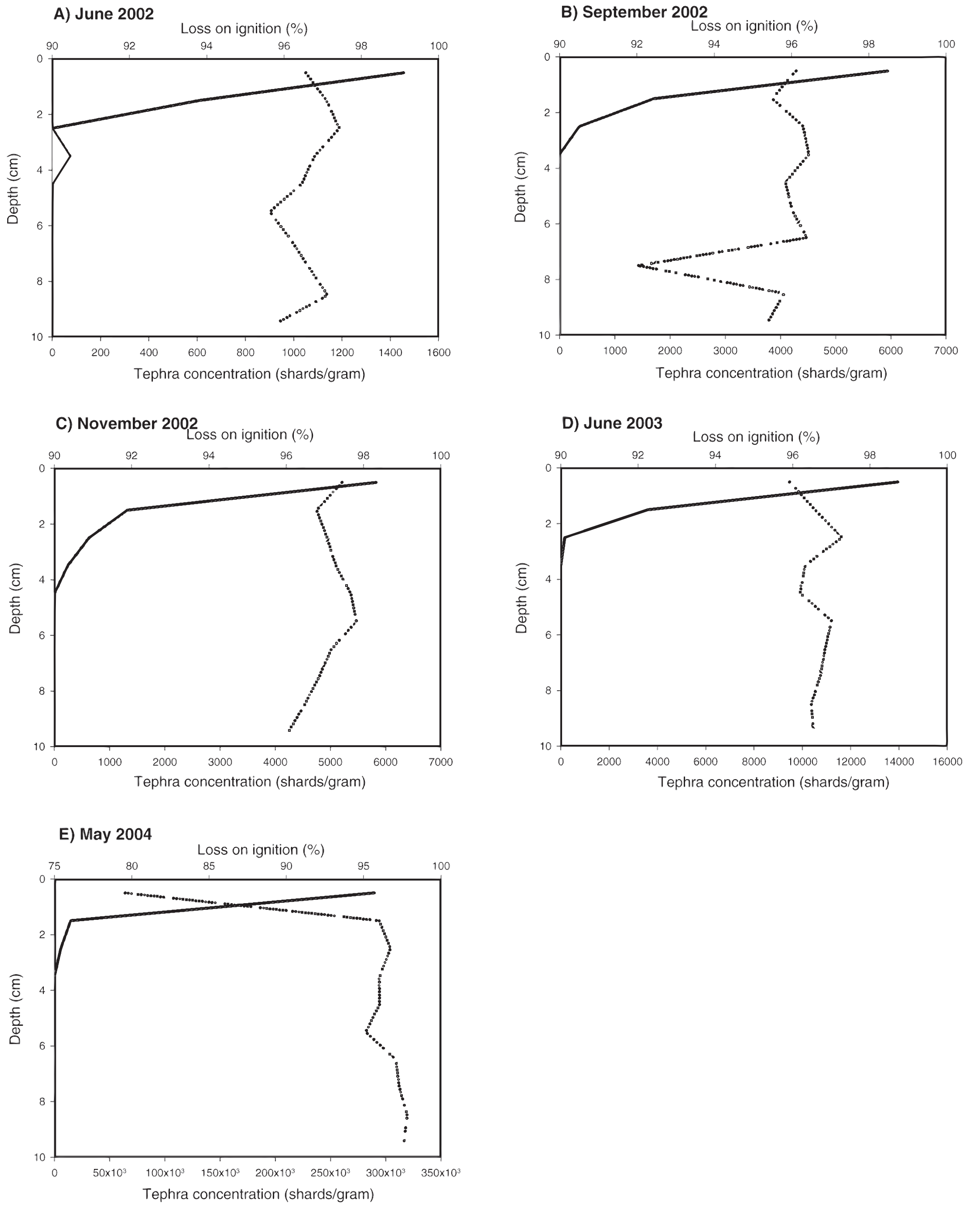

Fig. 3. Tephra concentration (solid line) and LOI profiles (dotted line) for Plot 15 at five intervals over the 24-month study period on a hummock site. Sampling is 1cm contiguous blocks; points are marked at the mid-point of their depth range. Note differences in scale between plots.

Kuva 3. Turpeen tuhkapitoisuus (partikkelia /gramma, kiinteä viiva) ja LOI profiili (hehkutushäviö, rasteriviiva) koealalla 15 mätäspinnalla. Näytteet on otettu viitenä eri ajankohtana 24 kk ajanjakson aikana turveprofiilista 1 cm välein. Huomaa kuvien erilainen mittakaava.

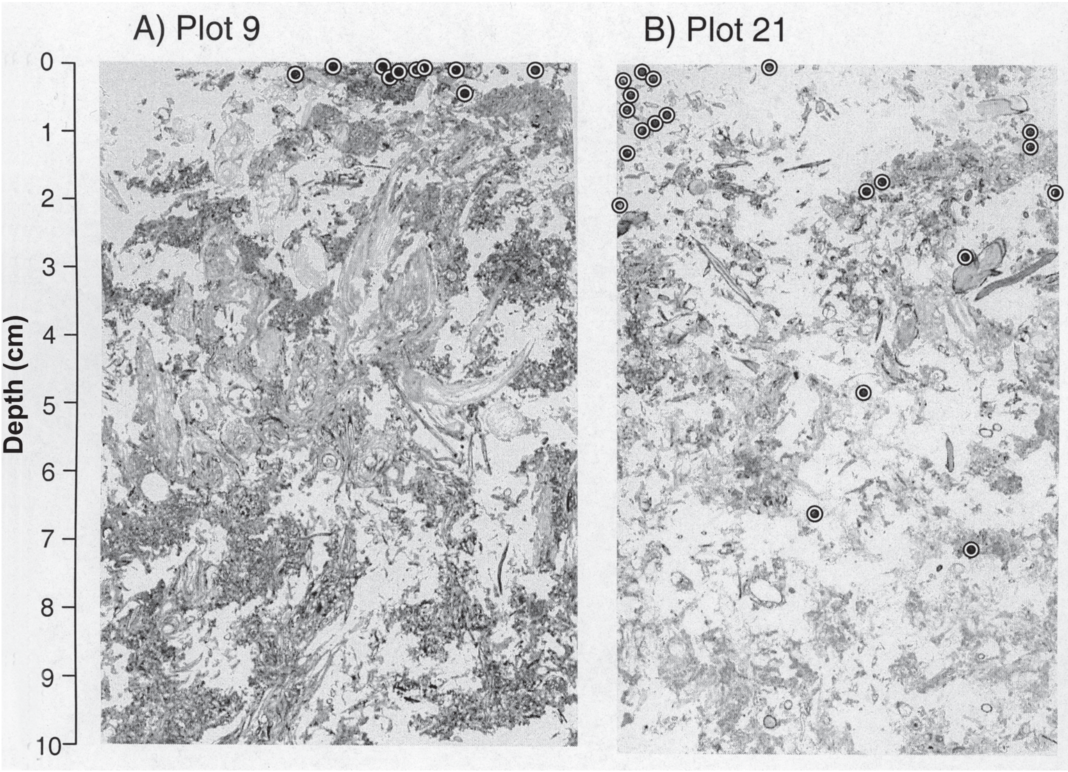

Fig. 4. Thin-sections from A) Plot 9 and B) Plot 21 showing location of tephra clusters. See text for notes on thin-section preparation and examination.

Kuva 4. Turveprofiilin ohutnäytteet koealalta 9 (A) ja koealalta 21(B), joihin merkitty tuhkarakeiden sijainti. Näytteiden valmistaminen esitetty tarkemmin tekstissä.

movement. Tephra shard concentrations are at their highest in the cores towards the centre of the plot (cores 9-B & 9-C) and lower in the peripheral cores (9-A & 9-D). The most likely explanation for this is unevenness in tephra application making any movement impossible to assess. During application, efforts were made to ensure even tephra application across the plot, however this is difficult to judge by eye and it is likely that areas at the centre of the plots received more. A further contributory factor may also be that tephra pathways through the overlying vegetation will serve to concentrate tephra in certain regions. These results provide no evidence for a horizontal movement of tephra towards the lower regions of the plot; concentrations are very similar in core B from a lower elevation point and core C from a higher elevation point.

The results from Plot 15 show an apparent trend of increasing tephra concentration through the two-year study period. Results from Plot 9 suggest an uneven distribution of tephra across this plot, so it is possible that this trend is purely coincidental. However the consistency of this increase suggests that this is unlikely; a more probable reason for the trend is that tephra moved from the overlying vegetation (which was not included in tephra preparations) into the upper peat during the course of the experiment. Although tephra concentration in the peat apparently increases through the study period, the tephra does not penetrate significantly further into the peat. The smaller tephra shards in Plot 9 penetrate further into the peat than the larger shards applied to Plot 15, presumably as the smaller shards can pass through smaller pores in the peat matrix and are less likely to be retained near the surface. This may suggest that tephra particle size can provide a further indication of the isochrone location, which may be particularly valuable where concentration profiles are complex. Further experiments would be required to investigate this.

The vertical distribution of tephra shown in these experiments would be reduced as peat accumulates and the tephra-containing peat is compressed on entering the catotelm. The large voids which occupy much of the thin-sections in these plots are absent from thin-sections taken from deeper peats, illustrating this compression (Payne et al. unpublished data).

The thin-section from Plot 9 is in general agreement with the pattern shown in the concentration plots. All tephra clusters located in this slide occur in the uppermost cm of peat. Given the smaller volume of material in the thin-section compared to the ashing preparations it is unsurprising that the 'tail' of declining tephra concentrations with depth is not represented in these results. The thin section sample from plot 21 shows a rather more complex pattern. In this thin section tephra penetrates significantly further into the peat, this has occurred over a very short period of time. The lowest shards recovered lie close to what appears to be a vertical channel; this is interesting as it suggests that such features may provide pathways through the peat. On the left side of the thin section, the greatest concentrations are in the uppermost cm, in keeping with results from other plots. However, on the right-hand side of the thin section, the greatest concentrations are somewhat below the surface, the reason for this difference is unclear. The greater tephra penetration in this slide is most likely due to the *Sphagnum*-dominated vegetation and more porous peat structure. Although it is possible that some distortion of tephra distribution has occurred during sample preparation, there is no indication that this has taken place.

By comparison to the results of Clymo and Mackay (1987), it appears that vertical movement of tephra through peat is probably no greater than that of pollen and possibly rather less. However, the differences in methodology and peat composition make an accurate comparison difficult. Due to the angular morphology and sharp edges of tephra shards it would seem reasonable to suppose that tephra is less liable to movement than generally sub-rounded pollen grains. Hall & Pilcher (2002) have suggested that tephra profiles may aid interpretation of other signals such as pollen. This may be true, however pollen and tephra particles cannot be assumed to react in the same way to environmental conditions. It seems likely that where a tephra profile is complex this may urge caution in interpretation of pollen signals, however a simple tephra profile cannot be taken as indication that pollen taphonomy is also simple.

Overall, the results provide generally good support for the use of tephrochronology in peatlands. In the majority of cores and plots, tephra remains in the uppermost centimetre of peat producing an isochrone which accurately represents the location of the peat surface at the time of tephra-deposition. However, some results are more complicated; core 9-C shows a secondary tephra peak and the thin-section of Plot 21 shows a complicated tephra distribution. The reasons for these complications are uncertain and will require further work.

This study highlights the importance of considering taphonomy in tephrochronological studies; tephra concentration profiles should always be constructed and where the profile deviates from an ideal unimodal distribution the isochrone should be treated with caution. This study has only used a limited number of experiments on a single site over a comparatively short period of time. Further experiments are necessary to improve our understanding of the dynamics of tephra taphonomy. Future studies should adopt an alternative approach to tephra application, should include vegetation in tephra preparations, investigate tephra movement in a greater variety of peat environments and could integrate experiments in more controlled laboratory conditions. Further studies using imaging techniques to investigate the micro-structure of palaeo-tephra layers may also prove valuable.

This study provides the first experimental evidence for the extent of post-depositional movement of tephra in peatlands. Results demonstrate that tephra movement is generally limited but that this may be dependent on the vegetation and peat structure at a locality.

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Tiivistelmä: Turvekerroksen ajoittaminen vulkaanisen tuhkan avulla

Tulivuoren purkaukset levittävät vulkaanista tuhkaa, joka turpeeseen kerrostuessaan muodostaa potentiaalisen mahdollisuuden arvioida turpeen ikää, kun purkauksen ajankohta tunnetaan. Tuhka voi kuitenkin liikkua turpeessa syvyyssuunnassa laskeutumisensa jälkeen ja siten aiheuttaa epävarmuutta turpeen ajoittamiseen. Tuhkan liikkuminen turpeessa on ollut kuitenkin heikosti tunnettua. Tässä tutkimuksessa suoritettiin kenttäkokeita eräällä Skotlantilaisella suolla tuhkan liikkuvuuden tutkimiseksi turpeessa. Kokeisiin sisältyi kolme koealaa, joilta tutkittiin tuhkan vertikaalista ja horisontaalista liikkuvuutta pintaturpeessa 24 kuukauden ajan sekä tuhkapartikkelien mikroskooppista vaihtelua. Turpeen tuhkapitoisuusprofiilit osoittivat, että valtaosa tuhkapartikkeleista jäi ylimpään senttimetrin paksuiseen turvekerrokseen ja syvimmilläänkin tuhkapartikkeleita vajosi 6 cm:n syvyyteen. Ohutleikenäytteistä tehdyt analyysit osoittivat, että tuhkan liikkuminen riippuu suuresti turpeen rakenteesta; varsinkin sen huokoisuudesta. Tutkimuksen perusteella vulkaanista tuhkaa voidaan melko luotettavasti käyttää turvekerroksen ajoittamiseen, mutta lisätutkimuksia tarvittaisiin, jotta voitaisiin sanoa miten hyvin menetelmä soveltuu käytettäväksi laajemmin mm. erityyppisissä turpeissa ja ympäristöolosuhteissa, joissa kerrostuminen on tapahtunut.

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