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Distal volcanic impacts on peatlands: Palaeoecological evidence from Alaska.

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ABSTRACT

Despite the fact that volcanic ash (tephra) layers are found preserved in peat deposits around the world, comparatively little research has investigated the impacts of distal volcanic emissions on peatlands. This study investigates the impacts of several late-Holocene volcanic eruptions on five peatlands in southern Alaska using a palaeoecological approach. Testate amoebae analysis, peat humification analysis and a basic analysis of plant macrofossil components were applied across 11 tephra layers. Changes in macrofossil and testate amoebae assemblages occur across several of the tephra layers. The humification results were unreliable because of a methodological problem, a finding which may have implications for other studies using this technique. Redundancy analyses on testate amoebae data show statistically significant changes associated with two tephras. The most likely causes of the impacts are volcanic gases, acidic precipitation or tephra-derived leachates. The finding that some tephras are associated with impacts whereas others are not may relate to the season of the eruption or meteorological conditions at the time of ash fall. These results suggest the sensitivity of peatlands and peatland microbial communities to distal volcanic products and imply that changes in key palaeoclimatic proxies may be caused by a mechanism independent of climate change. Implications of the results for peat-based palaeoclimatic studies are discussed, as are possible directions for future research.

KEYWORDS: peatlands, bogs, mires, volcanoes, volcanic impacts, tephra, crytotephras, palaeoecology, testate amoebae, humification, macrofossils.

Running title: Volcanic impacts on peatlands

INTRODUCTION

Ombrotrophic peatlands receive all their nutrients and moisture from the atmosphere. As such they are extremely sensitive to deposition of atmospheric pollutants. While there has been a large amount of work on the impact of anthropogenic pollutants on peatlands (e.g. Gorham et al. 1984, Proctor & Maltby 1998) there has been little investigation of the impact of natural pollutants. Peatlands are found in many mid- and high-latitude volcanic regions such as New Zealand, South America, the Asian North Pacific, and northwestern North America. Visible and microscopic tephra layers have been found preserved in peatlands around the world and illustrate the potential extent and frequency of volcanic impacts on peatlands (Zoltai 1988, Dugmore et al. 1995, St Seymour & Christanis 1995, Holmes et al. 1999, van den Bogaard & Schmincke 2002, Kilian et al. 2003, Hang et al. 2006, Gehrels et al. 2006). Volcanoes may be an important control on peatland functioning and development.

Volcanic impacts on peatlands: previous research

‘Neo’-ecological studies

Little neo-ecological research has addressed the potential impacts of volcanic products on peatlands. Griggs (1919) briefly noted the return of several species to an upland bog in southwest Alaska buried by tephra from the 1912 Katmai eruption, which covered a large number of peatlands (Rigg 1914). Perhaps significantly, Griggs' (1919) list did not include any *Sphagnum* species. Given this effective absence of direct ecological studies some authors have attempted experimental studies. Hotes et al. (2004) applied varying quantities of tephra and ground glass simulating tephra to plots on a mire in Hokkaido, Japan. Results showed substantial changes in pore water chemistry, with increases in pH, electrical conductivity, SiO_2, SO_4^{2-} and Na^+. Several changes in species composition were noticed with some species being lost, although many were later re-established. *Sphagnum* species were particularly affected with vascular plants increasing in relative abundance. Payne and Blackford (2005) applied small quantities of tephra and acids, both alone and in combination, to experimental plots on a bog in Scotland, with the aim of simulating products of the mid-Holocene Hekla-4 eruption. Impacts on plants were drastic at higher acid applications, but no impacts on peat humification or testate amoebae communities were apparent. Impacts on plant communities were still apparent in April 2008, almost six years after application. Impacts were only associated with acid application, plots with tephra applied alone showed no recorded changes. Gauci *et al.* (2005) applied Na_2SO_4 to a Scottish peatland over a period of 18 months at levels equivalent to the 1783 Laki eruption. Results showed a significant suppression of methane, although this effect was variable due to climate-driven changes in water table depth.

All these studies have limitations. The Hotes et al. (2004) experiment was limited by the use of non-volcanic glass in many of the plots and by the lack of consideration of chemicals adhering to tephra. The Payne & Blackford (2005) experiment was limited by uncertainty over the realism of the experimental scenario (Grattan & Gilbertson 1994). The Gauci et al. (2005) study did not apply tephra. All the studies monitored only a limited range of variables, but have shown enough to suggest the possibility of significant impacts on plant species composition, microbial communities and peat geochemistry.

Palaeoecological studies

Due to the inherent difficulties in direct ecological investigations of real volcanic impacts on peatlands and the uncertainty in experimental scenarios, an alternative approach is to use palaeoecological records. Due to the acidic and anoxic environment below the surface layers of peat, organic material does not fully decay and long sedimentary sequences are accumulated. Palaeoecological studies exploit this archive by analysis of the macrofossil plant remains, preserved organisms within the peat, or preserved particles such as pollen. Tephra layers are preserved within the peat and analysis of changes in the palaeoecological record across these layers provides an opportunity to investigate volcanic impacts (Blackford, 1997). The term ‘tephropalynology’ has recently been coined to refer to pollen studies across tephra layers (Newnham et al. 1998, Lowe and Hunt 2001, Edwards et al. 2004). A broader term ‘tephropalaeoecology’ may be appropriate to encompass studies based on other palaeoecological proxies.

Previous studies have shown impacts from proximal volcanic activity (Kuhry 1988) and large volcanic eruptions in the geological record (Crowley *et al*. 1994, Kovar-Eder *et al*. 2001). However, studies of distal volcanic impacts from Holocene eruptions have often shown variable evidence for impacts (Mehringer *et al*. 1977, Hotes *et al*. 2001, 2006). In New Zealand Giles *et al*. (1999) showed increases in degraded pollen and a particularly notable increase in *Leptospermum* pollen across the Holocene Kaharoa tephra. The most concerted study of volcanic impacts on peatlands has been in Britain and Ireland following the discovery of Icelandic cryptotephras (Dugmore 1989, Pilcher & Hall 1992, Dugmore *et al*. 1995) and suggestions of volcanic impacts from the Irish dendroclimatic record (Baillie & Munro 1988). Blackford *et al*. (1992) showed coincidence between a decline in *Pinus sylvestris* (scots pine) pollen and the mid-Holocene Hekla-4 cryptotephra in northern Scotland and suggested a causal relationship. Several other studies have found limited or no distinct changes associated with this and other Icelandic tephras (Bennett *et al*. 1992, Edwards *et al*. 1994, Hall *et al*. 1994, Charman *et al*. 1995, Caseldine *et al*. 1998, Hall 2003). In western Ireland Dwyer & Mitchell (1997) found that tephra layers were not associated with a regional vegetation change, but did find changes in several mire pollen types and the testate amoeba *Amphitrema flavum*, which they interpreted as a shift to wetter peat surface conditions. Where impacts have been noted some studies have suggested a climatic origin, but a direct impact on the mire system appears a more probable explanation (Birks 1994, Grattan *et al*. 1999).

Possible modes of volcanic impacts on peatlands

While previous research on volcanic impacts on peatlands has been limited, there is sufficient evidence to suggest that changes may occur. Several possible mechanisms can be suggested, based on studies of anthropogenic pollutants on peatlands and volcanic impacts on other ecosystems; these are outlined below.

1. **Indirect, climatic impact.** Volcanic eruptions produce large quantities of sulphurous gases which, following large explosive eruptions, combine with water to form sulphuric acid aerosols in the upper atmosphere. These aerosol particles are generally efficient scatterers but only weak absorbers of radiation at solar wavelengths leading to an increase in atmospheric albedo and tropospheric cooling. Large, sulphur-rich volcanic eruptions may cool the climate by a few tenths of a degree up to several degrees over a period of years (Self et al. 1981, Rampino & Self 1982, 1984, Scuderi 1990, McCormick *et al*. 1995, Zielinski 2000,

Gervais & MacDonald 2001). Changes in atmospheric circulation may also lead to changes in precipitation patterns. The surface wetness of ombrotrophic peatlands is directly linked to hydroclimate. Volcanic cooling may lead to reduced evapotranspiration and a wetter mire surface.

2. **Physical impact of tephra**. Distal tephra is primarily composed of sharp, angular shards of volcanic glass. Deposition of tephra may lead to abrasion of plant surfaces, inhibition of photosynthesis, blocking of stomata, increased reflectivity, inhibition of gas exchange between soil and atmosphere and crushing of plant tissues (Griggs 1922, Eggler 1948, Wilcox 1959, Cook *et al*. 1980, Bjarnason 1991, Clarkson & Clarkson 1994). Peatland plant communities may be particularly sensitive as plants are low-growing and include many bryophytes lacking a protective cuticle. Impacts on plants will have knock-on impacts on other aspects of the ecosystem.

3. **Impact on peatland hydrology.** A layer of tephra across the surface of a peatland might impact on the hydrology of the mire. Crowley *et al.* (1994) have suggested that deposition of thick tephra layers could lead to surface ponding while Hotes *et al.* (2004) have suggested that inclusion of tephra could lead to enhanced aeration of the upper layers of peat.

4. **Chemical impact of tephra and tephra leachates.** Although volcanic glass is generally preserved intact for thousands of years (Dugmore *et al*. 1992), elements may be released both on initial contact with water (cf. Wissmar *et al*. 1981) and through longer term leaching. Elements released by tephra leaching most commonly include Cl, S, Na, Ca, K, and Mg (Smith *et al*. 1983). Hodder *et al*. (1991) discussed evidence for enhanced Si, Fe, Mg and Ca in pore-waters adjacent to tephra layers preserved in peat and Hotes et al. (2004) noted detectable impacts on pore water chemistry from simulated tephra deposition. It is possible that tephra leachates might supply nutrients which are limiting in an oligotrophic ecosystem (such as K) or that tephra leachates may release elements that may be toxic to some organisms (such as Zn, Cu, Cd, Pb and Ba). Anthropogenic metal pollutants have been suggested to have caused damage to peatland bryophytes in northern England (Gorham *et al*. 1987).

5. **Volcanic gas and acids.** Volcanic eruptions release large quantities of gases into the atmosphere including CO_2, SO_2, HCl and HF (Wilcox 1959, Le Guern *et al*. 1988, Symonds *et al*. 1988, Delmelle *et al*. 2002). Volcanic compounds may be deposited as a gas, acidic precipitation, dry deposition, acidic aerosols and adhering to tephra particles (Rose 1977, Oskarsson 1980, Delmelle *et al*. 2001). Plants exposed to volcanic gases

may show signs varying from lesions and burnt spots to total defoliation and death (Parnell & Burke 1990, Clarkson & Clarkson 1994, Delmelle *et al*. 2002). Historical records following the 1783-4 Laki eruption in Iceland show the potential of volcanic gases to damage plants across a vast area (Thorarinsson 1981, Sigurdsson 1982, Camuffo & Enzi 1995, Grattan & Charman 1994, Grattan & Gilbertson 1994, Grattan & Pyatt 1994, Grattan *et al*. 1998, Thordarson & Self 2001). The sensitivity of bryophytes, and particularly *Sphagnum,* to acid deposition has been demonstrated in contemporary studies (Ferguson *et al*. 1978, 1980). Volcanic acid deposition could modify pH as the peat exchange complex is already strongly saturated by hydrogen ions so peatlands have little capacity for buffering inputs of acidity (Gorham *et al*. 1984). Acidification by anthropogenic acid rain has been widely noted (Proctor & Maltby 1998, Skiba *et al*. 1989, Sanger *et al*. 1994, Smith *et al*. 1993) but it is unclear whether a short-lived acid pulse would produce any lasting impacts. An increase in pH following deposition of volcanic products is also conceivable (Payne & Blackford 2005).

Aims of this study

This study adopts a palaeoecological approach to investigating potential volcanic impacts on peatlands, applying a broader range of palaeoecological techniques to a greater number of tephra layers than in previous studies.

Results are tested statistically to evaluate a volcanic impact explanation for observed changes. A multiple working hypothesis approach is used to investigate the potential cause of the impacts, based on the mechanisms described above.

SITES and METHODS

Sites and Fieldwork

Of the many areas of the world in which peatlands and volcanoes co-exist, the Pacific Northwest of North America, and specifically Alaska, was selected for this study because of the occurrence of numerous volcanoes (8% of the Earth's total) and the great abundance of undisturbed *Sphagnum* peatlands (45% of the state is classified as wetland). Peatlands were sampled in two general regions: the Kenai Peninsula of southcentral Alaska and the southeast Alaskan 'panhandle' around Juneau and Haines (Fig. 1). The Kenai Peninsula is comparatively close to a number of volcanoes, and several visible millimetre-scale tephra layers are present. Southeast Alaska is more remote from most Alaskan volcanoes and only cryptotephras, not visible in the field, are present (Payne and Blackford 2004, Payne et al. 2008). Peatlands were selected on the basis of maximum peat depth, lack of obvious anthropogenic disturbance and for ombrotrophy where possible. Two sites were cored in the Kenai Peninsula. **Moose Pass** is a small mire (c.100x100 m) lying in the base of a steep, glaciated valley in the northeastern Kenai Peninsula (60°30'N, 149° 26'W)(Fig. 1). **Sterling** is a large (c.200x300 m) kettle-hole peatland lying in the Kenai Lowlands at 60°31'N, 150° 31'W. Both mires are oligotrophic but may not be ombrotrophic. Three sites were also sampled in southeast Alaska. **Point Lena** is an ombrotrophic raised bog (c.300x200 m) lying between the Coast Mountains and the sea (Favourite Channel) near Juneau (58°23'N 134°44'W)(Dachnowski-Stokes 1941). **Eaglecrest** is a large (c.700x300 m) blanket mire in the valley of the Fish Creek, towards the northern end of Douglas Island (58°20'N 134°33'W). **Chilkoot Pond** is a small peatland on the isthmus of land dividing Lutak Inlet from Chilkoot Lake near Haines (59°19'N 135°33'W). The peat deposits at Chilkoot are adjacent to a large pond, and the lower peat deposits represent detrital material in-filling the pond. The vegetation of all five sites is broadly similar, including *Empetrum nigrum, Eriophorum* spp.*, Oxycoccus microcarpus, Cornus canadensis, Cladonia portentosa* and extensive *Sphagnum* carpets. Cores were extracted from the deepest areas of peat using a 50-mm bore Russian-pattern peat corer (Aaby & Digerfeldt 1986). Monolith blocks were cut out where the surface peat was too loose to allow coring.

Tephrostratigraphy

In the Kenai Peninsula sites tephras are visible to the naked eye, but in the cores from southeast Alaska only cryptotephras are present. Cryptotephra layers were identified by ashing and microscopy (Pilcher & Hall 1992). The glass geochemistry of all tephras was studied using electron probe microanalysis (EPMA); the findings of this work have been described previously (Payne 2005, Payne & Blackford 2004, 2008, Payne et al. 2008). The probable tephra sources are shown in Table 1. Concentration profiles for cryptotephras were constructed by adding a *Lycopodium* innoculum to allow a quantitative estimate of glass shard concentrations (Caseldine *et al*. 1998). For the visible tephra layers, shards were highly numerous and concentration profiles were approximated by calculating loss-on-ignition values across the tephras. Tephras of unknown age were either dated directly by radiocarbon or using previously derived age-depth models (Payne 2005).

The palaeoecological record

The palaeoecological record across the tephras was investigated at high resolution using either 5 mm or 10 mm-depth contiguous samples. Age-depth models for the sites suggest these samples represent between approximately 8 and 50 years of peat accumulation (Table 1). Cores were frozen to allow precise sub-sampling at high resolution. Three methods were applied: testate amoebae analysis, humification analysis and a basic plant macrofossil analysis. All three methods are standard techniques widely used in peatland palaeoclimate studies but may also be sensitive to different aspects of volcanic impacts on peatlands.

Peat humification was measured across tephras using the standard alkali-extraction and colorimetry method (Overbeck 1947, Aaby & Tauber 1975, Blackford & Chambers 1993). Peat humification is a measure of the degree of decomposition of peat, with more humified peats being more amorphous and darker in colour (Clymo 1983). In terms of volcanic impact, humification measurement may reflect any impacts on peatland hydrology and plant decomposition processes. The colorimetry method attempts to extract humic and other acids, which are products of the decomposition process. The darker the colour of the alkali extract, the higher the concentration of humic acids and the more humified the peat is considered to be. Recent studies have shown that the organic acids extracted are actually mostly lower weight fulvic acids, amino acids and polysaccharides rather than the humic acids conventionally assumed and a further concern is the extent to which these substances may be extracted from differing plant species (Caseldine et al. 2000, Yeloff & Mauquoy 2006). Humification was analysed using a method based on Blackford & Chambers (1993). Sub-samples (0.1g) of dried, ground peat were heated with 8% NaOH for an hour. Samples were diluted, filtered through Whatman 'Qualitative 1' filter paper and allowed to stand. Transmission was measured at 540 nm after four hours from initial mixing. The remaining dried peat was incinerated at 550° C to calculate loss-on-ignition (LOI). Transmission readings were corrected for LOI using the formula Hc=Hr/(1/LOI) where Hc is the corrected humification value, Hr is the measured transmission value and LOI is loss on ignition expressed as a proportion (Blackford & Chambers 1993).

Testate amoebae analysis was applied across all the tephra layers. Testate amoebae are unicellular micro-organisms (protists) which are abundant in peatlands and often found in palaeoecological studies (Charman, 2001). Testate amoebae communities are primarily controlled by hydrology with pH and nutrient state as secondary controls (Mitchell *et al*. 1999, Charman *et al*. 2001, Payne *et al*. 2006). In terms of volcanic impacts, testate amoebae were selected to show any impacts on the peatland microbial community, changing pH, and changes in water table depth. Samples were prepared using the standard water-based method of Hendon & Charman (1997). 1 cm^3 peat sub-samples were boiled in water for approximately 10 minutes, sieved at 300 μm to remove the coarse fraction and then back-filtered at 15 μm to remove fine, highly degraded organic particles. The resulting material was centrifuged at 3000 RPM for five minutes to concentrate the tests and slides prepared by mixing the remaining material with glycerol. Slides were examined at 400 X magnification and tests identified using a range of taxonomic literature (Deflandre 1929, 1936, Grospietsch 1964, Ogden & Hedley 1980, Ogden 1983, Luftenegger *et al*. 1988, Charman *et al*. 2000, Clarke 2003). The test-forming bdelloid rotifer *Habrotrocha angusticollis* was also counted and included in percentage calculations. The taxonomic scheme closely followed that employed by Payne *et al*. (2006).

Quantitative reconstruction of pH and depth to water table (DWT) changes was carried out using a transfer function derived from surface samples of southern Alaskan peatlands (Payne *et al*. 2006). The optimum two-component WA-PLS transfer function was used with boot-strapped error estimates calculated for each sample using 1000 cycles. The reconstructed values are termed testate amoebae-inferred pH (TI-pH) and testate amoebae-inferred depth to water table (TI-DWT).

An outline macrofossil analysis of the major peat components was undertaken to show any major impact of volcanic activity on the peat forming plant communities. Methods followed the first stage of the quadrat and leaf count (QLC) methodology of Barber *et al*. (1994). The >300 µm component of peat remaining from testate amoebae analysis was further cleaned using a jet of water, placed in a petri dish and examined at 50 X magnification. Peat components were separated into five categories: *Sphagnum* (including all *Sphagnum* and other bryophyte material), monocotyledons, Ericales (also including all shrub and woody remains), unidentifiable organic matter (UOM) and other material which cannot be easily assigned to other classes such as seeds and insect remains. A 10X10 mm grid was placed under the sample and the number of squares in which each of these components occurred was counted. This process was repeated four times for each sample and the mean calculated.

Data analysis

Most studies of tephra-impacts in the palaeoecological record have assessed impacts solely by qualitative inspection of the data. Here, we employ a quantitative hypothesis-testing approach using constrained ordination with an explanatory variable designed to simulate a volcanic impact (Lotter & Birks 1993, Eastwood *et al*. 2002). Previous studies have adopted two distinct approaches to modelling volcanic impacts. Initially Lotter & Birks (1993) modelled the volcanic impact as an exponential decay process from an arbitrarily defined value at the tephra layer. This approach has the disadvantage that the volcanic impact model is purely a conceptual construct with no empirical basis. More recently Barker (2000) and Eastwood *et al*. (2002) used the tephra concentration profile as the explanatory variable. Although this may seem the superior approach because it is based on real data, it is not applicable here. Tephra concentration profiles in peatlands represent not only the initial deposition phase, but also the post-depositional movement of tephra with downwards gravitational movement of tephra particles through the peat and upward translocation, most likely due to movement of tephra with plant growth or a rising water table (Payne et al. 2005). The tephra concentration profile has no direct relationship with the pattern and timing of volcanic impacts on the mire. Therefore in this study the approach employed is based on a conceptual model of volcanic impact, similar to that used by Lotter & Birks (1993). The model used here assumes that a volcanic event will be represented by a large impact at the time of tephra deposition, decreasing with time thereafter. In addition, it assumes that there will be some overall difference between conditions before and after the event. The explanatory variable (termed ‘Volcanic’) therefore consists of two components: an exponential decay model and a simple before (0) and after (1) nominal variable. The exponential decay function is identical to that used by Lotter & Birks (1993) and is defined as exp $x^{-\alpha t}$ where α is the decay constant, here given a value of 0.5 and t is sample time (in this case substituted by depth) after the tephra peak. The variable is assigned a value of 0 prior to the tephra peak and then a value of 100 at the tephra peak sample. Varying the initial value and the rate of decay makes little difference to the results obtained. For the data across layer ST 24, the tephra peak was taken to be the lower of the two LOI troughs. For the MP 27 data, the missing sample containing the tephra peak was excluded from the analysis and the tephra peak taken to be the sample directly above.

Ordination analyses were undertaken using redundancy analysis (RDA), the constrained form of principal components analysis (PCA), the most appropriate approach given the short compositional gradients (<1.4 standard deviations). Monte Carlo permutation tests (999 permutations) were used to provide a test of the null hypothesis that the species and explanatory data are unrelated and to provide an estimate of the significance level of any relationships. Humification and macrofossil results were partialled out to eliminate possible complications from testate amoebae vegetation preferences and test decomposition processes. Depth was also partialled out as a surrogate for time, to separate the affect of pre-existing environmental change, primarily longer-term climatic change.

In addition to the ordination analyses two other, more basic approaches were also tested. The sequences were zoned using several techniques (CONSLINK, CONISS, SPLITLSQ and SPLITINF) in ZONE v.1.2 (Juggins 1992). If the first division of assemblage data coincides with the position of the tephra then a significant change at the time of deposition may be suggested.

Analysis of similarity (ANOSIM) was used to test for a significant difference between testate amoebae communities above and below the tephra. The analysis was carried out using PAST ver 1.71 (Hammer et al. 2001) with a Bray-Curtis distance measure and 10,000 permutations. The sample including the tephra peak was excluded from the analysis. High values of the test statistic (R_{ANOSIM}) (approaching 1) indicate the samples within a group are more similar to each other than to any samples from another group.

RESULTS

Palaeoenvironmental analyses are discussed below for 11 tephra horizons from Moose Pass (MP 10, MP 27, MP 39), Sterling (ST 12, ST 24 and ST 36), Eaglecrest (ECR 100 and ECR 162), Point Lena (LNA 39 and LNA 100) and Chilkoot Pond (CHP 33) peatlands.

Macrofossil analysis

The evidence for impacts on the macrofossil record is variable between sites and proxies. Although some changes are subtle, others are relatively distinct (Fig. 2). Across tephras LNA 39 and MP 27 there is an increase in *Sphagnum*. This is the beginning of a sustained increase in LNA 39 and a short phase in MP 27. Across tephras ECR 162 and ST 12 there is a peak in UOM coincident with the tephra peak and in ST 12 this is accompanied by a distinctive peak of monocotyledons. Peaks in UOM were also seen noted coincident with three other southeast Alaskan tephra layers (Payne, 2005). While it is possible that increases in both UOM and *Sphagnum* could be related to tephra deposition, the evidence for an increase in UOM is more convincing. Profiles show peaks in UOM which are exactly coincident with tephra deposition, and which are of high magnitude. A further six sites show little evidence of any macrofossil changes coincident with the tephra (CHP 33, LNA 100, ECR 100, MP 10, MP 39 and ST 36). Across tephra ST 24 there is an increase in *Sphagnum* and decrease in monocotyledons, but these changes occur below the tephra peak.

Humification

The plots of transmission values across cryptotephras show that the glass concentration peak generally coincides with a trough in transmission values and is followed by increasing values (Fig. 2). In three of the plots this post-tephra increase in values is either minor or short-lived (CHP 33, ECR 162 LNA 100), but in two (ECR 100 and LNA 39) the increase marks the start of a prolonged trend. Correcting for loss on ignition makes little difference to the trends.

All the plots of transmission data across visible tephra layers (MP 10, MP 27, MP 39, ST 12, ST 24 and ST 36) show notable increases in raw transmission data but significant decreases in corrected transmission (Fig. 2). Increased raw transmission values are expected because of the relative reduction in quantity of organic material in the sample. Corrected values show transmission values decreased by over 20% in some sites; these are very substantial changes and should be easily visible with the naked eye. However, no such visible change can be seen in these samples, indicating that this pattern is an artefact of the methodology used rather than a genuine result. The correction factor applied to the raw data is derived from experiments conducted by Blackford & Chambers (1993) and usually makes minimal difference to the results when LOI values are high and mineral content therefore low. The large disparity between measured and corrected transmission values here suggests some aspect of humification measurement or correction is not working as it should where LOI values are low. The humification results are thus considered unreliable. This issue is discussed further below.

Testate amoebae

Impacts on testate amoebae are variable. Although some profiles show convincing evidence for major change coincident with tephra deposition, other profiles show little or no evidence (Fig. 3). Qualitatively there appear to be changes coincident with the tephra in several of the profiles- most distinctly in ECR 162, ECR 100, LNA 100 and ST 12. The ANOSIM results show significant pre- and post-tephra differences in all but two of the profiles (Table 2). R_{ANOSIM} values are moderately high, and highly significant for some profiles. However these findings do not provide unequivocal evidence for volcanic impact because the method does not account for antecedent trends. The zonation analysis results (Table 3) show that all techniques indicate a zone boundary adjacent to the tephra layer in four of the profiles: ECR 162, ECR 100, LNA 100 and ST 12. Using the RDA methodology and the strictest test- partialling out macrofossil data, humification and depth, the 'volcanic' variable explains a significant proportion of variance in two profiles: ST 12 and LNA 100 (Table 4).

In the data from ST 12 the most notable changes are a significant drop in abundance of *Amphitrema flavum* and a loss of *Hyalosphenia papilio* at the tephra peak. In LNA 100, *Amphitrema flavum* abundance declines below the tephra layer but is actually increasing at the position of the tephra peak. The most distinct changes at this site are a loss of *Difflugia pulex* and increases in *Amphitrema stenostoma* and *Amphitrema wrightianum*. Qualitative data inspection and zonation analysis also suggest changes in the ECR 162 and ECR 100 profiles. In ECR 100 this change is characterised by a loss of *A. flavum* and *H. papilio* and increases in *Difflugia tuberculata* and *Phryganella acropodia*. In

ECR 162 the data show a loss of *A. flavum* and increases in *Bullinularia indica* and *Heleopera sphagni*. Results from these four profiles show little similarity in response. In ST 12 and ECR 100 there is a distinct loss of *H. papilio*, but in LNA 100 there is an apparent increase. In three of the profiles there is a loss of *A. flavum*, however in LNA 100 percentages are actually increasing by the point of the tephra peak. ECR 162 shows a large increase in *B. indica*, however, in LNA 100 there is a slight decline in this taxon. Overall, none of the major taxa show a consistent response to tephra deposition in these four profiles. Table 5 shows changes in several major taxa across the tephra layer in all the analysed peat profiles. Changes are qualitatively assessed as an increase, decrease, no change or that the taxon is not sufficiently abundant to make a judgment. There is little consistency in these changes. For instance, *A.flavum* is judged to increase in abundance across three tephras and decrease in abundance across three others. On the strength of the evidence presented in this table, the most consistent impacts are on *A. catinus*, which increases in abundance across all four tephras in which a distinct change is noted. Equally, *P. acropodia* also increases across all tephras where a change is noted; however, some of these changes are indistinct.

There is no convincing evidence that certain testate amoebae species are particularly affected by volcanic impacts. Although several species show major changes coincident with tephra deposition these are generally not replicated between profiles. This lack of replication suggests that changes are not due to direct toxicity of volcanic products on some species. Instead it seems probable that changes are due to a volcanically-forced environmental change affecting profiles differently, depending on their pre-existing state.

To investigate the possible mechanism of these changes, the species data have been quantitatively interpreted using transfer functions for two environmental variables: DWT and pH. Initially, considering the four profiles in which impacts seem most distinct (LNA 100, ST 12, ECR 100 and ECR 162), there is little consistency in response. In terms of TI-DWT, the tephra peak coincides with minor peaks in ECR 162 and ST 12, a minor trough in ECR 100, and a declining trend in LNA 100. In terms of TI-pH, the tephra peak coincides with a peak in LNA 100, a minor peak in ECR 100, an increasing trend in ST 12, and little change or a minor trough in ECR 162. These results demonstrate an inconsistent response. Many of the apparent changes do not exceed the bootstrapped error estimates for the reconstructed values. One of the few consistent changes to exceed the error estimates is a general increase in TI-pH in ST 12. However, this trend starts from the base of the profile and cannot be attributed solely to a volcanic impact. A similar inconsistent TI-DWT and TI-pH response is also seen in the other profiles.

Overall, the testate amoebae results show evidence for a volcanic impact in some profiles but not in others. The apparent testate amoebae response to a volcanic impact appears to vary between tephras and does not produce a characteristic response in terms of species changes or TI-DWT and TI-pH. The lack of a consistent increase or decrease in inferred pH or DWT coincident with the tephra layer suggests that if the changes are volcanic in origin they are not due to the changing pH or surface moisture.

Consistency between proxies

Both macrofossils and testate amoebae (although most probably not humification) show evidence for changes coincident with tephra layers in some sites. Testate amoebae analysis is the most quantitative method used here. Our results suggest that impacts are most distinct for profiles ST 12 and LNA 100, and may also be present for ECR 100 and ECR 162 although the evidence is weaker. Macrofossil results show a distinct change across the ST 12 tephra with a peak in monocotyledons and UOM. Macrofossil data across ECR 162 also show a peak in UOM at the time of deposition of the tephra. No distinct macrofossil change is noted in LNA 100 and in ECR 100 a major macrofossil change is offset from the tephra peak by 2 cm. The macrofossil results show the best evidence for changes coincident with tephra deposition in profiles ECR 162, ST 12 and MP 27. In two of these, testate amoebae changes were also noted (ECR 162 and ST 12). In profile MP 27 there is only limited evidence for testate amoebae change coincident with the tephra peak. In many cases impacts shown with one proxy-record are not necessarily shown by the other.

DISCUSSION

Is there evidence for a volcanic impact?

The palaeoecological results provide some evidence for changes coincident with the deposition of the tephra layers, but these changes are not present in all profiles. Evidence is most convincing for the two profiles in which the volcanic impact model described a significant proportion of the variance in the testate amoebae data. These results show that not only is change occurring but also that this change is consistent with what would be expected as a response to a volcanic impact. A study of this nature can never exclude the possibility that changes may occur coincident with a volcanic eruption but have an independent cause. However, the possibility of a sufficiently large non-volcanic ‘event’ coinciding so exactly with an eruption must be very small. The results show that in some profiles and with some proxies there are changes coincident with tephra deposition that appear likely to have a volcanic cause. However, these changes were not found across all tephra layers and where they are found with one proxy-record they are not always found in the other.

Causes of the impact

Several working hypotheses to explain any apparent impacts were outlined in the introduction. The changes noted in the palaeoecological record can now be evaluated against each of these hypotheses.

1. **Indirect, climatic impact.** Volcanic gases and aerosols might lead to climatic cooling and a consequent increase in mire surface wetness which might be detectable here as a decrease in TI-DWT, increase in transmission, and increase in *Sphagnum* if sufficiently long-lived. The evidence here does not support this hypothesis. There is no replicated change in TI-DWT or the macrofossil record consistent with an increase in surface wetness.

2. **Physical impact of tephra deposition.** Tephra deposition might affect plant functioning, perhaps leading to a shift from bryophytes to monocotyledons. Possible impacts on testate amoebae or humification are unclear. The palaeoecological record does show an increase in monocotyledons in some profiles (most noticeable in ST 12), but not in others. Physical impacts seem unlikely given the low concentrations of tephra in the southeast Alaskan sites.

3. **Impact on peatland hydrology.** It is possible that tephra deposition might lead to a shift to either wetter or drier mire surface conditions. Although there is some evidence of a shift to drier-indicating macrofossil

components there is no replicated change in TI-DWT coincident with tephra deposition.

4. **Chemical impact of tephra and tephra-derived leachates.** The deposition of tephra might supply elements that could be either toxic or limiting nutrients. Supply of nutrients might increase the abundance of more nutrient-demanding species of plant and amoebae; increasing the abundance of monocotyledons relative to *Sphagnum* and perhaps increasing UOM abundance if decomposition was enhanced. The macrofossil data could conceivably be explained by changes in the nutrient supply although there is no obvious shift to testate amoebae taxa typical of more nutrient-rich conditions.

5. **Volcanic gas and acids.** Volcanic gas and acids might damage peatland plants perhaps leading to an increase in monocotyledons and UOM relative to bryophytes. The macrofossil data do provide some support for this suggestion. The impacts on testate amoebae are harder to predict. A change in microbial community due to sulphate deposition (Gauci et al. 2005) might lead to changes in the food source of some amoebae species. It is conceivable that these changes in the microbial food web could explain the testate amoebae response. Volcanic acid deposition could also lead to a change in peatland pH but the results here do not show a consistent change in TI-pH.

Taken overall, the palaeoecological evidence allows us to rule out the climatic and hydrological impact hypotheses, and the physical impact of tephra also appears unlikely. The chemical impact of tephra and the impact of volcanic gases and acids cannot be as easily ruled out and provide the most likely explanation for the apparent impacts observed in some profiles.

Reasons for differential response

These results show a variable response to tephra deposition. In some sites and with some tephra layers impacts appear quite distinct; however, in other locations no impacts are evident by these methods. There are several possible factors which could have contributed to these differing results.

One important factor might be the volume of an eruption. Larger-volume eruptions will produce more tephra which may travel further and which may have more adsorbed acids and other compounds. The results provide some indication that this may be an important factor. Of the four greatest apparent impacts (ECR 162, ECR 100, LNA 100 and ST 12), several tephras are from notably large-volume eruptions. The White River eruption, which formed the LNA 100 tephra, probably the Aniakchak eruption which formed the ECR 162 tephra, and perhaps the eruption of Augustine which is the most likely source of the ECR 100 tephra, may all be large-volume eruptions. However there is no evidence to suggest that the eruption that formed the ST 12 tephra was of particularly large magnitude, and apparent impacts of this tephra are significant. Therefore the role of eruption size is uncertain.

A second potentially important factor is the magnitude of the tephra layer as represented by the thickness of the visible layer or glass shard concentration (Table 1). Thicker tephra layers are likely to have greater impacts on peatlands in terms of tephra leachates and greater physical impacts. Of the tephras associated with greatest impacts here, however, there is no clear affect of tephra layer magnitude. The thicker visible tephras in south-central Alaska are not associated with greater apparent impacts than the cryptotephras in southeast Alaska. It therefore seems unlikely that this factor is critical.

A further important factor is the distance of the site from the source eruption. At greater distances, tephra may have more adsorbed volatiles (Rose 1977, Oskarsson 1980, Smith et al. 1993). Therefore, distal tephras could be associated with greater impacts than proximal layers regardless of the size of the layer. While some of the greatest apparent impacts are associated with tephras at great distance (e.g. ECR 162), impacts of the proximal ST 12 tephra also appear considerable.

It is also possible that impacts may be dependent on the season of an eruption. Modern studies of distal volcanic impacts have shown that plants are generally less sensitive to eruptions outside the growing season (Zobel & Antos 1997, Hotes et al. 2004). In winter, plants will be senescent and higher rainfall may serve to rapidly remove volcanic pollutants. Impacts may be particularly dependent on snow cover. Snow will stop volcanic products coming into direct contact with the peat surface. In spring snowmelt, volcanic products contained in the snow will be heavily diluted and may be removed by surface water flow. The sites in this study are snow-covered for much of the year; meteorological data show an average of around five months annual snow cover at Juneau and Haines and six months at Kenai. It is therefore possible that snow cover is a significant cause of differential impacts. This factor is difficult to quantify because there is very limited evidence for the season of ancient eruptions. An exception to this is the White River Ash (Eastern Lobe), which is correlated with the LNA 100 layer in this study. West & Donaldson (2002) presented geomorphological evidence that this tephra was produced in late autumn or very early winter. If the impacts of winter eruptions are reduced, impacts across LNA 100 should be minimal but this is actually one of the two tephras associated with the most conclusive impacts. However, West & Donaldson (2002) worked on sites that are both further north and at higher elevation than Point Lena and it is therefore conceivable that Point Lena could still have been unfrozen and snow-free at the time of the White River Ash eruption.

Tephra impacts may also be related to the nature of the site. Any one or more of site vegetation, hydrology and nutrient status could affect impacts. However, there is no clear evidence that the nature of the site is a significant factor. The most distinct apparent impacts were on the Point Lena and Sterling sites. These peatlands are quite different: Point Lena is an ombrotrophic raised bog whereas Sterling is a kettle-hole peatland. Different tephras deposited on the same peatland can have a quite different scale of impacts. Although ST 12 is associated with impacts, two other tephras of similar thickness (ST 24 and ST 36) in the Sterling profile are not. This result suggests that the variability of impacts is more likely to be due to some other factor and is not closely related to the nature of the site.

A further important factor may be the atmospheric conditions at the time of eruption. Analogues with anthropogenic air pollutants show the potential for prevailing meteorological conditions to lead to highly localised deposition of acidic pollutants (Davies et al. 1984). The interaction of meteorological conditions and topography could have led to localized heavy deposition of volcanic acids at some sites. The impacts of the same eruption at a similar distance could therefore have differed greatly through a region. This hypothesis could provide an explanation for the different apparent impacts but is difficult to evaluate directly, especially as for most tephras we do not have duplicate data from different sites.

In addition to these reasons why different tephras in different sites may or may not be associated with detectable impacts there are several methodological issues which may have led to impacts not being identified in this study. The most significant of these is sampling resolution. The sites studied here represent a range of peatland types and experience different climatic conditions. The peatlands therefore have different peat accumulation rates and these accumulation rates have changed through the Holocene as the mires have developed. The period of time represented by the sub-samples varies from approximately 8 to 50 years. It is therefore possible that the lack of detectable volcanic impacts in some of these sites is simply because the sampling resolution is insufficiently high. However, the two tephras which are associated with the most distinct impacts (ST 12 and LNA 100) are not the sites with the highest sampling resolution. Low resolution may account for the failure to detect more distinct impacts in the Eaglecrest site which has a relatively low accumulation rate but cannot explain the differences within the other sites. An additional complication is the possibility that accumulation rates may have varied in response to volcanic impacts (Caseldine et al. 1998, Blackford and Payne, unpublished data).

Another complication is the complexity of some shard concentration profiles. In two of the sites (LNA 39 and ST 24) the tephra profile was multimodal and it was difficult to determine where the isochron should be located. In another site (MP 27) the tephra layer itself precluded counting testate amoebae from a critical sample. These problems may hinder the ability to accurately identify any relationship between the tephra peak and palaeoecological change.

The above discussions have assumed that a volcanic impact will be represented starting coincident with or directly above the tephra layer, but this may not be the case. Firstly, location of the isochron may be complicated by post-depositional movement of tephra through the peat. Experimental work suggests that it is unlikely for the tephra *peak* to move (Payne et al. 2005) but the possibility cannot be totally excluded. Secondly, it is possible that a response to volcanic impacts may be lagged behind the event, although there is no obvious mechanism to support this. A final possibility is for a change in the palaeoecological record to start below the position of the tephra layer because amoebae may be alive some distance below the surface (Heal 1962, Corbett 1973) and can respond rapidly to environmental change (Lousier 1974, Clarke 2003). Although these mechanisms are possible, there is no convincing evidence that they have occurred in this study. In the sites in which distinct impacts were noted such impacts take place directly coincident with the tephra layer. In other profiles there are rarely any major changes either just below or just above the tephra layer.

Although methodological issues may have led to some problems in identifying impacts in some sites it does seem clear that there are real differences in the magnitude of impacts between sites and tephras. The most likely mechanisms determining why some tephras produce detectable impacts and others do not would seem to be the meteorological conditions at the time of eruption and the season of eruption.

Problems with the humification technique

The humification results discussed above appear to be unreliable across visible tephra layers. Readings that would normally represent significant, visible colour shifts in the peat stratigraphy were obtained across almost homogeneous core sections where tephras were present. A possible explanation is that some tephra particles were small enough to pass through the filter paper used in preparing the alkaline extract, and thereby reduced light transmission values. The filter paper used retains particles greater than 11 μm diameter, but particle-size analysis showed a significant proportion of tephra particles were smaller than this size (Payne & Blackford 2008). To test this hypothesis, humification was re-measured across one of the tephra layers using a higher standard of filtration. The ST36 tephra was selected, humification was measured as described previously but using double quantities (100 ml) of NaOH, so results are not directly comparable to those presented previously. Samples were filtered using the standard method (Whatman qualitative 1 filter paper), using a finer filter paper that retains particles greater than 8 μm diameter (Whatman 40) and using centrifugation (15 minutes at 4000 RPM). The pattern of transmission with the standard method shows the same trends as measured previously (Fig. 4). With centrifugation values were increased by 1-2%, particularly towards the centre of the sequence and with the finer filter paper values were elevated by up to 5%, although this was variable over the sequence (Fig. 4). The elevated values in the centrifuged and finer-filtered samples strongly suggest that tephra particles penetrated the filter paper used in the standard method. When the transmission values with the finer filter paper are corrected for LOI, the large drop in corrected values present with the normal filter was eliminated (Fig. 4).

The tephra layers in southeast Alaska are much smaller and correction for LOI makes very little difference to the values. However, in common with the humification profiles across the visible tephra layers, most of the profiles across the cryptotephra layers also show reduced transmission values coincident with the tephra peaks, consistent with an affect of tephra penetrating the filter paper. Although tephra shards are less abundant in these cryptotephra layers, the particle size is smaller, and so a greater proportion of particles may pass through the filter paper. In some profiles there are humification changes which are not consistent with tephra penetrating the filter paper. However, these changes are the exception- in the majority of profiles the most distinct change is reduced transmission coincident with the tephra peak. Several previous studies have measured humification across tephra layers using this methodology (e.g. Caseldine et al. 1998, Langdon & Barber 2004, Ellershaw 2004). The results shown here suggest that reduced transmission values coincident with tephra layers might be due to this methodological problem rather than a palaeoenvironmental change.

Volcanic impacts on peatlands: wider implications

This study provides evidence that volcanoes have the potential to affect distant peatlands. Apparent impacts can be detected in records of past microbial communities and, probably, past plant communities. The mechanism of these impacts is not certain but may relate to deposition of volcanic acids and other compounds adhering to tephra particles. The scale of impacts is variable between tephras; such variability may be due to the season of the eruption and the meteorological conditions prevalent at that time. While ecological experimentation can indicate the *potential* for volcanic eruptions to affect peatlands (Hotes *et al.* 2004, Payne et al. 2005), direct observations or palaeoecological studies are required to show that this actually takes place. This study provides the most intensive palaeoecological investigation of distal volcanic impacts on peatlands and the results have several implications for peatlands and the wider environment.

Perhaps the most significant possible implications relate to the volcano-climate system. Sulphate additions to peatlands have been shown to suppress methanogenesis (Gauci and Dise 2002). It is possible that deposition of volcanogenic sulphate on peatlands could suppress methane emissions, potentially reducing the atmospheric concentrations of an important greenhouse gas and reinforcing volcanic induced cooling (Stevenson *et al.* 2003, Gauci *et al.* 2005). This study provides the first direct evidence for the ability of distal volcanic eruptions to affect peatland microbial communities at a higher trophic level. Although it is not clear how testate amoebae changes might relate to changes in sulphate reducing bacteria and methanogenic archea, the results show microbial community changes associated with tephra deposition even at very distal locations. This process could have significant implications for the volcano-climate system.

Peatlands constitute a large resource of biodiversity including many species that are specially adapted to the unique physical environment of peatlands. Volcanic impacts could potentially have significant implications for many rare species. If impacts are as severe as implied by some ecological work

(Payne et al. 2005) then large impacts on sensitive plant populations could result. Knock-on impacts on insects and vertebrates are also possible which may have implications for populations of these species. Volcanic impacts might also have implications for human exploitation of peatlands such as peatland arboriculture, cranberry, or *Sphagnum* cultivation.

Implications for peatland palaeoclimatology

The results detailed here have important implications for peatland palaeoecology. Changes across tephra layers suggest changes in key proxy-climate records potentially can be caused by a mechanism independent of climatic change. It is possible that such changes could be mistaken for a short-term climatic change. Studies are increasingly using tephra layers to correlate sequences in different sites (e.g. Landon & Barber 2004, van den Bogaard *et al*. 2002) and therefore possibly risk mistaking volcanic impacts for simultaneous environmental changes between sites. While there is no particular indication that this is the case in the existing studies it is essential that the possibility be evaluated. Tephra cannot be automatically assumed to be an inert marker in a palaeoecological sequence. A search for visible tephra layers and cryptotephas should be undertaken routinely in palaeoecological studies from areas within a zone of potential tephra deposition.

Future research directions

Further research is required in a number of areas. As well as replicating this work in other field areas and with other tephras, studies could also take a variety of different approaches. Palaeoecological studies could employ a wider variety of proxies (chironomids, oribatid mites, diatoms, pollen and spores), geochemical analyses of peat, dendrological records from peatlands. A high as possible sampling resolution is likely to be essential to identify short-lived impacts. Modern ecological studies could attempt to monitor the after-effects of a real volcanic eruption. In regions such as Alaska and Kamchatka small- to medium-scale volcanic events are relatively frequent and peatlands are numerous so opportunities for studies of this type arrive with comparative regularity. The difficulty with this approach is the lack of baseline, pre-eruption data. Because of this problem, and the requirement to study responses to a broad range of scenarios, experimental studies are also valuable. Previous studies of this type are limited by their experimental scenarios; future studies should liase with volcanologists and tephrochronologists to establish the most likely scenarios for past and future volcanic impacts. Future studies should also attempt to investigate a wider range of variables including changes to gas flux, microbial communities, porewater chemistry and measures of plant health and abundance.

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REFERENCES

Aaby B., Digerfeldt G. 1986. Sampling techniques for lakes and bogs. In: Berglund B. (Ed.), Handbook of Holocene palaeoecology and palaeohydrology. Wiley, Chichester, UK.

Aaby B., Tauber H. 1975. Rates of peat formation in relation to degree of humification and local environment, as shown by studies of a raised bog in Denmark. Boreas. 4, 1-15.

Baillie M., Munro M. 1988. Irish tree rings, Santorini and volcanic dust veils. Nature. 332, 344-346.

Barber K. E., Chambers F. M., Maddy D., Stoneman R., Brew J.S. 1994. A sensitive high-resolution record of late Holocene climatic change from a raised bog in northern England. The Holocene. 4, 198-205.

Barker P., Telford R., Merdaci O., Williamson D., Taieb M., Vincens A., Gibert E. 2000. The sensitivity of a Tanzanian crater lake to catastrophic tephra input and four Millennia of climate change. The Holocene. 10, 303-10.

Begét J. E., Stihler S. D., Stone D. B. 1994. A 500-year-long record of tephra falls from Redoubt volcano and other volcanoes in upper Cook Inlet, Alaska. Journal of Volcanology and Geothermal Research. 62, 55-67.

Bennett K., Boreham S., Sharp M., Switsur V. 1992. Holocene history of environment, vegetation and human settlement on Catta Ness, Lunnasting, Shetland. Journal of Ecology. 80, 241-273.

Birks H. J. B. 1994. Did Icelandic volcanic eruptions influence the post-glacial vegetational history of the British Isles? Trends in Evolution and Ecology. 9, 312-314.

Bjarnason Á. H. 1991. Vegetation on lava fields in the Hekla area, Iceland. Acta Phytogeographica Suecica 77. University of Uppsala. Sweden.

Blackford J., Chambers F. 1993. Determining the degree of peat decomposition for peat-based palaeoclimatic studies. International Peat Journal. 5, 7-24.

Blackford J., Edwards K., Dugmore A., Cook G., Buckland, P. 1992. Icelandic volcanic ash and mid-Holocene Scots pine (Pinus sylvestris) pollen decline in northern Scotland. The Holocene. 2, 260-265.

Blackford, J., 1997. Volcanic Ash in Peat. In: Parkyn, L., Stoneman, R., Ingram, H.A.P. (Eds.) .Conserving Peatlands: Proceedings of the International Peatlands Conference. CAB International, Oxford, UK pp. 74-81.

Caseldine C., Hatton J., Huber U., Chiverrell R., Woolley N. 1998. Assessing the impact of volcanic activity on mid-Holocene climate in Ireland: the need for replicate data. The Holocene. 8, 105-111.

Caseldine C. J., Baker A., Charman D. J., Hendon D. 2000. A comparative study of optical properties of NaOH peat extracts: implications for humication studies. The Holocene. 10, 649-658.

Charman D.J., West S., Kelly A., Grattan J. 1995. Environmental change and tephra deposition: the Strath of Kildonan, Northern Scotland. Journal of Archaeological Science. 22, 799-809.

Charman D., Hendon D., Woodland W. 2000. The Identification of testate amoebae (protozoa: rhizopoda) from British oligotrophic peats. Quaternary Research Association Technical Guide Series. Cambridge, UK.

Charman, D. 2001. Biostratigraphic and palaeoenvironmental applications of testate amoebae. Quaternary Science Reviews. 20, 1753-1764.

Clague J. J., Evans S. G., Rampton V. N., Woodsworth G.J. 1995. Improved age estimates for the White River and Bridge River tephras, western Canada. Canadian Journal of Earth Sciences. 32, 1172-1179.

Clarke K. J. 2003. Guide to the Identification of Soil Protozoa – Testate Amoebae. Special publication 12. Freshwater Biological Association, Ambleside, UK.

Clarkson B. D., Clarkson B. R. 1994. Vegetation decline following recent eruptions on White Island (Whakaari), Bay of Plenty, New Zealand. New Zealand Journal of Botany. 32, 21-36.

Clymo R. 1983. Peat. In: Gore, A. (Ed.) Ecosystems of the World. 5A. Mires:Swamp, Bog, Fen and Moor. Elsevier, Amsterdam, The Netherlands.

Cook R., Barron J., Papendick R., Williams G. 1980. Impact on agriculture of the Mount St. Helens eruptions. Science. 211, 16-22.

Corbett S.A. 1973. An illustrated introduction to the Testate Rhizopods in Sphagnum, with special reference to the area around Malham Tarn, Yorkshire. Field Studies. 3, 801-838.

Crowley S., Dufek D., Stanton R., Ryer T. 1994. The effects of volcanic ash deposition on a peat-forming environment: Environmental disruption and taphonomic consequences. Palaios. 9, 158-174.

Dachnowski-Stokes A. 1941. Peat resources in Alaska. US. Department of Agriculture Technical Bulletin. 769, 1-84.

Davies T. D., Abrahams P. W., Trander M., Blackwood, I., Bimlecombe P., Vincent C.E. 1984. Black acidic snow in the remote Scottish Highlands. Nature. 312, 58-61.

Deflandres G. 1929. Le genre Centropyxis STEIN. Archiv fur Protistenkunde. 67, 322-375

Deflandre G. 1936. Etude monographique sur le genre Nebela Leidy (Rhizopoda-Testaceae). Annales de Protistologie. 5, 201-285.

Delmelle P., Stix J., Bourque C., Baxter P., Garcia-Alvarez J., Barquero J. 2001. Dry deposition and heavy acid loading in the vicinity of Masaya volcano, a major sulfur and chlorine source in Nicaragua. Environmental Science & Technology. 35, 1289-1293.

Delmelle P., Stix J., Baxter P., Garcia-Alvarez J., Barguero J. 2002. Atmospheric dispersion, environmental effects and potential health hazard associated with the low-altitude gas plume of Masaya volcano, Nicaragua. Bulletin of Volcanology. 64, 423-434.

Dugmore A. 1989. Icelandic volcanic ash in Scotland. Scottish Geographical Magazine. 105, 168-172.

Dugmore A., Larsen G., Newton A., Sugden D. 1992. Geochemical stability of fine-grained silicic Holocene tephra in Iceland and Scotland. Journal of Quaternary Science. 7, 173-183.

Dugmore A., Larsen G. & Newton A. 1995. Seven tephra isochrones in Scotland. The Holocene. 5, 257-266.

Dwyer R. B., Mitchell F. J. G. 1997. Investigation of the environmental impact of remote volcanic activity on north Mayo, Ireland, during the mid-Holocene. The Holocene. 7, 113-118.

Eastwood W., Tibby J., Roberts N., Birks H., Lamb H. 2002. The environmental impact of the Minoan eruption of Santorini (Thera): statistical analysis of palaeoecological data from Gölhisar, southwest Turkey. The Holocene. 12, 431-44.

Edwards K. J., Buckland P. C., Blackford J. J., Dugmore A. J., Sadler J. P. 1994. The impact of tephra: Proximal and distal studies of Icelandic eruptions, In: Stötter, J., Wilhelm, F. (Eds.), Environmental change in Iceland. Műnchener Geographische Abhandlungen Reihe B. Band. B12, 79-99.

Edwards K. J., Dugmore A. J., Blackford, J. J. 2004. Vegetational response to tephra deposition and land-use change in Iceland: a modern analogue and multiple working hypothesis approach to tephropalynology. Polar Record. 40, 113-120.

Eggler W. A. 1948 Plant communities in the vicinity of the volcano El Paricutin, Mexico, after two and a half years of eruption. Ecology. 29, 415-436.

Ellershaw M. 2004. Holocene climate change in the North Atlantic region: evidence from peat deposits. Unpublished PhD thesis. University of London. London. UK.

Ferguson P., Lee J., Bell J. 1978. Effects of sulphur pollutants on the growth of Sphagnum species. Environmental Pollution. 16, 151-162.

Ferguson P., Lee J. A. 1980. Some effects of bisulphate and sulphate on the growth of Sphagnum species in the field. Environmental Pollution. 21, 59-71.

Gauci V., Dise N. 2002. Controls on suppression of methane flux from a peat bog subjected to simulated acid rain sulfate deposition. Global Biogeochemical Cycles. 16, 1-11.

Gauci V., Dise N., Blake S. 2005. Long-term suppression of wetland methane flux following a pulse of simulated acid rain. Geophysical Research Letters. 32, L12804.

Gehrels M. J., Lowe D. J., Hazell Z., Newnham R. M. 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.

Gervais B., MacDonald G. 2001. Tree-ring and summer-temperature response to volcanic aerosol forcing at the northern tree-line, Kola Peninsula, Russia. The Holocene. 11, 499-505.

Giles T., Newnham R., Lowe D., Munro A. 1999. Impact of tephra fall and environmental change: a 1000 year record from Matakana Island, Bay of Plenty, North Island, New Zealand. In Firth, C., McGuire, W. (Eds.) Volcanoes in the Quaternary. Geological Society, London, UK.

Gorham E., Bayley S., Schindler D. 1984. Ecological effects of acid deposition upon peatlands: A neglected field in acid rain research. Canadian Journal of Fisheries and Aquatic Sciences. 41, 1256-1268.

Gorham E., Lee J. A., Anderson J., Bayley S. E., Clymo R. S., Havas M., Jeglum, J., Norton S. A., Schindler D. W., Urban N.R. 1987. Group summary report: Wetlands. In: Hutchinson, T. C., Meema, K. M. (Eds.), Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems. NATO ASI Series Vol.G16. Springer-Verlag, Berlin, Germany.

Grattan J., Charman D. 1994. Non-climatic factors and the environmental impact of volcanic volatiles: implications of the Laki fissure eruption of AD1783. The Holocene. 4, 101-106.

Grattan J., Gilbertson D. 1994. Acid-loading from Icelandic tephra falling on acidified ecosystems as a key to understanding archaeological and environmental stress in northern and western Britain. Journal of Archaeological Science. 21, 851-859.

Grattan J., Pyatt F. 1994. Acid damage to vegetation following the Laki fissure eruption in 1783- an historical review. The Science of the Total Environment. 151, 241-247.

Grattan J., Brayshay M., Sadler J. 1998. Modelling the distal impacts of past volcanic gas emissions. Quaternaire. 9, 25-35.

Grattan J., Gilbertson D., Charman D. 1999. Modelling the impact of Icelandic volcanic eruptions upon prehistoric societies and environment of northern and western Britain. In: Firth, C., McGuire, W. (Eds.), Volcanoes in the Quaternary. Geological Society, London, UK.

Griggs R. 1919. The character of the eruption as indicated by its effects on nearby vegetation. Ohio Journal of Science. 19, 173-209.

Griggs R. 1922. The Valley of Ten Thousand Smokes. National Geographic Society, Washington D.C., USA.

Grospietsch T. 1964. Monographische studie der gattung Hyalosphenia stein. Eingegangen. 26, 211-241.

Hall VA. 2003. Assessing the impact of Icelandic volcanism on vegetation systems in the north of Ireland in the fifth and sixth millennia BC. The Holocene. 13, 131-138.

Hall V., Pilcher J., McCormac F. 1994. Icelandic volcanic ash and the mid-Holocene Scots pine (Pinus sylvestris) decline in the north of Ireland: no correlation. The Holocene. 4, 79-83.

Hammer Ø., Harper D.A.T., Ryan P.D. 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica. 4. http://palaeo-electronica.org/2001_1/past/issue1_01.htm.

Hang T., Wastegård S., Veski S., Heinsalu A. 2006. First discovery of cryptotephra in Holocene peat deposits of Estonia, eastern Baltic. Boreas. 35, 644-649.

Heal O. 1962. The abundance and micro-distribution of testate amoebae (Rhizopoda:Testacea) in Sphagnum. Oikos. 13, 35-47.

Hendon D., Charman D. 1997. The preparation of testate amoebae (Protozoa: Rhizopoda) samples from peat. The Holocene. 7, 199-205.

Hodder A. P. W., De Lange P.J., Lowe D.J. 1991. Dissolution and depletion of ferromagnesian minerals from Holocene tephra layers in an acid bog, New Zealand, and implications for tephra correlation. Journal of Quaternary Science. 6, 195-208.

Holmes J., Hall V., Wilson P. 1999. Volcanoes and peat bogs. Geology Today. 15, 60-63.

Hotes S., Poschlod P., Sakai H., Inoue T. 2001. Vegetation, hydrology, and development of a coastal mire in Hokkaido, Japan, affected by flooding and tephra deposition. Canadian Journal of Botany. 79, 341-361.

Hotes S., Poschlod P., Takahashi H., Grootjans A.P., Adema E. 2004. Effects of tephra deposition on mire vegetation: a field experiment in Hokkaido, Japan. Journal of Ecology. 92, 624-634.

Hotes S., Poshcold P., Takahashi H. 2006. Effects of volcanic activity on mire development: case studies from Hokkaido, northern Japan. The Holocene. 16, 561-573.

Juggins S. 1992. The ZONE program, version 1.2. University of Newcastle. Newcastle Upon Tyne. UK.

Juggins S. 2003. C2 user guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle Upon Tyne. UK.

Kilian R., Hohner M., Biester H., Wallrabe-Adams H. J., Stern C. R. 2003. Holocene peat and lake sediment tephra record from the southernmost Chilean Andes (53-55 deg S). Revista Geologica de Chile. 30, 23-37.

Kovar-Eder J., Haas M., Hofmann C-C., Meller B. 2001. An early Miocene plant assemblage severely influenced by a volcanic eruption, Styria, Austria. Palaeontology. 44, 575-600.

Kuhry P. 1988. A palaeobotanical and palynological study of Holocene peat from the El Bosque mire, located in a volcanic area of the Cordillera Central of Colombia. Review of Palaeobotany and Palynology. 55, 19-72.

Langdon P. G., Barber K. E. 2004. Snapshots in time: precise correlations of peat based proxy climate records in Scotland using mid-Holocene tephras. The Holocene. 14, 21-33.

Lerbekmo J. F., Campbell F. A. 1969. Distribution, composition and source of the White River Ash, Yukon Territory. Canadian Journal of Earth Sciences. 6, 109-116.

LeGuern F., Faivre-Pierret R. X., Garrec J. P. 1988. Atmospheric contribution of volcanic sulphur vapor and its influence on the surrounding vegetation. Journal of Volcanology and Geothermal Research. 35, 173-178.

Lotter A., Birks H. 1993. The impact of the Laacher See tephra on terrestrial and aquatic ecosystems in the Black Forest, southern Germany. Journal of Quaternary Science. 8, 263-276.

Lousier J.D. 1974. Response of soil testacea to soil moisture fluctuations. Soil Biology and Biochemistry. 6, 235-239.

Lowe D. J., Hunt J. B. 2001. A summary of terminology used in tephra-related studies. In: Juvigné, E. T., Raynal, J-P. (Eds.), Tephras: Chronology, Archaeology. CDERAD éditeur, Goudet. Les Dossiers de l'Archéo-Logis. 1, 17-22.

Luftenegger G., Petz W., Berger H., Foissner W., Adams H. 1988. Morphological and biometric characterization of twenty-four soil testate amoebae (Protozoa, Rhizopoda). Archiv fur Protistenkunde. 136, 153-189.

McCormick M. P., Thomason L. W., Trepte C. R. 1995. Atmospheric effects of the Mt Pinatubo eruption. Nature. 373, 399-404.

Mehringer P. J.Jr., Arno S. F., Petersen K. L. 1977. Postglacial history of Lost Trail Pass Bog, Bitterroot Mountains, Montana. Arctic and Alpine Research. 9, 345-368.

Newnham R.M., Lowe D.J., Matthews B. 1998. A late-Holocene and prehistoric record of environmental change from Lake Waikaremoana, New Zealand. The Holocene. 8, 443-454.

Ogden C.G. 1983. Observations on the systematics of the genus Difflugia in Britain (Rhizopoda, Protozoa). Bulletin of the British Museum of Natural History (Zoology). 44, 1-73.

Ogden C. G., Hedley R. H. 1980. An atlas of freshwater testate amoebae. British Museum (Natural History) and Oxford University Press, London and Oxford, UK.

Oskarsson N. 1980. The interaction between volcanic gases and tephra: flourine adhering to tephra of the 1970 Hekla eruption. Journal of Volcanology and Geothermal Research. 8, 251-266.

Overbeck F. 1947. Studien zur hochmoorentwicklung in Nierdersachen und die Bestimmung der humifizierung bei stratigaphisch-pollenanalytischen mooruntersuchunsen. Planta. 35, 1-56.

Parnell R., Burke K. 1990. Impacts of acid emissions from Nevado del Ruiz volcano, Colombia, on selected terrestrial and aquatic ecosystems. Journal of Volcanology and Geothermal Research. 42, 69-88.

Payne R. 2005. Peatlands, volcanoes and climate: Ecological and palaeoecological studies in Alaska and Scotland. Unpublished PhD thesis. University of London. London. UK.

Payne R. J., Blackford J. J. 2004. Distal tephra deposits in southeast Alaskan peatlands. In: Emond D., Lewis L. (Eds.), Yukon Exploration & Geology 2003. Yukon Geological Survey, Whitehorse, Canada.

Payne R. J., Blackford J. J. 2005. Simulating the impacts of distal volcanic products upon peatlands in northern Britain: an experimental study on the Moss of Achnacree, Scotland. Journal of Archaeological Science. 32, 989-1001.

Payne R., Blackford J. 2008. Extending the late Holocene tephrochronology of the Kenai Peninsula, Alaska. Arctic.

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

Payne R., Kishaba K., Blackford J., Mitchell E. 2006. The ecology of testate amoebae in southcentral Alaskan peatlands: Building transfer function models for palaeoenvironmental inference. The Holocene. 16, 403-414.

Payne R., Blackford J., van der Plicht J. 2008. Using microtephras to extend regional tephrochronologies: An example from southeast Alaska and implications for hazard assessment. Quaternary Research.

Pilcher J., Hall V. 1992. Towards a tephrochronology for the Holocene of the north of Ireland. The Holocene. 2, 255-259.

Proctor M., Maltby E. 1998. Relations between acid atmospheric deposition and the surface pH of some ombrotrophic bogs in Britain. Journal of Ecology. 86, 329-340.

Rampino M., Self S. 1982. Historic eruptions of Tambora (1815), Krakatau (1883) and Agung (1963), their stratospheric aerosols and climatic impact. Quaternary Research. 18, 127-143.

Rampino M., Self S. 1984. Sulphur-rich volcanic eruptions and stratospheric aerosols. Nature. 310, 677-679.

Rigg G. 1914. Notes on the flora of some Alaskan Sphagnum bogs. The Plant World. 17, 167-182.

Rose W. I. 1977. Scavenging of volcanic aerosol by ash: atmospheric and volcanological implications. Geology. 5, 621-624.

Scuderi L. 1990. Tree-ring evidence for climatically effective volcanic eruptions. Quaternary Research. 34, 67-85.

Self S., Rampino M., Barbera J. 1981. The possible effects of large 19th and 20th century volcanic eruptions on zonal and hemispheric surface temperatures. Journal of Volcanology and Geothermal Research. 11, 41-60.

Sigurdsson H. 1982. Volcanic pollution and climate: The 1783 Laki eruption. Eos, Transactions of the American Geophysical Union. 63, 601-603.

Skiba U., Cresser M., Derwent R., Futty D. 1989. Peat acidification in Scotland. Nature. 337, 68-69.

Smith D. B., Zielinski R. A., Taylor H. E., Sawyer M. B. 1983. Leaching characteristics of ash from the May 18, 1980, eruption of Mount St. Helens volcano, Washington. Bulletin of Volcanology. 46, 103-124.

Smith C., Cresser M., Mitchell D. 1993. Sensitivity to acid deposition of dystrophic peat in Great Britain. Ambio. 22, 22-26.

Stevenson D. S., Johnson C. E., Highwood E. J., Gauci V., Collins W.J., Derwent R. G. 2003. Atmospheric impact of the 1783-1784 Laki Eruption: Part 1

Chemistry modelling. Atmospheric Chemistry and Physics Discussions. 3, 551-596.

St. Seymour K., Christanis K. 1995. Correlation of a Tephra Layer in Western Greece with a Late Pleistocene Eruption in the Campanian Province of Italy. Quaternary Research. 43, 46-54.

Symonds R., Rose W., Reed M. 1988. Contribution of Cl^- and F^- bearing gases to the atmosphere by volcanoes. Nature. 334, 415-418.

Thorarinsson S. 1981. Greetings from Iceland: Ash-falls and volcanic aerosols in Scandinavia. Geografiska Annaler. 63A, 109-118.

Thordarson T., Self S. 2001. Real-time observations of the Laki sulfuric aerosol cloud in Europe during 1783 as documented by Professor S. P. van Swinden at Franeker, Holland. Jökull. 50, 65-72.

Van den Bogaard C., Dörfler W., Glos R., Nadeau M.-J., Grootes P.M., Erlenkeuser H. 2002. Two tephra layers bracketing Late Holocene paleoecological changes in northern Germany. Quaternary Research. 57, 314-324.

Van den Bogaard C., Schmincke H-U. 2002. Linking the North Atlantic to central Europe: a high-resolution tephrochronological record from northern Germany. Journal of Quaternary Science. 17, 13-20.

West K. D., Donaldson J. A. 2002. Resedimentation of the late Holocene White River tephra, Yukon Territory and Alaska. In: Emond D. S., Weston L. H., Lewis L.L. (Eds.), Yukon Exploration and Geology 2001. Yukon Geological Survey. Whitehorse. Canada.

Wilcox R. 1959. Some effects of recent ash falls with especial reference to Alaska. Ohio Journal of Science. 49, 409-475.

Wissmar R. C., Devol A. H., Nevissi A. E., Sedell J. R. 1981. Chemical changes of lakes within the Mount St Helens blast zone. Science. 19, 175-178.

Yeloff D., Mauquoy D. 2006. The influence of vegetation composition on peat humification: implications for palaeoclimatic studies. Boreas. 35, 662-673.

Zielinski G. 2000. Use of paleo-records in determining variability within the volcanism-climate system. Quaternary Science Reviews. 19, 417-438.

Zobel D., Antos J. 1997. A decade of recovery of understorey vegetation buried by volcanic tephra from Mount St Helens. Ecological Monographs. 67, 317-344.

Zoltai S. 1988. Late Quaternary volcanic ash in the peatlands of central Alberta. Canadian Journal of Earth Science. 26, 207-214.

FIGURES and TABLES

Table 1. Details of tephra layers included in this study.

Tephra	**Probable source**	**Approximate age**	**Dating method**	**Visible or cryptotephra**	**Size of layer (Maximum shard concentration or thickness)**	**Palaeoecological sampling resolution**	**Further Details**
CHP 33	Mt. Churchill (Lena Tephra)	280-320 cal. BP	Radiocarbon	Cryptotephra	Maximum concentration c. 6.6 x10^5 shards g^{-1} dm	10 mm (c. 8 years)	Payne & Blackford (2004), Payne et al. (in press)
ECR 100	Possibly Augustine Volcano	c. 2840 cal.BP	Age-depth model	Cryptotephra	Maximum concentration c. 5.1 x10^4 shards g^{-1} dm	10 mm (c. 28 years)	Payne & Blackford (2004), Payne et al. (in press)
ECR 162	Aniakchak	5300-5030 cal. BP	Radiocarbon	Cryptotephra	Maximum concentration c. 2.2 x10^4 shards g^{-1} dm	10 mm (c. 50 years)	Payne & Blackford (2004), Payne et al. (in press)
LNA 39	Mt. Churchill (Lena Tephra)	280-320 cal. BP	Radiocarbon, correlation with CHP 33	Cryptotephra	Maximum concentration c. 2.9 x10^5 shards g^{-1} dm	10 mm (c. 8 years)	Payne & Blackford (2004), Payne et al. (in press)
LNA 100	Mt. Churchill (White River Ash)	1375-1290BP	Radiocarbon	Cryptotephra	Maximum concentration c. 6.7 x10^6 shards g^{-1} dm	10 mm (c. 17 years)	Payne et al. (in press), Clague et al. (1995), Lerbekmo &

							Campbell (1969)
ST 12	Possible Augustine Volcano	c. 250 cal. BP	Age-depth model	Visible tephra	2 mm thick layer	5 mm (c. 12 years)	Payne & Blackford (in press)
ST 24	Uncertain	c.500 cal. BP	Age-depth model	Visible tephra	5 mm thick layer	5 mm (c. 12 years)	Payne & Blackford (in press)
ST 36	Uncertain	c. 760 cal. BP	Age-depth model	Visible tephra	4 mm thick layer	5 mm (c. 12 years)	Payne & Blackford (in press)
MP 10	Augustine Volcano	AD 1883	Historical records	Visible tephra	10 mm thick layer	10 mm (c. 12 years)	Payne & Blackford (in press), Begét et al. (1994)
MP 27	Crater Peak- Mt. Spurr	c.300 cal. BP	Age-depth model and correlation to Begét et al. (1994)	Visible tephra	7 mm thick layer	10 mm (c. 12 years)	Payne & Blackford (in press), Begét et al. (1994)
MP 39	Crater Peak- Mt. Spurr	c.430 cal. BP	Age-depth model	Visible tephra	4 mm thick layer	10 mm (c. 12 years)	Payne & Blackford (in press)

Table 2. Results of ANOSIM comparing testate amoebae communities below and above the tephra-peak. Showing R_{ANOSIM} and P-values (ns= not significant at $P<0.05$).

Tephra	**R_{ANOSIM}**
CHP 33	0.43 ($P<0.05$)
ECR 100	0.54 ($P<0.05$)
ECR 162	0.67 ($P<0.0005$)
LNA 39	ns
LNA 100	0.68 ($P<0.01$)
ST 12	0.50 ($P<0.0001$)
ST 24	0.63 ($P<0.005$)
ST 36	0.52 ($P<0.005$)
MP 10	0.33 ($P<0.05$)
MP 27	ns
MP 39	0.51 ($P<0.01$)

Table 3. Zonation analysis of testate amoebae data across tephra layers using four methods (see text and Gordon & Birks 1972 for details). Zone boundaries highlighted in bold lie immediately adjacent to the tephra peak. Samples are labelled as depth of upper surface therefore a division of 30-31 lies between the samples from 30-31cm and 31-32cm.

	CHP33	ECR100	ECR162	LNA39	LNA100	ST12	ST24	ST36	MP10	MP27[1]	MP39
CONSLINK[2]	-	-	-	-	-	-	-	32.5-33	12-13	-	41-42
CONISS	30-31	**99-100**	**162-163**	43-44	**100-101**	**12-12.5**	23-23.5	32.5-33	11-12	23-24	41-42
SPLITLSQ	35-36	**99-100**	**162-163**	34-35	**100-101**	**12-12.5**	24.5-25	32.5-33	11-12	**26-28**	40-41
SPLITINF	**32-33**	**99-100**	**162-163**	35-36	**100-101**	**12-12.5**	24.5-25	32.5-33	11-12	23-24	40-41

[1] For the MP27 tephra no testate amoebae data were obtained from the 27-28 cm sample. This sample was therefore excluded from analysis.

[2] For many of the sequences CONSLINK did not give a single, most significant zone boundary.

Table 4. Results of RDA and variance partitioning exercise for testate amoebae data. Results are shown as percentage variance explained by each combination of explanatory variables and co-variables. Only significant correlations (P<0.05) are shown.

Source of variance	Explanatory variables	Covariables	CHP 33	ECR 100	ECR 162	LNA 39	LNA 100	ST 12	ST 24	ST 36	MP 10	MP 27	MP 39
Volcanic impacts	'Volcanic'	_	47 (P<0.05)				64 (P<0.05)	33 (P<0.05)	34 (P<0.05)				
Volcanic impacts independent of plant and humification change	'Volcanic'	Humification, macrofossils			30 (P<0.05)		27 (P<0.01)	26 (P<0.05)					
Volcanic impacts independent of plant, humification change and time	'Volcanic'	Humification, macrofossils, Depth					16 (P<0.005)	15 (P<0.05)					

Table 5. Changes in selected testate amoebae taxa across tephra layers. '↑' denotes an increase in abundance, '↓ ' denotes a decrease in abundance, '○' denotes no change in abundance, and '-' shows that the taxon is absent or only present in small quantities. '~' indicates that there is some uncertainty involved in the judgment.

	Amphitrema flavum	*Amphitrema stenostoma*	*Arcella Catinus* type	*Difflugia spp.*	*Hyalosphenia papilio*	*Phrygnalla Acropodia* type	*Trigonopyxis arcula*
CHP 33	↑	-	○	-	○	~ ↑	○
ECR 100	↓	↑	-	↑	↓	↑	↑
ECR 162	~ ↓	○	-	-	○	~ ↑	-
LNA 39[$]	↑	○	-	-	-	○	○
LNA 100	↑	↑	-	↓	↑	-	↓
ST 12[$]	↓	-	-	-	↓	~ ↑	~ ↑
ST 24	~ ↑	-	-	-	○	○	○
ST 36	-	~ ↓	↑	-	○	-	~↑
MP 10	-	-	↑	↓	-	-	○
MP 27*	-	○	↑	↓	-	-	↑
MP 39	-	-	↑	-	-	○	↓

* For the MP 27 tephra it was not possible to count testate amoebae for the sample containing the tephra peak. [$] For the LNA 39 and ST 24 tephras there is some uncertainty over the precise location of the tephra peak.

Figure and Table Captions

Fig. 1. Location map of the five peatland sites in southern Alaska, also showing major roads and the settlements of Haines, Skagway, Juneau and Anchorage.

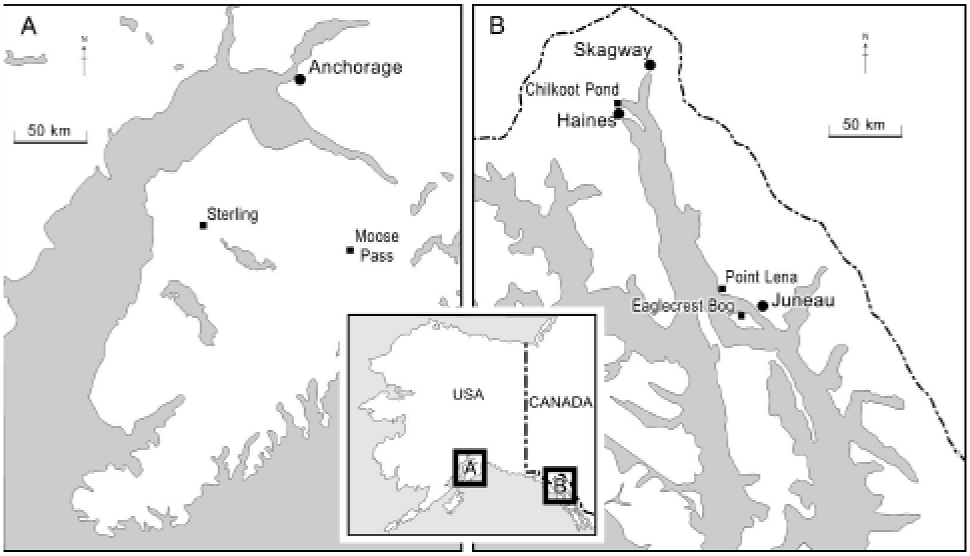
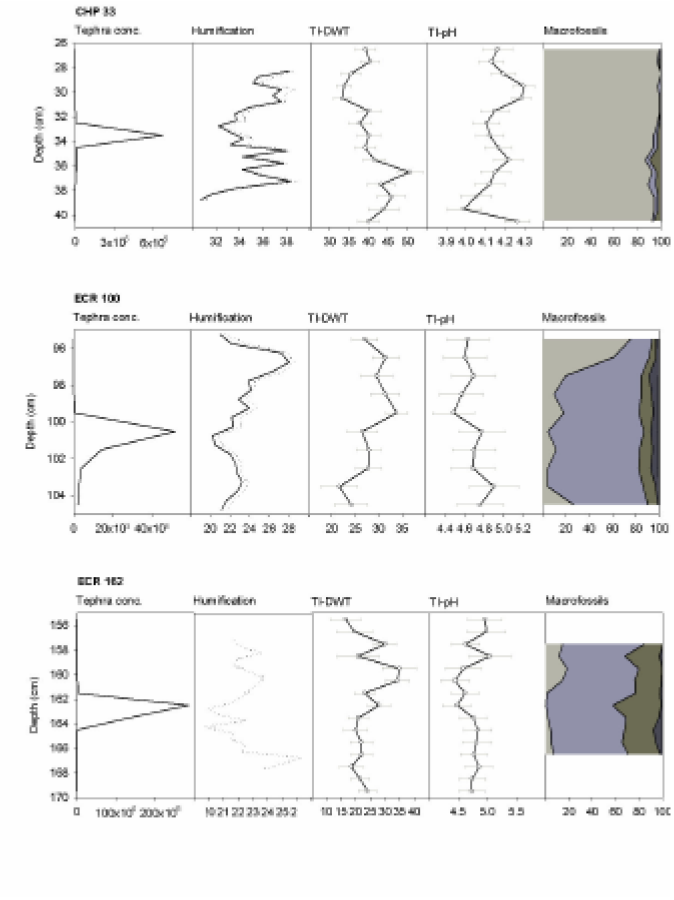
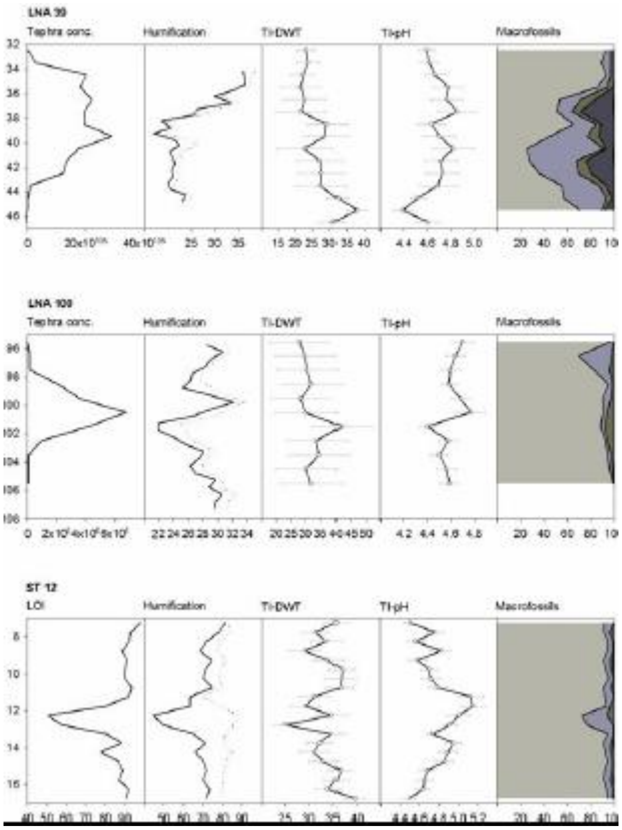
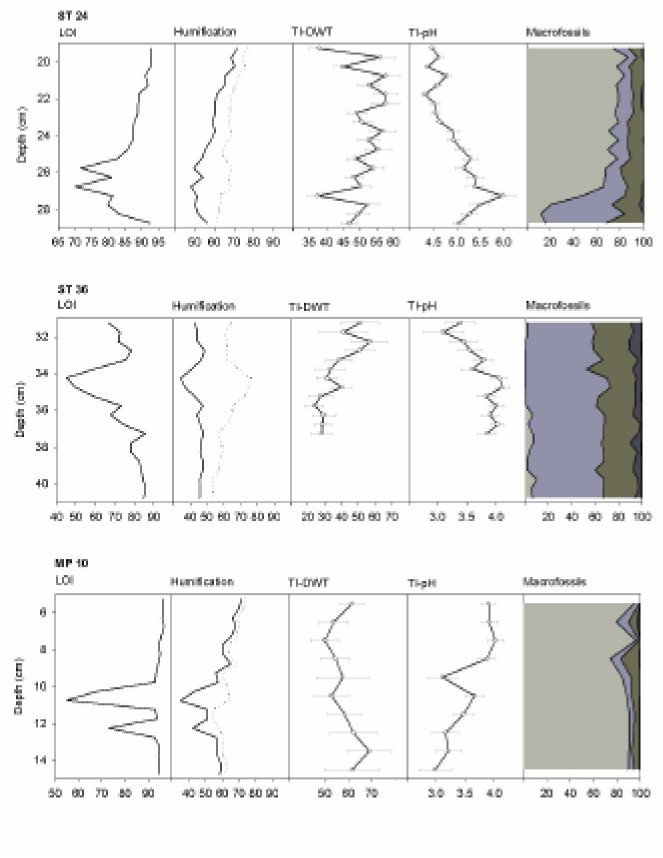


Fig 2. Summary plots of palaeoecological record across tephra layers showing glass shard concentration profile produced by the *Lycopodium* method (shards g dm^{-1}); colorimetric humification showing raw transmission (dotted line) and corrected values (solid line); testate amoebae inferred depth to water table (TI-DWT) and testate amoebae inferred pH (TI-pH) with bootstrapped error estimates and plant macrofossils in five classes: Sphagnum (S), Monocotyledons (M), Unidentified organic matter (U) and Other (O).


CHP 33
Tephra conc.
Humification
TI-DWT
TI-pH
Macrofossils
Depth (cm)
26
28
30
32
34
36
38
40
0
3x10⁵
6x10⁵
32
34
36
38
30
35
40
45
50
3.9
4.0
4.1
4.2
4.3
20
40
60
80
100
ECR 100
Tephra conc.
Humification
TI-DWT
TI-pH
Macrofossils
Depth (cm)
96
98
100
102
104
0
20x10³
40x10³
20
22
24
26
28
20
25
30
35
4.4
4.6
4.8
5.0
5.2
20
40
60
80
100
ECR 162
Tephra conc.
Humification
TI-DWT
TI-pH
Macrofossils
Depth (cm)
156
158
160
162
164
166
168
170
0
100x10³
200x10³
19
21
22
23
24
25
10
15
20
25
30
35
40
4.5
5.0
5.5
20
40
60
80
100


LNA 39
Tephra conc.
Humification
TI-DWT
TI-pH
Macrofossils
32
34
36
38
40
42
44
46
0
20x10
40x10
25 30 35
15 20 25 30 35 40
4.4 4.6 4.8 5.0
20 40 60 80 100
LNA 100
Tephra conc.
Humification
TI-DWT
TI-pH
Macrofossils
96
98
100
102
104
106
108
0 2x10 4x10 6x10
22 24 26 28 30 32 34
20 25 30 35 40 45 50
4.2 4.4 4.6 4.8
20 40 60 80 100
ST 12
LOI
Humification
TI-DWT
TI-pH
Macrofossils
8
10
12
14
16
40 50 60 70 80 90
50 60 70 80 90
25 30 35 40
4.4 4.6 4.8 5.0 5.2
20 40 60 80 100



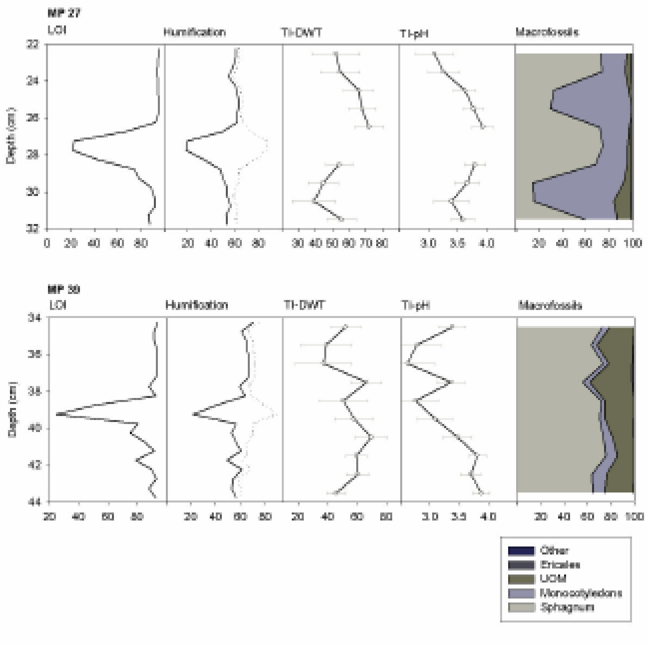
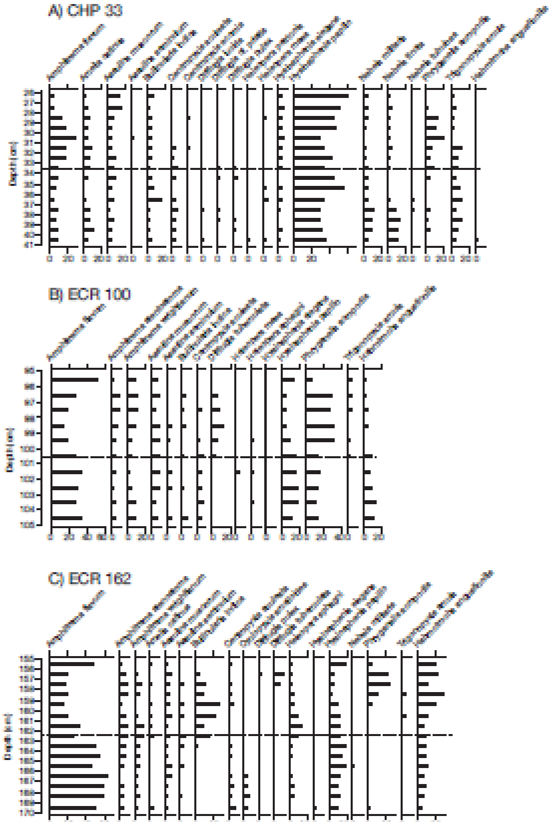
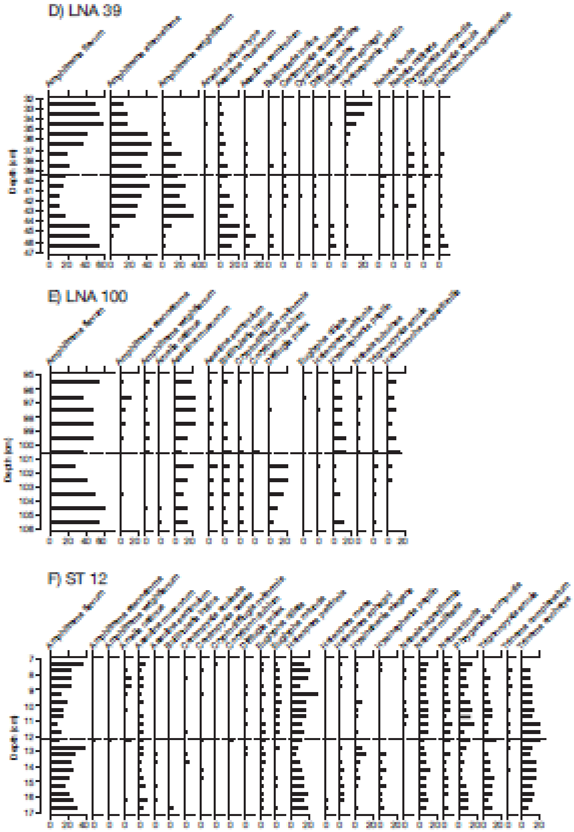
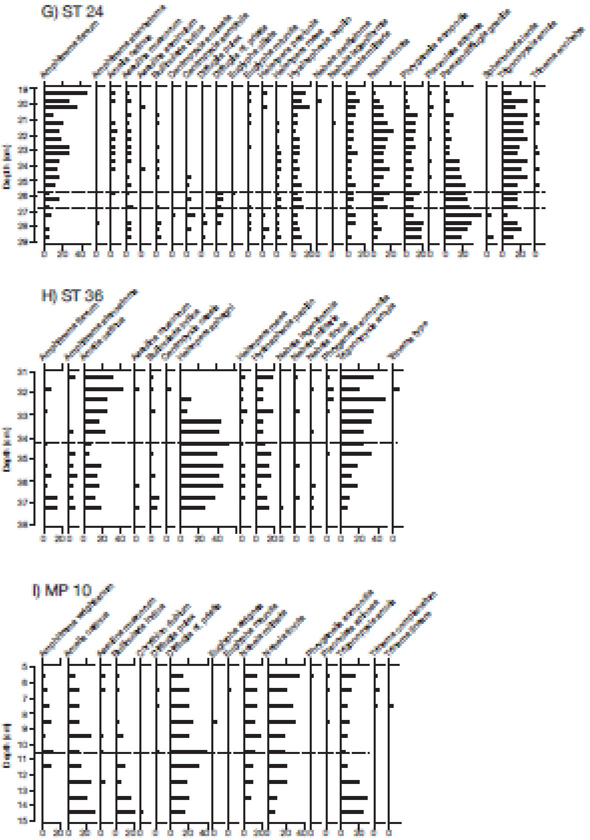


Fig 3. Testate amoebae diagrams across the eleven tephra layers showing percentage of major taxa and position of tephra peak (dotted line).


A) CHP 33
B) ECR 100
C) ECR 162
Depth (cm)


D) LNA 39
E) LNA 100
F) ST 12


G) ST 24
H) ST 36
I) MP 10

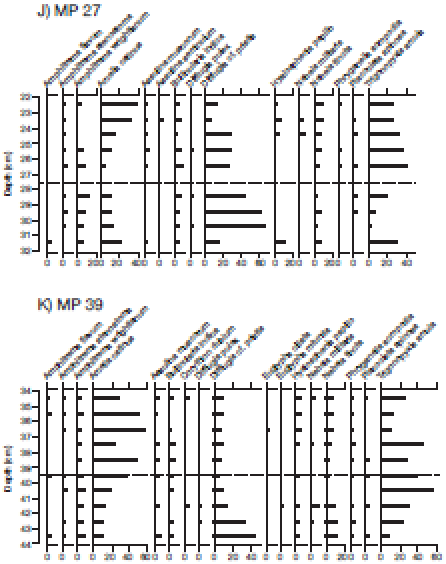

J) MP 27
K) MP 39

Fig 4. Transmission values across a tephra layer using methods of filtration (plot a) and transmission values using Whatman 40 filter paper corrected for loss on ignition (plot b).

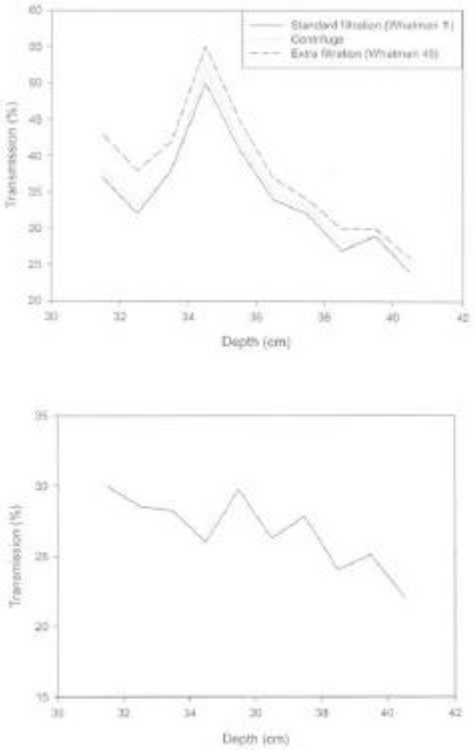


Table 1. Details of tephra layers included in this study.

Table 2. Results of ANOSIM comparing testate amoebae communities below and above the tephra-peak. Showing R_{ANOSIM} and P-values (ns= not significant at P<0.05).

Table 3. Zonation analysis of testate amoebae data across tephra layers using four methods (see text and Gordon & Birks 1972 for details). Zone boundaries

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