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2 **Distal volcanic impacts on peatlands: Palaeoecological evidence from Alaska.**

3

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1

2 **ABSTRACT**

3

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

1

2 **KEYWORDS:** peatlands, bogs, mires, volcanoes, volcanic impacts, tephra,
3 cryptotephra, palaeoecology, testate amoebae, humification, macrofossils.

4

5 Running title: Volcanic impacts on peatlands

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1

2 INTRODUCTION

3

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

18

19 Volcanic impacts on peatlands: previous research

20

21 'Neo'-ecological studies

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

1 significant suppression of methane, although this effect was variable due to
2 climate-driven changes in water table depth.

3 All these studies have limitations. The Hotes et al. (2004) experiment
4 was limited by the use of non-volcanic glass in many of the plots and by the
5 lack of consideration of chemicals adhering to tephra. The Payne & Blackford
6 (2005) experiment was limited by uncertainty over the realism of the
7 experimental scenario (Grattan & Gilbertson 1994). The Gauci et al. (2005)
8 study did not apply tephra. All the studies monitored only a limited range of
9 variables, but have shown enough to suggest the possibility of significant
10 impacts on plant species composition, microbial communities and peat
11 geochemistry.

12

13 Palaeoecological studies

14

15 Due to the inherent difficulties in direct ecological investigations of real
16 volcanic impacts on peatlands and the uncertainty in experimental scenarios,
17 an alternative approach is to use palaeoecological records. Due to the acidic
18 and anoxic environment below the surface layers of peat, organic material does
19 not fully decay and long sedimentary sequences are accumulated.

20 Palaeoecological studies exploit this archive by analysis of the macrofossil plant
21 remains, preserved organisms within the peat, or preserved particles such as
22 pollen. Tephra layers are preserved within the peat and analysis of changes in
23 the palaeoecological record across these layers provides an opportunity to

1 investigate volcanic impacts (Blackford, 1997). The term ‘tephropalynology’
2 has recently been coined to refer to pollen studies across tephra layers
3 (Newnham et al. 1998, Lowe and Hunt 2001, Edwards et al. 2004). A broader
4 term ‘tephropalaeoecology’ may be appropriate to encompass studies based on
5 other palaeoecological proxies.

6 Previous studies have shown impacts from proximal volcanic activity
7 (Kuhry 1988) and large volcanic eruptions in the geological record (Crowley *et*
8 *al.* 1994, Kovar-Eder *et al.* 2001). However, studies of distal volcanic impacts
9 from Holocene eruptions have often shown variable evidence for impacts
10 (Mehring *et al.* 1977, Hotes *et al.* 2001, 2006). In New Zealand Giles *et al.*
11 (1999) showed increases in degraded pollen and a particularly notable increase
12 in *Leptospermum* pollen across the Holocene Kaharoa tephra. The most
13 concerted study of volcanic impacts on peatlands has been in Britain and
14 Ireland following the discovery of Icelandic cryptotephra (Dugmore 1989,
15 Pilcher & Hall 1992, Dugmore *et al.* 1995) and suggestions of volcanic impacts
16 from the Irish dendroclimatic record (Baillie & Munro 1988). Blackford *et al.*
17 (1992) showed coincidence between a decline in *Pinus sylvestris* (scots pine)
18 pollen and the mid-Holocene Hekla-4 cryptotephra in northern Scotland and
19 suggested a causal relationship. Several other studies have found limited or no
20 distinct changes associated with this and other Icelandic tephra (Bennett *et*
21 *al.* 1992, Edwards *et al.* 1994, Hall *et al.* 1994, Charman *et al.* 1995, Caseldine
22 *et al.* 1998, Hall 2003). In western Ireland Dwyer & Mitchell (1997) found that
23 tephra layers were not associated with a regional vegetation change, but did

1 find changes in several mire pollen types and the testate amoeba *Amphitrema*
2 *flavum*, which they interpreted as a shift to wetter peat surface conditions.
3 Where impacts have been noted some studies have suggested a climatic origin,
4 but a direct impact on the mire system appears a more probable explanation
5 (Birks 1994, Grattan *et al.* 1999).

6

7 **Possible modes of volcanic impacts on peatlands**

8

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

14

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

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

6

7 **2. Physical impact of tephra.** Distal tephra is primarily composed of sharp,
8 angular shards of volcanic glass. Deposition of tephra may lead to
9 abrasion of plant surfaces, inhibition of photosynthesis, blocking of
10 stomata, increased reflectivity, inhibition of gas exchange between soil
11 and atmosphere and crushing of plant tissues (Griggs 1922, Egger 1948,
12 Wilcox 1959, Cook *et al.* 1980, Bjarnason 1991, Clarkson & Clarkson
13 1994). Peatland plant communities may be particularly sensitive as
14 plants are low-growing and include many bryophytes lacking a protective
15 cuticle. Impacts on plants will have knock-on impacts on other aspects of
16 the ecosystem.

17

18 **3. Impact on peatland hydrology.** A layer of tephra across the surface of a
19 peatland might impact on the hydrology of the mire. Crowley *et al.*
20 (1994) have suggested that deposition of thick tephra layers could lead
21 to surface ponding while Hotes *et al.* (2004) have suggested that
22 inclusion of tephra could lead to enhanced aeration of the upper layers
23 of peat.

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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 CO₂, SO₂, 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

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

18

19 **Aims of this study**

20

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

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

5

6 **SITES and METHODS**

7

8 **Sites and Fieldwork**

9

10 Of the many areas of the world in which peatlands and volcanoes co-
11 exist, the Pacific Northwest of North America, and specifically Alaska, was
12 selected for this study because of the occurrence of numerous volcanoes (8% of
13 the Earth's total) and the great abundance of undisturbed *Sphagnum* peatlands
14 (45% of the state is classified as wetland). Peatlands were sampled in two
15 general regions: the Kenai Peninsula of southcentral Alaska and the southeast
16 Alaskan 'panhandle' around Juneau and Haines (Fig. 1). The Kenai Peninsula is
17 comparatively close to a number of volcanoes, and several visible millimetre-
18 scale tephra layers are present. Southeast Alaska is more remote from most
19 Alaskan volcanoes and only cryptotephra, not visible in the field, are present
20 (Payne and Blackford 2004, Payne et al. 2008). Peatlands were selected on the
21 basis of maximum peat depth, lack of obvious anthropogenic disturbance and
22 for ombrotrophy where possible. Two sites were cored in the Kenai Peninsula.
23 **Moose Pass** is a small mire (c.100x100 m) lying in the base of a steep, glaciated

1 valley in the northeastern Kenai Peninsula (60°30'N, 149° 26'W)(Fig. 1).
2 **Sterling** is a large (c.200x300 m) kettle-hole peatland lying in the Kenai
3 Lowlands at 60°31'N, 150° 31'W. Both mires are oligotrophic but may not be
4 ombrotrophic. Three sites were also sampled in southeast Alaska. **Point Lena** is
5 an ombrotrophic raised bog (c.300x200 m) lying between the Coast Mountains
6 and the sea (Favourite Channel) near Juneau (58°23'N 134°44'W)(Dachnowski-
7 Stokes 1941). **Eaglecrest** is a large (c.700x300 m) blanket mire in the valley of
8 the Fish Creek, towards the northern end of Douglas Island (58°20'N 134°33'W).
9 **Chilkoot Pond** is a small peatland on the isthmus of land dividing Lutak Inlet
10 from Chilkoot Lake near Haines (59°19'N 135°33'W). The peat deposits at
11 Chilkoot are adjacent to a large pond, and the lower peat deposits represent
12 detrital material in-filling the pond. The vegetation of all five sites is broadly
13 similar, including *Empetrum nigrum*, *Eriophorum* spp., *Oxycoccus microcarpus*,
14 *Cornus canadensis*, *Cladonia portentosa* and extensive *Sphagnum* carpets.
15 Cores were extracted from the deepest areas of peat using a 50-mm bore
16 Russian-pattern peat corer (Aaby & Digerfeldt 1986). Monolith blocks were cut
17 out where the surface peat was too loose to allow coring.

18

19 **Tephrostratigraphy**

20

21 In the Kenai Peninsula sites tephras are visible to the naked eye, but in
22 the cores from southeast Alaska only cryptotephras are present. Cryptotephra
23 layers were identified by ashing and microscopy (Pilcher & Hall 1992). The glass

1 geochemistry of all tephras was studied using electron probe microanalysis
2 (EPMA); the findings of this work have been described previously (Payne 2005,
3 Payne & Blackford 2004, 2008, Payne et al. 2008). The probable tephra sources
4 are shown in Table 1. Concentration profiles for cryptotephras were
5 constructed by adding a *Lycopodium* inoculum to allow a quantitative
6 estimate of glass shard concentrations (Caseldine *et al.* 1998). For the visible
7 tephra layers, shards were highly numerous and concentration profiles were
8 approximated by calculating loss-on-ignition values across the tephras. Tephras
9 of unknown age were either dated directly by radiocarbon or using previously
10 derived age-depth models (Payne 2005).

11

12 **The palaeoecological record**

13

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

1 Peat humification was measured across tephras using the standard alkali-
2 extraction and colorimetry method (Overbeck 1947, Aaby & Tauber 1975,
3 Blackford & Chambers 1993). Peat humification is a measure of the degree of
4 decomposition of peat, with more humified peats being more amorphous and
5 darker in colour (Clymo 1983). In terms of volcanic impact, humification
6 measurement may reflect any impacts on peatland hydrology and plant
7 decomposition processes. The colorimetry method attempts to extract humic
8 and other acids, which are products of the decomposition process. The darker
9 the colour of the alkali extract, the higher the concentration of humic acids
10 and the more humified the peat is considered to be. Recent studies have shown
11 that the organic acids extracted are actually mostly lower weight fulvic acids,
12 amino acids and polysaccharides rather than the humic acids conventionally
13 assumed and a further concern is the extent to which these substances may be
14 extracted from differing plant species (Caseldine et al. 2000, Yeloff & Mauquoy
15 2006). Humification was analysed using a method based on Blackford &
16 Chambers (1993). Sub-samples (0.1g) of dried, ground peat were heated with
17 8% NaOH for an hour. Samples were diluted, filtered through Whatman
18 'Qualitative 1' filter paper and allowed to stand. Transmission was measured at
19 540 nm after four hours from initial mixing. The remaining dried peat was
20 incinerated at 550° C to calculate loss-on-ignition (LOI). Transmission readings
21 were corrected for LOI using the formula $H_c = H_r / (1/LOI)$ where H_c is the
22 corrected humification value, H_r is the measured transmission value and LOI is
23 loss on ignition expressed as a proportion (Blackford & Chambers 1993).

1 Testate amoebae analysis was applied across all the tephra layers.
2 Testate amoebae are unicellular micro-organisms (protists) which are abundant
3 in peatlands and often found in palaeoecological studies (Charman, 2001).
4 Testate amoebae communities are primarily controlled by hydrology with pH
5 and nutrient state as secondary controls (Mitchell *et al.* 1999, Charman *et al.*
6 2001, Payne *et al.* 2006). In terms of volcanic impacts, testate amoebae were
7 selected to show any impacts on the peatland microbial community, changing
8 pH, and changes in water table depth. Samples were prepared using the
9 standard water-based method of Hendon & Charman (1997). 1 cm³ peat sub-
10 samples were boiled in water for approximately 10 minutes, sieved at 300 µm
11 to remove the coarse fraction and then back-filtered at 15 µm to remove fine,
12 highly degraded organic particles. The resulting material was centrifuged at
13 3000 RPM for five minutes to concentrate the tests and slides prepared by
14 mixing the remaining material with glycerol. Slides were examined at 400 X
15 magnification and tests identified using a range of taxonomic literature
16 (Deflandre 1929, 1936, Grospietsch 1964, Ogden & Hedley 1980, Ogden 1983,
17 Luftenegger *et al.* 1988, Charman *et al.* 2000, Clarke 2003). The test-forming
18 bdelloid rotifer *Habrotrocha angusticollis* was also counted and included in
19 percentage calculations. The taxonomic scheme closely followed that
20 employed by Payne *et al.* (2006).

21 Quantitative reconstruction of pH and depth to water table (DWT)
22 changes was carried out using a transfer function derived from surface samples
23 of southern Alaskan peatlands (Payne *et al.* 2006). The optimum two-

1 component WA-PLS transfer function was used with boot-strapped error
2 estimates calculated for each sample using 1000 cycles. The reconstructed
3 values are termed testate amoebae-inferred pH (TI-pH) and testate amoebae-
4 inferred depth to water table (TI-DWT).

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

19

20 **Data analysis**

21

22 Most studies of tephra-impacts in the palaeoecological record have
23 assessed impacts solely by qualitative inspection of the data. Here, we employ

1 a quantitative hypothesis-testing approach using constrained ordination with an
2 explanatory variable designed to simulate a volcanic impact (Lotter & Birks
3 1993, Eastwood *et al.* 2002). Previous studies have adopted two distinct
4 approaches to modelling volcanic impacts. Initially Lotter & Birks (1993)
5 modelled the volcanic impact as an exponential decay process from an
6 arbitrarily defined value at the tephra layer. This approach has the
7 disadvantage that the volcanic impact model is purely a conceptual construct
8 with no empirical basis. More recently Barker (2000) and Eastwood *et al.*
9 (2002) used the tephra concentration profile as the explanatory variable.
10 Although this may seem the superior approach because it is based on real data,
11 it is not applicable here. Tephra concentration profiles in peatlands represent
12 not only the initial deposition phase, but also the post-depositional movement
13 of tephra with downwards gravitational movement of tephra particles through
14 the peat and upward translocation, most likely due to movement of tephra
15 with plant growth or a rising water table (Payne *et al.* 2005). The tephra
16 concentration profile has no direct relationship with the pattern and timing of
17 volcanic impacts on the mire. Therefore in this study the approach employed is
18 based on a conceptual model of volcanic impact, similar to that used by Lotter
19 & Birks (1993). The model used here assumes that a volcanic event will be
20 represented by a large impact at the time of tephra deposition, decreasing
21 with time thereafter. In addition, it assumes that there will be some overall
22 difference between conditions before and after the event. The explanatory
23 variable (termed 'Volcanic') therefore consists of two components: an

1 exponential decay model and a simple before (0) and after (1) nominal
2 variable. The exponential decay function is identical to that used by Lotter &
3 Birks (1993) and is defined as $\exp x^{-\alpha t}$ where α is the decay constant, here
4 given a value of 0.5 and t is sample time (in this case substituted by depth)
5 after the tephra peak. The variable is assigned a value of 0 prior to the tephra
6 peak and then a value of 100 at the tephra peak sample. Varying the initial
7 value and the rate of decay makes little difference to the results obtained. For
8 the data across layer ST 24, the tephra peak was taken to be the lower of the
9 two LOI troughs. For the MP 27 data, the missing sample containing the tephra
10 peak was excluded from the analysis and the tephra peak taken to be the
11 sample directly above.

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

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

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

13

14

15

16 **RESULTS**

17

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

22

23 **Macrofossil analysis**

1

2 The evidence for impacts on the macrofossil record is variable between
3 sites and proxies. Although some changes are subtle, others are relatively
4 distinct (Fig. 2). Across tephras LNA 39 and MP 27 there is an increase in
5 *Sphagnum*. This is the beginning of a sustained increase in LNA 39 and a short
6 phase in MP 27. Across tephras ECR 162 and ST 12 there is a peak in UOM
7 coincident with the tephra peak and in ST 12 this is accompanied by a
8 distinctive peak of monocotyledons. Peaks in UOM were also seen noted
9 coincident with three other southeast Alaskan tephra layers (Payne, 2005).
10 While it is possible that increases in both UOM and *Sphagnum* could be related
11 to tephra deposition, the evidence for an increase in UOM is more convincing.
12 Profiles show peaks in UOM which are exactly coincident with tephra
13 deposition, and which are of high magnitude. A further six sites show little
14 evidence of any macrofossil changes coincident with the tephra (CHP 33, LNA
15 100, ECR 100, MP 10, MP 39 and ST 36). Across tephra ST 24 there is an increase
16 in *Sphagnum* and decrease in monocotyledons, but these changes occur below
17 the tephra peak.

18

19 **Humification**

20

21 The plots of transmission values across cryptotephras show that the glass
22 concentration peak generally coincides with a trough in transmission values and
23 is followed by increasing values (Fig. 2). In three of the plots this post-tephra

1 increase in values is either minor or short-lived (CHP 33, ECR 162 LNA 100), but
2 in two (ECR 100 and LNA 39) the increase marks the start of a prolonged trend.
3 Correcting for loss on ignition makes little difference to the trends.

4 All the plots of transmission data across visible tephra layers (MP 10, MP
5 27, MP 39, ST 12, ST 24 and ST 36) show notable increases in raw transmission
6 data but significant decreases in corrected transmission (Fig. 2). Increased raw
7 transmission values are expected because of the relative reduction in quantity
8 of organic material in the sample. Corrected values show transmission values
9 decreased by over 20% in some sites; these are very substantial changes and
10 should be easily visible with the naked eye. However, no such visible change
11 can be seen in these samples, indicating that this pattern is an artefact of the
12 methodology used rather than a genuine result. The correction factor applied
13 to the raw data is derived from experiments conducted by Blackford &
14 Chambers (1993) and usually makes minimal difference to the results when LOI
15 values are high and mineral content therefore low. The large disparity between
16 measured and corrected transmission values here suggests some aspect of
17 humification measurement or correction is not working as it should where LOI
18 values are low. The humification results are thus considered unreliable. This
19 issue is discussed further below.

20

21 **Testate amoebae**

22

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

15 In the data from ST 12 the most notable changes are a significant drop in
16 abundance of *Amphitrema flavum* and a loss of *Hyalosphenia papilio* at the
17 tephra peak. In LNA 100, *Amphitrema flavum* abundance declines below the
18 tephra layer but is actually increasing at the position of the tephra peak. The
19 most distinct changes at this site are a loss of *Diffflugia pulex* and increases in
20 *Amphitrema stenostoma* and *Amphitrema wrightianum*. Qualitative data
21 inspection and zonation analysis also suggest changes in the ECR 162 and ECR
22 100 profiles. In ECR 100 this change is characterised by a loss of *A. flavum* and
23 *H. papilio* and increases in *Diffflugia tuberculata* and *Phryganella acropodia*. In

1 ECR 162 the data show a loss of *A. flavum* and increases in *Bullinularia indica*
2 and *Heleopera sphagni*. Results from these four profiles show little similarity in
3 response. In ST 12 and ECR 100 there is a distinct loss of *H. papilio*, but in LNA
4 100 there is an apparent increase. In three of the profiles there is a loss of *A.*
5 *flavum*, however in LNA 100 percentages are actually increasing by the point of
6 the tephra peak. ECR 162 shows a large increase in *B. indica*, however, in LNA
7 100 there is a slight decline in this taxon. Overall, none of the major taxa show
8 a consistent response to tephra deposition in these four profiles. Table 5 shows
9 changes in several major taxa across the tephra layer in all the analysed peat
10 profiles. Changes are qualitatively assessed as an increase, decrease, no
11 change or that the taxon is not sufficiently abundant to make a judgment.
12 There is little consistency in these changes. For instance, *A. flavum* is judged to
13 increase in abundance across three tephra and decrease in abundance across
14 three others. On the strength of the evidence presented in this table, the most
15 consistent impacts are on *A. catinus*, which increases in abundance across all
16 four tephra in which a distinct change is noted. Equally, *P. acropodia* also
17 increases across all tephra where a change is noted; however, some of these
18 changes are indistinct.

19 There is no convincing evidence that certain testate amoebae species
20 are particularly affected by volcanic impacts. Although several species show
21 major changes coincident with tephra deposition these are generally not
22 replicated between profiles. This lack of replication suggests that changes are
23 not due to direct toxicity of volcanic products on some species. Instead it

1 seems probable that changes are due to a volcanically-forced environmental
2 change affecting profiles differently, depending on their pre-existing state.

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

18 Overall, the testate amoebae results show evidence for a volcanic
19 impact in some profiles but not in others. The apparent testate amoebae
20 response to a volcanic impact appears to vary between tephras and does not
21 produce a characteristic response in terms of species changes or TI-DWT and
22 TI-pH. The lack of a consistent increase or decrease in inferred pH or DWT

1 coincident with the tephra layer suggests that if the changes are volcanic in
2 origin they are not due to the changing pH or surface moisture.

3

4 **Consistency between proxies**

5

6 Both macrofossils and testate amoebae (although most probably not
7 humification) show evidence for changes coincident with tephra layers in some
8 sites. Testate amoebae analysis is the most quantitative method used here.
9 Our results suggest that impacts are most distinct for profiles ST 12 and LNA
10 100, and may also be present for ECR 100 and ECR 162 although the evidence is
11 weaker. Macrofossil results show a distinct change across the ST 12 tephra with
12 a peak in monocotyledons and UOM. Macrofossil data across ECR 162 also show
13 a peak in UOM at the time of deposition of the tephra. No distinct macrofossil
14 change is noted in LNA 100 and in ECR 100 a major macrofossil change is offset
15 from the tephra peak by 2 cm. The macrofossil results show the best evidence
16 for changes coincident with tephra deposition in profiles ECR 162, ST 12 and MP
17 27. In two of these, testate amoebae changes were also noted (ECR 162 and ST
18 12). In profile MP 27 there is only limited evidence for testate amoebae change
19 coincident with the tephra peak. In many cases impacts shown with one proxy-
20 record are not necessarily shown by the other.

21

22 **DISCUSSION**

1

2 **Is there evidence for a volcanic impact?**

3

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

19

20 **Causes of the impact**

21

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

4

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

12

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

20

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

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

3

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

13

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

1

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

7 **Reasons for differential response**

8

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

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

1 particularly large magnitude, and apparent impacts of this tephra are
2 significant. Therefore the role of eruption size is uncertain.

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

12 A further important factor is the distance of the site from the source
13 eruption. At greater distances, tephra may have more adsorbed volatiles (Rose
14 1977, Oskarsson 1980, Smith et al. 1993). Therefore, distal tephtras could be
15 associated with greater impacts than proximal layers regardless of the size of
16 the layer. While some of the greatest apparent impacts are associated with
17 tephtras at great distance (e.g. ECR 162), impacts of the proximal ST 12 tephra
18 also appear considerable.

19 It is also possible that impacts may be dependent on the season of an
20 eruption. Modern studies of distal volcanic impacts have shown that plants are
21 generally less sensitive to eruptions outside the growing season (Zobel & Antos
22 1997, Hotes et al. 2004). In winter, plants will be senescent and higher rainfall
23 may serve to rapidly remove volcanic pollutants. Impacts may be particularly

1 dependent on snow cover. Snow will stop volcanic products coming into direct
2 contact with the peat surface. In spring snowmelt, volcanic products contained
3 in the snow will be heavily diluted and may be removed by surface water flow.
4 The sites in this study are snow-covered for much of the year; meteorological
5 data show an average of around five months annual snow cover at Juneau and
6 Haines and six months at Kenai. It is therefore possible that snow cover is a
7 significant cause of differential impacts. This factor is difficult to quantify
8 because there is very limited evidence for the season of ancient eruptions. An
9 exception to this is the White River Ash (Eastern Lobe), which is correlated
10 with the LNA 100 layer in this study. West & Donaldson (2002) presented
11 geomorphological evidence that this tephra was produced in late autumn or
12 very early winter. If the impacts of winter eruptions are reduced, impacts
13 across LNA 100 should be minimal but this is actually one of the two tephras
14 associated with the most conclusive impacts. However, West & Donaldson
15 (2002) worked on sites that are both further north and at higher elevation than
16 Point Lena and it is therefore conceivable that Point Lena could still have been
17 unfrozen and snow-free at the time of the White River Ash eruption.

18 Tephra impacts may also be related to the nature of the site. Any one or
19 more of site vegetation, hydrology and nutrient status could affect impacts.
20 However, there is no clear evidence that the nature of the site is a significant
21 factor. The most distinct apparent impacts were on the Point Lena and Sterling
22 sites. These peatlands are quite different: Point Lena is an ombrotrophic raised
23 bog whereas Sterling is a kettle-hole peatland. Different tephras deposited on

1 the same peatland can have a quite different scale of impacts. Although ST 12
2 is associated with impacts, two other tephras of similar thickness (ST 24 and ST
3 36) in the Sterling profile are not. This result suggests that the variability of
4 impacts is more likely to be due to some other factor and is not closely related
5 to the nature of the site.

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

16 In addition to these reasons why different tephras in different sites may
17 or may not be associated with detectable impacts there are several
18 methodological issues which may have led to impacts not being identified in
19 this study. The most significant of these is sampling resolution. The sites
20 studied here represent a range of peatland types and experience different
21 climatic conditions. The peatlands therefore have different peat accumulation
22 rates and these accumulation rates have changed through the Holocene as the
23 mires have developed. The period of time represented by the sub-samples

1 varies from approximately 8 to 50 years. It is therefore possible that the lack of
2 detectable volcanic impacts in some of these sites is simply because the
3 sampling resolution is insufficiently high. However, the two tephras which are
4 associated with the most distinct impacts (ST 12 and LNA 100) are not the sites
5 with the highest sampling resolution. Low resolution may account for the
6 failure to detect more distinct impacts in the Eaglecrest site which has a
7 relatively low accumulation rate but cannot explain the differences within the
8 other sites. An additional complication is the possibility that accumulation
9 rates may have varied in response to volcanic impacts (Caseldine et al. 1998,
10 Blackford and Payne, unpublished data).

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

18 The above discussions have assumed that a volcanic impact will be
19 represented starting coincident with or directly above the tephra layer, but
20 this may not be the case. Firstly, location of the isochron may be complicated
21 by post-depositional movement of tephra through the peat. Experimental work
22 suggests that it is unlikely for the tephra *peak* to move (Payne et al. 2005) but
23 the possibility cannot be totally excluded. Secondly, it is possible that a

1 response to volcanic impacts may be lagged behind the event, although there is
2 no obvious mechanism to support this. A final possibility is for a change in the
3 palaeoecological record to start below the position of the tephra layer because
4 amoebae may be alive some distance below the surface (Heal 1962, Corbett
5 1973) and can respond rapidly to environmental change (Lousier 1974, Clarke
6 2003). Although these mechanisms are possible, there is no convincing evidence
7 that they have occurred in this study. In the sites in which distinct impacts
8 were noted such impacts take place directly coincident with the tephra layer.
9 In other profiles there are rarely any major changes either just below or just
10 above the tephra layer.

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

17

18 **Problems with the humification technique**

19

20 The humification results discussed above appear to be unreliable across
21 visible tephra layers. Readings that would normally represent significant,
22 visible colour shifts in the peat stratigraphy were obtained across almost
23 homogeneous core sections where tephtras were present. A possible explanation

1 is that some tephra particles were small enough to pass through the filter
2 paper used in preparing the alkaline extract, and thereby reduced light
3 transmission values. The filter paper used retains particles greater than 11 μm
4 diameter, but particle-size analysis showed a significant proportion of tephra
5 particles were smaller than this size (Payne & Blackford 2008). To test this
6 hypothesis, humification was re-measured across one of the tephra layers using
7 a higher standard of filtration. The ST36 tephra was selected, humification was
8 measured as described previously but using double quantities (100 ml) of NaOH,
9 so results are not directly comparable to those presented previously. Samples
10 were filtered using the standard method (Whatman qualitative 1 filter paper),
11 using a finer filter paper that retains particles greater than 8 μm diameter
12 (Whatman 40) and using centrifugation (15 minutes at 4000 RPM). The pattern
13 of transmission with the standard method shows the same trends as measured
14 previously (Fig. 4). With centrifugation values were increased by 1-2%,
15 particularly towards the centre of the sequence and with the finer filter paper
16 values were elevated by up to 5%, although this was variable over the sequence
17 (Fig. 4). The elevated values in the centrifuged and finer-filtered samples
18 strongly suggest that tephra particles penetrated the filter paper used in the
19 standard method. When the transmission values with the finer filter paper are
20 corrected for LOI, the large drop in corrected values present with the normal
21 filter was eliminated (Fig. 4).

22 The tephra layers in southeast Alaska are much smaller and correction
23 for LOI makes very little difference to the values. However, in common with

1 the humification profiles across the visible tephra layers, most of the profiles
2 across the cryptotephra layers also show reduced transmission values
3 coincident with the tephra peaks, consistent with an affect of tephra
4 penetrating the filter paper. Although tephra shards are less abundant in these
5 cryptotephra layers, the particle size is smaller, and so a greater proportion of
6 particles may pass through the filter paper. In some profiles there are
7 humification changes which are not consistent with tephra penetrating the
8 filter paper. However, these changes are the exception- in the majority of
9 profiles the most distinct change is reduced transmission coincident with the
10 tephra peak. Several previous studies have measured humification across
11 tephra layers using this methodology (e.g. Caseldine et al. 1998, Langdon &
12 Barber 2004, Ellershaw 2004). The results shown here suggest that reduced
13 transmission values coincident with tephra layers might be due to this
14 methodological problem rather than a palaeoenvironmental change.

15

16 **Volcanic impacts on peatlands: wider implications**

17 This study provides evidence that volcanoes have the potential to affect
18 distant peatlands. Apparent impacts can be detected in records of past
19 microbial communities and, probably, past plant communities. The mechanism
20 of these impacts is not certain but may relate to deposition of volcanic acids
21 and other compounds adhering to tephra particles. The scale of impacts is
22 variable between tephras; such variability may be due to the season of the
23 eruption and the meteorological conditions prevalent at that time. While

1 ecological experimentation can indicate the *potential* for volcanic eruptions to
2 affect peatlands (Hotes *et al.* 2004, Payne *et al.* 2005), direct observations or
3 palaeoecological studies are required to show that this actually takes place.
4 This study provides the most intensive palaeoecological investigation of distal
5 volcanic impacts on peatlands and the results have several implications for
6 peatlands and the wider environment.

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

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

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

6

7 **Implications for peatland palaeoclimatology**

8

9 The results detailed here have important implications for peatland
10 palaeoecology. Changes across tephra layers suggest changes in key proxy-
11 climate records potentially can be caused by a mechanism independent of
12 climatic change. It is possible that such changes could be mistaken for a short-
13 term climatic change. Studies are increasingly using tephra layers to correlate
14 sequences in different sites (e.g. Landon & Barber 2004, van den Bogaard *et al.*
15 2002) and therefore possibly risk mistaking volcanic impacts for simultaneous
16 environmental changes between sites. While there is no particular indication
17 that this is the case in the existing studies it is essential that the possibility be
18 evaluated. Tephra cannot be automatically assumed to be an inert marker in a
19 palaeoecological sequence. A search for visible tephra layers and cryptotephra
20 should be undertaken routinely in palaeoecological studies from areas within a
21 zone of potential tephra deposition.

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23 **Future research directions**

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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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1 **FIGURES and TABLES**

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

3

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. 6.6×10^5 shards $\text{g}^{-1} \text{dm}$	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. 5.1×10^4 shards $\text{g}^{-1} \text{dm}$	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. 2.2×10^4 shards $\text{g}^{-1} \text{dm}$	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. 2.9×10^5 shards $\text{g}^{-1} \text{dm}$	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. 6.7×10^6 shards $\text{g}^{-1} \text{dm}$	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)

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4 **Table 2.** Results of ANOSIM comparing testate amoebae communities below and
5 above the tephra-peak. Showing R_{ANOSIM} and P-values (ns= not significant at
6 $P < 0.05$).

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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)

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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.

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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 ($P < 0.05$)					

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

	<i>Amphitrem a flavum</i>	<i>Amphitrema stenostoma</i>	<i>Arcella Catinus type</i>	<i>Diffflugia spp.</i>	<i>Hyalosphenia papilio</i>	<i>Phrygnalla Acropodia type</i>	<i>Trigonop yxis arcula</i>
CHP 33	↑	-	○	-	○	~ ↑	○
ECR 100	↓	↑	-	↑	↓	↑	↑
ECR 162	~ ↓	○	-	-	○	~ ↑	-
LNA 39^s	↑	○	-	-	-	○	○
LNA 100	↑	↑	-	↓	↑	-	↓
ST 12^s	↓	-	-	-	↓	~ ↑	~ ↑
ST 24	~ ↑	-	-	-	○	○	○
ST 36	-	~ ↓	↑	-	○	-	~ ↑
MP 10	-	-	↑	↓	-	-	○
MP 27[*]	-	○	↑	↓	-	-	↑
MP 39	-	-	↑	-	-	○	↓

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* For the MP 27 tephra it was not possible to count testate amoebae for the sample containing the tephra peak. ^s For the LNA 39 and

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ST 24 tephra there is some uncertainty over the precise location of the tephra peak.

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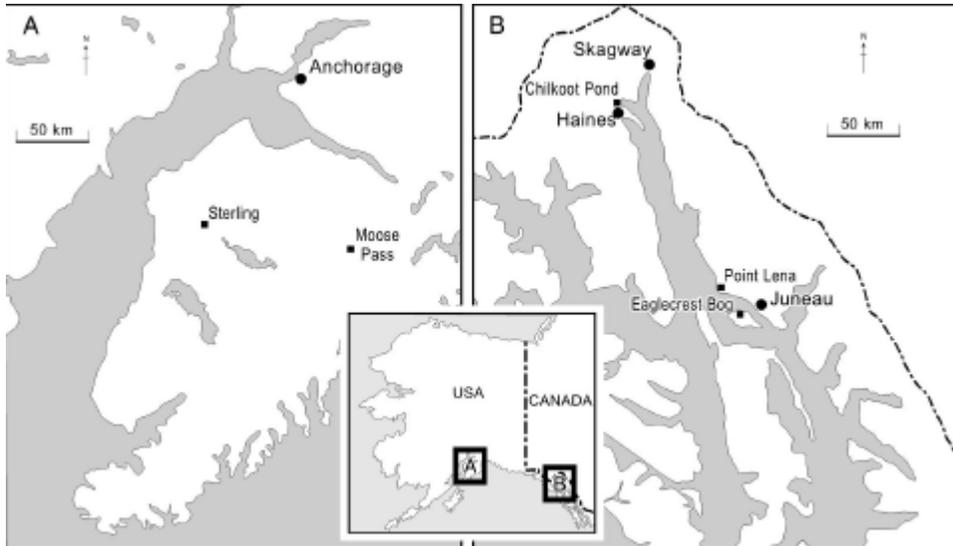
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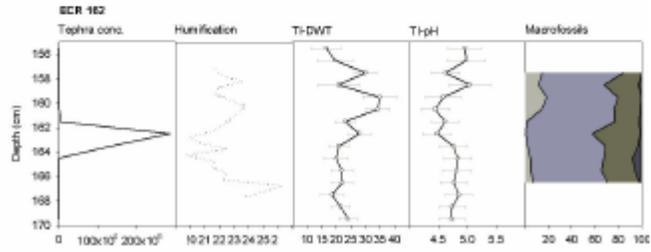
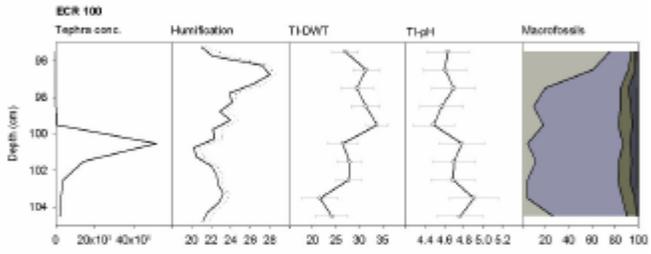
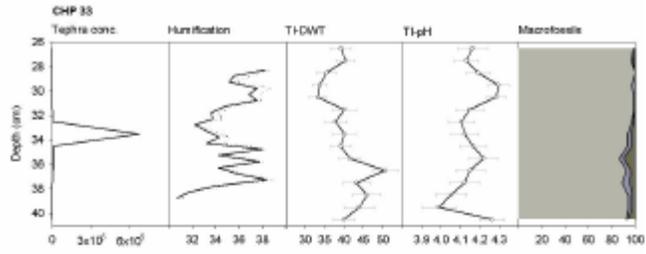
2 **Figure and Table Captions**

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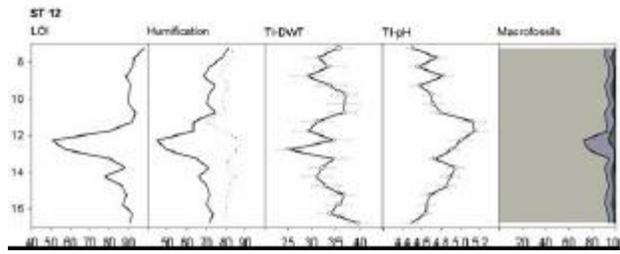
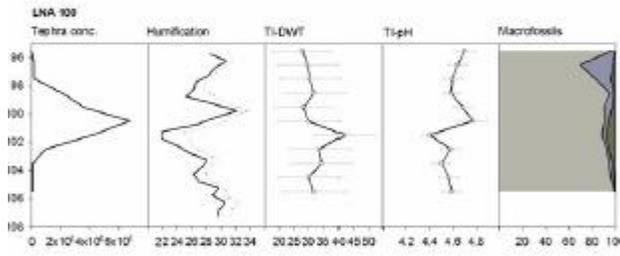
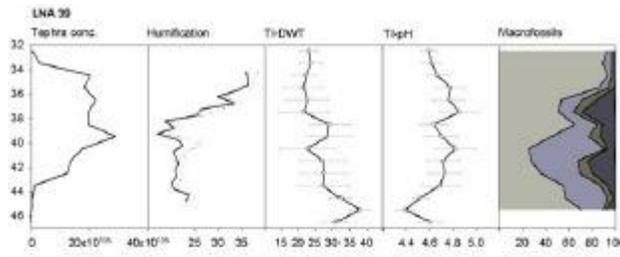
4 Fig. 1. Location map of the five peatland sites in southern Alaska, also showing
5 major roads and the settlements of Haines, Skagway, Juneau and Anchorage.



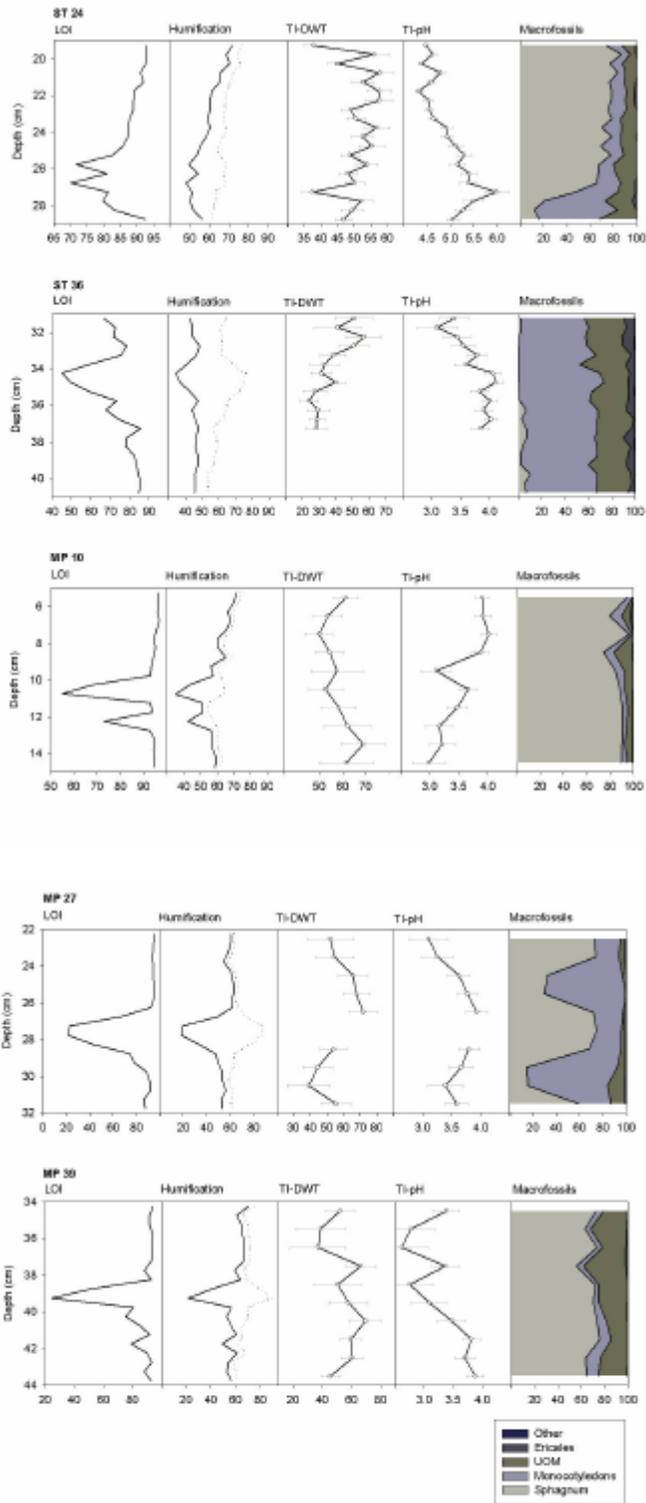
7 Fig 2. Summary plots of palaeoecological record across tephra layers showing
8 glass shard concentration profile produced by the *Lycopodium* method (shards g
9 dm^{-1}); colorimetric humification showing raw transmission (dotted line) and
10 corrected values (solid line); testate amoebae inferred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



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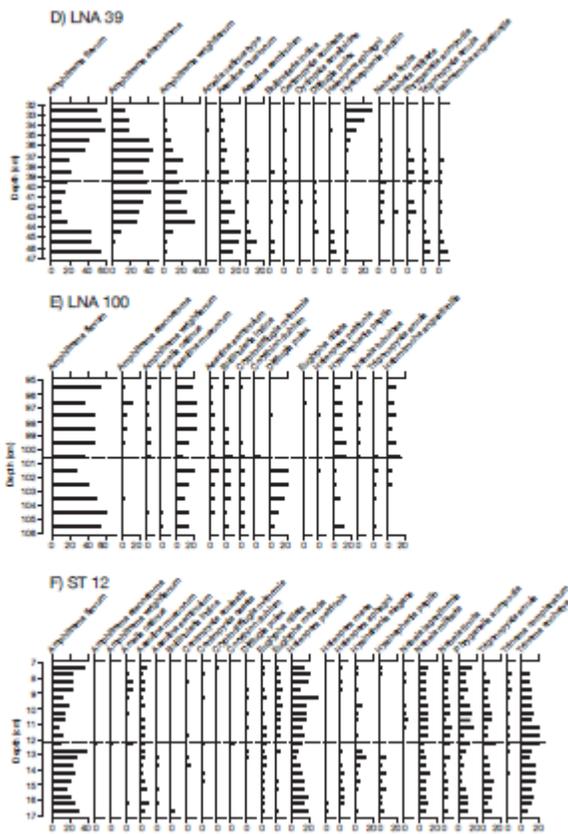


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3 Fig 3. Testate amoebae diagrams across the eleven tephra layers showing

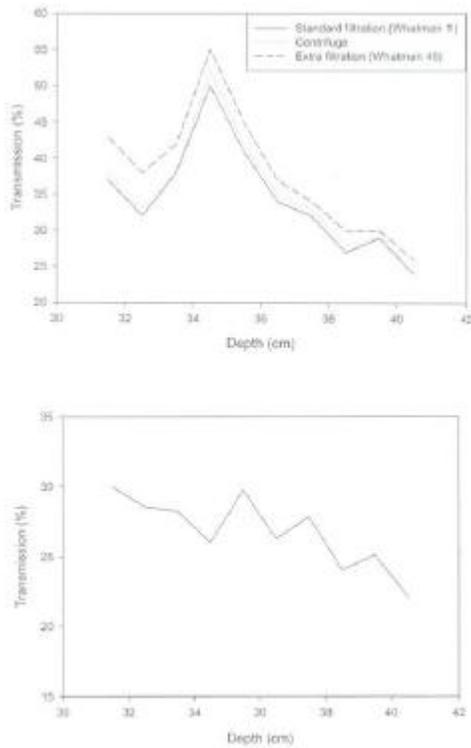
4 percentage of major taxa and position of tephra peak (dotted line).



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



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

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8 Table 2. Results of ANOSIM comparing testate amoebae communities below and
9 above the tephra-peak. Showing R_{ANOSIM} and P-values (ns= not significant at
10 $P < 0.05$).

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

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