Using palaeoecological techniques to understand the impacts of past volcanic eruptions

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ABSTRACT

Large volcanic eruptions may have major impacts on ecosystems through their physical, chemical and climatic affects. These impacts are stochastic and because the largest, most damaging volcanic events have not occurred in the recent past there is considerable interest in past eruptions as an analogue for possible future events. Palaeoecology is an essential tool to understand the environmental consequences of eruptions in the past. Here we review the processes by which volcanic eruptions affect ecosystems, how palaeoecological research can enhance our knowledge of palaeo-volcanic impacts and some of the challenges which such studies face. We focus particularly on tephropalaeoecological studies which address changes in the abundance of microfossils (e.g. pollen, diatoms, testate amoebae) across tephra layers preserved in sediments. In our discussion we stress the importance of impacts from volcanic tephra, volatiles and volcanically-induced climate change, which are likely to be the most spatially extensive impact mechanisms. We highlight the importance of considering the taphonomy of tephra and microfossils when attempting to identify volcanic impacts. We discuss the extent to which it is, and is not, possible to distinguish volcanic impacts from non-volcanic processes and random variability. The focus of this special issue is the Mediterranean and we conclude by discussing the particular issues which may apply in this region, including the availability of suitable archives and preservation conditions.

KEYWORDS: Tephra; Volcanic ash; Tephropalaeoecology; Tephropalynology; Volcanic impacts

Introduction

Volcanic eruptions have stochastic, but sometimes severe impacts on ecosystems and human societies. Long-term records of the impacts of volcanic eruptions and subsequent recovery are essential to gain a holistic understanding of the environmental consequences of volcanism. Serious scientific monitoring of volcanic impacts only began in the twentieth century and since this time there has been a limited range of eruptions. Many Holocene-active volcanoes have had no substantial eruptions in the modern era and some volcanic regions appear to have been relatively quiescent by historic standards. Only three eruptions since 1900 have reached VEI6 and two of these were more than a hundred years ago (Santa Maria 1902 and Novarupta 1912). Such large eruptions may also have impacts which last a very long period of time. Kilian et al. (2006) suggest that a mid-Holocene eruption of the Chilean volcano Mt Burney caused environmental changes which persisted for up to two thousand years. The impacts and recovery from volcanic eruptions have only been seriously monitored in a small number of instances and very few of these represent even moderately large eruptions. Long-term records are the only way we can understand the impacts of the largest eruptions and the only means we have of quantifying the full trajectory of subsequent recovery.

This review addresses the use of palaeoecological records to identify and reconstruct the impacts of volcanic eruptions. We first consider how volcanic eruptions affect ecosystems, and therefore the changes which we might expect to see represented in palaeoecological records. We follow this with a series of demonstrations of the potential of the approach by discussing selected case studies where previous research has used palaeoecology to address volcanic impacts. Some of the challenges which need to be addressed if the palaeoecological approach is to become more established are discussed. We conclude by addressing the problems and opportunities of this approach in the Mediterranean region, the particular focus of this special issue of *Quaternary International*.

What are the impacts of volcanic eruptions?

We begin by considering the ways by which volcanic eruptions may affect ecosystems to allow an assessment of how these may be represented in palaeoecological records. High quality ecological studies of the impacts of volcanic eruptions have only been conducted in the last few decades so the range in size and eruption style is limited but these can nevertheless provide a guide to the processes which have operated in the deeper past.

Volcanic impacts on the environment are complex primarily because eruptions are associated with multiple different hazards each of which is associated with many potential impacts. It is useful to consider hazards in simplified terms of concentric spatial zones surrounding a volcanic source (Fig. 1). In the 'blast zone' nearest to the volcano and typically no more than a few kilometres from the vent, impacts are likely to be severe for even relatively small eruptions. Hazards such as volcanic explosions, lava, pyroclastic density currents and intense tephra loading are likely to lead to near-total destruction of pre-existing ecosystems. Beyond this in a region we term the 'proximal zone' often spanning many tens of kilometres from the vent, impacts are likely to be more spatially heterogeneous. Locations affected by pyroclastic density currents, lava and lahars may still see near-total destruction but these impacts are unlikely to cover the entire area. In this zone topography is an important factor and with increasing distance from the vent hazards such as lava and lahars will be increasingly confined to pre-existing drainage features. Locations not directly affected by these extreme hazards are still likely to be affected by heavy tephra-loading, but with increasing distance from the vent some organisms may survive. Further still from the volcano in the 'distal zone', which may span up to more than a thousand kilometres, the key hazards arise from tephra, volcanogenic gases and volcanically-modified precipitation. Impacts will be variable and mediated by the extent of loading and the sensitivities and adaptability of the species and ecosystems concerned. The final zone of impacts may be hemispheric or global with ecosystems affected by climate change following the largest explosive eruptions. The extent of all these zones will be primarily determined by the magnitude and explosivity of the eruption and wind patterns and the sequence is unlikely to be as straightforward as that illustrated in Figure 1.

It is clear that only a relatively small proportion of global ecosystems will be affected by proximal hazards such as lava and lahars but a very substantial proportion of the global land surface is potentially exposed to distal impacts. This can be simply illustrated by assigning impact radii to all the Holocene-active volcanoes in the Smithsonian Institution database (Global Volcanism Programme, 2017) (Fig. 2). Using a 1000 km impact zone shows the *potential* for impacts throughout a large part of the global land surface. This is clearly an overly simplistic approach which does not account for factors such as the size of historic eruptions and wind directions, but nevertheless serves to demonstrate that volcanic eruptions are a truly global issue. Indeed, even regions more than 1000 km from the nearest volcano may still be exposed to volcanic products, as demonstrated for instance by findings of Holocene tephra in regions such as eastern North America (Pyne-O'Donnell et al., 2012) and western Russia (Wastegard et al., 2000). However, most eruptions are more modest in scale and have impacts primarily within a few kilometres of the vent.

How do volcanic eruptions affect the environment?

The available research suggests five general mechanisms by which volcanoes may affect ecosystems.

1. *Physical effects*. In blast zone and proximal sites the physical impacts of volcanic eruptions on ecosystems are obvious through mechanisms such as crushing or burial by lahars, pyroclastic flows or tephra; incineration by lava or pyroclastic material and direct destruction by explosive volcanic activity (Griggs, 1915; Eggler, 1948; Gorshkov and Dubik, 1970). However, such impacts only affect a relatively localised area in the immediate vicinity of the volcano (Fig. 1). In the distal zone the physical impacts of volcanic eruptions are primarily mediated by the properties of tephra (Fig. 3). Fine ash particles can have long atmospheric residence times (minutes to months), can travel hundreds of kilometres away from the volcano and can carry a variety of volatiles. Tephra may abrade external surfaces, irritate mucus membranes, block pores (including plant stomata), coat surfaces impeding plant photosynthesis and gas exchange and bury, weigh-down and crush organisms (Griggs, 1915; Wilcox and Coats, 1959). Tephra in the landscape may inhibit gas exchange between soil and atmosphere (Hinckley et al., 1984) and alter energy balance (Seymour et al., 1983). In aquatic systems tephra may block fish gills and increase turbidity, reducing light penetration and primary production (Ayris and Delmelle, 2012; Lallement et al., 2016). Tephra may modify the hydrology of landscapes, altering drainage patterns, impounding water and leading to flooding (Vucetich and Pullar, 1963).

2. *Chemical effects*. Volcanoes modify the chemical environment of ecosystems around them through production of volatiles and pyroclastic material. Volcanic gas can vary greatly in composition but frequently includes considerable quantities of CO_2, SO_2, H_2O and sometimes HCl and HF. Ecosystems can be exposed to these gases as both dry deposition (gaseous and particulate) and wet deposition (precipitation, aerosols) following contact with water. Impacts may include oxidation and acidification. Impacts on vegetation frequently resemble those of acidic air pollution with frequent observations of defoliation and necrosis (Parnell and Burke, 1990; Delmelle et al., 2002; Payne and Blackford, 2005). Further chemical inputs may come from the tephra itself. Studies of leachates from Mt St Helens 1980 tephra showed a host of heavy metals (Zn, Cu, Cd, F, Pb, and Ba) in sufficient concentrations to have biological impacts (Smith et

al., 1983). A corollary of these negative impacts is the possibility for enhanced growth as volcanic products may provide a supply of limiting nutrients such as P and K (Jones and Gislason, 2008).

3. *Climate effects*. Volcanic eruptions have the potential to modify climate by the production of stratospheric aerosol following large explosive events (Fig. 4). Following large historically-documented eruptions the scale of the cooling is in the order of <~1°C for several years, but with considerable variability between eruptions and monitoring sites (Angell and Korshover, 1985; Mass and Portman, 1989; Douglass and Knox, 2005). There is considerable debate about the potential climatic impacts of larger eruptions which have not occurred during the era of instrumental climate records (Scuderi, 1990; Jones et al., 1995; Zielinski, 2000) but most estimates suggest that even following the largest Holocene eruptions cooling is unlikely to greatly exceed 2°C and unlikely to last much more than a decade. For instance, the climactic eruption of Mount Mazama, Oregon (7682-7584 cal. years BP: Egan et al. (2015)) has a VEI value of 7 but is believed to have caused a relatively modest 0.6-0.7°C decrease in temperatures for 1-3 years in the northern hemisphere (Zdanowicz et al., 1999). On a more localised scale tephra are effective condensation nuclei, which may increase precipitation (Mass and Portman, 1989; Lathem et al., 2011; Ayris and Delmelle, 2012). In the very short term (days), volcanic impacts on weather may include heavy rainfall and lightning.

4. *Biological feedbacks*. Impacts on one component of an ecosystem are highly likely to have impacts on other components of that ecosystem even if those components are not directly affected. Thus, even if a plant species is entirely resilient to tephra deposition or acidic precipitation following an eruption, it nevertheless might still be affected by impacts on its predators, pathogens or competitor species. Impacts on any individual species will depend on position in the food-web and the responses of other species linked both directly and indirectly.

5. *Links to human activity*. A further feedback process concerns the impacts of volcanic activity on human populations and societies; the focus of several other papers in this special issue. Volcanic eruptions may cause population displacement and societal changes which lead changes in land-use. Given the dominant role of human activity in many of the world's ecosystems, changes in human use of the landscape as a consequence of volcanic activity will have consequences for ecosystems which may either ameliorate or intensify the direct impacts of volcanism. For instance, the abandonment of grazing land following an eruption may reduce pressure on vegetation, leading to more rapid post-eruption recovery (cf. (Dugmore et al., 2007)). Conversely, population displacement may concentrate human activity in certain areas, intensifying impacts and impeding recovery.

The biological consequences of these impacts are hugely variable. At the most extreme, volcanic processes can cause extensive mortality, even entirely eliminating life from a landscape and setting the stage for a classic primary succession (Fridriksson, 2013). Even beyond the immediate blast and proximal zones mortality due to volcanic effects seems apparent in most types of organism, ranging from microbes (Urrutia et al., 2007) to insects (Marske et al., 2007), fish (Hidayati et al., 2014; Lallement et al., 2016) and birds (Dalsgaard et al., 2007). Other species may increase in abundance to fill vacated niches or take advantage of new opportunities, for instance the decomposition of dead organisms (Staley et al., 1982) or supply of nutrients (Urrutia et al., 2007). Where there is no direct mortality there may still be reduction in growth rates. For instance, tree ring records graphically attest to reduced tree growth following volcanic disturbance (Stoffel and Bollschweiler, 2008; Bollschweiler et al., 2009). Volcanic impacts may lead to physiological changes and adaptations in organisms, for instance production of extended rhizomes (Antos and Zobel, 1985) or changes in xylem density in trees (Eggler, 1967). Volcanic modifications of the landscape may also lead to changes in the relationship between species, for instance changes in plant-pollinator relationships (Martínez et al., 2012) and changes in how raptors use the landscape (Cabezas-Cartes et al., 2014). All of these processes may lead to restructuring of ecosystems. The temporal duration of impacts is also highly variable. Some may be extremely transitory, others may have a duration of decades, centuries or even millennia (Kilian et al., 2006). There may be parallels with the impacts of air pollution where experimental studies have shown that there is considerable hysteresis in post-exposure recovery and some changes may be essentially irreversible (Isbell et al., 2013).

Mediators of volcanic impact

Numerous factors will serve to determine the magnitude and nature of impacts of volcanic products for a specific eruption in a specific location. Most obviously, impacts may be variable due to the nature of the eruption itself. For example, the volume of material ejected and the thickness of the resulting tephra layer with thicker tephras typically leading to greater impacts (Thorarinsson, 1979; Grishin et al., 1996) (Fig. 3). Following the 1980 eruption of Mt St Helens, Hinckley et al. (1984) demonstrated a strong relationship between reduction in horizontal and vertical growth of conifers and the tephra loading received. The composition of tephra and adsorbed volatiles can also be variable between eruptions which can lead to differing chemical impacts from leaching. For example, a high concentration of sulphur might cause a short-to-medium term decline in pH which might have deleterious consequences for plant growth (Cronin et al., 1998) whilst a high concentration of P might cause a long-term increase in soil fertility and productivity.

There is increasing evidence that the season of an eruption may also be an important factor in determining its impacts, particularly in high latitude regions. During the winter many plants will be senescent and therefore able to resist transient environmental changes which would have greater impacts in the growing season. In a field experiment in Japan, Hotes et al. (2004) found there was a greater impact of tephra deposition on a *Carex middendorffii-Sphagnum papillosum* raised mire community during the growing season due to the crushing effect of tephra on soft plant tissues while impacts in the autumn were less detrimental as resources were located in more robust storage tissues. In environments which are seasonally snow-covered the snow layer may protect plants and other organisms from immediate impacts, although there is also the possibility for delayed acute impacts upon snow-melt.

The nature of the environment on which volcanic products are deposited may also be important in determining impacts as ecosystems will react differently depending on their biogeochemical properties. For example, in regions where soils and lakes are poorly buffered due to acidic bedrock, volcanogenic sulphur could cause acidification to which better buffered environments would be resistant (Blackford et al., 1992). Similarly, impacts mediated by supply of nutrients such as P, K or Fe will be determined by the extent to which these nutrients are limiting in the environment. Topographic setting may also be significant. Tephra is not static in the landscape and may be transported by wind and water with some areas denuded and others receiving disproportionate quantities. Tephra thickness can vary across small distances and impacts mediated by tephra thickness are likely to be similarly spatially variable (Cutler et al., 2016; Blong et al., 2017). For instance, impacts from tephra in lakes are likely to be greater in lakes with larger catchment areas as the potential tephra supply is correspondingly greater (de Fontaine et al., 2007).

The combination of i) the complex spatial distribution of volcanic hazards, ii) the subsequent redistribution of volcanic products, and iii) the differing sensitivities of different locations and regions means that volcanic impacts are likely to show complex spatial patterning.

Detecting volcanic impacts using palaeoecology

Palaeoecological data has great potential to contribute to the understanding of volcanic impacts due to the limited number, limited eruption size and short duration of contemporary records. There is a long history of palaeoecological studies which have considered the role of volcanic forcing in a range of palaeoenvironmental records, including lake sediments (Mack et al., 1983; Abella, 1988), peat (Mehringer et al., 1977; Blinman et al., 1979; Payne, 2012), ice cores (Hammer et al., 1980), speleothems (Baker et al., 1995), corals (D'Arrigo et al., 2009) and tree rings (LaMarche and Hirschboeck, 1984). The focus of this review is sedimentary records of preserved remains of organisms (primarily plants and microorganisms) in terrestrial and freshwater environments such as peat bogs and lakes (Fig. 5), as these constitute the largest proportion of such research.

We focus particularly on *tephropalaeoecological* studies: those which have attempted to investigate volcano-induced environmental change by palaeoecological analysis across tephra layers preserved in sediments (Payne and Blackford, 2008). In essence, this approach uses the tephra layer to identify an eruption in a sedimentary record and aims to identify characteristic changes in the abundance of different organisms above and below the tephra to understand its impacts (Fig. 6). We can expect that some species may be positively affected by a volcanic event and may increase in abundance (‘species A’ in Fig. 6), some may be negatively affected by a volcanic event and may decline in abundance (‘species B’) and others may be insensitive to the event and show little change in abundance (‘species C’). We can characterise the response in terms of a ‘background’ phase below the tephra, an ‘impacts’ phase immediately following tephra deposition and a subsequent ‘recovery’ phase in which there is a trend towards prior conditions. In reality the situation is never as simple as in Fig. 6. We are typically dealing with many more species and their responses are rarely as straightforward and easily characterised as those of A, B and C . Any volcanic impact is often set against a background of pre-existing environmental change and it is frequently unclear whether deviations in the abundance of taxa can be taken to represent a volcanic impact or simply random noise.

The potential and problems of the tephropalaeoecology approach: selected case studies.

The potential and complexities of the tephropalaeoecological approach are perhaps best illustrated by introducing some specific examples. Here we discuss five case studies of research which has aimed to identify volcanic impacts with varying degrees of success. These case studies illustrate the potential for palaeoecology to provide information unattainable by other means but also demonstrate many of the practical issues with using palaeoecology to understand palaeo-volcanism.

The potential for tephropalaeoecology to identify *mechanisms* by which volcanic eruptions impact on ecosystems is nicely demonstrated by work in East Africa. Barker et al. (2000) investigated the response of diatom communities to tephra deposition in Lake Massoko, a crater lake in northern Tanzania. Following a large volcanic event at c.1190 BP (diffuse tephra <6cm thick) the authors identified an abrupt shift in diatom assemblages. The planktonic species *Synedra acus* replaced *Aulacoseira* spp. and persisted as the dominant species for c.110 years. The authors suggest that the change was due to tephra forming a 'cap' over basal sediments which limited P diffusion and increased the Si:P ratio. Such a mechanism for volcanic events modifying aquatic nutrient cycling is counter-intuitive and was not previously documented. It is only through tephropalaeoecological research that we understand the potential mechanisms at work and the long time-scales for subsequent recovery.

Another example which illustrates the potential, but also some problems, of the approach comes from Alaska. Blackford et al. (2014) investigated the mid-Holocene eruption of Aniakchak at a tundra site in northwestern Alaska. Across a 3-4 mm thick visible tephra layer the authors conducted high-resolution analyses of pollen, which may indicate impacts on vegetation, and oribatid mites, which may indicate impacts on the local environment. Samples of peat were AMS radiocarbon dated to identify any changes in peat accumulation. The pollen data showed a switch from Cyperaceae (sedge) to Poaceae (grass)-dominated vegetation across the tephra layer and the dating implied a ~100 year accumulation hiatus following the eruption (Fig. 7). These data imply relatively dramatic impacts of this overlooked eruption at over 1000 km from the volcano with vegetation change and impacts sufficiently severe to halt peat accumulation for an extended period. This could perhaps be due to volcanogenic sulphur deposition and illustrates the potential of the tephropalaeoecology approach to identify previously unappreciated impacts. However, other results also illustrate the complexity of interpretation which is frequently a feature of tephropalaeoecological studies. Data on oribatid mites from the same profile did not show a major change above the tephra but did show changes beginning just *below* the tephra. In this case these changes may still be of volcanic origin because oribatid mites may be living below the peat surface and therefore the samples *under* the tephra layer may still be recording mites living *after* the eruption. This clearly illustrates the importance of considering the taphonomy of the material being studied when making inferences. While taphonomy is a general issue in palaeoecology it becomes particularly critical for tephropalaeoecology because the resolution required is so fine and the events being considered so transient.

A recurrent issue in tephropalaeoecology is the (lack of) consistency between sites and studies. One of the most intensively investigated putative volcanic impact events recorded in pollen records is the impact of the Icelandic Hekla 4 eruption (c. 2310BCE (Pilcher et al., 1995)) in the British Isles. In peatland sites in northern Scotland Blackford et al. (1992) showed coincidence between cryptotephra deposition and a well-known decline in *Pinus* (Pine) pollen. The authors proposed the impact of volcanic acids or a volcanic-induced climate change as conceivable mechanisms which might explain this change. However, soon after this study further work, this time in Northern Ireland, failed to identify any such synchronicity (Hall et al., 1994b). Many further studies followed with some suggested to provide evidence for impacts on vegetation, and others not (Charman et al., 1995; Dwyer and Mitchell, 1997; Caseldine et al., 1998) (Fig. 8). A recent meta-analysis (Payne et al., 2013) has suggested that only in the original Altnabreac site studied by Blackford et al. (1992) was evidence for a link between volcanism and vegetation change very convincing. While this does not disprove the idea that Hekla 4 had impacts on vegetation in Britain, it does show that the evidence for this theory is currently weak and any impacts were probably spatially complex. This example nicely illustrates some of the difficulties involved in using palaeoecological data to assess volcanic impacts on the environment, particularly at long distances, and the critical need for replication. The case of Hekla 4 in the British Isles is particularly complicated because studies were trying to identify impacts at the margins of where they are likely to have occurred and against a backdrop of pre-existing environmental change.

A study of the impacts of tephra deposition from the climactic eruption of Mount Mazama, Oregon on a forest environment in Washington, USA also illustrates some of the ambiguity around the identification of tephra as a driver of change (Egan, 2016; Egan et al., 2016). Pollen analyses were carried out on lake sediment cores from the lake fringe and the centre of the lake, representing local and regional vegetation (Jacobson and Bradshaw, 1981; Prentice, 1985), respectively and containing tephra layers of 7-50 mm thickness. Notable in this study is the variability in apparent response within the same catchment. Fig. 9 clearly illustrates a marked change in vegetation following tephra deposition recorded in the centre of the lake with an increase of *Tsuga heterophylla* (Western Hemlock) and Cupressaceae (Cypress family) and a decrease of *Pseudotsuga menziesii* (Douglas Fir). However, data analyses showed no statistically significant impact of the tephra, with changes suggested more likely to be climate driven. This demonstrates the difficulty of distinguishing volcanic impacts from coincident non-volcanic environmental change. In this case fine-resolution sampling demonstrates that the changes observed actually begin beneath the tephra layer, highlighting the importance of high resolution analyses. Conversely, analyses from a lake fringe sediment core indicated a local impact of tephra deposition with changes to open habitat vegetation (increase of Cyperaceae and decrease of Poaceae) and aquatic macrophytes (overall decline but an increase of *Pediastrum*) but considerable inter-sample variability (Fig. 10). The authors suggested that Poaceae would have been completely buried by the tephra and aquatic macrophytes declined due to increased turbidity of the water, whilst Cyperaceae had a positive response due to adaptability such as perennial organs allowing shoots to penetrate through the tephra, and *Pediastrum* increased due to the influx of nutrients (Haberle et al., 2000). This case study clearly demonstrates issues with identifying true drivers of change as well as the importance of multi-core analyses and the potential for intra-site variability in response.

The issue of replicability is also illustrated by a study of diatom changes in response to tephra deposition in three Mexican lakes (Telford et al., 2004). Lago de Zirahúen contained six tephra layers of 0.5-9 cm thickness with only one showing a diatom response. Pátzcuaro contained nine tephras with four showing an impact and Zacapu Swamp contained six tephra deposits with four affecting the diatoms. Telford *et al.,* (2004) suggested three possibilities for the varying responses 1) insufficient tephra was deposited in some events, 2) the nutrients supplied by tephra were not limiting to the pre-tephra ecosystem, 3) the lakes into which the tephra fell had high variability so the tephra effects could not be distinguished from natural change. There was also some uncertainty about the cause of the changes as they occurred at the same time as climate changes. It was concluded that the longevity of these changes suggested indirect impacts via a change in the catchment nutrient cycle.

Collectively these examples illustrate the ways in which palaeoecological studies can contribute to knowledge of volcanic impacts, but also some of the difficulties involved.

Key challenges

While many tephropalaeoecological studies have successfully identified significant impacts from volcanic eruptions, others have been more ambiguous, reaching no clear consensus due to the difficulty in distinguishing any volcanic 'signal' from background variability (Blackford et al., 1992; Hall et al., 1994b). Perhaps the greatest challenge to the use of palaeoecological records to understand the impacts of volcanic activity is in making links between records of volcanism and those of palaeoecological change. It is fundamentally impossible to prove cause-effect relationships with palaeoecological data so a degree of judgement will always be required. It will be clear from the preceding discussion that the number of potential impact mechanisms at work is large, and plausible responses varied and complex. For instance, if we consider the example of tree-rings: both anomalously narrow *and* anomalously wide rings have been attributed to volcanic activity e.g. (Baillie and Munro, 1988; Pearson et al., 2009). It is not always straightforward to determine whether a palaeoecologically-observed change is due to a volcanic event purely on the basis of the nature of the response so chronology becomes critical.

Particularly problematic are studies which attempt to infer links between palaeoecological change and volcanic activity based on chronology alone, without direct evidence from the stratigraphic profile. Such studies are particularly prone to what Baillie (1991) has called 'suck in' and 'smear': the tendency of researchers to attribute links between events which may be unrelated on the basis of (often limited) chronologies. Or, to follow Sadler and Grattan (1999) in quoting Renfrew and Grayson (1979) '*an eruption here, a destruction there, a plague somewhere else -- all are too easily linked in hasty surmise*'. However, even when we do have direct evidence to place a volcanic event in context with biostratigraphic data, linking change in biota to volcanism remains complicated and subjective. The case will be strongest where evidence is replicated between cores and sites and consistent with what might be expected from ecological studies. Crucial to this is that geochemical analyses underlying correlations are sufficiently secure to be sure that the same tephra is being compared, this is particularly important in regions where tephras are numerous. There is also a strong case for the use of appropriate statistical tools to address these questions (Birks, 1994; Payne et al., 2013). While statistics can never prove cause-effect, they can help us address questions such as: is this change part of pre-existing trend? Is it consistent with what we might expect to see following a volcanic eruption? How does the magnitude of (inferred) impact vary between sites?

A frequent assumption of tephropalaeoecological studies is that both tephra and the fossils being analysed are stable in the stratigraphic column, but it is clear that this is not always the case. In lake and marine sediments there is considerable evidence for secondary deposition and differential taphonomy (McCoy, 1981; Anderson et al., 1984; Boygle, 1999). Tephra can have extended vertical distribution due to mixing processes such as bioturbation and can be displaced in the stratigraphy (Anderson et al., 1984; Thompson et al., 1986; Beierle and Bond, 2002; Davies et al., 2007; Blong et al., 2017). In peatlands movement of tephra appears to be less pronounced but still considerable (Payne et al., 2005; Payne and Gehrels, 2010), particularly when sites are disturbed by human activity (Swindles et al., 2013). Concentration profiles of cryptotephra frequently show considerable dispersion and often secondary peaks, requiring difficult judgements about which horizon exactly should be considered to mark the eruption. There is similar evidence for post-depositional movement of many of the microfossils which are the focus of palaeoecological study (Clymo and Mackay, 1987). Linking tephra profiles and palaeoecological records requires a judgement to be made about the taphonomy of both the tephra and the microfossils analysed.

Key principals for future tephropalaeoecological research.

We propose four key principals which should inform future tephropalaeoecological research. We suggest that future studies should be:

1) Informed by ecology. There is a wealth of ecological literature on volcanic impacts which can and should be used to plan palaeoecological studies and interpret tephropalaeoecological data.
2) Hypothesis-driven. There is a tendency for tephropalaeoecological studies to invoke post-hoc justification to link a specific palaeoecological change to volcanic activity. Some of these arguments are tenuous.
3) Quantitative. Statistical methods cannot prove that change in a palaeoecological record is due to a volcanic eruption but they can help exclude other possibilities and detect if it is part of a longer-term trend. Too many previous studies have been entirely subjective.
4) Replicated. Evidence for volcanic-induced environmental change cannot be considered entirely convincing if it only comes from a single core.

Using palaeoecology to detect the impacts of volcanic eruptions in the Mediterranean region.

We conclude this review by considering the application of palaeoecology to understand volcanic impacts in the Mediterranean basin. Eastwood (2004) puts forward three arguments for the particular importance of palaeoecological research in the Mediterranean region: the potential for long records which are not truncated by glaciation, the role of the region at the climatic and biogeographic frontier of Africa and Europe, and the long history of human occupation and civilisation. The region also contains numerous active volcanoes, particularly in the Aegean Arc and Italy, with the Campanian Ignimbrite/Y5 eruption the most significant eruption in Europe over the past 100,000 years (Pyle et al., 2006). Consideration of the impacts of such volcanic eruptions is an important theme in Mediterranean palaeoecology. While many challenges are common to other regions, some are particularly acute here. One frequently significant challenge is simply the availability of suitable archives. The most extensive use of palaeoecological records to investigate volcanic impacts has been in the temperate and boreal zone, largely because in this region suitable archives are more widespread. In the temperate and boreal zones peatlands and lakes are numerous, often have organic sediments which are amenable to radiocarbon dating and many sites are comparatively undisturbed. In arid regions such as the Mediterranean suitable study sites are much rarer. Peatlands and lakes are scarcer in the landscape and often considerably disturbed due to the long history of human occupation (Andrieu et al., 2000). However, very long sediments records do exist in certain locations (Tzedakis, 1993).

A related additional challenge is the adequate preservation of macro/microfossils within these deposits as decomposition can often degrade the quality of the record. This is a problem for any palaeoecologists working in the Mediterranean as the nature of the arid landscape means that microfossils such as pollen are often deposited in oxidised environments. Identifying volcanic impacts in palaeoecological records requires a focus on changes which are often transient and set against a changing background. Records which are suitably chronologically and taxonomically resolved are important prerequisites and achieving both can be challenging in this region.

The specific features of Mediterranean ecosystems may also affect their sensitivity to volcanic hazards. A key environmental pressure in Mediterranean regions is drought and typical species are adapted to deal with these conditions. In plants these adaptations include thick cuticles, small coriaceous leaves, deep rooting systems and small, protected, stomata (Galmés et al., 2007; Nardini et al., 2014). Many of these adaptations are likely to also benefit species in terms of resistance to volcanic impacts; small leaves will trap less tephra, thick cuticles will limit the impacts of acid deposition and leachates, deep roots may limit the impacts of tephra leachates.

Several studies have utilised palaeoecology to understand volcanic impacts in this region although often with some ambiguity in interpretation. Eastwood et al. (2002) assessed the impact of 4 cm thick tephra from the 'Minoan' eruption of Santorini (Thera) ~3300 ^{14}C yrs BP on vegetation at Gölhisar in south west Turkey. Their pollen analysis revealed a slight decline in total land pollen, however, the authors considered that this was more likely to reflect the dilution effect of sediment input, rather than actual pollen production suppression. Margari et al. (2009) assessed the impacts of tephra deposition (1-44 cm thickness) from the Campanian Ignimbrite (Y-5) eruption, and a Hellenic Arc eruption (possibly Nisyros) on vegetation on Lesvos, Greece. The Y-5 eruption is thought to have caused an increase in aquatic Umbelliferae due to tephra blocking the drainage system and promoting flooding. The deposits from both the Campanian Ignimbrite (Y-5) eruption and Hellenic Arc eruption coincided with reduced arboreal populations and increased grasses which could be explained by volcanic mechanisms such as acid deposition, defoliation and decreased temperatures. However, arboreal populations began to decrease prior to tephra deposition and coincided with Heinrich events 4 (for the Y-5 deposit) and 5 (for the Hellenic Arc deposit). Margari et al., (2009) could not conclude that tephra deposition had an impact on vegetation, and it is perhaps more likely that the changes detected were a result of climate change. Wutke et al. (2015) analysed the aquatic impacts of seven Campanian tephra deposits on Lago Grande di Monticchio, southern Italy between 40,000 and 38,000 years BP. Diatom analyses revealed an increase in diatom productivity due to the influx of silica from thicker deposits (> 5 mm). This was especially the case following the Campanian Ignimbrite eruption, which deposited the thickest tephra layer (230 mm) and impacts lasted for up to >1240 years due to secondary deposition. Diatom populations showed no response after the deposition of thinner deposits.

These three examples illustrate some of the problems discussed previously with the identification of cause-effect relationships and the differentiation of volcanic impacts from ongoing environmental change and background noise. They also highlight some of the factors that need to be considered when assessing impacts of tephra such as the tephra layer thickness and the influence of secondary tephra deposition. Despite some of the uncertainties, the Mediterranean region does offer tephropalaeoecologists the opportunity to improve our understanding of volcanic impacts. Compared to other regions such as the Pacific north west of North America, the potential of tephropalaeoecology has been little exploited. This is likely to be due to the availability, suitability and preservation of the archives in the Mediterranean, but given the long-term volcanic influence on this region it is essential that more studies of this nature are conducted.

Conclusions

Palaeoecological studies have proved themselves to be of considerable value to help understand the impacts of volcanic eruptions. Distal volcanic impacts remain particularly poorly understood, particularly for larger eruptions which can only be studied by palaeoecology. There are several issues that make assessing volcanic impacts problematic, such as the difficulty of identifying cause-effect relationships and the problem of distinguishing impacts from ongoing trends and background noise. Traditionally, evidence of impact is based on the interpretation of a single sediment core which may not be representative of a whole catchment or region. Many studies have assessed the impacts of volcanic activity using a coarse sampling resolution and have not considered the longer-term environmental context on which any volcanic impact is superimposed. There is an increasing body of research which has attempted to resolve some of these issues using statistics, but current statistical tools remain relatively crude. Furthering our understanding of volcanic impacts and factors that may govern the impact is essential if we are to gain a holistic understanding of the impacts of volcanic eruptions in the environment. Future studies need to focus on replicating results, both within a site and a region, maximising resolution and exploiting the potential of the approach for a greater variety of locations, regions and eruptions. This is especially important for the Mediterranean where tephropalaeoecological studies are relatively rare.

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Figure captions

Fig. 1 Schematic of associated hazards from volcanic eruptions and the potential spatial extent of ecological impacts.

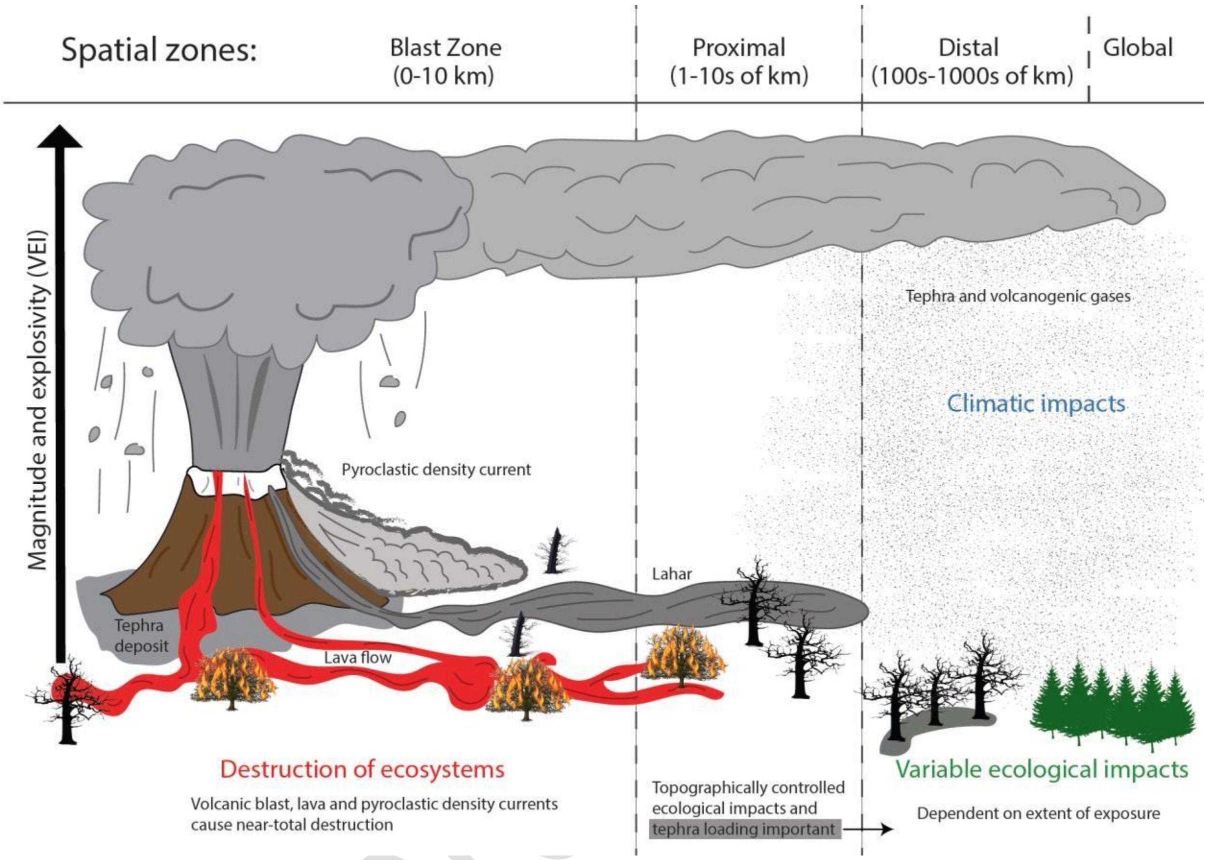


Fig. 2 Locations of Holocene active volcanoes based on data from the Smithsonian Institution Global Volcanism Program (Global Volcanism Programme, 2017), showing location of all listed volcanoes (red triangles) and 1000 km radii (pink shading).

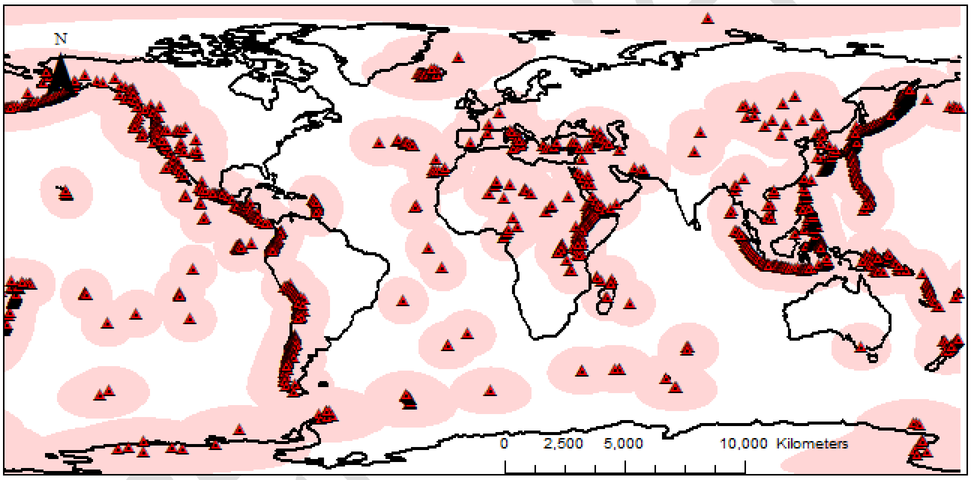


Fig. 3 Relationship between tephra loading and impacts on vegetation, adapted from Grishin et al. (1996). Impacts may vary between ecosystems and may be driven by mechanisms other than tephra such that the relationship between tephra loading and ecological change can be non-linear. However, tephra thickness provides a useful and easily measured metric.

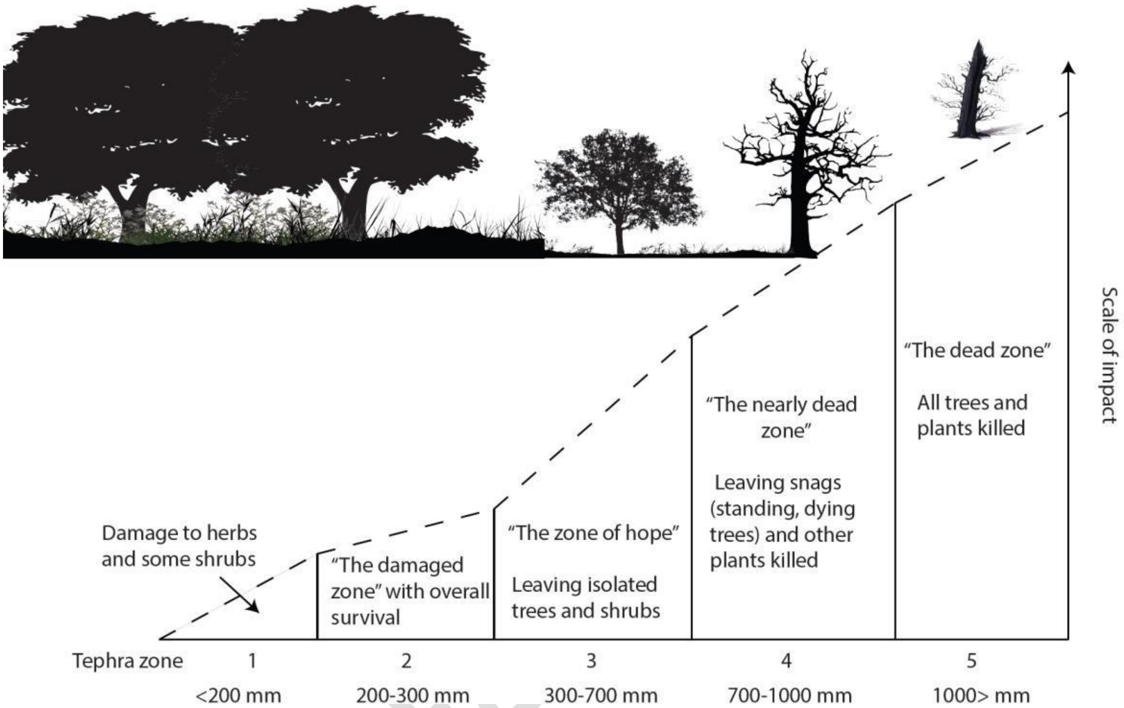


Fig. 4 Mechanisms of climate change following a volcanic eruption (not to scale). Material injected into the stratosphere in the largest eruptions can include tephra and gaseous components such as water vapour, sulphur dioxide and hydrochloric acid. The sulphur dioxide transforms into sulphuric acid aerosols which increase the Earth's albedo and warm the stratosphere by absorbing infrared radiation. Eventually, the aerosols are transported down to the troposphere where they can alter cloud properties.

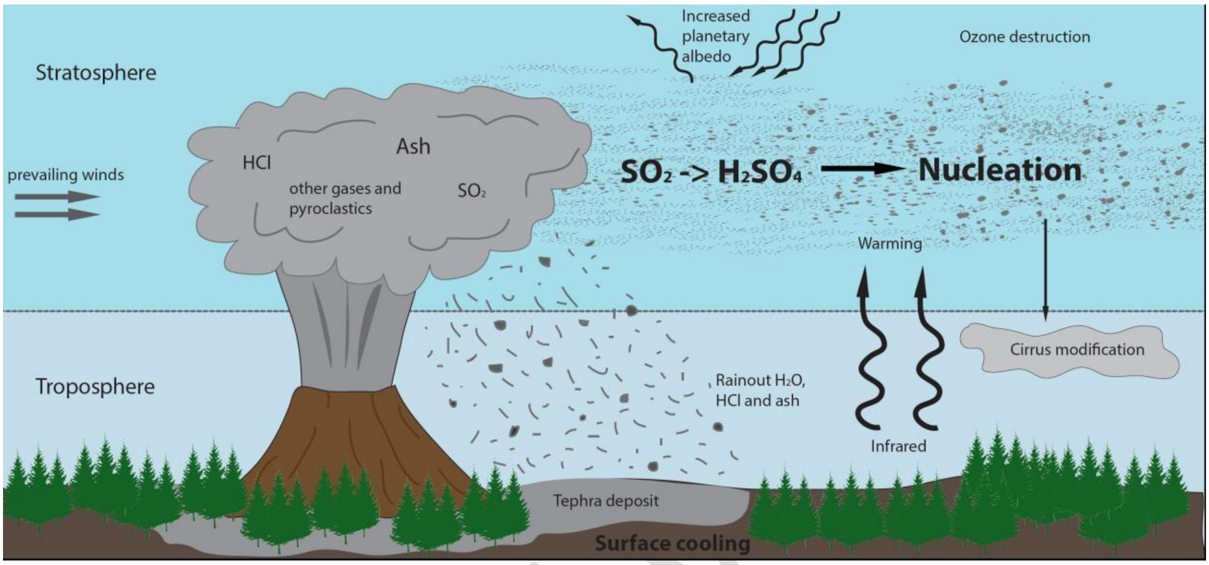


Fig. 5 Examples of microfossils commonly used to infer impacts of volcanic eruptions on terrestrial and aquatic environments. (a) Pollen grains used for terrestrial impacts, (b) diatoms used for aquatic impacts.

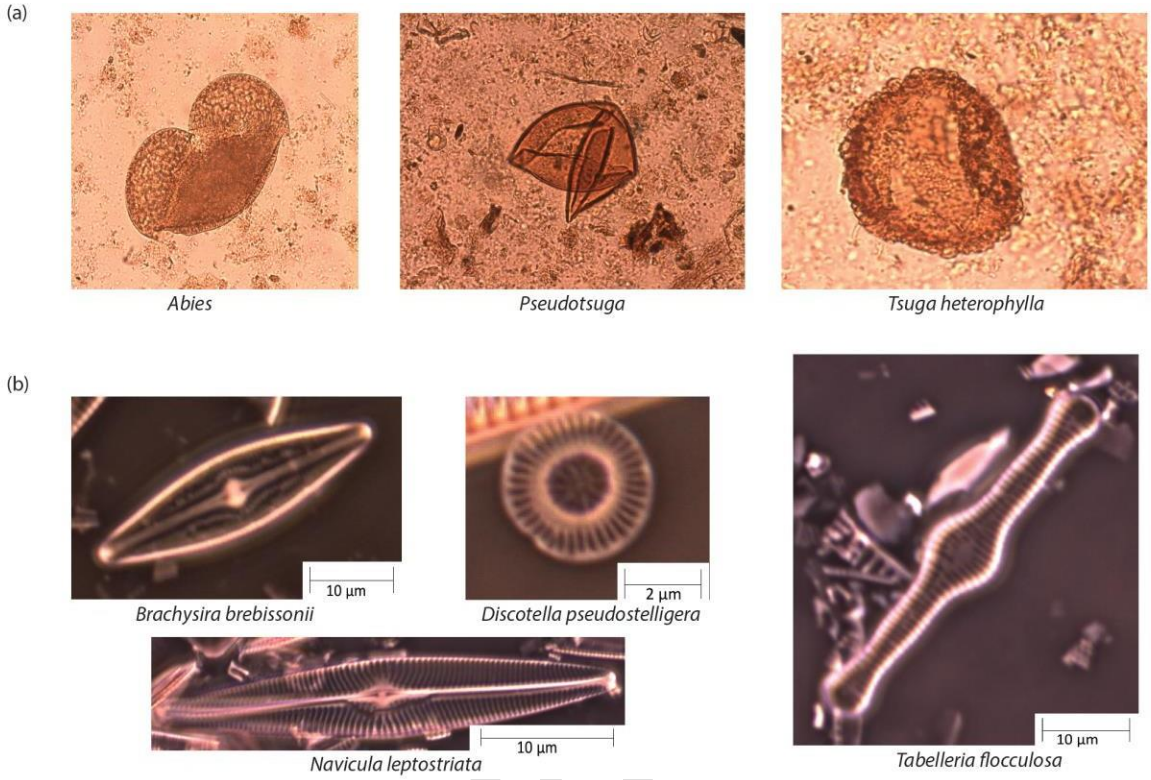


Fig. 6. Schematic illustrating the principles of the tephropalaeoecology approach. See text for explanation.

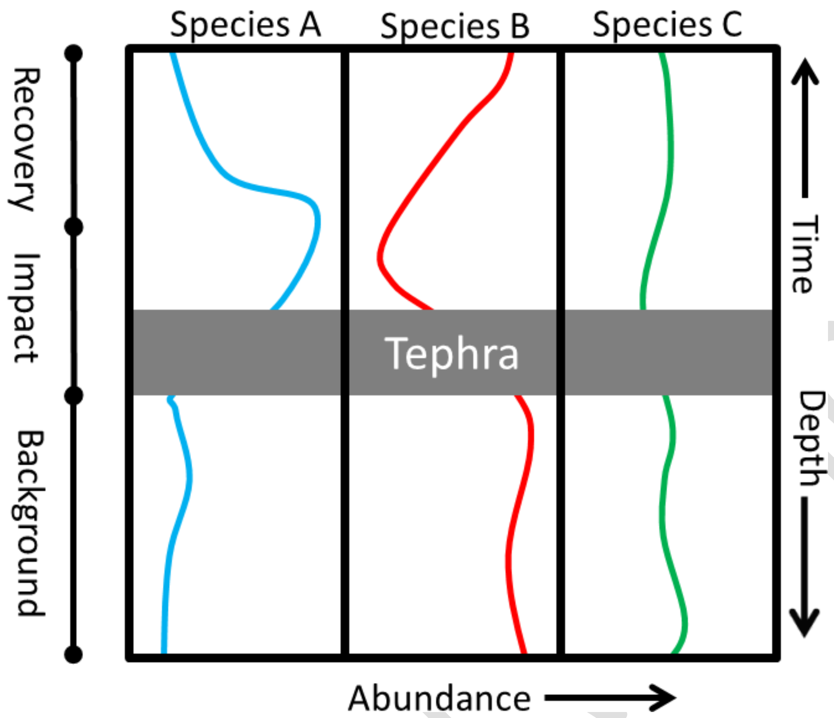


Fig. 7. Summary plot of palaeoecological change across Aniakchak II tephra in northwestern Alaska, showing abundance of two pollen taxa (Cyperaceae and Poaceae) and an oribatid mite.

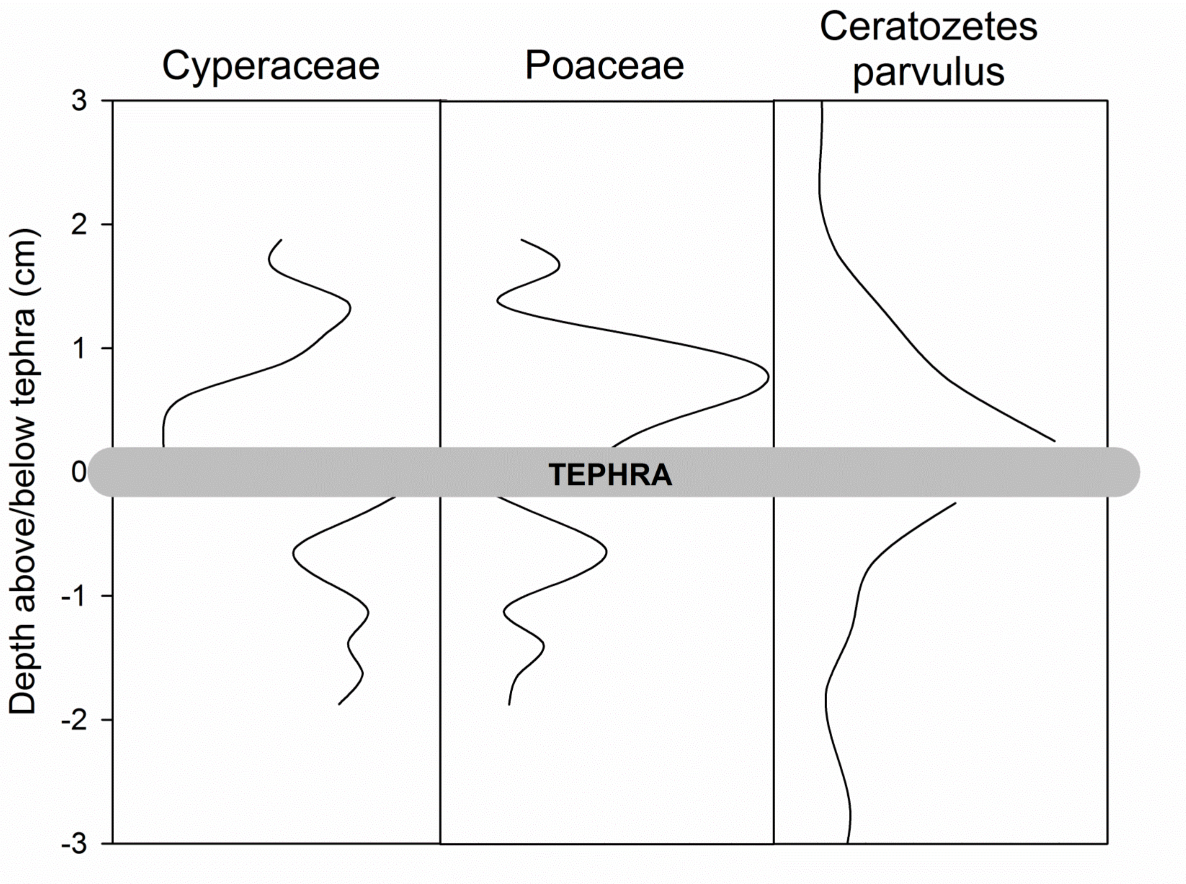


Fig. 8. Trends in *Pinus* pollen across tephra layers believed to represent Hekla-4 in British and Irish sites. Data digitised from original publications (Bennett et al., 1992; Blackford et al., 1992; Hall et al., 1994a; Hall et al., 1994b; Charman et al., 1995; Weir, 1995; Caseldine et al., 1998), see Payne et al. (2013) for further details. There is some ambiguity in the positioning of the tephra peak in some records and digitisation is likely to have introduced some error. Results are presented on a depth rather than age scale because sites have variable quality chronologies, some with no external age control beyond the tephra itself. X-axis scales omitted for clarity due to inconsistency between studies.

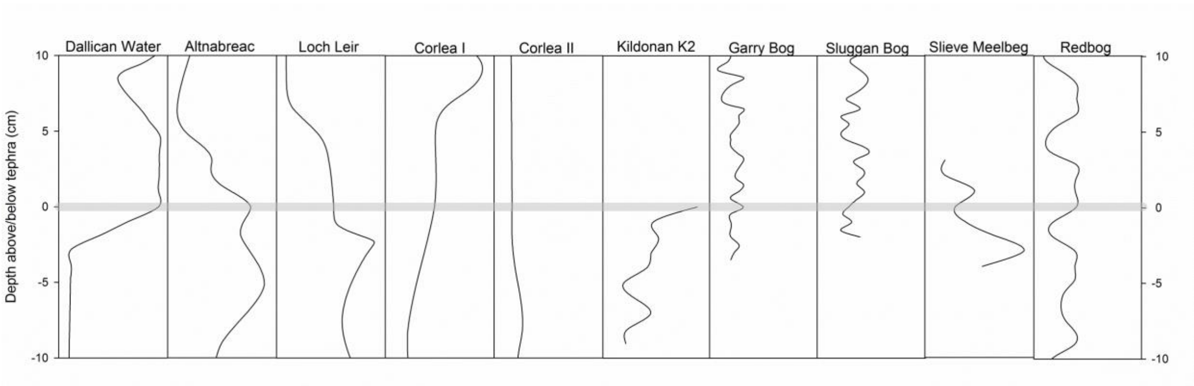


Fig. 9. Summary plot of palaeoecological change across Mazama tephra from the central core at Moss Lake, Washington, showing abundance of *Tsuga heterophylla* and Cupressaceae following tephra deposition. Mazama tephra is 40 mm thick.

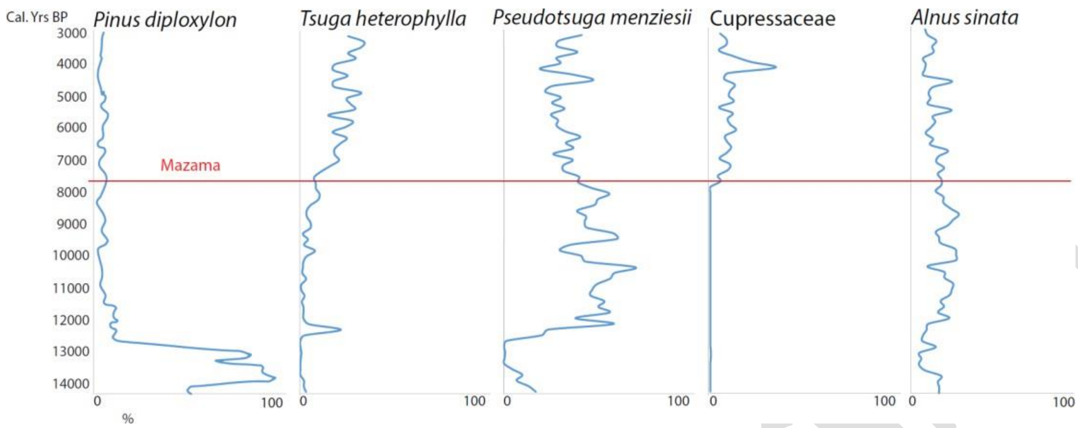
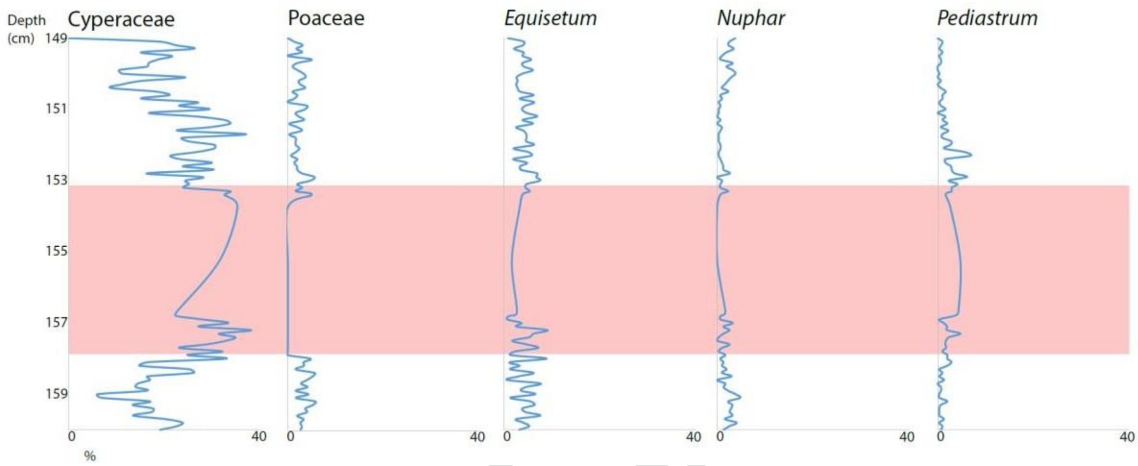


Fig. 10. Summary plot of high-resolution palaeoecological change across Mazama tephra (shaded band) from the fringe lake core at Moss Lake, Washington, showing discrete increases of Cyperaceae and *Pediastrum* and a decrease of Poaceae. Results are presented on a depth rather than age scale because of poor chronological control (beyond the tephra itself) due to an age reversal. Mazama tephra is approximately 50 mm thick, but the boundaries are not well defined.



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