Testing the ‘Laacher See hypothesis’: a health hazard perspective

Felix Riede*†, Oliver Bazely$

† *AHRC Centre for the Evolution of Cultural Diversity, Institute of Archaeology, University College London, 31-34 Gordon Square, London WC1H 0PY*

$ *Department of Geography, University of Cambridge, Downing Place, Cambridge CB2 3EN*

* *Tel.: +44 (0)20 7679 4607; E-mail address: f.riede@ucl.ac.uk*

Abstract

It has recently been suggested that the Laacher See volcanic eruption, which occurred around 13,000 years ago, initiated significant demographic fluctuations along the northern periphery of Late Glacial human settlement and that these led to a number of material culture transformations. The origins of the Southern Scandinavian Bromme culture and the northeastern European Perstunian culture as well as the temporary abandonment of Central European regions have been linked to this eruption. However, it remains unclear precisely which aspects of the eruption stimulated Late Glacial foragers to abandon their traditional ways of life. Paradoxically, the culture-historical impact of the eruption appears greater further away from the eruptive centre. Here, we investigate one potential middle-range link between the Laacher See eruption and Late Glacial fauna and foragers: tephra as a health hazard. We use laser-diffraction particle-size analysis to quantitatively investigate tephra from one site with a secure Late Glacial archaeological deposit. In addition, we use values previously reported in the literature and a predictive model to calculate the hazard potential along a transect of two of the three major Laacher See tephra fans. Our results show that the Laacher See tephra may have posed a potential health hazard and that its hazard potential may have increased with distance from the vent. To our knowledge this is the only study that attempts to quantify the changing grain-size composition of tephra fall-out longitudinally in this way, at least with regard to a prehistoric eruption. We close by discussing, more speculatively, other possible health-pertinent effects of the Laacher See eruption and suggest ways in which future work can further evaluate the impact of this eruption on Late Glacial populations.

Keywords: Late Glacial; Laacher See-eruption; volcanic health hazard; large tanged point cultures; grain-size analysis

1. Introduction

Around 13,000 years ago, the Laacher See volcano, located in present-day western Germany, erupted catastrophically (Schmincke et al., 1999). With a calculated magnitude (*M*; see Mason et al., 2004) of ~ 5.8, the Laacher See eruption (LSE) was one of the largest volcanic events of the Late Pleistocene in the Northern Hemisphere. In the course of the eruption, near-vent ejecta devastated some 1,400 km^2 of land and a total estimated area of more than 225,000 km^2 was affected by tephra (Fisher and Schmincke, 1984) falling out of a Plinian eruption column that may have reached a height of 40 km (van den Bogaard et al., 1990). The River Rhine was dammed up to form a large lake, which subsequently drained catastrophically (Park and Schmincke, 1997) depositing flood-wave debris far downstream. The thick near-vent tephra blanket has covered and so preserved animal tracks (Baales and von Berg, 1997), burned wood landscapes and other macro-botanical remains (Baales et al., 1999), as well as some of the most remarkable archaeological sites of the Late Glacial (Baales, 2002; 2006).

Although it has long been known that Laacher See tephra (LST) occurs in regions far removed from the eruptive centre, recent years have seen renewed interest in this event and its associated distal tephra deposits for two reasons. First, the occurrence of isochronous tephra layers in terrestrial and marine climatic records can act as a useful marker for linking such sequences and for constructing more robust climate change models (Davies et al., 2002). In particular, recent developments in the detection and analysis of crypto- or microtephra (Blockley et al., 2005; Turney et al., 2004) have opened up many new areas, previously considered unaffected by volcanic fall-out, for investigation. LST, which is known to be widespread (van den Bogaard and Schmincke, 1985) and is well investigated chemically (Harms and Schmincke, 2000; Wörner and Schmincke, 1984), has played a critical role in this field of research (e.g., Blockley et al., 2008; Davies et al., 2005; Turney et al., 2006).

Second, it has been suggested that the LSE and its associated fall-out set in motion a series of demographic fluctuations along the northern periphery of Late Glacial human settlement and that these led to material culture transformations clearly visible in the archaeological record (Riede, 2007; 2008). In particular, the origins of the Southern Scandinavian Bromme culture and the eastern European Perstunian culture as well as the virtually complete abandonment of Central European regions(the Thuringian Basin) have been linked to this event (Fig. 1). Typologically impoverished and regionally distinct, the material culture and settlement structure of the Bromme and Perstunian cultures contrast sharply with those of the preceding Federmesser groups. A quantitative analysis of the large tanged points that are characteristic of these two post-LSE techno-complexes (Riede, in press) shows that they were used as tips for spear-thrower propelled darts, whereas the Federmesser points are clearly associated with bow-and-arrow technology (Rozoy, 1985). On the basis of the demographic model of Henrich (2004) for the loss of technological complexity in isolated groups living at low population densities, and by using calibrated ^{14}C dates as proxies for population density, it has been suggested that traditional trade, exchange and communication routes were disrupted by the LST fall-out as people avoided the affected regions.

Fig. 1

In formulating this ‘Laacher See hypothesis’ – that the LSE led to significant demographically mediated material culture change at the end of the Allerød – we noted that the mechanistic links between the eruption itself and contemporaneous flora, fauna and foragers remain obscure (Riede, 2007). It is well attested that the LSE impacted on continental-scale climatic patterns on an annual or decadal scale (Baales et al., 2002; Birks and Lotter, 1994; Graf and Timmreck, 2001; Litt et al., 2003; Schmincke, 2006). However, climatic changes such as unusual optical phenomena or increased precipitation cannot readily be related to prehistoric technological change. An additional challenge to the Laacher See hypothesis is the fact that the nature of the archaeological impact appears to change and perhaps even become more pronounced further removed from the eruptive centre along a proximal-to-distal transect of at least the northeastern fall-out fan. So far, most work has focused on the proximal regions where recent excavations have discovered the first site on top of the LST (Baales and Jöris, 2001; 2002; Grimm, 2004; Waldmann et al., 2001). Despite the total destruction of proximal landscapes, foragers evidently moved back after a relatively short time. Ecosystem recovery studies on more recent eruptions indicate that the re-colonisation of volcanic deposits by pioneer species can proceed at a fairly rapid pace, although this is usually restricted to tropical latitudes (Dale et al., 2005; Edwards, 2005). Equally, however, it should be noted that there remains a striking contrast between pre- and post-LSE Federmesser settlement density in the Rhineland and that intermittent or even seasonal visits do not equate to re-occupation. Dumond (2004, p. 113), for instance, reports that the indigenous foragers who lived close to Katmai (Alaska) volcano which erupted in 1912 with a magnitude far below that of the LSE 'were returning to that area in summers for hunting but felt it was still impossible to live there'. Importantly, he then goes on to argue that volcanic eruptions had a major impact on the prehistoric demography and culture history of Alaska (see also Maschner 2000 and Maschner and Jordan 2008). A more thorough assessment of the impact of the LSE on Late Glacial foragers living in proximal regions therefore will have to wait until further fieldwork has rectified the taphonomic bias against post-eruption sites.

Here, we investigate one potential mechanistic link that may have affected foragers living in the medial and distal fall-out areas: tephra as a health hazard. Air-fall tephra can be very fine-grained and as such pose a significant respiratory hazard to animals as well as people. This issue has been investigated thoroughly in the context of hazard mitigation procedures for on-going and future eruptions (Baxter, 2000; 2005; Horwell, 2007; Horwell and Baxter, 2006). In this study we present a systematic assessment of the changing dynamics of the health hazard potential of the LST along both the northeastern as well as the southwestern fall-out lobes. Anchored by a laser-diffraction particle-size analysis of tephra from the Late Glacial rock-shelter site of Bettenroder Berg IX (Grote, 1990) we use values reported in the literature to estimate the respiratory health hazard of other locales up 370 km away from the eruptive centre. Our results show that the LST may indeed have posed a potential health hazard and that its hazard potential may have increased with distance from the vent. We also discuss, more speculatively, other possible health-pertinent effects of the Laacher See eruption and suggest ways in which future work can further investigate the impact of this eruption on Late Glacial populations.

2. Volcanic tephra as health hazard

Volcanoes can affect people in a multitude of ways (Baxter, 2005; Blong, 1984; Chester, 2005). While proximal hazards – lava and pyroclasitc flows, suffocating gases, high-velocity volcanic bombs etc. – are often more spectacular and more immediately lethal, medial and distal fall-out should not be ignored in its potentially harmful effects (Edwards et al., 1994; Thorarinsson, 1979). The hazard dimensions of tephra fall-out change with distance from source primarily because the grain-size composition of the fall-out trends towards more fine-grained along this axis (Óskarsson, 1980). While it is known that the relationship between distance-from-vent and tephra fall-out thickness is not linear (Pyle, 1989), the relationships between distance-from-vent and particle size composition and chemical load can be modelled and have been investigated empirically (Kittleman, 1979). While we will return to the potential chemical hazard of LST later in this paper, we now introduce the respiratory health effects of fine-grained tephra.

The investigation of the health hazards of volcanic tephra is important because an ever-increasing number of people (currently ~ 9% of the world population or some 455 million people) live within zones of high volcanic risk, especially in poorer countries (Small and Naumann, 2001) undergoing rapid urbanization (Chester et al., 2001). Often widespread, tephra can affect large numbers of people and with volcanic events being rare in most parts of the world, experience of how to deal with the consequences is often lacking. The eruption of Mount St. Helens (USA) in 1980 stimulated a research programme into the health effects of distal tephra fall-out (Baxter et al., 1983) and there now exists a number of clinical, epidemiological and volcanological studies, recently reviewed by Horwell and Baxter (2006). These indicate that 'most explosive eruptions form fine, respirable ash which could be the cause of an acute or chronic health hazard for the exposed populations' (Horwell and Baxter, 2006, p. 20).

Acute manifestations of tephra-related health effects, which have been observed during or following the eruptions of Mount St. Helens (USA), Cerro Negro (Nicaragua), Mount Ruapehu (New Zealand), Guagua Pichincha (Ecuador) and Irazu (Costa Rica), include asthma attacks, bronchitis, breathlessness, chest tightness and wheezing. These are brought on by fine-grained tephra particles entering and lining the airways. To previously undiagnosed people, especially children, the onset of asthma attacks can be frightening. In the elderly, they can be fatal. The effects of prior sufferers' afflictions can be exacerbated (Baxter et al., 1983). On the whole mortality is low, but people's day-to-day performance and wellbeing can be severely reduced, while morbidity is raised. In addition to acute effects, long-term (years to decades) exposure to respirable tephra, analogous to occupational exposure to fine dust, could potentially lead to the development of chronic conditions such as silicosis or chronic obstructive pulmonary disease (COPD). Both are brought on by respirable particles penetrating deeply into the lungs, leading to scarring in the case of silicosis and the irreversible narrowing of the airways and chronic mucous hypersecretion in COPD (International Agency for Research on Cancer, 1997). Cases of chronic respiratory health effects following volcanic eruptions have not yet been observed, but the database is minimal and the risk remains difficult to quantify.

In order to assess the health hazard potential of a given volcanic eruption and its tephra fall-out, it is essential to obtain accurate measurement of the grain-size distribution, especially at the lowest end of the size distribution. Particles only become hazardous at sizes < 15 µm (aerodynamic diameter) and can penetrate deeper into the pulmonary system as size decreases. Particles < 10 µm (the 'thoracic fraction') may cause asthma and severe breathing difficulties, and those < 4 µm (the 'respirable fraction') will settle in the alveoli bringing with them the greatest health hazard (Fig. 2). Horwell (2007) has recently presented a comprehensive review and comparison of different grain-size analysis techniques, including data on the grain-size distribution of a number of on-going, recent and historic eruptions. Building on her work, we present the first systematic analysis of the changing grain-size distribution of a prehistoric eruption along a medial-to-distal fall-out transect for two of the three major fall-out lobes. To our knowledge this is the only study that attempts to quantify the changing grain-size composition of tephra fall-out in this way.

Fig. 2

----

3. Materials and methods

We have conducted a systematic review of the literature dealing with the LSE going back to the late 19th century when the occurrence of LST outside the immediate near-vent area was first being discussed (e.g., Brauns, 1886; Sandberger, 1882). A geo-referenced database, named *LSTbase*, has been assembled containing at present over

330 known find localities of LST, their associated distance-from-vent and deposit thickness as well as, where available, details of their archaeological association, chemical signature or heavy minerals composition, and sedimentary context. Preliminary versions of this database can be obtained from the corresponding author upon request and it will soon be made publically available. From this database we have first plotted the relationship between fall-out thickness and distance-from-vent (Fig. 3) in order to better divide the fall-out lobes into proximal, medial and distal regions, and to assess at what distances particular effect types should be expected to dominate. We then extracted from the database all available grain-size data, which covers both the northeastern as well as the southwestern fall-out lobe. Details of these samples and the analytical methods used to obtain the grain-size values are given in Table 1. Where only the sub-63 µm fraction has been reported, we have used the predictive model of Horwell (2007) to calculate the health-pertinent fraction in those samples.

Table 1

Fig. 3

In addition to this literature-based analysis, we have carried out a semi-systematic sampling programme of the northeastern fall-out lobe. A total of N = 7 samples were collected from localities between c. 120 and 580 km distance from the eruptive centre (Fig. 4 and Table 2). However, as it is essential to analyze only pure, non-reworked tephra, only two of the samples yielded useable results. Of these, the most proximal from the Herbstlabyrinth-Adventhöhle cave system (Dorsten and Harries, 2006) yielded only material too coarse-grained (1 - 5 mm) for meaningful grain-size analysis using laser-diffraction. There are also doubts as to how the tephra was deposited in the cave and whether fluvial action may have removed the fine fraction. Given the thicknesses still observed at sites at this and greater distances, however, indirect health-related effects may have played only a minor role here.

Fig. 4

Table 2

The remaining locality, the rock-shelter Bettenroder Berg IX, yielded tephra sufficiently fine-grained to pose as a respiratory hazard. Using pedological methods, Ahl and Meyer (1994) already determined that this tephra represents a pure and primary deposit, devoid of organic contaminants. The sample analyzed here was obtained from Dr. Klaus Grote who originally excavated at Bettenroder Berg (Grote 1994). Following Horwell (2007), the sample was dried in an oven at ~90 °C for 24 h, then sieved to < 1 mm diameter (0 Phi) to ensure that grains greater than 2000 mm aerodynamic diameter were not analysed. Any organic material was removed manually. The samples did not contain significant material greater than 1 mm diameter, making adjustment of the results to take into account coarser fractions not included in the laser diffraction analysis unnecessary. We then proceeded with the laser-diffraction analysis particle-size analysis using a Malvern Mastersizer 2000 HydroMU laser diffractometer, and following the method described in detail by Horwell (2007). Laser-diffraction is the method of choice for measuring the size distributions of powders. Frechen (1952) reports refractive indices (RI) for LST minerals from Andernach, Kernberg, Luttersee and Frankleben that range from 1.535 to 1.506, giving a mean RI of 1.521, close to that of the AD 79 eruption of Vesuvius (RI = 1.526), which was similar in chemical composition (i.e., phonolitic) to the LSE, albeit much smaller. More specifically, the light gray tephra from Andernach, Luttersee c and Frankleben b, similar in colour to that from Bettenroder Berg and possibly from the same eruption phase, gave RI of between 1.513 and 1.520. In our analyses, we varied the RI from 1.506 to 1.532, noting that the finest fraction seems least affected by this variation (Fig. 5). In the remainder of this paper, we use the RI = 1.520 values.

An absorption coefficient of 0.1 was used and water as the suspension medium; each sample was run ten times and averaged for the final value. The data from the size bins provided by the laser diffractometer were then interpolated to reflect the health-pertinent fractions. Horwell (2007) has shown that grain-size analysis using laser-diffraction is robust in relation to variation in these instrument settings, and the settings used here are well within the recommended range.

Fig. 5

The grain-size distribution (see Fig. 5) has a typically bimodal shape (Pyle, 1989), is consistent with published values from other eruptions (Horwell, 2007), and improves on previously reported values for the nearby deposits at Bettenroder Berg I obtained by sieving and settling methods (Ahl and Meyer, 1994). The grain-size value for the Bettenroder Berg IX tephra reported here matches the (calculated) PM_{10} (particulate matter < 10 µm) value reported by Ahl and Meyer if the (lower) error fit is taken into account. Importantly, at both sites there is a direct stratigraphic association of LST with Late Glacial archaeology. LST is preserved consistently in the rock-shelters lining the River Leine, near Göttingen (Grote, 1988; 1990; 1994; 1999; Grote and Freese, 1982). At Bettenroder Berg I and IX the LST reaches a thickness of 20 - 40 cm and directly overlies Federmesser assemblages including (at Bettenroder Berg I) the remains of a large cervid whose skull protrudes into the tephra (Fig. 6). Although there are scant traces of human presence from the period some time after the LSE but before the onset of the GS-1/Younger Dryas cooling episode, there is no consistent evidence for a sustained and demographically viable human presence in this area until the Mesolithic (Fiedler, 1994; also Riede, 2007; 2008).

As Horwell (2007) makes clear the grain-size distributions obtained by different analytical techniques are not directly comparable. In addition, the discrepancy between the PM_{10} values reported by Jungerius et al. (1968) and the figures for the same fraction calculated using their data (< 63 µm) and the method of Horwell (2007) raises the possibility of a bias in this part of the dataset. However, this appears to be a systematic bias inherent in this otherwise coherent dataset suggesting that although the values themselves may not be correct, a trend can nonetheless be observed. Jungerius and colleagues do not provide enough details regarding the sample provenance and processing for this discrepancy to be evaluated further. For these reasons we caution that the results of all grain-size analyses reported here, summarized in Table 3, may not represent the true picture of changing grain-size composition for the LST. Nonetheless they do show that the health hazard potential of the LST may have increased with distance from vent and as an inverse of deposit thickness.

Fig. 6

Table 3

----

4. Discussion and conclusion

A combined consideration of previously published grain-size distributions of the LST with high-resolution laser-diffraction grain-size analysis of a further, newly obtained tephra sample allows us to better assess the potential health hazard of this prehistoric eruption. A comparison with published grain-size distribution values for other eruptions shows that the LSE may have posed an above-average health hazard, as could be expected given the magnitude of the LSE and that 'the greater the explosivity of the eruption, the more fine material is produced' (Horwell et al., 2007, p. 667). Although our total sample size is small, the available data indicate that grain-size related health effects may at the least have been a contributing factor in the demographic and cultural transformations following the LSE.

The stable ratios of the various grain-size fractions reported by Horwell (2007) imply that the reduction of tephra particle size with distance-from-vent reaches a plateau at some distance. It is therefore difficult to ascertain whether the increase in the health-pertinent fraction of the LST suggested here is an artefact of the different analytical methods used in the various studies or whether it reflects a real pattern. Given that the most distal LST localities beyond 370 km are not represented in our sample, and given that the decrease in grain-size between Luttersee (250 km) and Frankleben (370 km) is negligible, it is possible that this grain-size plateau was reached at approximately this distance. Importantly, however, we demonstrate empirically here that the LST did contain a health-hazardous grain-size component, even if this was fairly moderate. Therefore, this mechanism – further aggravated perhaps by chemical effects also linked to grain-size (Horwell et al., 2007; Horwell et al., 2003a; Horwell et al., 2003b) – may go some way towards resolving the apparent paradox that the culture-historical impact of the LSE seems to have been more pronounced in regions affected by distal fall-out. Given our small sample size, the present study should be seen as preliminary. A larger-scale, systematic sampling programme may be able to produce further samples suitable for laser-diffraction grain-size analysis and in so doing may substantially revise our preliminary suggestions outlined here.

Was an irritation of the lungs, asthma and bronchitis enough to result in a long-term abandonment of vast tracts of landscape following tephra deposition? Few detailed case studies of how more recent foraging populations responded to volcanic eruptions are known (Dumond, 2004; Maschner 2000; Maschner and Jordan 2008; VanderKoek and Nelson, 2007) and these do indicate that re-location may have been a major means of hazard-mitigation (see also: Rowley, 1985), especially in cases of rare and large eruptions where threats were immediate and stocks of traditional knowledge regarding eruptions and adequate responses to them low (Blong, 1982; Cronin and Cashman, 2007). Hunter-gatherers certainly would have been highly vulnerable given that volcanic fall-out poses a significant economic and ecological challenge even for industrialized nation states (Blong, 1984). By the same token, health hazard effects are likely to have acted in concert with other mechanisms, such as fluoride poisoning of people as well as (and perhaps more importantly) of game animals (Cronin et al., 2000). Anecdotal reports also speak of severe and ultimately lethal increases in dental wear as people and animals ingest significant amounts of tephra-laden vegetation (Trowbridge, 1976). Both the chemical load as well as the mechanical properties of distal tephra fall-out have contributed substantially to the direct and indirect impacts of other past eruptions (e.g., Edwards et al., 1994; Grattan and Gilbertson, 2000; Grattan et al., 2007; Grattan et al., 2005). Fluoride, with which the lower LST phase (LLST) – the one that participated preferentially in the distal NE fall-out – is 'extremely…enriched' (Harms and Schmincke, 2000, p. 90), causes enamel to soften (Fejerskov et al., 1988) and this may further compound already increased tooth wear due to mechanical abrasion. Ancient fluoride in teeth does not survive post-depositional alteration (Hillson, 2005), but future work may, for instance, profitably investigate the hardness of LST in comparison with that of human as well as key Late Glacial prey species' teeth.

In sum, the LSE is highly likely to have affected contemporaneous forager populations indirectly. While some of these effects, for instance those on mental health (Adams and Adams, 1984) and religious life (Chester, 2005) are elusive archaeologically others are within our empirical grasp. The analysis presented here, of the respiratory health-pertinent particle-size fractions of the Laacher See tephra fall-out, constitutes a first attempt to test the Laacher See hypothesis by indicating that this mechanism could plausibly have contributed to produce the remarkable culture-historical effects recorded in the archaeological record.

Acknowledgements

Martin Theuerkauf kindly shared his data on the LST in northeastern Germany and provided samples. Jaqueline Strahl also provided LST data and arranged the sampling of the Paddenluch. Klaus Grote kindly provided the samples from Bettenroder Berg IX, Ingo Dorsten those of the Herbstlabyrinth-Adventhöhle, and Susanne Jahns those from Langes Fenn. F.R. conducted this research as part of a British Academy Post-doctoral Fellowship and in addition is generously funded by the D.M. McDonald Fund (Laacher See Project). The encouragement of Peter Baxter (Medical School, Cambridge) advice and comments of Claire Horwell (Durham) have contributed substantially to the completion of this research.

Figure captions

Fig. 1. A schematic map of the forager population movements in the wake of the LSE, as suggested by Riede (2007; 2008). The basis of this figure are Jacobi's (1980), Taute's (1968) and Kozlowski's (1975) maps of find locales with large tanged points (+) and large tanged points together with Federmesser (⊕) along the Late Glacial settlement periphery, with additions from Breest and Gerken (in press). The eruption phase sequence and tephra distribution is from Schmincke et al. (1999). FMG = Federmesser-Gruppen.

Fig. 2. Schematic diagram of the human lungs and airways showing the penetration depths of differently sized particles. From Horwell and Baxter (2006).

Fig. 3. Distance-from-vent plotted against deposit thickness on a semi-log scale. ■ = NE fall-out lobe, • = SW fall-out lobe. See Fisher and Schmincke (1984) for similar plots from other eruptions and Schumacher and Schmincke (1990) for a grain-size analysis of proximal LSE deposits. Note that some of these thickness values are considerable and even if they do not constitute primary deposits point to the ready availability of tephra in the landscape for some time after the eruption. Thorarinsson (1958) determined for eruptions c. 600-700 years old that tephra becomes compacted to one-third its original thickness. Considering the known values collated in *LSTbase* and this correction factor, the thickness values provided by van den Bogaard and Schmincke (1985) and on subsequently published distribution maps may need to be corrected upwards if they are to reflect the original thickness of the tephra blanket. For the impact of heavy tephra fall on flora and fauna see Blong (1984) and www.maf.govt.nz/mafnet/rural-nz/emergency-management/volcanoes/volcano-erruption-impact.

Fig. 4. A map showing the total estimated tephra distribution of the main LSE phases, and the samples used in this study. Based on Schmincke et al. (1999).

Fig. 5. The shape of the grain-size distribution of the LST at Bettenroder Berg IX. Grain-size is plotted, in µm (equivalent spherical diameter, ESD) on a log-scale, using varying RI settings.

Fig. 6. The stratigraphy at Bettenroder Berg I. The tephra is layer VI. From Grote (1990).

References

Adams, P.R., Adams, G.R., 1984. Mount Saint Helens's ashfall: Evidence for a disaster stress reaction. American Pychologist 39**,** 252-260.

Ahl, C., Meyer, B., 1994. Zur bodenkundlich-sedimentologischen Horizontabfolge der Hauptabris im Buntsandsteingebiet von Reinhausen. In: Grote, K. (Ed.), Die Abris im südlichen Leinebergland bei Göttingen. Archäologische Befunde zum Leben unter Felsschutzdächern in urgeschichtlicher Zeit. Isensee Verlag, Oldenburg, pp. 37-52.

Baales, M., 2002. Vulkanismus und Archäologie des Eiszeitalters am Mittelrhein. Die Forschungsergebnisse der letzten dreissig Jahre. Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz 49**,** 43-80.

Baales, M., 2006. Final Palaeolithic environment and archaeology in the Central Rhineland (Rhineland-Palatinate, western Germany): conclusions of the last 15 years of research. Anthropologie 110**,** 418-444.

Baales, M., Bittmann, F., Kromer, B., 1999. Verkohlte Bäume im Trass der Laacher See-Tephra bei Kruft (Neuwieder Becken). Ein Beitrag zur Datierung des Laacher See-Ereignisses und zur Vegetation der Alleröd-Zeit am Mittelrhein. Archäologisches Korrespondenzblatt 28**,** 191-204.

Baales, M., Jöris, O., 2001. Zwischen Nord und Süd. Ein spätallrödzeitlicher Rückenspitzen-Fundplatz bei Bad Breisig, Kr. Ahrweiler (Mittelrhein, Rheinland-Pfalz). Die Kunde N.F. 52**,** 275-292.

Baales, M., Jöris, O., 2002. Between North and South - a site with backed points from the final Allerod: Bad Breisig, Kr. Ahrweiler (Central Rhineland, Germany). Anthropologie 106**,** 249-267.

Baales, M., Jöris, O., Street, M., Bittmann, F., Weninger, B., Wiethold, J., 2002. Impact of the Late Glacial Eruption of the Laacher See Volcano, Central Rhineland, Germany. Quaternary Research 58**,** 273-288.

Baales, M., von Berg, A., 1997. Tierfährten in der allerödzeitlichen Vulkanasche des Laacher See-Vulkans bei Mertloch, Kreis Mayen-Koblenz. Archäologisches Korrespondenzblatt 27**,** 1-12.

Baxter, P.J., 2000. Impacts of eruptions on human health. In: Sigurdsson, H. (Ed.), Encyclopaedia of Volcanoes. Academic Press, San Diego, CA., pp. 1035-1056.

Baxter, P.J., 2005. Human impacts of volcanoes. In: Martí, J., Ernst, G.G.J. (Eds.), Volcanoes and the Environment. Cambridge University Press, Cambridge, pp. 273-303.

Baxter, P.J., Ing, R., Falk, H., Pliakaytis, B., 1983. Mount St. Helens eruptions: the acute respiratory effects of volcanic ash in a North American community. Archives of Environmental Health 38**,** 138-143.

Birks, H.J.B., Lotter, A.F., 1994. The impact of the Laacher See Volcano (11000 yr B.P.) on terrestrial vegetation and diatoms. Journal of Paleolimnology 11**,** 313-322.

Blockley, S.P.E., Pyne-O'Donnell, S.D.F., Lowe, J.J., Matthews, I.P., Stone, A., Pollard, A.M., Turney, C.S.M., Molyneux, E.G., 2005. A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. Quaternary Science Reviews 24**,** 1952-1960.

Blockley, S.P.E., Bronk Ramsey, C., Lane, C.S., Lotter, A.F., 2008. Improved age modelling approaches as exemplified by the revised chronology for the Central European varved lake Soppensee. Quaternary Science Reviews 27**,** 61-71.

Blong, R.J., 1982. The Time of Darkness. Local legends and volcanic reality in Papua New Guinea. University of Washington Press, Seattle, WA.

Blong, R.J., 1984. Volcanic Hazards. A Sourcebook on the Effects of Eruptions. Academic Press, Sydney.

Brauns, R., 1886. Bimssteine auf primärer Lagerstätte von Görzhausen bei Marburg. Zeitschrift der deutschen geologischen Gesellschaft 38**,** 234-236.

Breest, K., Gerken, K., in press. Sassenholz 78 und 82 – Zwei mehrphasige Fundstellen mit Bromme-Spitzen im Ldkr. Rotenburg (Wümme). Ein Diskussionsbeitrag zu den kulturellen Einflüssen und Beziehungen spätpaläolithischer und mesolithischer Gruppen im nördlichen Niedersachsen. Die Kunde N.F. 58.

Chester, D.K., 2005. Volcanoes, society, and culture. In: Martí, J., Ernst, G.G.J. (Eds.), Volcanoes and the Environment. Cambridge University Press, Cambridge, pp. 404-439.

Chester, D.K., Degg, M., Duncan, A.M., Guest, J.E., 2001. The increasing exposure of cities to the effects of volcanic eruptions: a global survey. Environmental Hazards 2**,** 89-103.

Cronin, S.J., Cashman, K.V., 2007. Volcanic Oral Traditions in Hazard Assessment and Mitigation. In: Grattan, J., Torrence, R. (Eds.), Living Under The Shadow. Cultural Impacts of Volcanic Eruptions. Left Coast Press, Walnut Creek, CA., pp. 175-202.

Cronin, S.J., Manoharan, V., Hedley, M.J., Loganathan, P., 2000. Fluoride: A review of its fate, bioavailability, and risks of fluorosis in grazed-pasture systems in New Zealand. New Zealand Journal of Agricultural Research 43**,** 295-321.

Dale, V.H., Delgado-Acevedo, J., MacMahon, J., 2005. Effects of modern volcanic eruptions on vegetation. In: Martí, J., Ernst, G.G.J. (Eds.), Volcanoes and the Environment. Cambridge University Press, Cambridge, pp. 227-249.

Davies, S.M., Branch, N.P., Lowe, J.J., Turney, C.S.M., 2002. Towards a European tephrochronological framework for Termination 1 and the Early Holocene. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 360**,** 767-802.

Davies, S.M., Hoek, W.Z., Bohncke, S.J.P., Lowe, J.J., O'Donnell, S.P., Turney, C.S.M., 2005. Detection of Lateglacial distal tephra layers in the Netherlands. Boreas 34**,** 123-135.

Dorsten, I., Harries, D., 2006. Fund von Laacher-See-Bims im Herbstlabyrinth-Adventhöhlen-System (Hessen). Speläologische Arbeitsgemeinschaft Hessen e.V.: www.sah-breitscheid.de/veroffentlichungen.

Dumond, D.E., 2004. Volcanism and History on the Northern Alaska Peninsula. Arctic Anthropology 41**,** 112-125.

Edwards, J.S., 2005. Animals and volcanoes: survival and revival. In: Martí, J., Ernst, G.G.J. (Eds.), Volcanoes and the Environment. Cambridge University Press, Cambridge, pp. 250-272.

Edwards, K.J., Buckland, P., Blackford, J.J., Dugmore, A., Sadler, J.P., 1994. The Impact of Tephra: Proximal and Distal Studies of Icelandic Eruptions. In: Stötter, J., Wilhelm, F. (Eds.), Environmental Change in Iceland. Münchner Geographische Abhandlungen, Reihe B, Band 12. GEOBUCH, Munich, pp. 79-100.

Fejerskov, O., Manji, F., Baelum, V., Møller, I.J., 1988. Dental fluorosis - a handbook for health workers. Munksgaard, Copenhagen.

Fiedler, L., 1994. Alt- und mittelsteinzeitliche Funde in Hessen. Theiss, Stuttgart.

Fisher, R.V., Schmincke, H.-U., 1984. Pyroclastic Rocks. Springer-Verlag, Berlin.

Frechen, J., 1952. Die Herkunft der spätglazialen Bimstuffe in mittel- und süddeutschen Mooren. Geologisches Jahrbuch 67**,** 209-230.

Graf, H.-F., Timmreck, C. (2001). A general climate model simulation of the aerosol radiative effects of the Laacher See eruption (10,900 B.C.). Journal of Geophysical Research 106: 14747-14756.

Grattan, J., Gilbertson, D.D., 2000. Prehistoric “settlement crisis”, environmental changes in the British Isles, and volcanic eruptions in Iceland: An exploration of plausible linkages. In: McCoy, F.W., Heiken, G. (Eds.), Volcanic Hazards and Disasters in Human Antiquity. The Geological Society of America, Boulder, CO., pp. 33-42.

Grattan, J., Michnowicz, S., Rabartin, R., 2007. The Long Shadow: Understanding the Influence of the Laki Fissure Eruption on Human Mortality in Europe. In: Grattan, J., Torrence, R. (Eds.), Living Under The Shadow. Cultural Impacts of Volcanic Eruptions. Left Coast Press, Walnut Creek, CA., pp. 153-174.

Grattan, J., Rabartin, R., Self, S., Thordarson, T., 2005. Volcanic air pollution and mortality in France 1783–1784. Comptes Rendus De l’Academie Des Sciences Serie II 337**,** 641-651.

Grimm, S.B., 2004. Ein spätallerödzeitlicher Fundplatz bei Bad Breisig, Kreis Ahrweiler. Berichte zur Archäologie an Mittelrhein und Mosel 9**,** 11-32.

Grote, K., 1988. Die Buntsandsteinabris im südniedersächsischen Bergland bei Göttingen. Erfassung und Untersuchung ihrer ur- und frühgeschichtlichen Nutzung (1983 - 1987). Die Kunde N.F. 39**,** 1-43.

Grote, K., 1990. Das Buntsandsteinabri Bettenroder Berg IX im Reinhäuser Wald bei Göttingen - Paläolithikum und Mesolithikum. Archäologisches Korrespondenzblatt 20**,** 137-147.

Grote, K., 1994. Die Abris im südlichen Leinebergland bei Göttingen. Archäologische Befunde zum Leben unter Felsschutzdächern in urgeschichtlicher Zeit. Isensee Verlag, Oldenburg.

Grote, K., 1999. Vom Leben unter Felsschutzdächern. Jäger und Sammler in Südniedersachsen am Ende der letzten Eiszeit. In: Boetzkes, M., Schweitzer, I., Vespermann, J. (Eds.), EisZeit. Das große Abenteuer der Naturbeherrschung. Begleitbuch zur gleichnamigen Ausstellung. Jan Thorbecke Verlag, Hildesheim.

Grote, K., Freese, H.-D., 1982. Die Felsschutzdächer (Abris) im südniedersächsischen Bergland - Ihre archäologischen Funde und Befunde. Nachrichten aus Niedersachsens Urgeschichte 51**,** 17-70.

Harms, E., Schmincke, H.-U., 2000. Volatile composition of the phonolitic Laacher See magma (12,900 yr BP): implications for syn-eruptive degassing of S, F, Cl and H_2O. Contributions to Mineralogy and Petrology 138**,** 84-98.

Henrich, J., 2004. Demography and Cultural Evolution: How Adaptive Cultural Processes Can Produce Maladaptive Losses - the Tasmanian Case. American Antiquity 69**,** 197-214.

Hillson, S., 2005. Teeth. Second Edition. Cambridge University Press, Cambridge.

Horwell, C.J., 2007. Grain-size analysis of volcanic ash for the rapid assessment of respiratory health hazard. Journal of Environmental Monitoring 9**,** 1107-1115.

Horwell, C.J., Baxter, P.J., 2006. The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. Bulletin of Volcanology 69**,** 1-24.

Horwell, C.J., Fenoglio, I., Ragnarsdottir, K.V., Sparks, R.S.J., Fubini, B., 2003. Surface reactivity of volcanic ash from the eruption of Soufrière Hills volcano, Montserrat, West Indies with implications for health hazards. Environmental Research 93**,** 202-215.

Horwell, C.J., Sparks, R.S.J., Brewer, T.S., Llewellin, E.W., Williamson, B.J., 2003. Characterization of respirable volcanic ash from the Soufrière Hills volcano, Montserrat, with implications for human health hazards. Bulletin of Volcanology 65**,** 346-362.

Horwell, C.J., Fenoglio, I., Fubini, B., 2007. Iron-induced hydroxyl radical generation from basaltic volcanic ash. Earth and Planetary Science Letters 261, 662-669.

International Agency for Research on Cancer, 1997. Silica, some silicates, coal dust and para-aramid fibrils. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 68. International Agency for Research on Cancer, Lyon.

Jacobi, R.M., 1980. The Upper Palaeolithic in Britain, with special reference to Wales. In: Taylor, J.A. (Ed.), Culture and Environment in Prehistoric Wales. British Archaeological Reports (British Series) 76. Oxbow, Oxford, pp. 15-99.

Jungerius, P.D., Riezebos, P.A., Slotboom, R.T., 1968. The age of Eifel Maars as shown by the presence of Laacher See ash of Allerød age. Geologie En Mijnbouw 47**,** 199-205.

Kittleman, L.R., 1979. Geologic Methods in Studies of Quaternary Tephra. In: Sheets, P.D., Grayson, D.K. (Eds.), Volcanic Activity and Human Ecology. Academic Press, London, pp. 49-82.

Kleissle, K., Müller, H.M., 1969. Neue Fundpunkte spätglazialer Bimsaschen im Nordosten der DDR. Geologie 18**,** 600-607.

Köhn, M., 1928. Korngrössenbestimmung vermittels Pipettanalyse. Tonindustrie-Zeitung und keramische Rundschau 53, 729-731.

Kozlowski, S.K., 1975. Quelques Remarques sur le Brommien. Acta Archaeologica 46.

Lang, H.D., 1954. Ein Alleröd-Profil mit eingelagertem Laacher-See-Tuff bei Marburg/Lahn. Neues Jahrbuch für Geologie und Paläontologie-Monatshefte 8**,** 362-372.

Litt, T., Schmincke, H.-U., Kromer, B., 2003. Environmental response to climatic and volcanic events in central Europe during the Weichselian Lateglacial. Quaternary Science Reviews 22**,** 7-32.

Mason, B.G., Pyle, D.M., Oppenheimer, C., 2004. The size and frequency of the largest explosive eruptions on Earth. Bulletin of Volcanology 66**,** 735-748.

Maschner, H.D.G., 2000. Catastrophic Change and Regional Interaction: The Southern Bering Sea in a Dynamic World System. In: Appelt, M., Berglund, J., Gulløv, H.C. (Eds.), Identities and Cultural Contacts in the Arctic. The Danish National Museum & Danish Polar Centre, Copenhagen, pp. 252-265.

Maschner, H.D.G., Jordan, J.W., 2008. Catastrophic Events and Punctuated Culture Change: The Southern Bering Sea and North Pacific in a Dynamic Global System. In: Papagianni, D., Layton, R.H., Maschner, H.D.G. (Eds.), Time and Change. Archaeological and Anthropological Perspectives on the Long-Term in Hunter-Gatherer Societies. Oxbow, Oxford, pp. 95-113.

Newhall, C.G., Self, S., 1982. The Volcanic Explosivity Index (VEI): an estimate of explosive magnitude for historical volcanism. Journal of Geophysical Research 87**,** 1231-1238.

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

Park, C., Schmincke, H.-U., 1997. Lake Formation and Catastrophic Dam Burst during the Late Pleistocene Laacher See Eruption (Germany). Naturwissenschaften 84**,** 521-525.

Pyle, D.M., 1989. The thickness, volume and grainsize of tephra fall deposits. Bulletin of Volcanology 51**,** 1-15.

Riede, F., 2007. Der Ausbruch des Laacher See-Vulkans vor 12.920 Jahren und urgeschichtlicher Kulturwandel am Ende des Alleröd. Eine neue Hypothese zum Ursprung der Bromme Kultur und des Perstunien. Mitteilungen der Gesellschaft für Urgeschichte 16**,** 25-54.

Riede, F., 2008. The Laacher See-eruption (12,920 BP) and material culture change at the end of the Allerød in Northern Europe. Journal of Archaeological Science 35**,** 591-599.

Riede, F., in press. The loss and re-introduction of bow-and-arrow technology: a case study from the Southern Scandinavian Late Palaeolithic. Lithic Technology.

Rowley, S., 1985. Population Movements in the Canadian Arctic. Études/Inuit/Studies 9**,** 3-21.

Rozoy, J.-G., 1985. The Revolution of the Bowmen in Europe. In: Bonsall, C. (Ed.), The Mesolithic in Europe. John Donald, Edinburgh, pp. 13-28.

Sandberger, F., 1882. Das Alter der Bimsstein-Gesteine des Westerwaldes und der Lahngegend. Zeitschrift der deutschen geologischen Gesellschaft 34**,** 806-811.

Schmincke, H.-U., 2006. Environmental impacts of the Lateglacial eruption of the Laacher See Volcano, 12.900 cal BP. In: von Koenigswald, W., Litt, T. (Eds.), 150 years of Neanderthal Discoveries. Terra Nostra, Bonn, pp. 149-153.

Schmincke, H.-U., Park, C., Harms, E., 1999. Evolution and environmental impacts of the eruption of Laacher See Volcano (Germany) 12,900 a BP. Quaternary International 61**,** 61-72.

Schumacher, R., Schmincke, H.-U., 1990. The lateral facies of ignimbrites at Laacher See volcano. Bulletin of Volcanology 52**,** 271-285.

Small, C., Naumann, T., 2001. The global distribution of human population and recent volcanism. Environmental Hazards 3**,** 93-109.

Strahl, J., 2005. Zur Pollenstratigraphie des Weichselspätglazials von Berlin-Brandenburg. Brandenburger geowissenschaftliche Beiträge 12**,** 87-112.

Taute, W., 1968. Die Stielspitzen-Gruppen im nördlichen Mitteleuropa. Ein Beitrag zur Kenntnis der späten Altsteinzeit. Böhlau Verlag, Köln.

Textor, C., Sachs, P.M., Graf, H.-F., Hansteen, T.H., 2003. The 12 900 years BP Laacher See eruption: estimation of volatile yields and simulation of their fate in the plume. In: Oppenheimer, C., Pyle, D.M., Barclay, J. (Eds.), Volcanic Degassing. Geological Society, London, pp. 307-328.

Theuerkauf, M., 2002. Die Laacher See-Tephra in Nordostdeutschland: Paläoökologische Untersuchungen mit hoher zeitlicher und räumlicher Auflösung. Greifswalder Geographische Arbeiten 26**,** 171-174.

Thorarinsson, S., 1958. The Öræfajökull Eruption of 1362. Acta Naturalia Islandica II**,** 1-99.

Thorarinsson, S., 1979. On the Damage Caused by Volcanic Eruptions with Special Reference to Tephra and Gases. In: Sheets, P.D., Grayson, D.K. (Eds.), Volcanic Activity and Human Ecology. Academic Press, London, pp. 125-160.

Trowbridge, T., 1976. Alaska's Volcanoes. Northern Link in the Ring of Fire. Alaska Geographic 4**,** 70-73.

Turney, C.S.M., Lowe, J.J., Davies, S.M., Hall, V., Lowe, D.J., Wastegård, S., Hoek, W.Z., Alloway, B., SCOTAV and INTIMATE Members, 2004. Tephrochronology of Last Termination Sequences in Europe: a protocol for improved analytical precision and robust correlation procedures (a joint SCOTAV–INTIMATE proposal). Journal of Quaternary Science 19**,** 111-120.

Turney, C.S.M., van den Burg, K., Wastegård, S., Davies, S.M., Whitehouse, N.J., Pilcher, J.R., Callaghan, C., 2006. North European last glacial–interglacial transition (LGIT; 15–9 ka) tephrochronology: extended limits and new events. Journal of Quaternary Science 21**,** 335-345.

van den Bogaard, P., Schmincke, H.-U., 1985. Laacher See Tephra: A widespread isochronous late Quaternary tephra layer in Central and Northern Europe Geological Society of America Bulletin 96**,** 1554-1571.

van den Bogaard, P., Schmincke, H.-U., Freundt, A., Park, C., 1990. Evolution of Complex Plinian Eruptions: the Late Quarternary Laacher See Case History. In: Hardy, D.A., Keller, J., Galanopoulos, V.P., Flemming, N.C., Druitt, T.H. (Eds.), Thera and the Aegean World III. Volume 2: Earth Sciences. The Thera Foundation, London.

VanderKoek, R., Nelson, R.E., 2007. Ecological Roadblocks on a Constrained Landscape: The Cultural Effects of Catastrophic Holocene Volcanism on the

Alaska Peninsula, Southwest Alaska. In: Grattan, J., Torrence, R. (Eds.), Living Under The Shadow. Cultural Impacts of Volcanic Eruptions. Left Coast Press, Walnut Creek, CA., pp. 133-152.

Waldmann, W., Jöris, O., Baales, M., 2001. Nach der Flut - Ein spätallerødzeitlicher Rückenspitzen-Fundplatz bei Bad Breisig. Mit einem Beitrag von Julian Wiethold. Archäologisches Korrespondenzblatt 31**,** 173-184.

Weyl, R., 1961. Geländebefund und Petrographie der Bimsschicht. Notizblatt des hessischen Landesamts für Bodenforschung 89**,** 333-335.

Wolters, S., 1999. Spät- und postglaziale Vegetationsentwicklung im Bereich der Fercher Berge südwestlich von Potsdam. Gleditschia 27**,** 25-44.

Wörner, G., Schmincke, H.-U., 1984. Mineralogical and Chemical Zonation of the Laacher See Tephra Sequence (East Eifel, W. Germany). Journal of Petrology 25**,** 805-835.