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Invited review article

Prospects and pitfalls in integrating volcanology and archaeology: A review

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ABSTRACT

Volcanic eruptions and interactions with the landforms and products these yield, are a constant feature of human life in many parts of the world. Seen over long timespans, human–volcano interactions become stratified in sedimentary archives containing eruptive products and archaeological remains. This review is concerned with charting the overlapping territory of volcanology and archaeology and attempts to plot productive routes for further conjoined research. We define archaeological volcanology as a field of study that brings together incentives, insights, and methods from both volcanology and from archaeology in an effort to better understand both past volcanism as well as past cultural change, and to improve risk management practices as well as the contemporary engagement with volcanism and its products. There is an increasing appreciation that understanding these human impacts and manifold human-volcano interactions requires robust multi-, inter- or even trans-disciplinary collaboration. Our review is written in the hope of providing a clearinghouse resource that (i) maps the many forms of past human-volcano interactions, (ii) provides study design templates for how to integrate archaeological perspectives into investigations of past volcanism, and (iii) makes suggestions for how the insights gained from such an archaeological volcanology can be integrated into reducing contemporary and future vulnerability amongst at-risk communities.

Contents

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1. Introduction

In 1762, Johann Winckelmann reported on the discoveries of the ancient Roman cities of Pompeii and Herculaneum, buried by the 79 CE eruption of Mount Vesuvius, around present-day Naples (Winckelmann, 1762). These discoveries were instrumental in the development of archaeology as a scientific discipline and in raising public awareness of how past volcanism has interacted with contemporaneous societies (Schnapp, 1996; Trigger, 2006). Around the same time, volcanology was developing its scientific foundation, too, and the many artistic and textual representations of the excavations and the eruptions of Vesuvius in 1767 and 1794 by William Hamilton and others are an integral part of volcanology's own intellectual genesis (e.g. Kozák and Cermák, 2010; Pyle, 2017; Sigurdsson, 2015). Indeed, the notion of a moment frozen in time coupled with the somewhat unsavoury dark heritage appeal of the memento mori represented by Pompeii (cf. Scarlett and Riede, 2019) has given rise to an obstinate idiom employed to label supposedly similar scenarios elsewhere (Holmberg, 2013) as we well as to countless dramatizations of the two cities' fiery demise (Pomeroy, 2008).

Beginning with the landmark publication by Sheets and Grayson (1979) more than 40 years ago, numerous edited volumes have formed a consistent if perhaps somewhat ad hoc scaffold for what can be termed 'archaeological volcanology' (Barnes and Soda, 2019; Grattan and Torrence, 2007; McGuire et al., 2000; Riede, 2015; Torrence and Grattan, 2002). Supporting this scaffold are many special issues devoted to this topic, most often published in broad-interest Quaternary science journals (e.g. Cashman and Giordano, 2008; Riede, 2016). Furthermore, dedicated albeit usually brief chapters that conjoin the topics of past volcanism and archaeology also feature in major volcanological and archaeological overview resources such as the *Encyclopedia of Volcanology* (Sheets, 2015), the *Encyclopedia of Global Archaeology* (Riede, 2020), or the *Encyclopedia of Archaeological Sciences* (Elson and Ort, 2018).

Despite this substantial body of work, epistemic and practical challenges to working across disciplines remain. For instance, in many textbook introductions to volcanology, the discussions of archaeology and, more broadly, discussions of humanities/social science contributions are placed at the end and afforded much less depth (e.g. Lockwood and Hazlett, 2010). Conversely, standard textbooks in archaeology afford little space to volcanoes and their eruptions, although many such books do place considerable emphasis on the broader relationship between climatic and environmental changes and changes in culture (e.g. Cunliffe, 2015; McCorriston and Field, 2020; Scarre, 2005). These observations are not meant to suggest that all textbooks in volcanology need to be re-written to include extensive treatments of social science/humanities approaches, theories, and methods. The latter discipline's corpus of literature here is extensive, highly diverse as well as notoriously contradictory. As an echo of John Snow's acrimonious 'two culture' rhetoric (cf. Snow, 1959), these differences in prioritisation do hint, in our view, at deep-seated differences in epistemic standards and intellectual practices across these two disciplines which often lead to major differences in the ways in which data are generated, analysed, and interpreted. In very concrete terms, this rift between natural scientific and engineering approaches to hazards and disasters on the one hand and social science and humanities approaches on the other finds its expression in marked differences in funding (see Alexander, 1995, 1997). These historical contingencies have left us with a form of "subordinate interdisciplinarity" (Padberg, 2014, p. 104) reflected in substantially different professional incentives, terminologies, core conferences, journals, and education and funding structures.

It is not often that the divisions between volcanology and archaeology make headlines but in the summer of 2019, news articles with titles such as 'Pompeii row eruptions between rival scientific factions' (Devlin, 2019) and declarations that irresponsible excavation at the iconic site embodies an 'act of vandalism to volcanology' (Solly, 2019) appeared in high-profile journalism outlets. These were the result of a letter published in *Nature* by Scandone et al. (2019) imploring that the shared heritage that the site represents requires conservation of not only the culture history but also the geological history that the stratigraphy holds. As the authors of the letter stated, "these archaeological and volcanic histories together offer a unique insight into how societies live and die in the shadow of a volcano. It is alarming, therefore, that volcanic deposits are being sacrificed during archaeological excavations" (Scandone et al., 2019, p. 174).

In contrast to the balance of funding in favour of volcanology, at the iconic site of Pompeii, the higher enthusiasm of the tourist public for the archaeological remains and the large amount of political support and funding from Italian and EU sources for the Great Pompeii Project that launched in 2012 make archaeology the dominant field. The volcanologists counter that the high price of valuing one of the sciences over the other in such a site leads to an impoverished image of the fuller context. In the case of Vesuvius, arguably, the destruction of the past deposits endangers life in the case of future eruptions as it prevents a greater understanding of the volcano's past behaviour. As volcanologist Chris Kilburn explains (Solly, 2019), the conjoined context is essential as the archaeological remains can indicate how the pyroclastic flows swept around buildings in order to improve building methods both there and elsewhere in the world and protect future populations. We can think of no better reason for the conjoined archaeological volcanology perspective than this.

The present review is part of a special issue with the title 'Environmental and societal impacts of past volcanic eruptions – integrating the geosciences with the historical, anthropological, and archaeological sciences'; our review is a community effort that has been sourced through repeated conference sessions – at major meetings such as the Cities on Volcanoes (CoV) conferences, the WAC (World Archaeological Congress) and Society for American Archaeology (SAA) meetings, and the European Geosciences Union (EGU) and INQUA (International Union for Quaternary Research) congresses – throughout the last years and our combined decades-long experience working at the interface between volcanology and archaeology. It also draws more tacitly on our experiences writing, editing – not least those of the special issue at hand – and reviewing papers that are intended to be read across disciplines. In this review, we seek not to critique but to reflect on how we as archaeologists and volcanologists together can take our interdisciplinary endeavour forward. This contribution therefore seeks to survey the current disciplinary landscape that makes up the territory in which archaeological volcanologists operate. In doing so, we map out the prospects and pitfalls of combining volcanological and archaeological perspectives. We here draw specifically on a range of case studies, each of which addresses different aspects and analytical scales – from a single site to a region to a continent; from a Pompeii-like moment to time measured in multiple generations – at the intersection between archaeology and volcanology. Through the presentation of these cases we reflect on where archaeological expertise and data can make a contribution to the larger endeavour of better understanding past human societies, their histories and interactions with volcanism as well as better understanding past volcanism itself. In reviewing these cases, we argue for a judicious rejection of sensationalist claims of human impacts while not forgetting that the human dimensions brought into play by the investigation of past impacts can make a substantial impact on how volcanic risks are understood in the present. We highlight the already existing methodological overlap between the concerned disciplines around sediments, stratigraphies and maps, but we also stress that, as a humanities/social science discipline, archaeology has much more to offer in terms of understanding past human interactions with volcanoes and their eruptions in a theoretically and empirically grounded manner. On this combined basis, we argue, archaeological volcanology could assist in uncovering deeper understandings of these interactions in the past and contribute to reducing risk in the present and future.

2. What's in a name? Volcanology – geology – geoarchaeology – environmental archaeology – environmental humanities

2.1. Disciplinary relationships

Volcanology is a subfield of *geology* concerned with the full spectrum of volcanic activity, its origin, and its products. *Geoarchaeology* is a specialized subfield of *archaeology* aimed at understanding past human life, site formation processes, and the origin and circulation of raw materials. Geoarchaeology uses methods adopted and adapted from geology (Pollard, 1999) that increasingly utilize digital and remote sensing techniques (e.g. Siart et al., 2018). Geoarchaeology nests within a wider subfield of *environmental archaeology* that draws on a range of methods also derived from disciplines such as ecology and zoology (e.g. Albarella, 2001; Dincauze, 2000; French, 2003). Environmental archaeology is – despite somewhat differing intellectual origins and trajectories – also part of a wider movement in the humanities towards environmental concerns that are frequently termed the *environmental humanities* (Bergthaller et al., 2014; Emmett and Nye, 2017; Hulme, 2011) or *geohumanities* (Dear, 2015). This label is applied to a loose congregation of social science/humanities disciplines (history, literature studies, philosophy) that are concerned with, on the one hand, a re-integration of the environment as a serious aspect of study as well as with, on the other, researchers' ethical and political engagements with contemporary environmental change (see Hussain and Riede, 2020 for a recent review from a specifically archaeological perspective).

At one end of the spectrum, then, archaeology is a field and laboratory science seeking correlations between natural and societal change. Here, it has much in common with physical volcanology; natural points of contact are stratigraphic sequences, fieldwork, and analytical techniques related to, for instance, radiometric dating. At the opposite end of the spectrum, archaeology overlaps with emerging subfields such as *critical physical geography* (Lave et al., 2018), the so-called *political geology* of the Anthropocene (Swanson, 2016) or *social geology* (Stewart and Gill, 2017) and its subfield *social volcanology* (Donovan, 2010), an intellectual territory that is no longer foreign at all to volcanology (e.g. Bobette and Donovan, 2019; Donovan, 2017; Donovan and Oppenheimer, 2014; Fearnley et al., 2018).

3. Journal rankings and impact factors

Each academic discipline and its various sub-disciplines have their own specific societies and attendant publication outlets; archaeology and volcanology are no exception. While major interdisciplinary conferences in principle offer meeting places, such conferences are often prohibitively expensive and are very strongly biased towards disciplinary in-groups in their attendance. The difference in journal outlets is expressed clearly in a heuristic survey of ranked journal lists and their impact factors divided into a high classificatory level of disciplines – geology and archaeology respectively – and select sub-disciplines such as volcanology and environmental archaeology (Table 1). This comparison is not intended to be fully rigorous or exhaustive but serves as a shorthand for disciplinary differences when it comes to publication avenues and incentives. There is little overlap as to where volcanologists and environmental archaeologists commonly publish, although the overlap that does exist, at the higher classificatory level, offers a starting point for those seeking to read or publish across disciplinary communities. Given the difference in impact factors – they are generally lower for archaeology – the incentive for volcanologists to publish in conventional archaeology or even more specific environmental archaeology journals is, given the current academic reward structure, limited. This is part of a larger academic context of impact factors and how the incentive system is changing the sciences (see, for instance, Chapman et al., 2019); its role in maintaining disciplinary subordinance cannot be overlooked.

4. Bridging epistemic differences in integrating the geosciences with the historical, anthropological, and archaeological sciences

Rightly, climate change and extreme events afford a great deal of public, political and scientific interest. Volcanic eruptions have been in the limelight of this interest because they have been identified as important contributors to climate change, both past (e.g. Fiedel et al., 1995; Sigl et al., 2015; Zielinski, 2000) as well as future (Bethke et al., 2017). In part, these high-profile studies are driven by the increasing number of major ice-coring projects that – thanks to major methodological improvements – are now efficiently able to detect ash samples and their correlates (e.g. Abbott and Davies, 2012). In addition, methodological improvements in modelling the influence of volcanic eruptions on climate at different scales are providing more precise hypotheses for how eruptions of different magnitudes and at different locations influence climate (e.g. Giorgetta et al., 2013; Timmreck et al., 2016; Toohey et al., 2019).

One of the highest-profile investigations of past volcanism and its potential societal consequences of the last few years concerns the sixth century CE. Initially, this debate was seeded by Stothers and Rampino (1983) who suggested that written sources potentially speak of long-distance climate effects of a major tropical eruption. That the sixth century CE was a period of major societal change has not escaped the attention of archaeologists and historians. Especially in Europe, where this period is also known as Late Antiquity, the argument is now being made that consecutive volcanic eruptions in different parts of the world – Central America (Dull et al., 2001, 2019), Papua-New Guinea (Stothers and Rampino, 1983) and Iceland (Luongo et al., 2017) perhaps – led to decadal-scale climatic changes in the Northern Hemisphere and, along with this, societal upheaval and change (Büntgen et al., 2016; Toohey et al., 2016). Thanks to this series of volcanic events, its impact on climate and the subsequent downstream influence of these perturbations on society, the middle of the sixth century has been described as “the worst time to be alive” (Gibbons, 2018, p. 733).

The studies cited above are the result of extensive and groundbreaking collaborations between volcanologists, climate scientists, historians, and archaeologists. We do not question these results ourselves but note the subsequent debate regarding the methodologies and datasets chosen for linking ice-core discoveries to climate effects (Büntgen et al., 2017; Helama et al., 2017). Besides the difficulties in interpreting and articulating different palaeoenvironmental proxies, the additional interpretative step from volcanically disturbed climate to its societal impact has also drawn criticism. First, we note that the notion of major societal change in the years following 535–6 CE has been around in the popular (Keys, 1999) and archaeological literature for many years, especially for Northern Europe. Beginning with the precocious work of Morten Axboe (1999, 2001) and the subsequent local and regional studies by Karen Høilund Nielsen (2000, 2005, 2006), major demographic and cultural changes using archaeological datasets had already been suggested for Northern Europe. Furthermore, philological work focusing on Nordic mythology and in particular on the eschatological aspects have long suggested that climate cooling may have been at the heart of the so-called Fimbulwinter (Gräslund, 2008; Nordvig and Riede, 2018). Joel Gunn's (2000) edited volume presented a global comparative perspective of these, suggesting that, while impacts may not have been global, a complex mosaic of societal perturbations can be dated to the second half of the sixth century CE. Later still, these studies were supplemented with further regional investigations in Sweden (Löwenborg, 2012) and the Baltic area (Tvauri, 2014). Gräslund and Price (2012) and Price and Gräslund (2015) offer a comprehensive summary of this work *prior* to the emergence of the novel ice core and modelling work.

Table 1
A list of the top 18 journals and their impact factors at the high classificatory level of (A) 'geology' and (B) 'archaeology' as well as at the lower classificatory subfield level of (C) 'volcanology' and (D) 'environmental archaeology', ranked by their h5-index. Journal h-data from Google Scholar. The journal selection and ranking within the categories 'geology' and 'archaeology' is from Google Scholar, the list of journals in the category 'volcanology' is from https://all-geo.org/volcan01010/2014/03/the-most-important-journals-in-volcanology/ and in the category 'environmental archaeology' from Carleton and Collard (2020), capped at 16 and supplemented with the subfield-specific journals *Environmental Archaeology* and *Geoarchaeology*. Note how limited the co-occurrence of target journals is. Note also that many important works within archaeology are still published in analog-only books and edited volumes. * journals that occur on both the 'geology' and 'environmental archaeology' list.

	A – Geology			B – Archaeology		
#	Publication	h5-index	h5-median	Publication	h5-index	h5-median
1	Gondwana Research	71	115	Journal of Archaeological Science	54	69
2	Earth-Science Reviews	69	93	Journal of Cultural Heritage	30	43
3	Quaternary Science Reviews*	63	86	Journal of Archaeological Method and Theory	26	43
4	Lithos	56	74	Antiquity	26	32
5	Geology	56	72	Journal of Anthropological Archaeology	25	32
6	Precambrian Research	55	80	International Journal of Heritage Studies	24	39
7	Geomorphology	54	70	Radiocarbon	24	35
8	Tectonophysics	51	64	Archaeometry	23	30
9	Journal of Asian Earth Sciences	48	58	International Journal of Osteoarchaeology	23	30
10	Quaternary International*	46	59	Vegetation History and Archaeobotany	23	27
11	Ore Geology Reviews	44	57	World Archaeology	21	28
12	Climate of the past	43	56	American Antiquity	19	27
13	Tectonics	40	51	Archaeological and Anthropological Sciences	19	25
14	Palaeogeography, Palaeoclimatology, Palaeoecology	40	48	The Journal of Island and Coastal Archaeology	18	23
15	Geological Society of America Bulletin	39	57	Journal of Archaeological Science: Reports	18	20
16	Geological Society, London, Special Publications	38	45	European Journal of Archaeology	17	23
17	Marine Geology	37	52	Cambridge Archaeological Journal	16	23
18	Geoscience Frontiers	36	64	Geoarchaeology	16	22
	Mean impact factors	49	67		23	32

	C - Volcanology			D - Environmental Archaeology		
1	Nature Geoscience	96	133	Quaternary Science Reviews*	63	86
2	Journal of Geophysical Research	89	121	Journal of Archaeological Science	54	69
3	Geophysical Research Letters	87	116	Quaternary International*	46	59
4	Earth-Science Reviews	69	93	The Holocene	31	36
5	Earth and Planetary Science Letters	63	80	Quaternary Research	27	33
6	Philosophical Transactions of the Royal Society of London A	56	78	Antiquity	26	32
7	Geology	56	72	Journal of Anthropological Archaeology	25	32
8	Journal of Volcanology and Geothermal Research	43	54	Archaeometry	23	30
9	Journal of Human Evolution	42	56	International Journal of Osteoarchaeology	23	30
10	Geochemistry Geophysics Geosystems	42	55	World Archaeology	21	28
11	Geological Society of America Bulletin	39	57	American Antiquity	19	27
12	Journal of Petrology	36	47	Archaeological and Anthropological Sciences	19	25
13	Contributions to Mineralogy and Petrology	36	48	Cambridge Archaeological Journal	16	23
14	Reviews in Mineralogy and Geochemistry	35	58	Geoarchaeology	16	22
15	Bulletin of Volcanology	28	38	Environmental Archaeology	16	20
16	U.S. Geological Survey Professional Paper	–	–	African Archaeological Review	15	21
17	Geophysical Monograph	–	–	Archaeological Prospection	14	17
18	Geological Society of London Memoir	–	–	Archaeofauna	5	6
	Mean impact factors	54	74		26	33

There is little doubt that the publication of the new volcanological perspectives on the suggested crisis of the sixth century CE has stimulated much additional work. In Japan, for instance, archaeological excavations of early and middle 6th-century CE eruptions of Mt. Haruna, northwest of Tokyo, may enhance understanding the worldwide volcanic crisis at this time (cf. Barnes and Soda, 2019). In Norway, investigations targeting various archaeological proxies for demographic, economic and political change are also lending support to the notion of a major crisis (Gundersen, 2019; Solheim and Iversen, 2019); attempts to read contemporary runic sources as reflecting climatic deterioration are also receiving renewed attention (Holmberg et al., 2020). In sum, the evidence for both major climate change as well as significant societal changes in the sixth century has been growing and continues to do so.

Despite this vigorous and long-term accumulation of evidence for a relationship between volcanism and climate, and between climate and society, historians and archaeologists have repeatedly raised critical voices. These doubt the robusticity of postulated causal connections between climate change and cultural change. Even those who specialise in the study of past disasters as reflected in historical archives caution that arriving at strong inferences is as difficult as it is important (van Bavel and Curtis, 2016; van Bavel et al., 2019). Also some authorities specialising in the period around the sixth century CE would dismiss (Wickham, 2005) or at least qualify (Moreland, 2018; Widgren, 2012) such forms of environmental determinism. In addition, also quantitatively-minded analysts express reservations about our ability to discern causal relations in such data with great confidence (e.g. Carleton et al., 2018). Surveying the multiple perspectives taken to understand what happened in the sixth century CE has served to highlight some of the remaining challenges associated with integrating volcanology with the historical sciences. We highlight the double inference, each associated with its own difficulties, from volcanic eruption to climate and from climate to society. There are substantial epistemological transfers required at each step.

Most pertinently, the latter inference from climate change to societal change has been critiqued for a lack of robust middle-range theory – explicit causal mechanisms that link climate change specifically to the societal changes observed in the textual and archaeological sources – and for a strongly deterministic underlying model of culture change. Our review of this particular case study has also been motivated by the wish to pull together relevant literature from across the volcanology/historical sciences divide. As we have argued, these fields each operate within their own spheres of publication outlets and citations. A perusal of the archaeological literature on the sixth-century crisis cited here clearly shows that these are to be found well *outside* of the standard volcanological literature, and that they would often not be captured by major electronic databases that are commonly trawled in literature searches. In moving forward, we urge workers to directly engage the arguments of critics and to be more explicit regarding the potential mechanisms that may link past climate change to broadly contemporaneous changes in human societies. As is reflected in a very broad range of disaster literature, the events tend to simply reveal underlying social inequalities or cultural patterns (Kelman, 2020; Oliver-Smith, 2002); environmental events such as volcanic eruptions may be important impetuses of culture change but they always underdetermine the specific forms that such changes take (Hussain and Riede, 2020). Hence, a simple language of causality is fraught.

The continued search for more precise chronological alignments of volcanic eruptions and their consequences with historical and archaeological datasets is essential for exploring the potential causal role of volcanic eruptions in the human past. At the same time, however, we suggest that further important insights can be obtained by exploring how emerging 'new materialist' movement such as the geohumanities – part of the wider environmental humanities engagement – and their focus on 'geosocialities' (Clark et al., 2018; Palsson and Swanson, 2016) articulate with the already well-established theories of culture change in archaeology. That said, the increased refinement of field and laboratory methods as well as archaeology's ever stronger disciplinary alliance with computational approaches (e.g. eco-informatics) offer new and powerful methods of linking environmental change to cultural changes documented in the archaeological record. Together with continued improvements in chronologies, isotopic and biomolecular methods – as well as in traditional field and archive research – paint a promising future also for archaeological volcanology.

5. From stratigraphies to communities – cultivating the interfaces of archaeology and volcanology

5.1. From strata to societies

In the above, we have used the sixth-century CE case study to demonstrate the disciplinary imbalance between volcanology and the historical sciences, not in attempt to put blame or to criticise any of the cited work. Instead, we used the case to chart the epistemic and practical differences in the generation, handling, and interpretation of data. The sixth-century case study is also particularly complex as it involves global processes, multiple complex and large datasets, and multiple steps of inference. The absence of such steps leads to interpretations like that of the monumental site of Borobudur in Java, long-proposed in nineteenth and twentieth-century literature to have been abandoned due to a catastrophic eruption of Merapi in 1006 CE that prompted the Mataram empire to abandon Central Java. This theory was repeated enough to congeal into fact and yet no volcanological or archaeological data supports it (Murwanto et al., 2004; Newhall et al., 2000).

In the following, therefore, we turn to a series of themes, explicated through other relatively well-studied instances of past volcano-society interactions, in order to frame what we see as some of the most salient interfaces – empirical, conceptual, methodological – of archaeology and volcanology.

Both volcanology and archaeology are earthbound disciplines: rocks, sediment, sedimentary matrices, and the stratigraphic sequences form constitute some of our most basic sources of information. While there are differences in approaches, the methods we use to analyse these are the most obvious common denominator between the disciplines of archaeology and volcanology. Moreover, volcanic ejecta are regularly encountered during archaeological field or laboratory work, especially now that advanced cryptotephra detection techniques are increasingly mainstreamed into the geoarchaeological toolkit (e.g. Lane and Woodward, 2017; Lane et al., 2014; Riede and Thastrup, 2013). While not as spectacular as massive near-vent deposits and their often evidently destructive effects on human settlements, cryptotephra has become a vital tool in chronological correlation across archives – ice-cores, marine and terrestrial palaeoenvironmental records as well as archaeological stratigraphies (Davies, 2015; Davies et al., 2012).

In addition to its role as isochron, tephra itself may also have served as an agent of impact. Its hazardous properties – detrimental for animals, people and infrastructure – are well known from recent eruptions (e.g. Cronin et al., 2003; Horwell and Baxter, 2006; Jenkins et al., 2015; Wilson et al., 2015). These insights have been used to generate specific hypotheses about how past eruptions may have affected contemporaneous ecologies and societies, for instance, concerning the far-field impacts of the ~13kyr BP Laacher See eruption on hunter-gatherer communities in Northern Europe (Blong et al., 2018; Riede, 2008; Riede and Bazely, 2009; Riede and Wheeler, 2009), of the ~7630 yr BP Mazama eruption on hunter-gatherer communities in subarctic Canada (Oetelaar, 2015; Oetelaar and Beaudoin, 2005), and of the ~3600 yr BP Aniakchak eruption on hunter-gatherer-fisher groups across Alaska (Vanderhoek and Nelson, 2007). By the same token, it is important to note that the impacts of tephra fall on pre-modern communities may not always have been detrimental, as long-term collaborative work around Sunset Crater demonstrates (Box 1).

Being able to detect tephra in the field and lab can solve important chronological questions; knowing its many properties can lead to the formulation of productive hypotheses and facilitate their tests. By the same token, the analyses of sedimentary deposits of caves and rock shelters were an important stimulus to the development of geoarchaeology (cf. Mallol and Goldberg, 2017). If there is evidence of prehistoric human occupation or use of a cave and if tephra is discovered in the cave stratigraphy, then the material culture that the caves contain intersect with volcanic events and ejecta. The challenge is to understand whether and how volcanism affected the cave inhabitants. After the Chaitén eruption in Chile in 2008, for instance, local residents became aware of the presence of a prehistoric rock art complex at Vilcún during efforts to reconstruct their community. Following this discovery, an international transdisciplinary team was formed to conserve the rock art and collect data from the shell middens, ceramic and lithic material, and faunal remains the cave contains. Using major and trace-element glass shard geochemistry at least ten eruptions with tephra distribution comparable or greater than the 2008 eruption have occurred since the Last Glacial Maximum (c. 18kya cal BP), prior to which point the stratigraphic record is largely absent due to glaciation (Alloway et al., 2017a, 2017b). The direction of the cave openings mean that consistent layers of tephra are not present in the caves, yet what is preserved is evidence of human occupation during repeated volcanic events. Radiocarbon dating of the human activity episodes recorded in the cave suggests overlap with at least two and possibly more explosive Holocene eruptions of Chaitén.

From a strictly archaeological vantage, learning more about the human use of the cave in prehistory will be of help in better understanding the use of the past landscape, especially at the times of the multiple Holocene eruptions of Chaitén. Volcanism is implicated in important transformations in the way people used and occupied the Patagonian landscape since at least the early Holocene (Prieto et al., 2013). Connection of the prehistoric Chaitén area to the larger region is indicated through the presence of artefacts made from the distinctive, translucent grey obsidian from Chaitén throughout the western archipelago (Méndez et al., 2012). Moreover, rock art similarities with the Vilcún designs in the coastal area of Valdivia (e.g. Adán and Godoy, 2006) and the Mapuche indigenous culture area to the north suggest to some researchers ties to the larger region (Labarca et al., 2016). The intersections between Chaitén volcanism and local communities in the past then serve as a backdrop against which to catalyse community engagement and risk reduction (Box 2).

In Europe as well, many cave and rock-shelter sites offer the opportunity to jointly investigate the records of volcanic eruptions and human occupation, at times going far back into the Pleistocene (e.g. Lowe et al.,

Box 1
Small eruption, big effects – Sunset Crater (1085–1090 CE)

Sunset Crater Volcano is an ~300-m-high basalt cinder-cone located in the pine forests of northern Arizona, approximately 20 km north of the city of Flagstaff. As part of a 25 km Arizona Department of Transportation road-widening project, archaeologists investigated 41 prehistoric sites in the path of road construction (Elson, 2011). The road (US89) ran 5 km west of Sunset Crater and all project area sites were within the ashfall zone. Since the 1930s, when pit house structures were found sealed beneath a layer of black volcanic cinders, the Sunset Crater eruption has been known to have impacted the prehistoric occupation (Colton, 1932). Sunset Crater is famous for being the first volcano to be dated using tree-rings, to 1064 CE (Smiley, 1958). Later researchers, using paleomagnetic data, suggested a 200-year duration (Pilles, 1979). Therefore, investigating Sunset Crater and the effect the eruption had on local populations was a major research theme of the US89 archaeological project. As expected, soon after beginning excavations, primary black basalt cinders were found in a prehistoric cultural context, and a volcanologist joined the project. Ultimately, the project turned into a true collaborative undertaking involving archaeologists, volcanologists, geoarchaeologists, and dendrochronologists.

The US89 project research suggests that the highly-entrenched 1064 CE date and 200-year duration, as determined by earlier researchers, were incorrect for a number of reasons. New dates were produced by re-examining the tree-ring samples used by Smiley and by new paleomagnetic, dendro-chemical and Strontium isotope analyses. Sunset Crater erupted for only a few months to a year sometime between 1085 and 1090 CE, when nearby areas were densely populated by small, prehistoric farming groups (Elson et al., 2002, 2007; Ort et al., 2008a, 2008b). These data are of great importance because adapting to a onetime short-term event is very different than adapting to a long-term repeated event. Lava and volcanic tephra were deposited over an area of 2300 km^2, dramatically changing the physical landscape and, almost certainly, the ideological world view of the prehistoric inhabitants. The eruption caused large-scale abandonment, creating a very conservative estimate of 1000–2000 volcano refugees, although the actual number may be closer to 5000. The refugees lost both their homes and their agricultural fields. Casts made of corn impressions in basalt agglutinate – formed from corn that was intentionally placed next to an active hornito and covered with lava – indicate that the corn was immature and not yet ready to harvest, suggestive of a mid-summer eruption (Elson et al., 2002). Around 50 of these 'corn rocks' were recovered at a habitation site 4 km removed from the Sunset Crater lava, suggesting that they may have been ritual items indicative of an ideological change.

Conversely and somewhat counterintuitively, the deposition of a thin, moisture-retaining cinder mulch, 3–10 cm thick, allowed low elevation areas previously too dry to farm to now be settled. Experimental agricultural plots covered with varying depths of Sunset Crater cinders were constructed under the direction of the project botanist, and corn only grew when covered with 3–10 cm of cinder mulch; corn did not germinate in areas without cinders or in areas with more than 15 cm of cinders (Waring, 2011). Isopach mapping of Sunset Crater cinder deposition shows an area of almost 600 km^2 under 15 cm of tephra which would almost certainly have been abandoned, at least temporarily. Despite the stress of the eruption, the prehistoric populations who inhabited this area not only thrived, they prospered, eventually building some of the largest village sites in the northern Southwest US. Within five to ten years following the eruption, volcano refugees began to settle low elevation areas that were covered by a thin cinder mulch, including sites within Wupatki National Monument, a geoheritage tourist destination.

The US89 project investigations suggest that the inhabitants of the Sunset Crater area were, in many ways, prepared or 'exapted' (sensu Larson et al., 2013) to deal with the eruption, due to: (1) The absence of a strictly hierarchical social system allowed for rapid, site-level decision-making; social organization was mostly at the household level, so decisions could be made quickly using real-time information on the disaster; evacuation was not hindered by waiting for information to come down from the top of the hierarchy, such as what happened with hurricane Katrina and the COVID-19 virus; (2) the Sunset Crater area is on the margins of where agriculture can occur due to cold temperatures and limited precipitation, so a risk-reduction agricultural strategy was already in place based on the cultivation of numerous small plots spread over a variety of microenvironments; therefore, while some crops may be destroyed by the disaster, those in other locations may survive; (3) a flexible settlement system, with kin over a large area; it is likely that kin are present in areas unaffected by the disaster; and, (4) the ability to freely migrate into relatively nearby areas not impacted by the eruption and to rebuild settlements quickly from materials at hand. In line with White's (1974) notion of flexible 'pre-industrial' disaster resilience, these factors are seen as key traits that allowed for this successful adaptation. In terms of the applicability of the Sunset Crater research to modern situations, the data suggest that disaster response may be more effective when small groups have decision making authority and particularly the authority to use whatever means they can to leave the affected area. Therefore, organization and authority on a smaller level – the neighbourhood or ward – may prevent the deaths that occur while people wait for information on what to do to come down the hierarchy. A strict hierarchical social organization may not be an efficient way to deal with disasters (cf. Sheets, 2012).

2012). Quite spectacular yet little-known finds of well-preserved tephra from the Laacher See eruption occur in the area along the River Leine in Central Germany. These were expertly investigated already in the 1980s (Grote and Freese, 1982), albeit only with archaeological aims in mind, and published almost exclusively in German. At a distance of 230 km from the eruptive centre, some of these sites contain tephra layers 20–40 cm thick – values substantially higher than those otherwise stated in the literature. No doubt the secluded nature of the rock shelter or cave interior prevented erosion of the tephra to the extent found in open-air sites. Here, these cave sites serve as important repositories of tephra. Not only may accompanying cultural materials be useful in dating the tephra, the sedimentary contexts revealed through archaeological excavation provide a different kind of archive than normally investigated by field volcanologists.

One incidental effect of the recent improvements in cryptotephra detection and analysis is that the ash distributions of many eruptions are being significantly revised. While it has long been known to Quaternary scientists that the volcanic ash of this eruption sealed a Late Pleistocene land-surface including archaeological sites and that its tephra also occurred at some distance from the eruptive centre (e.g. Behlen, 1905; Frechen, 1952), it was not until the 1990s that wider impacts of the eruption outside of the proximal zone were considered (Thissen, 1995). Only in the 2000s did more in-depth studies of potential proximal (Baales et al., 2002) and distal (Riede, 2008) impacts of this eruption on contemporaneous ecosystems and societies appear.

Since then, the compilation of fallout occurrences throughout Europe (Riede et al., 2011) and the targeted excavation of small

Box 2
Case study in social-historical volcanology – Chaitén (2008 CE)

On May 2, 2008, the Chaitén volcano in north-western Patagonia erupted unexpectedly. At the time, Chaitén was ranked 40th out of 95 geologically active volcanoes in the national threat score and was not being actively monitored (Lara et al., 2013). This was the first explosive rhyolitic eruption to have occurred globally in the past century and many local residents were not even aware that Chaitén was a volcano. The eruption prompted the largest evacuation in Chile's history, with approximately 4000 residents evacuated over a period of two days to a city 12 h away by ferry. Both explosive and effusive activity continued for two years (Amigo et al., 2013).

Chaitén residents were unable to return prior to 2011 and recovery from the eruption event is still ongoing. Many residents who returned lacked running water or electricity until 2012. A series of sub-plinian columns, pyroclastic density currents, and thick tephra fall caused a complex lahar-flood that filled the Chaitén River channel and then an avulsion of the river that divided the town. As of the publication date of this article, a significant portion of the resettled town on the southern portion below the new river channel still lacks those basic services.

To commemorate local experience and memory of the 2008 eruption and encourage tourism, a local heritage organization, ProCultura, secured funding to build a museum that is unique in South America. It is located within a block of conserved houses destroyed by the lahar flow from the 2008 eruption and construction was completed in 2020. The museum will contain narratives of the eruption and evacuation as well as the stress and chaos that residents felt during the period that they were not permitted to return to their homes. Art created during art therapy sessions with University of Chile psychologists in 2012 and 2019 will be an important component of the displays. The museum will also contain archaeological interpretations and data from archaeological excavations, imagery of a prehistoric rock art cave discovered following the resettlement of the town, immersive art-science work (Holmberg and Burbano, 2020), and live-streamed data monitoring from the volcano. The museum will provide information for important sites of geoheritage – or better, geo-cultural heritage – in the area that visitors may want to visit. The most recent eruption of Chaitén represents an important contemporary example of how eruptive activity can alter landscape and coastal use. The obvious threats to the town from future lahars inherent to its relocation in its original spot, commemoration of the eruption, and awareness of the longer time depth of human intersection with the volcanic landscape are all shared components of this museum which will additionally host space for visiting students and researchers and be a site of art residencies.

caves as sediment traps for both tephra and archaeological remains (Riede et al., 2018; Sauer et al., 2018) have been at the core of renewed investigation of the Laacher See eruption's possible impact on contemporaneous societies. In assembling the database of known Laacher See tephra finds, many important existing data points, some even associated with information on geochemistry, grain size, or shard morphology, have been revealed. A large number of these data points are not new, come from the literature of other disciplines not commonly accessed by volcanologists (palynology, pedology, paleoecology), and are often in languages other than English. Many of these papers are published in more regionally specific venues, site reports, or even edited volumes or books, making them only moderately accessible through standard database searches. Putting together these stratigraphic data has aided in understanding both the eruption itself and the relationship of the eruption to cultural changes in its wake. It has also highlighted that the most significant societal changes in the wake of the eruption occurred beyond the margins of the fallout lobes (Riede, 2017a).

5.2. Assessing tephra-induced landscape change from artefact distributions

A remarkable laboratory for archaeological volcanology is provided by Japan. Accounting for around 10% of the world's active volcanoes, Japan is well-covered with tephra from explosive eruptions (Machida and Arai, 2011). Practitioners of 'tephroarchaeology' (Soda, 2019) – which has a long tradition in Japanese geoarchaeology – assess volcanic impacts on societies from the deep past to historic times (Barnes and Soda, 2019; Shimoyama, 2002). Although the extraordinary potential for preservation under tephra is widely appreciated, many in Japan (e.g. Moriwaki et al., 2016) utilize tephra layers primarily as isochrons, without assessment of their effects on landscapes and people's lives. Reported here are occupational patterns, known through artefactual analyses, that were affected by volcanic eruptions in the Late Pleistocene and early Holocene.

The Kirishima volcanic zone in southern Kyushu is coincident with the Kagoshima Graben and entails ten active volcanoes. Their eruptions constituted hazards for populations throughout millennia (cf. Kuwahata, 2016; Shimoyama, 2002), including two catastrophic eruptions: from Aira, re-dated to 30kya BP (Smith et al., 2013), and Kikai, re-dated to 7300 yr BP (Machida and Sugiyama, 2002). Given the massive and almost certainly rapid deposition of ignimbrites in the proximal zone around the eruptive centre, any nearby hunter-gatherer communities were likely exterminated in both these eruptions. Discontinuities in Palaeolithic stone tools in the former and hunter-gatherer pottery in the latter indicate depopulation, cultural impacts, and later recolonization.

The Aira eruption (450 km^3 DRE, VEI 7) caused pyroclastic flow deposits radiating 60 km in southern Kyushu, some of them 300 m thick, while co-ignimbrite tephra fallout (Aira-TN or AT) extended over 1000 km into northern Honshu. A new collation of stone artefact data (Fujiki, 2019) indicates that before the eruption, across southern Kyushu scrapers were made of obsidian while other tools were made of hornfels; after the eruption, the obsidian source was inaccessible. Some groups living on the south-eastern Kyushu coast survived, and these people switched to making all their stone tools from local hornfels. After an as yet indeterminate time, groups using these tools again spread out through southern Kyushu, colonizing the newly defined landscape of pyroclastic pumice flow plateaus.

The Kikai eruption (170 km^3 DRE, VEI 7) extruded pyroclastic flows up to 80 km radius and deposited Akahoya tephra (K-Ah) up to 20 cm depth throughout Shikoku Island and the Inland Sea area (Kuwahata, 2019) and reached into northern Honshu. In contrast to earlier work which postulated the decimation of Jomon groups throughout Kyushu, recent correlation of pottery types indicates that the same ceramic type continued, only changing significantly four centuries after the eruption. In contrast to the population replacement model (Machida, 2002), Kuwahata (2019) argues for more intensive regional interaction bringing about change. Mountainous Japan has only 14% flat plains, and hunter-gatherer communities were mobile and focused on mountain resources, suggesting that outside pyroclastic flow areas in Kyushu and some lowland regions, tephra fallout of any thickness did not destroy lifeways. The recently obtained data have facilitated a major qualification of earlier models of human impacts, but more research is needed on floral recovery and its relation to time lags in landscape reoccupation (cf. Hotes et al., 2010).

6. Archaeological volcanology and volcanic risk communication

In regions such as Japan, understanding the risks posed by its many volcanoes is vital for risk reduction. Adding elements of human impacts lends strong affective elements to how risks, resilience and vulnerability can be discussed not only as a feature of the natural environment but also as properties contingent on societal constellations (cf. Barclay et al., 2008). The Kirishima volcano group in Kyushu, Japan has erupted many times since the above listings and tephra impacts are more hazardous to modern urban, sedentary society. The current Sakurajima and Shinmoedake eruptions are particularly worrying as magma for the latter was likely drawn from the Aira chamber (Brothelande et al., 2018); Sakurajima, erupting continuously since 1955, is parasitic on the Aira caldera rim. Given the near-field devastation of the Pleistocene Aira eruption, several cities within pyroclastic flow ranges are vulnerable to a future catastrophic eruption (see Suzuki, 2018). Japan, in principle, provides an ideal natural laboratory for studying the variable human impacts of volcanic eruptions in the past and to use this in contemporary risk assessments, management and outreach. In terms of an integration with international science, however, language and practice barriers persist; much of the Japanese literature remains inaccessible to scholars elsewhere and collaborations remain, with notable exceptions, relatively few.

In contrast to the Kirishima context where volcanic risks are fairly evident, the central European Eifel volcanic zone referred to above represents a situation of low-frequency but potentially high-magnitude volcanism. The mantle plume underneath the Laacher See remains in place (Zhu et al., 2012), however, and intermittent earthquakes (Hensch et al., 2019) and low-level degassing (Goepel et al., 2014) bear witness to the remaining risks. Interestingly, at least one recent volcanological study is seriously rethinking the risks posed should renewed eruption activity take place here, although its focus is restricted to building damage alone (Leder et al., 2017). Including narratives of past eruptions and their impacts allows for more effective communication of the potential threat that such an eruption would pose to society more broadly (Donovan and Oppenheimer, 2018). The latter assessment, in turn, articulates with recent calls for more scenario thinking in relation to major and possibly existential risks inherent in low-frequency/high-magnitude hazards (Denkenberger and Blair, 2018; Riede, 2017b; Woo, 2019).

7. Lessons learned and future perspectives

The twenty-first century and its era of wide-ranging changes in the Earth system make improved understanding of the complex intersections between the geophysical world and human cultures of critical importance (e.g. Florindo and McEntee, 2020). This period also overlaps with what is called by some the ‘environmental turn’ or even the ‘geological turn’ in the humanities (e.g. Dear, 2015; Bonneuil, 2015; Yusoff, 2013, 2018). The challenge of integrating multiple disciplines across social and physical sciences is a “wicked” problem, however, particularly in volcanic contexts where scientific interpretations are drawn into policy decisions or hazards awareness (Donovan, 2019). While interdisciplinary research that entwines geosciences with social science considerations is acknowledged to be highly important when considering volcanic contexts (e.g. Hayes et al., 2020; Jenkins et al., 2013), the integration of archaeology within this interdisciplinarity is not seamless. The enthusiasm for and preoccupation with interdisciplinarity in the academy does not lead to its easy incorporation or even easy definition (Barry and Born, 2013) – those volcanologists working in geography departments will recognise the difficulties that commonly arise in such conversations across disciplinary fences, difficulties that are reified through institutional structures, often inflexible curricula and compartmentalised funding structures.

In reviewing a series of themes and case studies in archaeological volcanology, it has been our intention to distill recommendations for future work. These way-markers are offered from our particular perspective of archaeologists who have the privilege to be working routinely with volcanologists, on volcanoes, and on projects ultimately concerned with understanding the social interactions of past human societies with volcanoes and volcanic eruptions. Against the background of these studies, we would stress that archaeological sites are often high-quality sources of volcanological information regarding eruption frequency, extent of fallout, and the hazardous properties of tephra fallout. Furthermore, archaeological sites can provide an important repository of volcanological data and materials; they are often very carefully excavated, facilitating detailed investigations of emplacement dynamics. In addition, archaeological materials robustly associated with a given eruption facilitate precise dating, and they can offer important insights into past human impacts, which in turn can act as a major amplifier of public attention as well as, not least, funding.

Understanding the specific impacts of volcanic eruptions on past societies, whether through their influence on climate or through other more direct impact mechanisms, is nested within the wider ambition to bring climate and environment back into the study of history (Janku et al., 2012; Mauch and Pfister, 2009). Such an integration offers the potential of not only better understanding past episodes of volcanism and their human impacts but also of framing contemporary volcanic risks within culturally specific contexts of understanding and action (Pfister, 2009; Schenk, 2015). Following Caseldine and Turney (2010), we see a need for increased interdisciplinarity but would also urge for a greater mutual recognition of the epistemological and practical differences between volcanology and archaeology. Ideally, such differences should be addressed at the level of study design (cf. Arponen et al., 2019) and mitigated by joined investigations, be they in the field, the lab or the archives (Alagona and Simon, 2010).

Finally, combined volcanic-archaeological sites are important draws for tourism globally (Erfurt-Cooper et al., 2015; Sigurdsson and Lopes-Gautier, 2000). Although volcano tourism is not without its dangers (Erfurt-Cooper, 2011) – the tragic 2019 Whakaari/White Island eruption being the latest example – geo-heritage outreach and valorisation can bolster sustainable tourism and provide local economic benefit (Erfurt-Cooper and Cooper, 2010; Németh et al., 2017), especially when combined with associated cultural assets. As also noted by Erfurt-Cooper et al. (2015), the most efficacious valorisation deliberately draws on the darker side of volcanic eruptions. The opposite is true of the Chaitén volcano case discussed above, however; the nearby Pumalin Park hosts 15,000 visitors a year in the high season (January–March) or at least did prior to the COVID-19 pandemic. In building a museum to commemorate the 2008 eruption as well as the geo-cultural heritage of the rock art cave, Chaitén positions itself as a tourist destination for the kinds of tourists (hikers, ecotourists) that are drawn to Pumalin. Rather than a focus on an event of ‘disaster’, the museum and town celebrate a sense of renewal in a dynamic environment (Holmberg, 2020). Similarly, the numerous coupled archaeology/volcanology museums around the Laacher See caldera and the Eifel geopark itself serve as an entry point for a better public understanding of this volcanic zone and its hazards (Bitschene and Schüller, 2011; Erfurt-Cooper, 2010).

In reviewing the relationship between cultural and geological heritage, Scarlett and Riede (2019) have recently shown that there also are substantial differences in conceptual frameworks and practice between these professions. Those authors welcome the recent developments in geoheritage but also point out that museums and similar institutions should be seen as inherently concerned with both cultural and natural history. Treated holistically and ambitiously, heritage institutions may serve as powerful platforms of public engagement and social action vis-à-vis risk and resilience (cf. Cameron et al., 2013; Rees, 2017). New interdisciplinary hybrids such as the geohumanities and social volcanology – or the archaeological volcanology we have reviewed here – lend themselves particularly well to this museal articulation. Bringing together the natural scientific excitement and acumen of volcanology with the affective and narrative expertise of the humanities/social sciences in general and of archaeology in particular offers a powerful alliance in producing and disseminating the knowledge needed for the Anthropocene.

Like volcanologists and other geologists (e.g. Stewart and Gill, 2017; Stewart and Lewis, 2017), archaeologists, too, are deeply concerned with making their research sustainable, actionable and relevant (Cooper and Sheets, 2012; Isendahl and Stump, 2019; Jackson et al., 2018; Riede, 2019). Inclusive approaches under the umbrella of community archaeology (cf. Moshenska and Dhanjal, 2011) have been adopted in volcanic settings, for instance on Montserrat (Ryzewski and Cherry, 2012), and could be readily transferred to other volcanically active areas in order to supplement other social volcanology approaches.

Interdisciplinarity and certainly transdisciplinarity are not easily achieved, however (Foster, 1999; Frodeman and Mitcham, 2007). Not every problem requires them, nor does every researcher need to aspire to them. Yet, the key to many impactful contributions to science and society is found in the interstices between disciplines and we have addressed the chasm and reviewed the bridges between volcanology and archaeology in particular. Volcanologists tend to adopt specific eruptions, volcanoes, or volcanic systems as their object of interest, while archaeologists tend to focus on certain sites, periods, or 'cultures'. Volcanologists seek to explain aspects of natural history; archaeologists seek to understand past social life and the patterns and processes of culture change. Challenges to epistemic integration remain but can, we believe, be resolved. Along with this special issue of *the Journal of Volcanology and Geothermal Research*, the review offered here may serve as a resource in finding such solutions.

CRediT authorship contribution statement

Felix Riede: Conceptualization, Writing - original draft, Writing - review & editing. **Gina L. Barnes:** Conceptualization, Writing - original draft, Writing - review & editing. **Mark D. Elson:** Writing - original draft. **Gerald A. Oetelaar:** Writing - original draft. **Karen G. Holmberg:** Conceptualization, Writing - original draft, Writing - review & editing. **Payson Sheets:** Writing - original draft.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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