Volcanism and Global Plague Pandemics: Towards an Interdisciplinary Synthesis

During the last two millennia, the bacterial pathogen *Yersinia pestis* has been responsible for three recorded plague pandemics: the First Pandemic (beginning with the Justinianic plague of 541 and lasting from the sixth to eighth centuries), the Second Pandemic (beginning with the Black Death and lasting from the fourteenth until the nineteenth century), and the Third Pandemic (from the late eighteenth century onwards).[1] Climate influences many of the factors which affect the spread of *Y. pestis*.[2] In the most basic terms, climate conditions might favour plague-associated host species and therefore potentially result in epidemic and pandemic episodes, a process known as a trophic cascade.[3] In the case of plague host species we are

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[1] N.C. Stenseth, B.B. Atshabar, M. Begon, S.R. Belmain, E. Bertherat, E. Carniel, K.L. Gage, H. Leirs and L. Rahalison, Plague: past, present, and future, *PLoS Medicine* 5(1) (2008) e3; D.C. Stathakopoulos, *Famine and Pestilence in the Late Roman and Early Byzantine Empire: a Systematic Survey of Subsistence Crises and Epidemics*, Abingdon, 2016; D.M. Wagner, J. Klunk, M. Harbeck, A. Devault, N. Waglechner, J.W. Sahl, J. Enk, D.N. Birdsell, M. Kuch and C. Lumibao, *Yersinia pestis* and the Plague of Justinian 541–543 AD: a genomic analysis, *The Lancet Infectious Diseases* 14 (2014) 319–326; K.L. Kausrud, M. Begon, T.B. Ari, H. Viljugrein, J. Esper, U. Büntgen, H. Leirs, C. Junge, B. Yang and M. Yang, Modeling the epidemiological history of plague in Central Asia: palaeoclimatic forcing on a disease system over the past millennium, *BMC Biology* 8 (2010) 112; J. Kelly, The Great Mortality: An Intimate History of the Black Death, New York, 2005; C.A. Benedict, *Bubonic Plague in Nineteenth-Century China*, Stanford, 1996, 1.

[2] N.C. Stenseth, N.I. Samia, H. Viljugrein, K.L. Kausrud, M. Begon, S. Davis, H. Leirs, V.M. Dubyanskiy, J. Esper and V.S. Ageyev, Plague dynamics are driven by climate variation, *Proceedings of the National Academy of Sciences* 103 (2006) 13110–13115.

[3] Kausrud, Begon, Ari, Viljugrein, Esper, Büntgen, Leirs, Junge, Yang and Yang, Modeling the epidemiological history of plague in Central Asia; B.V. Schmid, U. Büntgen, W.R. Easterday, C. Ginzler, L. Walløe, B. Bramanti and N.C. Stenseth, Climate-driven introduction

referring to a bottom-up trophic cascade, where a climatic change will benefit primary producers and subsequently impact population dynamics of species within the primary producers' food web. Therefore climate conditions favourable to host rodents' food supply may lead to an increase in rodent populations and hence increased plague prevalence. However, this mechanism is unlikely to apply in a simple and uniform way on a global scale because of the different responses to climate of varying host species from differing environments.[4] Bacterial vector diseases such as plague are particularly complex because their transmission depends on the relationship between bacterium, vectors and hosts. Limitations in available data mean it is often difficult to observe the processes involved, especially on a global scale.[5] Therefore despite evidence suggesting that climate mediates plague prevalence on regional scales, climate's role in historical pandemic episodes is far from fully understood.[6]

Volcanism has significant effects on global climate. At the most basic level, a major volcanic eruption can have a cooling effect on climate because the expulsion of particles into the Earth's atmosphere blocks solar radiation. Stothers (1999) observed that volcanism regularly correlated with periods of pandemic across Europe and the Middle East.[7] One

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of the Black Death and successive plague reintroductions into Europe, *Proceedings of the National Academy of Sciences* USA 112 (2015) 3020–3025.

[4] L. Xu, Q. Liu, L.C. Stige, T.B. Ari, X. Fang, K.-S. Chan, S. Wang, N.C. Stenseth and Z. Zhang, Nonlinear effect of climate on plague during the third pandemic in China, *Proceedings of the National Academy of Sciences* 108 (2011) 10214–10219.

[5] T.B. Ari, S. Neerinckx, K.L. Gage, K. Kreppel, A. Laudisoit, H. Leirs, N.C. Stenseth, Plague and climate: scales matter, *PLoS Pathogens* 7 (2011) e1002160.

[6] Stenseth, Samia, Viljugrein, Kausrud, Begon, Davis, Leirs, Dubyanskiy, Esper and Ageyev, Plague dynamics; Kausrud, Begon, Ari, Viljugrein, Esper, Büntgen, Leirs, Junge, Yang and Yang, Modeling the epidemiological history of plague in Central Asia.

[7] R.B. Stothers, Volcanic dry fogs, climate cooling, and plague pandemics in Europe and the Middle East, *Climatic Change*, 42 (1999) 713–723.

explanation for this appears to be that global cooling following large eruptions correlates with periods of poor harvests and famine, as observed following the massive eruption of the Indonesian volcano Mount Tambora in 1815.[8] Malnutrition negatively influences human immunity and therefore could exacerbate a pandemic episode. Periods of famine can also lead to large scale population movement and therefore increase the spread of locally isolated diseases facilitating the progression from endemic to epidemic. In fact, though, the connections between volcanism, climate and disease are likely to be very much more complex than this. It is clear, for example, that volcanism does not only cause cooling: it has other effects on global climate, and these effects vary from one eruption to the next. This suggests that it is possible that there are less well understood connections between volcanic eruptions, climate and plague pandemics which go beyond the disruption and malnutrition caused by food shortages.[9]

In fact, relatively little work has been done to explore possible volcanism-climate-plague connections. The exception is the First Pandemic. A number of scholars have suggested that volcanism may have influenced the First Pandemic through the cooling of the

[8] S. Guillet, C. Corona, M. Stoffel, M. Khodri, F. Lavigne, P. Ortega, N. Eckert, P.D. Sielenou, V. Daux and O.V. Churakova, Climate response to the Samalas volcanic eruption in 1257 revealed by proxy records, *Nature Geoscience* 10 (2017) 123–128; H. Huhtamaa and S. Helama, Distant impact: tropical volcanic eruptions and climate-driven agricultural crises in seventeenth-century Ostrobothnia, Finland, *Journal of Historical Geography* 57 (2017) 40–51; R.B. Stothers, Climatic and demographic consequences of the massive volcanic eruption of 1258, *Climatic Change* 45 (2000) 361–374; C. Oppenheimer, Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815, *Progress in Physical Geography* 27 (2003) 230–259; A further case study of an earlier eruption having large societal impact can be found in, G. C. Jacoby, K. W. Workman and R. D. D'Arrigo, 1999. Laki eruption of 1783, tree rings, and disaster for northwest Alaska Inuit, *Quaternary Science Reviews* (1999) pp.1365-1371.

[9] U.E. Schaible and H.E. Stefan, Malnutrition and infection: complex mechanisms and global impacts, *PLoS Medicine* 4 (2007) e115.

Late Antique Little Ice Age (LALIA).[10] Most strikingly, though, volcanic impact on the Second Pandemic (which began with the Black Death of the mid-fourteenth century) has hardly been discussed. This is despite the fact that the pandemic occurred in a prolonged period of volcanically perturbed climate and within a century of the largest volcanic eruption of the Common Era, that of another Indonesian volcano, Samalas, in 1257.[11] The possible impact of volcanism upon climate and therefore society over varying spatial and temporal scales is likely

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[10] D. Keys, *Catastrophe: An Investigation into the Origins of the Modern World*, New York, 1999; D. Stathakopoulos, Reconstructing the climate of the Byzantine world: state of the problem and case studies, J. Laszlovszky and P. Szabó (Eds), *People and Nature in Historical Perspective*, Budapest, 2003, 251-55; U. Büntgen, V.S. Myglan, F.C. Ljungqvist, M. McCormick, N. Di Cosmo, M. Sigl, J. Jungclaus, S. Wagner, P.J. Krusic and J. Esper, Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD, *Nature Geoscience* 9 (2016) 231–236; K. Harper, *The Fate of Rome: Climate, Disease, and End of an Empire,* Princeton and Oxford, 2017, 218-20, 254; T.P. Newfield, Mysterious and mortiferous clouds: the climate cooling and disease burden of Late Antiquity, A. Izdebski and M. Mulryan (Eds), *Environment and Society in the Long Late Antiquity*, Leiden, 2019, 279-83

[11] F. Lavigne, J-P. Degeai, J-C. Komorowski, S. Guillet, V. Robert, P. Lahitte, C. Oppenheimer, M. Stoffel, C.M. Vidal, Surono, I. Pratomo, P. Wassmer, I. Hajdas, D.S. Hadmoko and E. de Belizal, Source of the great A.D. 1257 mystery eruption unveiled, Samalas volcano, Rinjani Volcanic Complex, Indonesia, *Proceedings of the National Academy of Sciences* 110 (2013); B.M.S. Campbell, *The Great Transition: Climate, Disease and Society in the Late Medieval World*, Cambridge, 2016, 56-8; G.H. Miller, Á. Geirsdóttir, Y. Zhong, D.J. Larsen, B.L. Otto-Bliesner, M.M. Holland, D.A. Bailey, K.A. Refsnider, S.J. Lehman and J.R. Southon, Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, *Geophysical Research Letters* 39 (2012); Guillet, Corona, Stoffel, Khodri, Lavigne, Ortega, Eckert, Sielenou, Daux and Churakova, Climate response to the Samalas volcanic eruption in 1257.

to be highly complex and would require detailed investigation on a case-by-case basis drawing on historical and archaeological data.[12]

The purpose of this paper is to demonstrate the urgent need for more collaborative multi-disciplinary work to deepen our understanding of global plague pandemics. This is achieved through the suggestion and evaluation of novel mechanisms linking volcanism, climate and plague. Several previous authors, including Atwell and McMichael, have investigated possible links between volcanism and epidemics. Others have explored the impact of climate change on the three *Y. pestis* driven pandemics including Schmid at al. and Kausrud et al. Fewer authors have addressed mechanisms linking volcanically mediated climate change and a *Y. pestis* pandemic episode, although this has been explored by McMichael and Newfield.[13] The present article is, to our knowledge, unique in advancing an interdisciplinary interpretative synthesis of previous literature and novel data analysis to investigate the potential impact of volcanism upon all three recorded plague pandemics of the last two millennia. It should be noted that our methodology varied from primarily literature review when investigating the First Pandemic to climatic data analysis for the later pandemics.

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[12] J. Haldon, L. Mordechai, T.P. Newfield, A.F. Chase, A. Izdebski, P. Guzowski, I. Labuhn and N. Roberts, History meets palaeoscience: consilience and collaboration in studying past societal responses to environmental change, *Proceedings of the National Academy of Sciences* (2018) 3210–3218.

[13] W. S. Atwell, Volcanism and short-term climatic change in East Asian and world history, c. 1200-1699. *Journal of World History* (2001), 29-98 ; A. J. McMichael, Insights from past millennia into climatic impacts on human health and survival, *Proceedings of the National Academy of Sciences* 109, no. 13 (2012): 4730-4737 ; T. P. Newfield, Mysterious and mortiferous Clouds: The climate cooling and disease burden of Late Antiquity, *Late Antique Archaeology* (2016): 89-115; B. V. Schmid, Büntgen, W.R. Easterday, C. Ginzler, L. Walløe, B. Bramanti, and N. C. Stenseth, Climate-driven introduction of the Black Death and successive plague reintroductions into Europe *Proceedings of the National Academy of Sciences* (2015), 3020-3025 ; Kausrud, Begon, Ari, Viljugrein, Esper, Büntgen, Leirs, Junge, Yang and Yang, Modeling the epidemiological history of plague in Central Asia

This is due to limited spatially resolved climate data covering the First Pandemic as well as limited documentary evidence around the initiation, early transmission and influence of plague at this time.[14]

Each of the three *Y. pestis* pandemic episodes occurred in periods of cooling which were potentially influenced by very large halogen and sulphur rich volcanic eruptions identified through the timing of the Global Volcanic Forcing (GVF) events[15] (Fig. 1). However, the timing of volcanism, cooling and pandemic outbreak is inconsistent across each period. Moreover, evidence does not yet exist to link volcanism with each pandemic event through a single mechanistic pathway. The first recorded case of the First Pandemic (541, Pelusium, Egypt) occurred simultaneously and four years after two eruptions which dramatically cooled summer temperatures in the northern hemisphere for several years.[16] The Black Death began roughly eighty years after the 1257 Samalas eruption and is therefore independent of the direct sulphate-induced summer cooling caused by that eruption. That said, the Black Death is coincident with the beginning of the Little Ice Age (LIA), which may be attributed in part to a period of intense late thirteenth century volcanism (including Samalas) and sea ice/ocean feedbacks.[17] Later eruptions might have contributed to cooling including the possibly the eruption of Hekla (Iceland) in 1341.[18]

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[14] L. Mordechai, M. Eisenberg, T. P. Newfield, A. Izdebski, J. E. Kay and H. Poinar, The Justinianic Plague: An inconsequential pandemic?, *Proceedings of the National Academy of Sciences* 116 (2019), 25546-25554

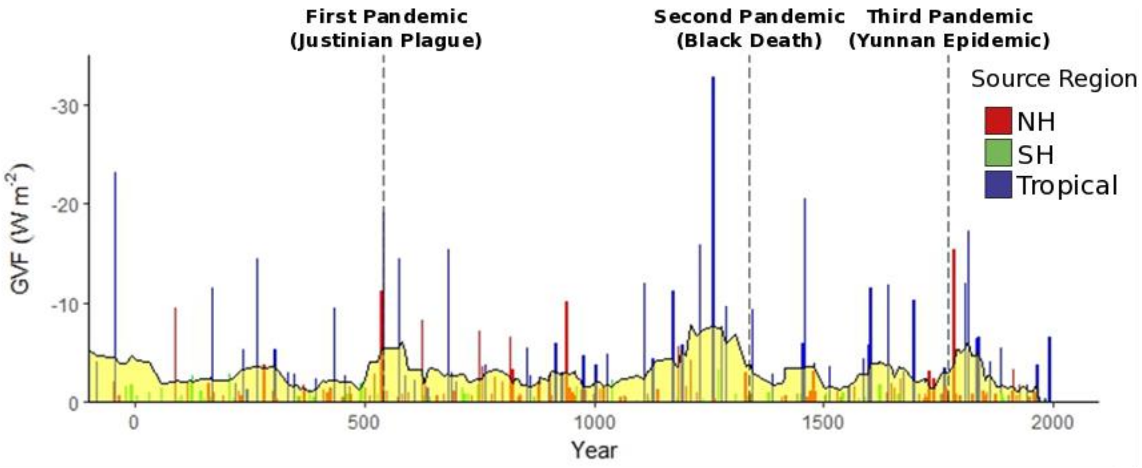
[15] GVF is an index constructed through the combination of ice core records of sulphate flux from the Northern and Southern Hemispheres scaled on a single temporal axis.

[16] Büntgen, Myglan, Ljungqvist, McCormick, Di Cosmo, Sigl, Jungclaus, Wagner, Krusic and Esper, Cooling and societal change.

[17] Miller, Geirsdóttir, Zhong, Larsen, Otto-Bliesner, Holland, Bailey, Refsnider, Lehman and Southon, Abrupt onset of the Little Ice Age.

[18] H. K. Roscoe, The risk of large volcanic eruptions and the impact of this risk on future ozone depletion, *Natural Hazards (*2001), 231-246.

Fig. 1. Volcanic forcing and plague pandemics over the Common Era



The Third Pandemic provides another different scenario. The first recorded case in 1772 in Yunnan Province, South China[19], actually preceded several significant eruptions including the major eruption of 1808/9, the location of which is currently unknown, and that of Tambora in 1815. However, the epidemic remained small-scale and isolated within Yunnan province until the 1860s when it began spreading to the rest of China.[20] It is therefore possible that volcanism may have influenced the subsequent spread of the new pandemic from Yunnan province, across China and ultimately across the world.

It appears, then, that if volcanism is connected with plague pandemics then these connections take various forms. In this paper, each pandemic episode will be examined

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[19] Benedict, *Bubonic Plague in Nineteenth-Century China*, 60.

[20] T. Ben-Ari, S. Neerinckx, L. Agier, B. Cazelles, L. Xu, Z. Zhang, X. Fang, S. Wang, Q. Liu, N.C. Stenseth, Identification of Chinese plague foci from long-term epidemiological data, *Proceedings of the National Academy of Sciences* 109 (2012) 8196–8201; Benedict, *Bubonic Plague in Nineteenth-Century China*, 47-51; L. Xu, L.C. Stige, H. Leirs, S. Neerinckx, K.L. Gage, R. Yang, Q. Liu, B. Bramanti, K.R. Dean and H. Tang, Historical and genomic data reveal the influencing factors on global transmission velocity of plague during the Third Pandemic, *Proceedings of the National Academy of Sciences* 116 (2019) 11833–11838.

separately to unravel potential casual links between large volcanic eruptions and plague expansion into global pandemics. This work is not exhaustive and is intended to illustrate the need for further multidisciplinary research.[21]

THE FIRST PANDEMIC

The First Pandemic began with the Justinianic plague in 541-4. Enormous death tolls numbering in the tens of millions have been proposed, and widespread impacts on the rise and fall of empires have been suggested. However, recent work has called into question the role of the First Pandemic in broad historical explanatory frameworks, and it has been demonstrated that there is insufficient evidence to support previous assumptions about widespread very heavy mortality. This new work calls into question the very idea of a “First Pandemic”. The authors of these recent studies point out the need for geographically-specific work to identify the location and severity of sixth- and seventh-century plague outbreaks, but it is nevertheless clear that plague was present during this period and it appears to have had a significant impact in certain places at certain times.[22] The arrival of plague in the sixth century occurred during a period of heightened volcanic activity (Fig. 1), and the evidence of the presence of sulphates in ice cores demonstrates that it coincided with a large volcanic eruption in 539/540, the location of which appears to have been Ilopango in El Salvador.[23] The 539/540

[21] Haldon, Mordechai, Newfield, Chase, Izdebski, Guzowski, Labuhn and Roberts, History meets palaeoscience.

[22] Mordechai, Eisenberg, Newfield, Izdebski, Kay and Poinar, The Justinianic Plague: An inconsequential pandemic?; L. Mordechai and M. Eisenberg, Rejecting catastrophe: the case of the Justinianic Plague, *Past and Present* 244 (2019), 3-50.

[23] M. Toohey, K. Krüger, M. Sigl, F. Stordal, H. Svensen, Climatic and societal impacts of a volcanic double event at the dawn of the middle ages, *Climatic Change* 136 (2016) 401–412; R. A. Dull, J. R. Southon, S. Kutterolf, K. J. Anchukaitis, A. Freundt, D. B. Wahl, P. Sheets, P. Amaroli, W. Hernandez, M. C. Wiemann, C. Oppenheimer, Radiocarbon and geologic

eruption is one of a cluster of eruptions (including others in 536 and 547) which together contributed to a prolonged period of cooling lasting until the late seventh century. Short-term volcano-induced cooling caused by the blocking of solar radiation is likely to have been extended because a sudden drop in temperatures would have led to an expansion of sea ice, which reflects solar radiation and causes further cooling.[24] The prolonged period of cooling is known as the Late Antique Little Ice Age (LALIA) and represented a century and a half of depressed global temperatures. This cool period is identifiable through the field of dendroclimatology, that analyses annual tree rings, the growth of which depended primarily on temperature in regions of high latitude or altitude.[25] Aside from this prolonged cooling, each individual volcanic eruption caused intense short-term cooling leading to crop failure, severe famine and large scale population loss across Eurasia.[26] The combination of rapid volcanically driven climatic change and prolonged cooling of the LALIA influenced the production of food. Shortages and concomitant malnutrition may have depressed people's resilience to disease and therefore increased the impact of plague mortality. It may also have contributed to the

evidence reveal Ilopango volcano as source of the colossal 'mystery' eruption of 539/40 CE, *Quaternary Science Reviews*, 222 (2019).

[24] Büntgen, Myglan, Ljungqvist, McCormick, Di Cosmo, Sigl, Jungclaus, Wagner, Krusic and Esper, Cooling and societal change; Miller, Geirsdóttir, Zhong, Larsen, Otto-Bliesner, Holland, Bailey, Refsnider, Lehman and Southon, Abrupt onset of the Little Ice Age; Toohey, Krüger, Sigl, Stordal and Svensen, Climatic and societal impacts.

[25] Büntgen, Myglan, Ljungqvist, McCormick, Di Cosmo, Sigl, Jungclaus, Wagner, Krusic and Esper, Cooling and societal change.

[26] R. D'arrigo, D. Frank, G. Jacoby, N. Pederson, Spatial response to major volcanic events in or about AD 536, 934 and 1258: frost rings and other dendrochronological evidence from Mongolia and northern Siberia: comment on RB Stothers,'Volcanic dry fogs, climate cooling, and plague pandemics in Europe and the Middle East' (Climatic Change, 42, 1999), *Climatic Change* 49 (2001) 239–246.

spread of plague by causing movements of people or encouraging the hoarding of grain benefiting rodent populations.[27]

According to the Byzantine historian Prokopios of Caesarea, the plague began in Pelusium, a relatively small Egyptian port city at the eastern edge of the Nile Delta.[28] From Pelusium, it spread westwards to Alexandria and eastwards to Gaza during the mid-late summer of 541. In the spring of 542 it arrived in Constantinople and spread through the eastern Mediterranean and North Africa. In 543, the plague arrived in Italy, southern France and Spain.[29] Recovered ancient DNA (aDNA) evidence suggests that *Y. pestis* spread as far from coastal Mediterranean as modern-day Bavaria and Britain. These data also suggest that the strains of *Y. pestis* responsible for the pandemic were now extinct variants, which were functionally similar to the strains responsible for the subsequent two pandemics.[30]

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[27] Newfield, Mysterious and mortiferous clouds, 280, 282-3.

[28] P. Allan, The "Justinianic" plague, *Byzantion* 49 (1979), 6.

[29] D. Ch. Stathakopoulos, *Famine and Pestilence in the Late Roman and Early Byzantine Empire: A Systematic Survey of Subsistence Crises and Epidemics*, Abingdon and New York, 113-6.

[30] M. Harbeck, L. Seifert, S. Hänsch, D.M. Wagner, D. Birdsell, K.L. Parise, I. Wiechmann, G. Grupe, A. Thomas and P. Keim, *Yersinia pestis* DNA from skeletal remains from the 6th century AD reveals insights into Justinianic Plague, *PLoS Pathogens* 9 (2013) e1003349; Y.-C. Sun, C.O. Jarrett, C.F. Bosio and B.J. Hinnebusch, Retracing the evolutionary path that led to flea-borne transmission of *Yersinia pestis*, *Cell Host & Microbe* 15 (2014) 578–586; M. Keller, M. A. Spyrou, C. L. Scheib, G. U. Neumann, A. Kröpelin, B. Haas-Gebhard, B. Päffgen, J. Haberstroh, A. Ribera i Lacomba, C. Raynaud, C. Cessford, R. Durand, P. Stadler, K. Nägele, J. S. Bates, B. Trautmann, S. A. Inskip, J. Peters, J. E. Robb, T. Kivisild, D. Castex, M. McCormick, K. I. Bos, M. Harbeck, A. Herbig, J. Krause, Ancient *Yersinia pestis* genomes from across Western Europe reveal early diversification during First Pandemic (541-70), *Proceedings of the National Academy of Sciences* 116 (2019), 12363-12372

There are a number of theories about the origin of the First Pandemic and its spread prior to the first historical evidence of its effects.[31] In particular, there has been a lot of discussion about whether the plague arrived in Pelusium from East Africa or directly from Asia. Both suggestions are compatible with rapid climate change caused by volcanic activity, but limited data mean these causal links are speculative. The idea that the plague originated in East Africa is now unsustainable because aDNA evidence indicates that the strain of Y. Pestis which caused the sixth-century plague came from Asia. The closest extant strain of *Y. pestis* to that of the First Pandemic has only been identified in the Tian Shan Mountains (Kyrgyzstan). It has been suggested, therefore, that this is a likely source region for the First Pandemic.[32] This hypothesis is further substantiated by the fact that this region is close to the site of the first recorded cases of the Black Death near Issyk-Kul (Kyrgyzstan). Even so, in his recent analysis of the various hypotheses for the origins of the Justinianic Plague, Newfield is mindful that contemporaries thought the plague had arrived from West Asia or East Africa. He pointed out that it is possible the disease originated in Asia but arrived in Europe from a reservoir closer to the Mediterranean, perhaps in East Africa.[33] The possibility of a reservoir closer to Europe than plague's central Asian point of origin is also a likely explanation for recent evidence for the diversity of strains of *Y. pestis* associated with the First Pandemic in Europe.[34]

[31] Newfield, Mysterious and mortiferous clouds, 279-82.

[32] G.A. Eroshenko, N.Y. Nosov, Y.M. Krasnov, Y.G. Oglodin, L.M. Kukleva, N.P. Guseva, A.A. Kuznetsov, S.T. Abdikarimov, A.K. Dzhaparova and V.V. Kutyrev, *Yersinia pestis* strains of ancient phylogenetic branch 0. ANT are widely spread in the high-mountain plague foci of Kyrgyzstan, *PLoS One* 12 (2017) e0187230.

[33] Newfield, Mysterious and mortiferous clouds, 279, 281.

[34] Keller et al., Ancient *Yersinia pestis* genomes, 12368.

Transport of *Y. pestis* to the Mediterranean may have been facilitated by climatic cooling which was associated, as explained above, with volcanism.[35] For example, if plague arrived from Asia by trade routes linking the Roman Empire and southwest Asia via the Red Sea, perhaps indirectly if the plague took hold in East Africa first, cooling may have allowed infected hosts and vectors to survive the northwards journey to Pelusium; the temperatures experienced in transit would usually be beyond the tolerable range of vectors during post-harvest transport (33-40˚C). Another possibility is that plague arrived in the Roman Empire from Central Asia overland. Stathakopoulos has suggested a possible mechanism here linked with volcano-induced climate change. He raised the possibility that drought caused by volcanism forced nomads who had come into contact with plague to migrate westwards from Persia into the Roman Empire in 536.[36] As Newfield pointed out, though, this hypothesis raises a lot of further questions including how and why plague passed into the Roman Empire via what is now Syria seemingly unnoticed by contemporaries.[37]

It is feasible that the 536 and 539/540 eruptions may have influenced plague's initiation in Central Asia. Tropical eruptions may have increased precipitation across the arid and otherwise precipitation-limited Asian steppe, however this suggestion is regularly challenged due to discrepancy between general circulation modelling methods and proxy records, and therefore should be treated cautiously.[38]. Several previous authors have suggested that

[35] A. J. McMichael, Insights from past millennia into climate impacts on human health and survival, *Proceedings of the National Academy of Sciences*, .109 (2012), 4730-4737.

[36] Stathakopoulos, Reconstructing the climate,254.

[37] Newfield, Mysterious and mortiferous clouds, 281-2.

[38]M. Mohtadi, M. Prange and S. Steinke. Palaeoclimatic insights into forcing and response of monsoon rainfall. *Nature*, 533(7602) (2016) pp.191-199.: K.J. Anchukaitis, B. M.Buckley, E.R. Cook, B.I. Coo, R.D. D'Arrigo and C.M. Ammann, Influence of volcanic eruptions on the climate of the Asian monsoon region. *Geophysical Research Letters*, 37(22) (2010):

increased rainfall may have had a catalytic effect in the zoonosis region through the trophic cascade mechanism and then have also contributed to plague's introduction to Europe from this region.[39]

The impact of the prolonged LALIA cooling on Mediterranean and Eurasian societies may have enabled plague to establish itself within human populations, and would otherwise have only caused a minor regional epidemic with a limited death toll.[40] Although the dearth of historical documentation and high resolution spatially resolved climate data hinder investigations of the First Pandemic, increasing availability of genomic data is providing a valuable new resource. Possible mechanisms linking volcanism, climate change and the First Pandemic have been suggested here, but we also highlight the urgency of further collaborative interdisciplinary research to clarify and test these suggestions.

Büntgen, Myglan, Ljungqvist, McCormick, Di Cosmo, Sigl, Jungclaus, Wagner, Krusic, Esper, Cooling and societal change

[39] Eroshenko, Nosov, Krasnov, Oglodin, Kukleva, Guseva, Kuznetsov, Abdikarimov, Dzhaparova and Kutyrev, *Yersinia pestis* strains of ancient phylogenetic branch 0; Schmid, Büntgen, Easterday, Ginzler, Walløe, Bramanti and Stenseth, Climate-driven introduction of the Black Death; K.L. Kausrud, H. Viljugrein, A. Frigessi, M. Begon, S. Davis, H. Leirs, V. Dubyanskiy and N.C. Stenseth, Climatically driven synchrony of gerbil populations allows large-scale plague outbreaks, *Proceedings of the Royal Society of London B: Biological Sciences* 274 (2007) 1963–1969; Stenseth, Samia, Viljugrein, Kausrud, Begon, Davis, Leirs, Dubyanskiy, Esper and Ageyev, Plague dynamics are driven by climate variation.

[40] Büntgen, Myglan, Ljungqvist, McCormick, Di Cosmo, Sigl, Jungclaus, Wagner, Krusic and Esper, Cooling and societal change; J. Haldon, N. Roberts, A. Izdebski, D. Fleitmann, M. McCormick, M. Cassis, O. Doonan, W. Eastwood, H. Elton, S. Ladstätter, The climate and environment of Byzantine Anatolia: integrating science, history, and archaeology, *Journal of Interdisciplinary History* 45 (2014) 123.

THE SECOND PANDEMIC

The Black Death which began the Second Pandemic is the most infamous plague outbreak, and it caused a reduction in human populations across Europe of between 10-60%.[41] The current earliest reference to human plague deaths during the first pandemic is a disease outbreak in the Caspian region, following an earthquake, which may have been plague.[42] References to deaths from disease on gravestones from Issyk-Kul (Kyrgyzstan) dated to 1338/9 provide the next evidence of the spread of plague and the initiation of the second pandemic.[43] Further documentary evidence is consistent with plague's initiation in Central Asia prior to its arrival on the northern side of the Black Sea in 1346.[44] An early reference to plague spreading in Asia prior to its arrival in Europe occurs in the account of Ibn Al-Wardi, a contemporary Arab scholar. He suggested that 'The disease began in the land of darkness' (interpreted as Western Siberia) and that 'pestilence raged in the east for 15 years before arriving in the west', which suggests a start date around 1331.[45] This closely coincides with the death of the Mongol Great Khan Jijaghatu Toq-Temur and his sons of an unknown illness in 1332 and Chinese evidence for a very serious epidemic in Hopei province in the previous

[41] The best summary of the literature on mortality rates is Ole J. Benedictow, *The Black Death 1346-1353: The Complete History*, Woodbridge, 2004.

[42] H. Barker, Laying the corpses to rest: grain, embargoes, and *Yersinia pestis* in the Black Sea, 1346-1348, *Speculum*, forthcoming 2021. Barker's article is available here https://osf.io/preprints/bodoarxiv/rqn8h/ (accessed 17 August, 2020).

[43] P. Slavin, Death by the lake: mortality crisis in early fourteenth-century Central Asia, *Journal of Interdisciplinary History* 50 (2019) 87–88.

[44] Campbell, *The Great Transition*, 242; Barker, Laying the corpses to rest: grain, embargoes, and *Yersinia pestis* in the Black Sea.

[45] Slavin, Death by the lake, 86. For a translation of Al-Wardi which includes this extract, see John Aberth, ed., *The Black Death: The Great Mortality of 1348-50, A Brief History with Documents*, New York, 2005, 17.

year.[46] Recent work indicates that the Black Death crossed the Black Sea from north to south in grain shipments in which infected rats and fleas were transported in 1347 thence arriving in Constantinople and Italian cities.[47]

Genetic evidence suggests the *Y. pestis* strain which caused the Second Pandemic came from a Central Asian source on the Tibetan plateau or in the Tian Shan mountain range on the border between China, Kyrgyzstan and Kazakhstan.[48] The most recent aDNA evidence suggests that a strain basal to all second pandemic *Y. pestis* strains was active in Laishevo (roughly 2000km north east of the Crimean Peninsula) prior to introduction to Europe at the beginning of the Black Death in 1347.[49] Work on the genome of *Y. pestis* indicates that there was a period of sudden diversification shortly before or coincident with the Black Death in which the strain responsible for the mid-fourteenth century outbreak emerged. This sudden genetic diversification is referred to as the 'big bang'. Work on the historic mutation rate of the genome has dated the 'big bang' to a median date of 1268 within a range from 1142 to 1339

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[46] Kelly, Great Mortality, 6.

[47] Barker, Laying the corpses to rest.

[48] Y. Cui, C. Yu, Y. Yan, D. Li, Y. Li, T. Jombart, L.A. Weinert, Z. Wang, Z. Guo, L. Xu, Historical variations in mutation rate in an epidemic pathogen, *Yersinia pestis*, *Proceedings of the National Academy of Sciences USA* 110 (2013) 577–582; Eroshenko, Nosov, Krasnov, Oglodin, Kukleva, Guseva, Kuznetsov, Abdikarimov, Dzhaparova, Kutyrev, *Yersinia pestis* strains of ancient phylogenetic branch 0.

[49] M. A. Spyrou, M, Keller, R. I. Tukhbatova, C. L. Scheib, E. A. Nelson, A. A. Valtueña, G. U. Neumann, D. Walker, A. Alterauge, N. Carty, and C. Cessford, Phylogeography of the second plague pandemic revealed through analysis of historical Yersinia pestis genomes. *Nature communications* (2019), 1-13.

at a 95% confidence interval.[50] Further work is required to determine the geographic origin of this event as the pervious hypothesis of a Central Asian genesis as suggested by Cui et al., (2013) will have to be rationalised with the most recent finding of a basal Black Death strain in Laishevo.[51] The mid thirteenth century – several decades before the Black Death – was one of the most volcanically active periods of the Common Era with many similarities to the early to mid sixth century which saw the initiation of the First Pandemic. During both the sixth and thirteenth centuries there were repeated high-sulphate tropical eruptions which may have contributed to centuries of subsequent cooling through the LALIA and the Little Ice Age (LIA) respectively.[52]

On the Central Asian steppe near to Issyk-Kul, a warm and increasingly wet period – beneficial for plague prevalence within local host communities – persisted from 1280 to 1350.[53] However, further south in the Himalayas, LIA cooling began at the start of the fourteenth

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[50] Cui, Yu, Yan, Li, Li, Jombart, Weinert, Wang, Guo, Xu, Historical variations in mutation rate, 580; Monica H. Green, Taking “pandemic” seriously: making the Black Death global, *The Medieval Globe* 1 (2014), 37-9.

[51] Spyrou, Keller, Tukhbatova, Scheib, Nelson, Valtueña, Neumann, Walker, Alterauge, Carty and Cessford, Phylogeography of the second plague pandemic revealed through analysis of historical Yersinia pestis genomes.

[52] Büntgen, Myglan, Ljungqvist, McCormick, Di Cosmo, Sigl, Jungclaus, Wagner, Krusic, Esper, Cooling and societal change; Miller, Geirsdóttir, Zhong, Larsen, Otto-Bliesner, Holland, Bailey, Refsnider, Lehman, Southon, Abrupt onset of the Little Ice Age.

[53] K.S. Treydte, G.H. Schleser, G. Helle, D.C. Frank, M. Winiger, G.H. Haug, J. Esper, The twentieth century was the wettest period in northern Pakistan over the past millennium, *Nature* 440 (2006) 1179; Stenseth, Samia, Viljugrein, Kausrud, Begon, Davis, Leirs, Dubyanskiy, Esper, Ageyev, Plague dynamics are driven by climate variation.

century with the cooling progressively spreading north.[54] Any link between plague and climate is difficult to prove, but Schmid et al. developed a quantitative method using evidence of historic plague outbreaks after the Black Death and climate data to indicate that plague was repeated reintroduced into Europe from reservoirs in parts of Asia as a result of climatic factors. In particular, they suggested that a peak in warm conditions favouring plague host species followed by continuous cooling would negatively influence host species, exacerbating plague infection, transmission to alternate species and gradual westward progression.[55] The interaction of heterogeneous climatic change across the Central Asian region and plague host species dynamics may be key to understanding the initiation of the Black Death.

The 1257 Samalas eruption was the greatest of the suite of thirteenth century eruptions, and it was the largest single sulphate injection of the Common Era as recorded in bi-polar ice cores.[56] It should be noted, however, that Samalas' climatic influence is debated due to regular discordance between model predictions and proxy records.[57] Moreover, there is a significant disparity in the dates of this eruption and the initiation of the Black Death. However, the dating to around 1268 of the 'big bang' diversification of *Y. pestis* which produced the strain responsible for the Black Death coincides more closely with the eruption

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[54] A.V. Rowan, The 'Little Ice Age'in the Himalaya: A review of glacier advance driven by Northern Hemisphere temperature change, *The Holocene* 27 (2017) 292–308.

[55] Schmid, Büntgen, Easterday, Ginzler, Walløe, Bramanti, Stenseth, Climate-driven introduction of the Black Death and successive plague reintroductions into Europe.

[56] M. Sigl, M. Winstrup, J. McConnell, K. Welten, G. Plunkett, F. Ludlow, U. Büntgen, M. Caffee, N. Chellman, D. Dahl-Jensen, Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature* 523 (2015) 543–549.

[57] M. Stoffel, M. Khodri, C. Corona, S. Guillet, V. Poulain, S. Bekki, J. Guiot, B.H. Luckman, C. Oppenheimer, N. Lebas, Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years, *Nature Geoscience* 8 (2015) 784–788.

of Samalas, and the spread of the new strain might be connected with the volcanically mediated cooling of the LIA.

Cooling and warming: a mechanism for the spread of plague

Climatic reconstructions can be used to interrogate the potential links between volcanic activity – particularly the Samalas eruption of 1257 – and the plague epidemic in Central Asia which would become the Black Death. This analysis is based on the high spatial resolution (2°x2°) PAGES Asia 2K Asian summer (JJA) temperature reconstruction, a database developed using multiple sets of climate proxy data including tree ring data, ice core data and other sources. We validated the PAGES Asia 2K data against the N-TREND (Eastern Eurasian Region) data to confirm the replicability of the higher spatial resolution PAGES data set.[58] PAGES Asia 2K was used here to identify temporal and spatial summer temperature change across Central Asia (Fig. 2) over the interval covering the emergence of the Black Death pandemic (1250—1350).[59] The region was subdivided into two areas. The zoonosis area (64-86°E,38-48°N) – that is the area in which it is suggested that the new strain of *Y. pestis* was first transmitted from animals to humans – encompasses Issyk-Kul as well as the Lake Balkhash region of Kazakhstan. This area harbours a permanent plague host species, the great gerbil (*Rhombomys opimus)*. It also encompasses the Tian Shan mountain range, a potential genetic source region.[60] The zoonosis area as defined here is to the north of the monsoon limit and is

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[58] R. Wilson, K. Anchukaitis, K.R. Briffa, U. Büntgen, E. Cook, R. D'arrigo, N. Davi, J. Esper, D. Frank, B. Gunnarson, Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context, *Quaternary Science Reviews* 134 (2016) 1-18.
[59] E.R. Cook, P.J. Krusic, K.J. Anchukaitis, B.M. Buckley, T. Nakatsuka, M. Sano, Tree-ring reconstructed summer temperature anomalies for temperate East Asia since 800 CE, *Climate Dynamics* 41 (2013) 2957–2972.

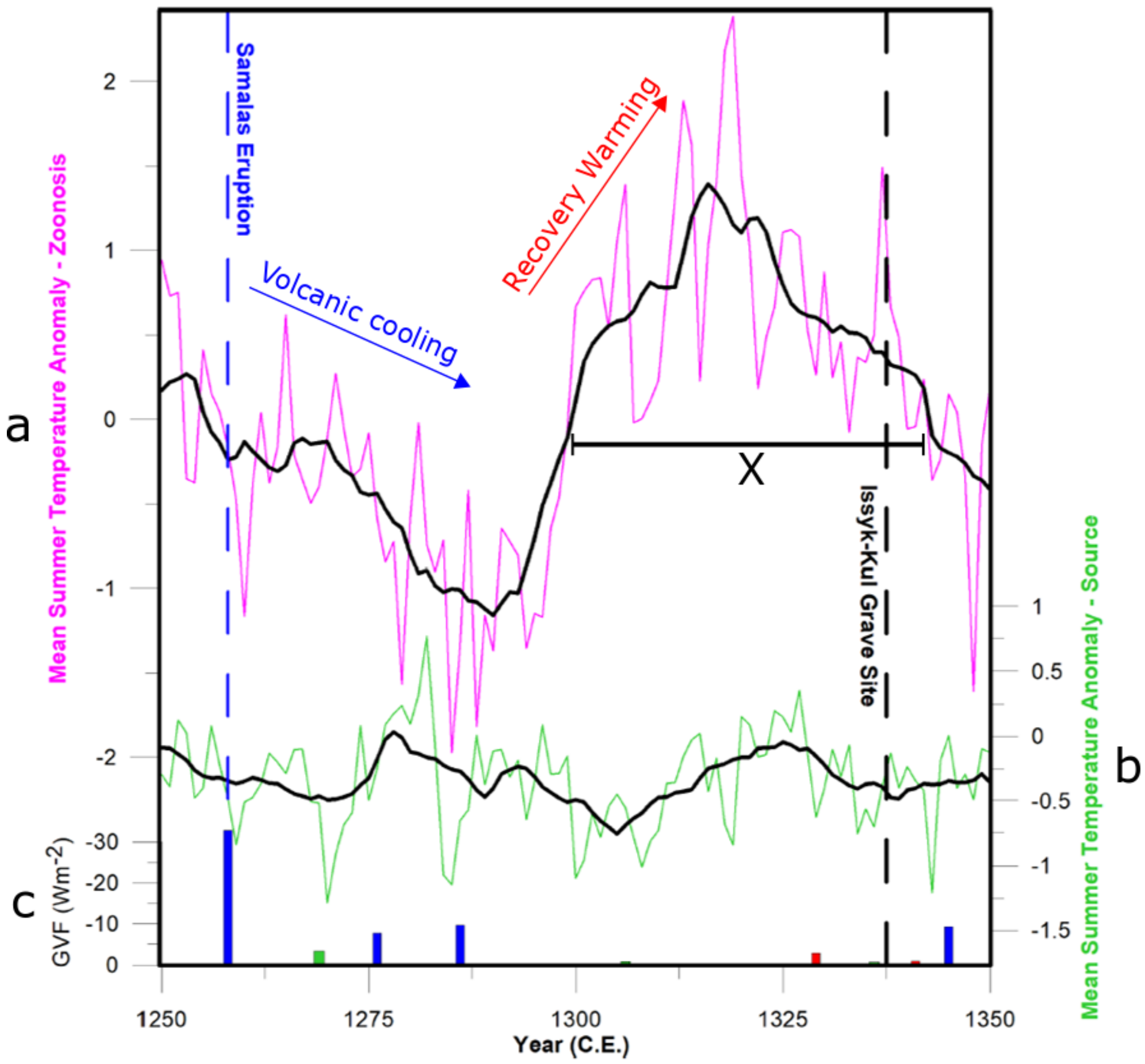
[60] Eroshenko, Nosov, Krasnov, Oglodin, Kukleva, Guseva, Kuznetsov, Abdikarimov, Dzhaparova, Kutyrev, *Yersinia pestis* strains of ancient phylogenetic branch 0.

within Arid Central Asia (ACA) where climate is driven predominantly by the westerlies. The source area (90-110°E, 30-40°N) is defined here based on the work of Cui et al. It is the area encompassing the highest diversity of *Y. pestis* strain isolates and is therefore likely to be the original source of the strain of *Y. pestis*, which caused the Black Death.[61] The source area straddles the current Asian summer monsoon limit and the climate in this area is therefore driven by the Asian monsoon system.[62]

[61] Cui, Yu, Yan, Li, Li, Jombart, Weinert, Wang, Guo, Xu, Historical variations in mutation rate.

[62] F.-H. Chen, J.-H. Chen, J. Holmes, I. Boomer, P. Austin, J.B. Gates, N.-L. Wang, S.J. Brooks, J.-W. Zhang, Moisture changes over the last millennium in arid Central Asia: a review, synthesis and comparison with monsoon region, *Quaternary Science Reviews* 29 (2010) 1055–1068.

Fig. 2. Comparison of temperature variations within the source and zoonosis areas across the period of the Black Death pandemic



Both areas experienced immediate cooling following the Samalas eruption lasting 3—4 years, followed by an initial partial recovery. However, three further moderate (-3 to -10 Wm^{-2} Global Volcanic Forcing (GVF) eruptions identified in bipolar ice core records occurred in quick succession following Samalas, leading to 1285 being the fourth and eighth coolest year of the PAGES Asia 2K Asian summer temperature record within the source and zoonosis areas respectively.[63] Temperature for the source and zoonosis areas diverged after

[63] Cook, Krusic, Anchukaitis, Buckley, Nakatsuka, Sano, Tree-ring reconstructed summer temperature anomalies.

1285, with the zoonosis area beginning to warm intensely while temperatures continued to decrease in the source area. A forty-year period of sustained anomalous warmth (Fig. 2, X) within the zoonosis area peaked in ~1318 with a maximum temperature of 23.1˚C (σ of reconstruction = 0.33˚C[64]), the warmest reconstructed temperature for this area across the entire 1,200 year PAGES Asia 2K record. The temperature within the zoonosis area increased from 19°C at the post-volcanism temperature minimum to 23.1°C in ~1318, which is within the optimum transmission temperature range of *Y. pestis* via *X. cheopis*, thereby potentially catalysing zoonosis.[65] Warm conditions can promote epizootics within Central Asia, particularly when coupled with increased rainfall.[66] Palmer Drought Severity Index (PDSI) reconstructions suggest that the intense and geographically isolated warming within the zoonosis area in the years ~1318 coincided with high rainfall, providing climatically optimum conditions for *Y. pestis* zoonosis through the trophic cascade mechanism.[67] Following the peak in recovery warming in 1318, temperatures consistently fall as global climate transitions into the new norm of the LIA, which may have been driven by the

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[64] Cook, Krusic, Anchukaitis, Buckley, Nakatsuka, Sano, Tree-ring reconstructed summer temperature anomalies.

[65] A.M. Schotthoefer, S.W. Bearden, J.L. Holmes, S.M. Vetter, J.A. Montenieri, S.K. Williams, C.B. Graham, M.E. Woods, R.J. Eisen, K.L. Gage, Effects of temperature on the transmission of *Yersinia pestis* by the flea, *Xenopsylla cheopis*, in the late phase period, *Parasites & Vectors* 4 (2011) 191.

[66] Kausrud, Begon, Ari, Viljugrein, Esper, Büntgen, Leirs, Junge, Yang, Yang, Modeling the epidemiological history of plague in Central Asia; Schmid, Büntgen, Easterday, Ginzler, Walløe, Bramanti, Stenseth, Climate-driven introduction of the Black Death.

[67] E.R. Cook, K.J. Anchukaitis, B.M. Buckley, R.D. D'Arrigo, G.C. Jacoby, W.E. Wright, Asian monsoon failure and megadrought during the last millennium, *Science* 328 (2010) 486–489; Ari, Neerinckx, Gage, Kreppel, Laudisoit, Leirs, Stenseth, Plague and climate: scales matter.

thirteenth century volcanism[68]. The cooling-warming mechanism suggested here is represented in Figure 3.

The termination of this interval of anomalous warmth coincides with the earliest evidence suggesting human plague victims (1338/9) although earlier unrecorded victims may also have existed. This is the same mechanism of peak warming and prolonged cooling suggested by Schmid et al. to have driven repeated reintroductions of plague into Europe during the Black Death.[69] We suggest that the warming period represented regional recovery following volcanically induced cooling. The following cooling period leading to the first recorded plague deaths was the early initiation of LIA across Asia driven by thirteenth century volcanism and sustained sea ice/ocean feedbacks.[70]

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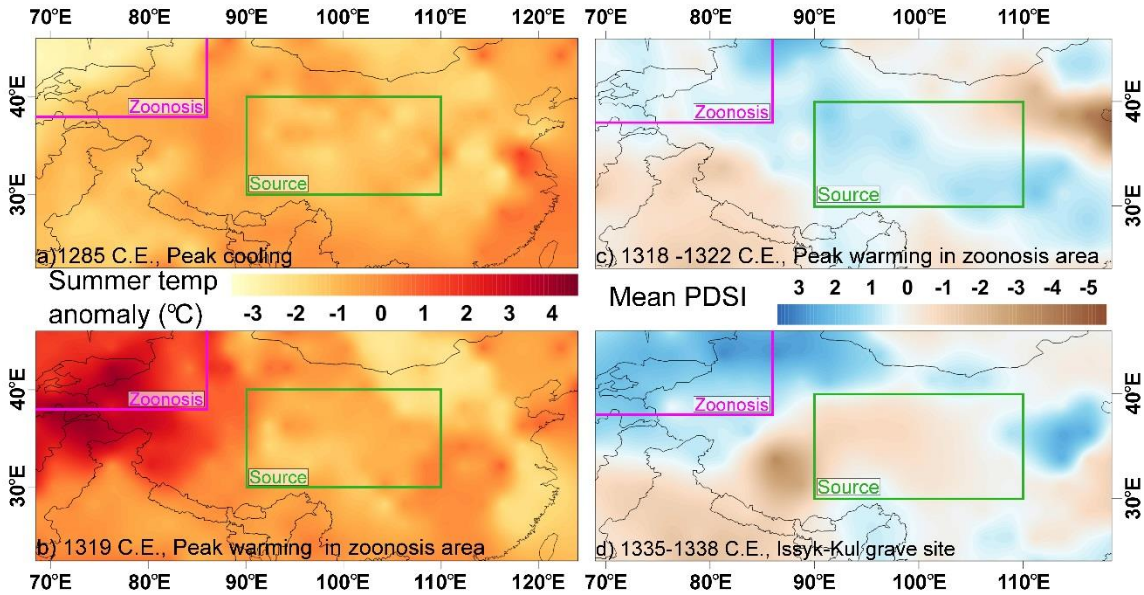
[68] Miller, Geirsdóttir, Zhong, Larsen, Otto-Bliesner, Holland, Bailey, Refsnider, Lehman, Southon, Abrupt onset of the Little Ice Age.

[69] Schmid, Büntgen, Easterday, Ginzler, Walløe, Bramanti and Stenseth, Climate-driven introduction of the Black Death, 3022.

[70] Rowan, The 'Little Ice Age' in the Himalaya; Miller, Geirsdóttir, Zhong, Larsen, Otto-Bliesner, Holland, Bailey, Refsnider, Lehman, Southon, Abrupt onset of the Little Ice Age.

Fig. 3 Contoured summer temperature anomaly and PDSI maps across short-term periods of interest for *Y. pestis* host and vector populations



The role of warfare and bad weather

The combined effects of human activity and bad weather may have further contributed to the spread of plague in the zoonosis area described above. These include the impact of disruption caused by the Mongols and adverse weather conditions caused by the massive eruption of Samalas in 1257.

As mentioned above, gravesites from the Nestorian Christian community near Issyk-Kul provide early plausible evidence of plague fatalities preceding the well documented arrival of plague in Europe in 1346. Other evidence suggests that the early-fourteenth-century Nestorian Christian community in this area was isolated and beleaguered, and the health of this small and vulnerable community may have influenced pandemic initiation.[71] In 1338/9 the Nestorian Christian population lived deep within the boundaries of the Mongol empire. The

[71] Schaible, Stefan, Malnutrition and infection.

Mongol Empire expanded in the thirteenth century to its furthest reaches, stretching from the Pacific Ocean in Eastern China to Eastern Europe in the west.[72] The area south of Lake Balkhash (encompassing Issyk-Kul) was established as pasture by the Mongols in 1250. However, this was short lived, because by the mid fourteenth century warfare had drastically deteriorated agricultural lands. It is likely that this deterioration of pasture will have impacted host rodent species in the area, possibly affecting contact between human and rodent populations.[73] Unrest caused by military campaigns waged between the Mongol Khanates may have affected the Issyk-Kul area too. For example, in a brief conflict in 1315 the Yuan Khanate (eastern) moved deep into Chaghadaid territory (central) and reached their winter pastures near Issyk-Kul. Yuan soldiers are reported to have 'looted their wives and children'.[74] Nestorian Christian communities were also threatened by increasing Islamization in Central Asia around the same time, potentially making them more susceptible to infection through general ill health and malnourishment.

It is suggested above that rapid climate change in the late thirteenth and early fourteenth centuries was connected to the spread of the new strain of *Y. pestis*. It also, of course, had direct and immediate effects on human populations including the early Second Pandemic victims in Issyk-Kul. Some of this climate change can be linked to the 1257 Samalas

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[72] D. Morgan, The decline and fall of the Mongol Empire, *Journal of the Royal Asiatic Society* 19 (2009) 427–437; M. Biran, The Mongols in Central Asia from Chinggis Khan's invasion to the rise of Temür: The Ögödeid and Chaghadaid realms, in: A.F. N. Di Cosmo and P. Golden (Eds), *The Cambridge History of Inner Asia: The Chinggisid Age*, Cambridge, 2009, 46–66.

[73] Slavin, Death by the lake, 70, 71, 79.

[74] L. Yingsheng, War and peace between the Yuan Dynasty and the Chaghadaid Khanate (1312-1323), in: R. Amitai, M. Biran (Eds), *Mongols, Turks and Others: Eurasian Nomads and the Sedentary World*, Leiden, 2005, 349.

eruption. Samalas affected much of China, then occupied by the Mongol Empire, initially through cooling during the late 1250s and then through torrential rain and flooding in the early 1260s. Flooding was followed by severe droughts which contributed to food shortages.[75] There are similar reports of dire weather conditions affecting population resilience through impact on agriculture across the northern hemisphere from Japan to Northern Europe.[76] However further work is required to assess volcanic impacts directly relatable to the Issyk-Kul Nestorian populations at the time of pandemic initiation, possibly due to the initiation of the LIA.

Significant agricultural disruption also occurred across Europe prior to *Y. pestis'* introduction. 'Plagues' had a serious impact on sheep populations via 'sheep scab' which affected British flocks in 1279—1280 and the 1310s and on cattle populations via the 'Great Bovine Pestilence' of 1319—1320 prior to the Black Death. The sheep scab event appears to have been isolated to England, whereas there are records of bovine pestilence across much of Northern Europe from 1315-1325. Several much smaller regional sheep scab epidemics occurred across England throughout the thirteenth century, however the 1279-1280 event is the first date where there appears to be national synchrony in infection. The unstable Eurasian climate following the Samalas eruption is thought to have contributed to the 1279-1280 sheep scab outbreak England due to cold and wet conditions for several years prior providing in ideal environment for activity of the scab mites. The bovine pestilence spread Westward across Europe from Bohemia to Ireland from 1315-1321 and is a striking precursor to Plague which spread in the same direction roughly 30 years later.[77] Unlike plague and sheep scab however the bovine pestilence was not a vector disease and is thought to have been caused by

[75] Atwell, Volcanism and short-term climatic change.

[76] Guillet, Corona, Stoffel, Khodri, Lavigne, Ortega, Eckert, Sielenou, Daux, Churakova, Climate response to the Samalas volcanic eruption in 1257.

[77] P. Slavin. Epizootic Landscapes: Sheep Scab and Regional Environment in England in 1279–1280. *Landscapes* 17, no. 2 (2016): 156-170.

Rinderpest virus, however this remains speculative and further work is required to confirm this.[78]

These pastoral epidemics of the early fourteenth century were accompanied by severe dislocation in the arable sector, most notably the Great Famine of 1315—17 which was certainly the result of unusual weather conditions.[79] Poor harvests and animal disease influenced the health of human populations across the Britain and mainland Europe. Famine and nutritional deficit caused by respective shortages of grain (contributing to 70—80% of daily caloric intake) and dairy products (10—15% caloric intake) would have had a negative impact on the health of the entire population but would have been particularly damaging to less wealthy people who lived close to the margins of subsistence. Nevertheless, it should be noted that little bias is observed in plague burials towards individuals with tell-tale skeletal stress markers which are symptomatic of survival through famine.[80]

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[78] T.P. Newfield. A cattle panzootic in early fourteenth–century Europe. *Agricultural History Review* 57, no. 2 (2009): 155-190.

[79] Campbell, *The Great Transition*, 142–3, 209, 218-9; P. Slavin, The 1310s event, in: S. White, C.M.F. Pfister (Eds), *The Palgrave Handbook of Climate History*, London, 2018, 506; T.P. Newfield, A cattle panzootic in early fourteenth–century Europe, *Agricultural History Review* 57 (2009) 155–190.

[80] S. DeWitte, P. Slavin, Between famine and death: England on the eve of the Black Death—evidence from paleoepidemiology and manorial accounts, *Journal of Interdisciplinary History* 44 (2013) 37–60; J.M. Grove, Climatic change in northern Europe over the last two thousand years and its possible influence on human activity, in: G. Wefer, W. H. Berger, K.-E. Behre, E. Jansen, *Climate Development and History of the North Atlantic Realm*, Berlin, 2002, 313–326; S.N. DeWitte, Setting the stage for medieval plague: Pre-black death trends in survival and mortality, *American Journal of Physical Anthropology* 158 (2015) 441–451.

Overall, a mechanism is suggested here which links the intense volcanism of the thirteenth century – and especially the enormous Samalas eruption of 1257 – with the zoonosis and spread of the new strain of *Y. pestis* which would go on to cause the Black Death. It is also argued that rapid climate change in the late thirteenth and early fourteenth centuries weakened human populations in Central Asia and Europe, making them more vulnerable to a pandemic.

THE THIRD PANDEMIC

Historic data from the Third Pandemic suggest a much larger lag period between initial small regional epidemics and the start of international, pandemic spread. This lag may be more apparent than genuine. Fewer records survive from the First and Second pandemics meaning we may not be aware of smaller regional epidemics preceding much more widespread mortality in the earlier periods. The earliest epidemic record, interpreted as bubonic plague, from the Third Pandemic is from Heqing in the west of the Chinese province of Yunnan in 1772.[81] Plague then spread across Yunnan province for the remainder of the eighteenth century and into the nineteenth century with the first epidemic peak occurring in Yunnan in 1864, before expanding east, eventually reaching Hong Kong in 1894.[82] Plague then spread internationally through shipping routes; it reached the Americas for the first time at the turn of the twentieth century.[83]

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[81] Benedict, Bubonic Plague in Nineteenth-Century China, 60.

[82] Z. Sun, Z. Zhang, Q. Liu, B. Lyu, X. Fang, S. Wang, J. Xu, L. Xu, B. Xu, Identifying the spatiotemporal clusters of plague occurrences in China during the Third Pandemic, *Integrative Zoology*, advance online version: doi: 10.1111/1749-4877.12411; Benedict, *Bubonic Plague in Nineteenth-Century China*, 18-51; M. Drancourt, D. Raoult, Molecular insights into the history of plague, *Microbes and Infection* 4 (2002) 105–109.

[83] M.J. Echenberg, Pestis redux: The initial years of the third bubonic plague pandemic, 1894-1901, *Journal of World History* 13 (2002) 442; .J.Z. Adjemian, P. Foley, K.L. Gage, J.E.

Genetic evidence recovered from aDNA of plague victims suggests the plague strain that initially spread from China/Central Asia at the beginning of the Black Death following the 'big bang' diversification event later spread back to Asia.[84] A descendant of this strain (1.ORI, orientalis) was then responsible for the Third Pandemic and may have been maintained in plague foci proximal to Yunnan – likely the Qinghai—Tibet Plateau – before reintroduction to human populations in the eighteenth century.[85]

A large epidemic in Moscow, Russia is also concurrent with the start of the early epidemic in Yunnan. The outbreak in Moscow began in the spring of 1770 after progressing north from the Black Sea in the preceding years. Plague in Moscow then peaked in September 1771 killing tens of thousands. Extraordinary weather conditions prevailed and may have facilitated the spread of the disease. These included highly changeable seasons and prolonged torrential rain which Alexander thought were 'possibly a product of volcanic dust veils'.[86] The eruption of Hekla (Iceland), which began in April 1766 and continued until May of 1768 is the only eruption which could have caused these dust veils, if indeed they were a

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Foley, Initiation and spread of traveling waves of plague, *Yersinia pestis*, in the western United States, *The American Journal of Tropical Medicine and Hygiene* 76 (2007) 365.

[84] M.A. Spyrou, R.I. Tukhbatova, M. Feldman, J. Drath, S. Kacki, J.B. de Heredia, S. Arnold, A.G. Sitdikov, D. Castex, J. Wahl, Historical *Y. pestis* genomes reveal the European black death as the source of ancient and modern plague pandemics, *Cell Host & Microbe* 19 (2016) 874–881.

[85] G. Morelli, Y. Song, C.J. Mazzoni, M. Eppinger, P. Roumagnac, D.M. Wagner, M. Feldkamp, B. Kusecek, A.J. Vogler, Y. Li, *Yersinia pestis* genome sequencing identifies patterns of global phylogenetic diversity, *Nature Genetics* 42 (2010) 1140–1143; Y. Cui, East to West or West to East: Plague Spread after the Black Death, *Infectious Diseases and Translational Medicine* 2 (2016) 58–59.

[86] J.T. Alexander, *Bubonic Plague in Early Modern Russia: Public Health and Urban Disaster*, Oxford, 2003,102.

cause of the unusual weather.[87] Despite limited sulphate loading identified in ice cores, the Hekla eruption coincided with a period of cooling identifiable in temperature reconstructions across both Eastern and Western Eurasia.[88] Even so, a causal link between Hekla and the cooling requires further investigation. More importantly, perhaps, Hekla represented the beginning of a suite of eruptions which each caused significant cooling: Laki (Iceland) 1783, the unknown 1808/1809 tropical eruption, and the Tambora (Indonesia) eruption of 1815 which caused the infamous 'year without summer'.[89] These subsequent eruptions obviously did not affect the epidemic in Russia which was short lived. However, the plague epidemic in Yunnan was still ongoing and would become the Third Pandemic. It is suggested here that the series of eruptions culminating in Tambora in 1815 did affect the development of the most recent pandemic.

Several studies have emphasised the importance of the spatial scale of plague studies, as well as heterogeneous responses to climatic change.[90] Using previously published climatic

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[87] M.H. Janebo, T. Thordarson, B.F. Houghton, C. Bonadonna, G. Larsen, R.J. Carey, Dispersal of key subplinian–Plinian tephras from Hekla volcano, Iceland: implications for eruption source parameters, *Bulletin of Volcanology* 78 (2016) 66; Sigl, Winstrup, McConnell, Welten, Plunkett, Ludlow, Büntgen, Caffee, Chellman, Dahl-Jensen, Timing and climate forcing.

[88] Wilson, Anchukaitis, Briffa, Büntgen, Cook, D'arrigo, Davi, Esper, Frank, Gunnarson, Last millennium northern hemisphere summer temperatures from tree rings.

[89] T. Thordarson, S. Self, Atmospheric and environmental effects of the 1783–1784 Laki eruption: A review and reassessment, Journal of Geophysical Research: Atmospheres 108(D1) (2003); Sigl, Winstrup, McConnell, Welten, Plunkett, Ludlow, Büntgen, Caffee, Chellman, Dahl-Jensen, Timing and climate forcing.C.C. Raible, S. Brönnimann, R. Auchmann, P. Brohan, T.L. Frölicher, H.F. Graf, P. Jones, J. Luterbacher, S. Muthers, R. Neukom, Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effects, Wiley Interdisciplinary Reviews: Climate Change 7 (2016) 569–589.

[90] Ari, Neerinckx, Gage, Kreppel, Laudisoit, Leirs, Stenseth, Plague and climate: scales matter; Xu, Liu, Stige, Ari, Fang, Chan, Wang, Stenseth, Zhang, Nonlinear effect of climate.

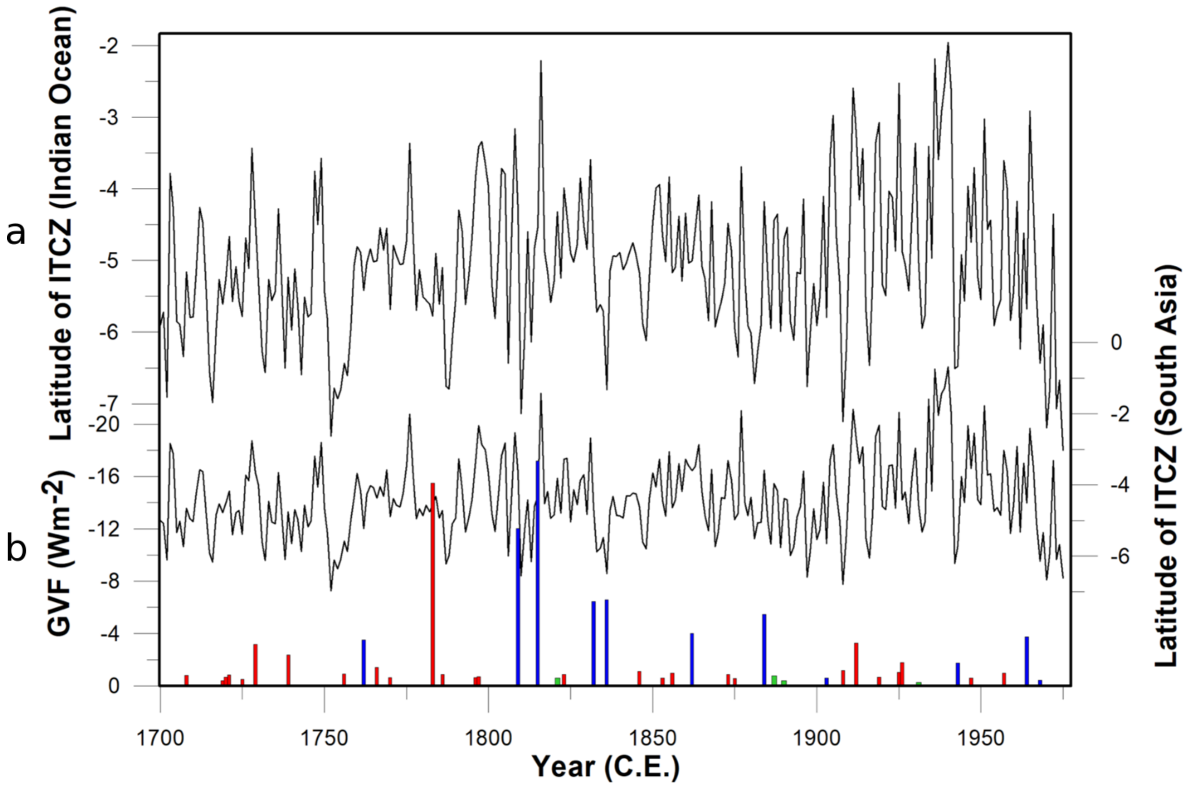
and epidemic data from Yunnan province, the potential impact of late eighteenth/early nineteenth century volcanism on plague in the region has been assessed.[91] There is little historical reference to the weather across Yunnan at the start of the regional epidemics. However, the regional response to volcanic loading can be identified to a limited degree within the proxy records. The Hekla eruption is unlikely to have had much impact on South China's climate due to the limited sulphate injection. However, the 1783 Laki eruption had a considerable impact on climates in the northern hemisphere and high latitude volcanism such as Laki may cause weakening of the Indian and Asian monsoon systems, in part identifiable by southward movement of the Intertropical Convergence Zone (ITCZ).[92] If such a weakening occurred this would lead to dryer conditions across southern China, which can contribute to increased plague risk due to host species populations exhibiting a negative correlation to precipitation.[93] Immediately following Laki a rapid deflection of the ITCZ to the south is observed (Fig. 4), and this may have helped to catalyse early epidemic expansion in Yunnan.

Fig. 4. Reconstruction of ITCZ locations across the period of cooling following volcanic loading of the early nineteenth century

[91] N.J. Steiger, J.E. Smerdon, E.R. Cook, B.I. Cook, A reconstruction of global hydroclimate and dynamical variables over the Common Era, *Scientific Data* 5 (2018) 180086; Sun, Zhang, Liu, Lyu, Fang, Wang, Xu, Xu, Xu, Identifying the spatiotemporal clusters of plague.

[92] A. Schmidt, K. Carslaw, G. Mann, M. Wilson, T. Breider, S. Pickering, T. Thordarson, The impact of the 1783–1784 AD Laki eruption on global aerosol formation processes and cloud condensation nuclei, *Atmospheric Chemistry and Physics* 10 (2010) 6025–6041.

[93] Xu, Liu, Stige, Ari, Fang, Chan, Wang, Stenseth, Zhang, Nonlinear effect of climate.



The unknown 1808/1809 eruption and Tambora were both large stratospheric sulphate injections and, like Laki, had an impact on regional precipitation. Tambora may have caused a weakening of the summer monsoon systems visible in proxy records with India and South Eastern Asia showing dry conditions through the summer of 1816.[94] This is not clearly corroborated by the proxy data (Fig. 4). However, the volcanic eruptions appear to be an inflection point leading to progressively drier climate across Yunnan. Moreover, both eruptions coincide with roughly ten years of severely depressed temperatures (Fig. 5). Conversely, anomalously wet conditions occurred across northern parts of Asia.[95] This may have provided ideal conditions for plague host species across Asia. Northern host species populations within precipitation limited areas respond positively to increased precipitation, whereas southern host

[94] Raible, Brönnimann, Auchmann, Brohan, Frölicher, Graf, Jones, Luterbacher, Muthers, Neukom, Tambora 1815 as a test case, 576.

[95] Raible, Brönnimann, Auchmann, Brohan, Frölicher, Graf, Jones, Luterbacher, Muthers, Neukom, Tambora 1815 as a test case, 576.

species respond positively to dry conditions.[96] This illustrates the potential catalytic impact that tropical and specifically Indonesian eruptions such as Tambora and Samalas can have on plague ecology across Asia.

The Tambora eruption had a huge impact on Yunnan province with historic sources suggesting winter flooding reported from 1815 onwards and depressed summer temperatures causing repeated crop failures. This led to famine persisting across the region from 1815—1818.[97] Following the famine and as climate recovered, rodent populations may have increased much faster than the human population, with a low point in human population resilience likely coinciding with an increase in rodent populations and hence an increase in plague transmission and progression eastward. The earliest peak in the epidemic in Yunnan (1864) coincides with a period of prolonged high PDSI values (Fig. 5). Xu et al state that under extreme precipitation conditions plague is likely to increase within the year of rainfall.[98] As the high PDSI values persist for many years, the cumulatively positive impact on plague prevalence may have caused the first epidemic peak in Yunnan and arguably facilitated the expansion of the Third Pandemic. Following the initial epidemic episode, it is difficult to link increasing epidemics with volcanic impacts for the Third Pandemic. The impact of climate and

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[96] Kausrud, Begon, Ari, Viljugrein, Esper, Büntgen, Leirs, Junge, Yang, Yang, Modeling the epidemiological history of plague in Central Asia; Stenseth, Atshabar, Begon, Belmain, Bertherat, Carniel, Gage, Leirs, Rahalison, Plague: past, present, and future; L. Xu, L.C. Stige, K.L. Kausrud, T.B. Ari, S. Wang, X. Fang, B.V. Schmid, Q. Liu, N.C. Stenseth, Z. Zhang, Wet climate and transportation routes accelerate spread of human plague, *Proceedings of the Royal Society of London B* 281 (2014) 20133159.

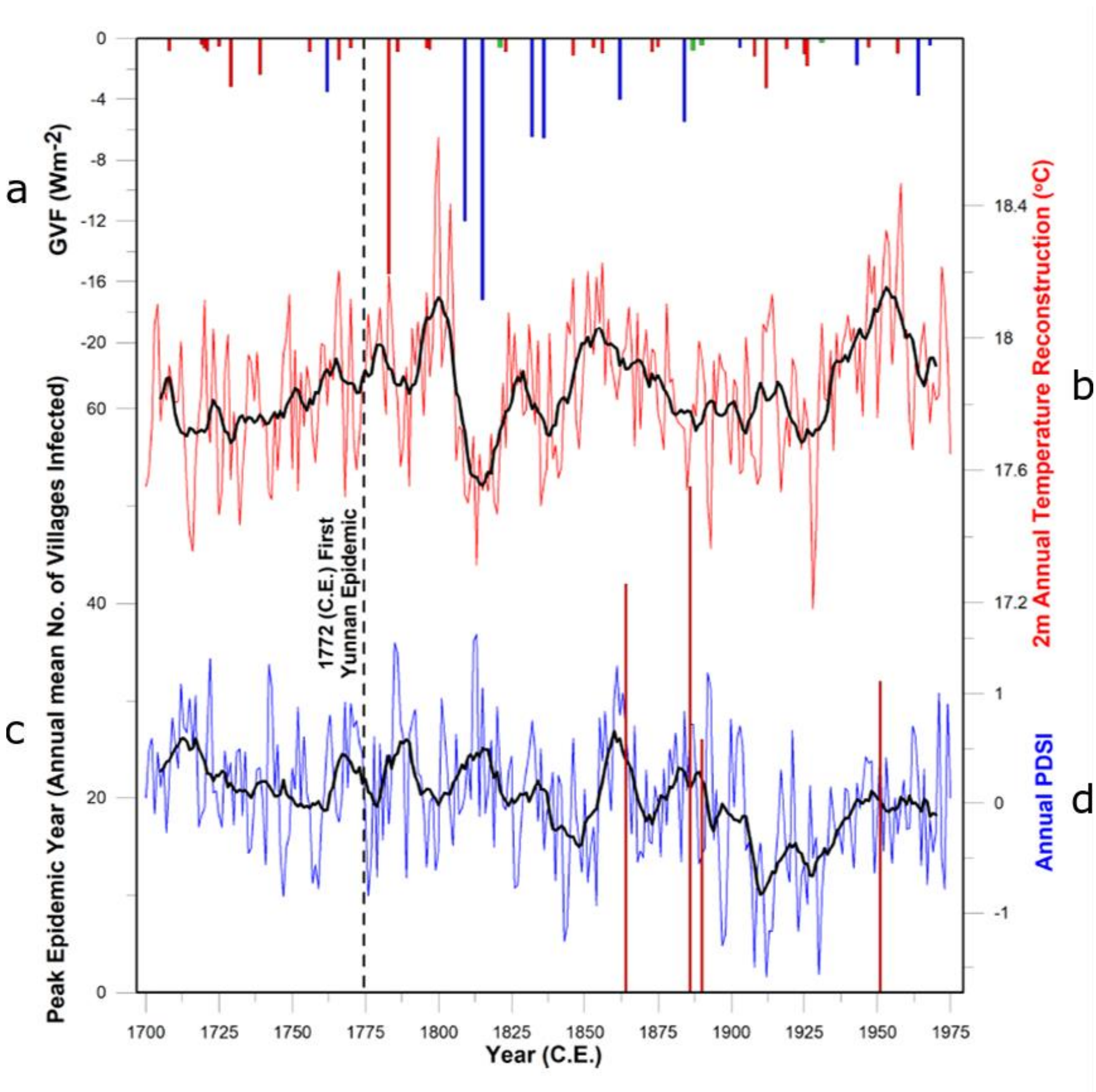
[97] S. Cao, Y. Li, B. Yang, Mt. Tambora, climatic changes, and China's decline in the nineteenth century, *Journal of World History* (2012) 587-607.

[98] Xu, Liu, Stige, Ari, Fang, Chan, Wang, Stenseth, Zhang, Nonlinear effect of climate on plague during the third pandemic in China.

hence volcanism may be best utilised to understand the initiation of epidemics where host dynamics are still a driving factor. Following human infection, epidemiology and analysis of transport links may better explain disease progression – especially given the increasingly connected nineteenth and twentieth centuries in which the Third Pandemic unfolded.[99]

[99] Xu, Stige, Kausrud, Ari, Wang, Fang, Schmid, Liu, Stenseth, Zhang, Wet climate and transportation.

Fig. 5. Comparison of temperature variations across Yunnan province prior to and during the Third Pandemic



CONCLUSIONS

Each of the described pandemic episodes of the last two millennia were caused by the *Y. pestis* bacterium. Aside from this fact, though, there are few commonalities between the pandemics: patterns of mortality and even of symptoms appear to have varied from one pandemic to the next.[100] These differences highlight the fact that the form of each pandemic is dictated by a multitude of highly changeable factors specific to the environment and time period in which it occurred.

Suggesting commonalities in the causes of the pandemics is rendered difficult by the lack of similarities between the episodes. It is notable, though, that all three pandemics coincided with periods of significant volcanic activity, and a series of connections between volcanism and plague are possible. The First and Second Pandemics coincide with periods of prolonged climatic change through the LALIA and the LIA respectively, both partly driven by a suite of high sulphate and halogen volcanic eruptions. Both these periods were characterised by globally depressed temperatures, increasingly erratic weather events and subsequently depleted crop yields.[101] Examples of agricultural disruption and hence malnutrition and ill health are common early in the LIA, with much of northern Europe suffering famine conditions in the early fourteenth century and with famine conditions expanding south by middle of the century.[102] During the Third Pandemic, Tambora and the unknown 1808/1809 eruption caused a similar depression of Northern Hemisphere temperatures with Yunnan province suffering terribly through crop failure immediately after the eruption and further until the middle of the nineteenth century.[103] This close succession of large scale volcanic eruptions is also

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[100] G. Christakos, R.A. Olea, H.-L. Yu, Recent results on the spatiotemporal modelling and comparative analysis of Black Death and bubonic plague epidemics, *Public Health* 121 (2007) 700-720; S.K. Cohn Jr, The Black Death: end of a paradigm, *American Historical Review* 107 (2002) 703-738.

[101] Büntgen, Myglan, Ljungqvist, McCormick, Di Cosmo, Sigl, Jungclaus, Wagner, Krusic, Esper, Cooling and societal change; DeWitte, Setting the stage for medieval plague.

[102] Slavin, The 1310s event; B.M.S. Campbell, The European mortality crises of 1346–52 and advent of the Little Ice Age, in: M. Shuh and D. Collet (Eds), *Famines During the 'Little Ice Age' (1300-1800): Socionatural Entanglements in Premodern Societies*, Cham, 2018, 19–41.

[103] S. Cao, Li, Yang, Mt. tambora, climatic changes, 599.

analogous with first pandemic which began immediately following the 536 C.E. and 540 C.E. eruptions. The combination of the two closely timed eruptions in the nineteenth century may have caused a long term climate perturbation. However, unlike the sixth century and thirteenth century eruptions, a mechanism leading to more prolonged cooling through sea-ice-ocean feedback mechanisms is as yet unknown. Nevertheless, there is sufficient evidence to render plausible the idea that the climatic conditions in which each pandemic flourished were mediated by volcanic eruptions.

Volcanism also facilitated conditions which enabled plague to thrive in other ways. The brief recovery period across Central Asia following the spikes in thirteenth-century volcanism may have produced optimum zoonosis conditions leading to initial or early Second Pandemic human infection. Much further work is required to test this suggestion. Such work is possible through the integration of plague or host distribution and demographic models with palaeoclimatic data. The development of mechanistic pathways linking volcanic eruptions, climatic perturbations and historic plague data across varying spatial and temporal scales should be developed within interdisciplinary teams to facilitate better understanding of past pandemics and thus to permit us better to predict future risk.

Captions

Fig. 1

Global volcanic forcing estimates grouped by eruption latitude are shown; Northern Hemisphere (red), Southern Hemisphere (green) and tropical (blue) with an eleven year running mean of all eruptions (yellow). Earliest evidence of fatalities during pandemic episodes illustrated (black dashed), respectively: the Justinianic Plague in 541, Black Death in 1338 and the Yunnan epidemic (an early outbreak of the Third Pandemic) in 1772.

Source: M. Sigl, M. Winstrup, J. McConnell, K. Welten, G. Plunkett, F. Ludlow, U. Büntgen, M. Caffee, N. Chellman and D. Dahl-Jensen, Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature* 523 (2015) 543–549.

Fig. 2

(**a**) Mean summer temperature anomaly across the zoonosis area (PAGES Asia 2K) with 0 equivalent to 20.9°C. The black '**X**' marks an approximately 40-year period of intense and persistent warming within the zoonosis area, encompassing the two warmest years in the zoonosis area over the complete record (1318—19). (**b**) Mean summer temperature anomaly across the source area (PAGES Asia 2K) with 0 equivalent to 13.3°C. (**c**) Global volcanic forcing estimates separated by eruption latitude; Southern Hemisphere (green), Northern Hemisphere (red) and tropical (blue)

Sources: For (a) and (b) see text. For (c): M. Sigl, M. Winstrup, J. McConnell, K. Welten, G. Plunkett, F. Ludlow, U. Büntgen, M. Caffee, N. Chellman and D. Dahl-Jensen, Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature* 523 (2015) 543–549.

Fig. 3

The left hand panels represent contoured temperature reconstructions for the date of peak cooling following the volcanic forcing period in the source and zoonosis area (**a**) 1285 C.E. and the peak warming of the recovery period within the zoonosis area (**b**) 1319 C.E. The right hand panels represent contoured PDSI reconstructions from the period of peak warming within the zoonosis area (**c**) 1318-1322 C.E. and the period of the Issyk-Kul grave site as well as a significant later warming peak (**d**) 1335-1338 C.E.

Sources: See text.

Fig. 4

(**a**) Reconstruction of the ITCZ latitude across the Indian Ocean (**b**) Reconstruction of the ITCZ Latitude across South Asia (**c**) Global volcanic forcing estimates separated by eruption latitude; Southern Hemisphere (green), Northern Hemisphere (red) and tropical (blue).

Sources: For (a) and (b) N.J. Steiger, J.E. Smerdon, E.R. Cook, B.I. Cook, A reconstruction of global hydroclimate and dynamical variables over the Common Era, *Scientific Data* 5 (2018) 180086. For (c) M. Sigl, M. Winstrup, J. McConnell, K. Welten, G. Plunkett, F. Ludlow, U.

Büntgen, M. Caffee, N. Chellman, D. Dahl-Jensen, Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature* 523 (2015) 543-549.

Fig. 5

(**a**) Global volcanic forcing estimates separated by eruption latitude; Southern Hemisphere (green), Northern Hemisphere (red) and tropical (blue). (**b**) Mean annual temperature reconstruction (2m) across Yunnan Province (96-115°E,20-30°N). (**c**) Peak epidemic years across Yunnan Province, bar height represents the annual average of villages infected during the epidemic. (**d**) Mean annual PDSI across Yunnan Province.

Sources: (a) M. Sigl, M. Winstrup, J. McConnell, K. Welten, G. Plunkett, F. Ludlow, U. Büntgen, M. Caffee, N. Chellman, D. Dahl-Jensen, Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature* 523 (2015) 543-549; (b) and (d) N.J. Steiger, J.E. Smerdon, E.R. Cook, B.I. Cook, A reconstruction of global hydroclimate and dynamical variables over the Common Era, *Scientific Data* 5 (2018) 180086; (c) Z. Sun, Z. Zhang, Q. Liu, B. Lyu, X. Fang, S. Wang, J. Xu, L. Xu, B. Xu, Identifying the spatiotemporal clusters of plague occurrences in China during the Third Pandemic, *Integrative Zoology*, advance online version: doi: 10.1111/1749-4877.12411.