Campanian Ignimbrite volcanism, climate, and the final decline of the Neanderthals

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ABSTRACT

The eruption of the Campanian Ignimbrite at ca. 40 ka coincided with the final decline of Neanderthals in Europe. Environmental stress associated with the eruption of the Campanian Ignimbrite has been invoked as a potential driver for this extinction as well as broader upheaval in Paleolithic societies. To test the climatic importance of the Campanian eruption, we used a three-dimensional sectional aerosol model to simulate the global aerosol cloud after release of 50 Tg and 200 Tg SO_2. We coupled aerosol properties to a comprehensive earth system model under last glacial conditions. We find that peak cooling and acid deposition lasted one to two years and that the most intense cooling sidestepped hominin population centers in Western Europe. We conclude that the environmental effects of the Campanian Ignimbrite eruption alone were insufficient to explain the ultimate demise of Neanderthals in Europe. Nonetheless, significant volcanic cooling during the years immediately following the eruption could have impacted the viability of already precarious populations and influenced many aspects of daily life for Neanderthals and anatomically modern humans.

INTRODUCTION

The Campanian Ignimbrite (CI) was one of the largest volcanic cataclysms in Europe during the past 200 k.y., and likely injected a significant quantity of SO_2 into the stratosphere (Zielinski et al., 1996; Signorelli et al., 1999; Costa et al., 2012). The ca. 40 ka eruption of the CI approximately coincided with the final decline of Neanderthals (Higham et al., 2014), with the early stages of Heinrich event 4 (Fedele et al., 2008), and with dramatic territorial and cultural advances among anatomically modern humans (Mellars, 2004). Consequently, the roles of climate, hominin competition, and volcanic sulfur cooling and acid deposition have been vigorously debated as causes of Neanderthal extinction (Banks et al., 2008; Fedele et al., 2008; Lowe et al., 2012; Fitzsimmons et al., 2013).

The decline of Neanderthals in Europe began well before the CI eruption. Radiocarbon dating has shown that at the time of the CI eruption, anatomically modern humans had already arrived in Europe (e.g., Douka et al., 2014), and the range of Neanderthals had steadily diminished (Higham et al., 2014). Tephra-based correlations of five early human sites in the Mediterranean also indicate that the Middle to Upper Paleolithic transition predated the CI eruption, implying that by ca. 40 ka, anatomically modern humans were established in these locations (Lowe et al., 2012). However, the ages of the final Neanderthal sites across Eurasia overlap with that of the CI eruption (De Vivo et al., 2001; Higham et al., 2014). The importance of the CI eruption for the demise of these last surviving Neanderthal populations thus remains to be evaluated, and is the focus of this paper.

The trachytic Campanian Ignimbrite erupted from the Phlegraean Fields on the Bay of Naples (Italy). The Plinian and co-ignimbrite plumes, which may have reached altitudes exceeding 30 km (Costa et al., 2012), facilitated wide-reaching dispersal of volcanic ash and of SO_2, which rapidly forms sulfate aerosol. One of the largest pre-Holocene sulfate spikes preserved in the Greenland Ice Sheet Project Two (GISP2) ice core has been attributed to the CI eruption (Zielinski et al., 1996; Fedele et al., 2008).

To test whether volcanism may have triggered the collapse of the final surviving Neanderthal communities, we have completed three-dimensional coupled global climate simulations of the CI eruption that include aerosol microphysics, radiative transfer, and boundary conditions appropriate for the last glacial period. The extent of halogen degassing from the CI eruption is uncertain, but current data suggest it was limited. CI matrix glass does not show evidence for halogen loss relative to melt inclusions (Signorelli et al., 1999). Halogens may exsolve into a co-existing fluid phase, but kinetic effects limit further halogen degassing during explosive eruptions (Balcone-Boissard et al., 2010). Furthermore, ash fall (and deposition of halogens scavenged from the column) was likely most severe close to the vent (Pyle et al., 2006; Costa et al., 2012), whereas hold-over Neanderthal populations were scattered around Europe (Higham et al., 2014). For these reasons, we focus on the environmental effects of volcanic sulfur rather than halogens or ash fall. We calculate the distribution and intensity of both sulfate deposition and climatic cooling. We compare our results with the spatiotemporal patterns of site occupation by Neanderthals and anatomically modern humans to explore hominin vulnerability and resilience in the face of environmental stress.

METHODS

In this study, we use the National Center for Atmospheric Research (NCAR) Whole Atmosphere Community Climate Model (CESM1[WACCM]) coupled to the Community Aerosol and Radiation Model for Atmospheres (CARMA), a sectional aerosol model (Toon et al., 1988; English et al., 2013; Marsh et al., 2013), to simulate the evolution of the size distribution of CI sulfate aerosols. We then use the results to prescribe the properties of the stratospheric aerosol cloud in our coupled global climate simulations with the NCAR Community Earth System Model (CESM1) (Hurrell et al., 2013) with appropriate boundary conditions. This two-step simulation process was necessary because the large computational burden of CARMA hinders our ability to complete the ensemble of model runs needed to assess the impact of the CI eruption. Our model does not include aerosol heating, which has been shown to influence the dispersal of sulfates from tropical eruptions (e.g., Aquila et al., 2012).

To determine the volcanic injection parameters, we relied on published studies of CI ash dispersal (Costa et al., 2012), CI petrology (Signorelli et al., 1999), and erupted volume (Scarpati et al., 2014). Costa et al. (2012) found that the pattern of CI ash dispersal is most consistent with a late autumn or early winter eruption. Estimates for the volume of the collapsing phase range from 67 km^3 dense rock equivalent (DRE) (Scarpati et al., 2014) to 280 km^3 DRE (Costa et al., 2012). For this range of volumes, the sulfur content of CI glass inclusions—Signorelli et al. (1999) measured a mean difference between glass inclusions and matrix of ~0.10 wt% SO_2—implies that the eruption delivered ~50–250 Tg SO_2 (25–125 Tg S) to the stratosphere, assuming negligible removal in the troposphere.

Here we consider two injection scenarios: release of 50 Tg SO_2 (25 Tg S) and 200 Tg SO_2 (100 Tg S), each occurring across three days in early December at 18–30 km altitude above the Bay of Naples. Each eruption simulation begins

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the January before the eruption and runs a total of 5 yr (at which time the burden of sulfur in the atmosphere has reached near-background levels; see Fig. 1A). Because to our knowledge no comprehensive map of glacial extent is available for this precise time period, we adopted Last Glacial Maximum (LGM) paleogeography from the PMIP3/CMIP5 model intercomparison projects, as configured by Brady et al. (2013). Paleoclimate proxies suggest that ice sheet extent was slightly greater and the climate was slightly colder under LGM conditions than at 40 ka. To bracket the uncertainties associated with our assumed paleogeography, we also completed a set of present-day simulations (see the GSA Data Repository[1]).

RESULTS AND DISCUSSION

We focus on the two main sources of European-wide environmental stress from the CI eruption: sulfate deposition accompanied by ecosystem acidification (Fitzsimmons et al., 2013), and climatic cooling due to a dramatic increase in aerosol optical depth (Fedele et al., 2008; Fitzsimmons et al., 2013). Acidification is a function of the rate and duration of acid deposition and the buffering capacity of an ecosystem (Skeffington, 2006). The size distribution and mass burden of aerosols, along with their global distribution, control the aerosol optical depth (Fig. 1) and the magnitude of the resultant cooling (Fig. 2).

To evaluate our 50 Tg SO_2 and 200 Tg SO_2 emissions scenarios, we compare CARMA model results to sulfate in the GISP2 core from central Greenland (Zielinski et al., 1996). We use the GISP2 age model (Meese et al., 1997) to convert the sulfate peak concentrations (Zielinski et al., 1996) associated with the CI eruption to sulfate deposition of ~70 kg/km^2 at the core site (see the Data Repository). For stratospheric emission of 50 Tg SO_2, the CARMA model estimates sulfate deposition in Greenland ranging from 100 to 400 kg/km^2 (Fig. 3A), whereas 200 Tg SO_2 emission results in deposition of 300–1200 kg/km^2 in Greenland (Fig. 3B).

Global climate models can overpredict the sulfate deposition measured in ice core records (Gao et al., 2007; Toohey et al., 2013). Though multiple ice core records would be more representative and would provide better constraints on volcanic emissions (Gao et al., 2007; Cole-Dai, 2010), only one volcanic sulfate ice core record is available from 40 ka (Zielinski et al., 1996). If this GISP2 core retains a faithful and regionally representative archive of sulfate deposition from this time, and allowing for model overestimation of deposition, then the range of sulfur emis-

[1]GSA Data Repository item 2015145, additional details of model input, data sets, and sensitivity tests, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

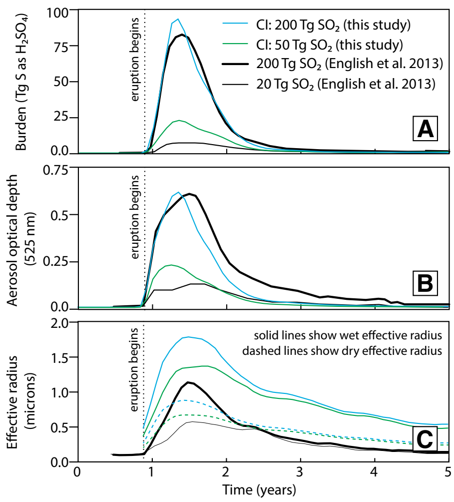

Figure 1. Characteristics of the aerosol cloud in our Community Aerosol and Radiation Model for Atmospheres (CARMA; Toon et al., 1988) simulations of the Campanian Ignimbrite (CI) eruption and comparison with a previous study. A: Global sulfate burden (in Tg S as H_2SO_4) (total aerosol mass depends on sulfate-water ratios). B: Globally averaged aerosol optical depth. C: Globally averaged effective radius in microns, weighted by surface area. Maximum aerosol optical depths and sulfur burdens are similar to results from English et al. (2013), but wet effective radii are substantially higher. This difference may result from higher latitude and more concentrated initial distribution of our sulfur emissions, as well as from differences in horizontal model resolution.

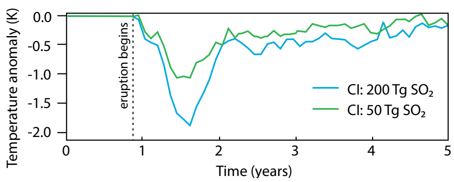

Figure 2. Three-member ensemble mean globally averaged monthly temperature anomalies, from simulations of Campanian Ignimbrite (CI) eruption that include a fully coupled ocean model along with calculated aerosol forcing from the 50 Tg SO_2 and 200Tg SO_2 scenarios under Last Glacial Maximum conditions.

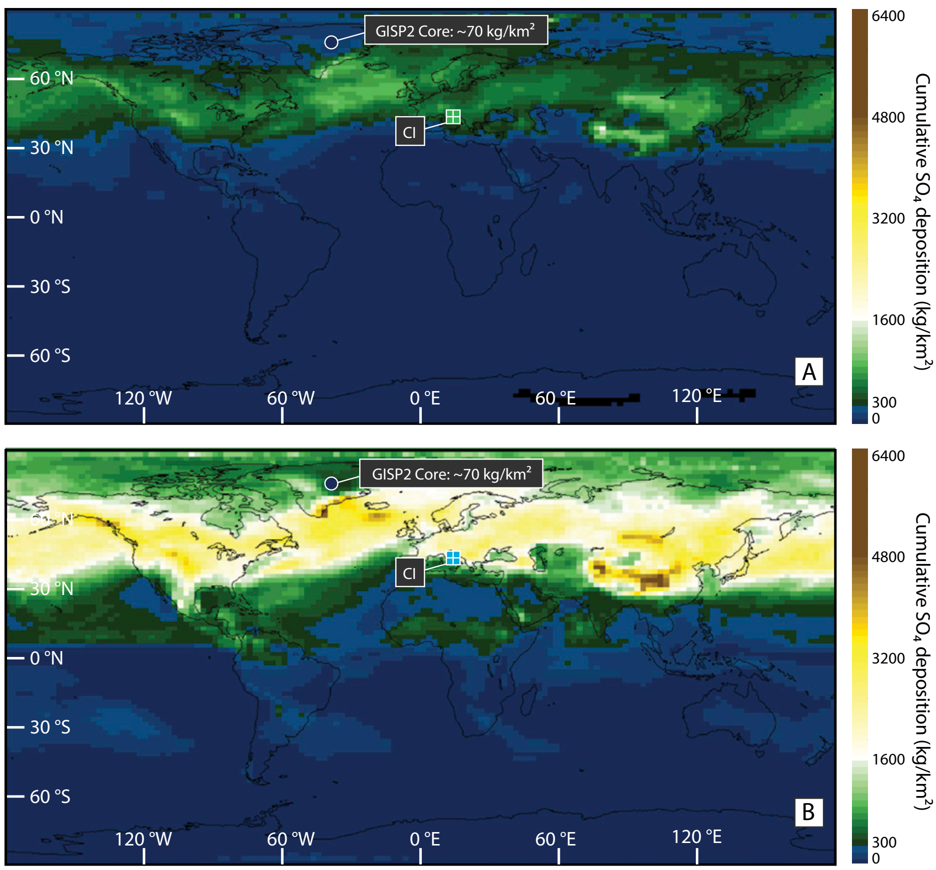

Figure 3. Cumulative global sulfate deposition from simulations of the Campanian Ignimbrite (CI) eruption. A: Following 50 Tg SO_2 release. B: Following 200 Tg SO_2 release. Base maps are ICE-5G last glacial topography (Peltier, 2004). Location of CI eruption is shown on each panel (symbol colors match those in Fig. 1). GISP2—Greenland Ice Sheet Project Two.

sions we consider here (from 50 to 200 Tg SO_2) is consistent with the ice core record.

The significant sulfate deposition in both emission scenarios (Fig. 3) motivates an assessment of the likelihood of environmental acidification (Fitzsimmons et al., 2013). The critical long-term loading above which present-day European ecosystems may sustain damage has been estimated at 48–17,000 kg SO_4^{2-} km^{-2} yr^{-1}; aquatic ecosystems are among the most sensitive to acid deposition (Skeffington, 2006). In both of our emissions scenarios, sulfate deposition in Europe reaches this critical loading range during the year following the eruption. However, in our CARMA simulations deposition declines rapidly after the first year, falling to <1% of these peak deposition rates by the fifth year after the eruption. Because critical loads quantify the response to chemical stresses sustained for long periods (Skeffington, 2006), most ecosystems were probably unharmed by this brief spike in sulfate deposition.

Close to the caldera, halogen acidification and ash fall could have been severe (Giaccio et al., 2008; Pyle et al., 2006; Costa et al., 2012). Several eruption-proximal sites in Italy, where ash deposition reached tens of centimeters (Giaccio et al., 2008), have been interpreted as settlements that were abandoned in the immediate aftermath of the eruption (Fitzsimmons et al., 2013). The combined effects of ash fall and halogen deposition may have disrupted the anatomically modern human communities that had replaced Neanderthals in Italy by this time (Douka et al., 2014), but because these stresses are localized around the eruption site, they were not relevant to the demise of the final Neanderthal groups scattered elsewhere in Europe. Stratospheric injection of chlorine and heavy halogens can also trigger ozone depletion (e.g., Millard et al., 2006). If future work uncovers evidence for significant halogen emissions from the CI eruption, the implications for stratospheric chemistry could be reassessed.

To test the relevance of volcanic cooling to Neanderthal extinction, we compare surface temperature anomalies associated with sulfur release (Figs. 2 and 4) with the distribution of hominin sites with ages that overlap at the 95% confidence level with the age of the CI eruption (Fig. 4). Temperature anomalies are calculated relative to control runs without volcanism. The most intense cooling occurs in Eastern Europe and Northern Asia. In these regions, temperature anomalies reach −6 °C in the simulations with 50 Tg SO_2 emissions, and −9 °C in the simulations with 200 Tg SO_2 emissions. In both cases, Neanderthal and anatomically modern human sites in Western Europe experience annually averaged cooling of <5 °C in the year following the eruption (Fig. 4 insets), with smaller temperature decreases for several subsequent years. For comparison, Neanderthals and anatomically modern humans survived stadial-interstadial temperature swings during the last glacial that often exceeded 5 °C (Martrat et al., 2004). However, onset of volcanic cooling was particularly abrupt (Fig. 2).

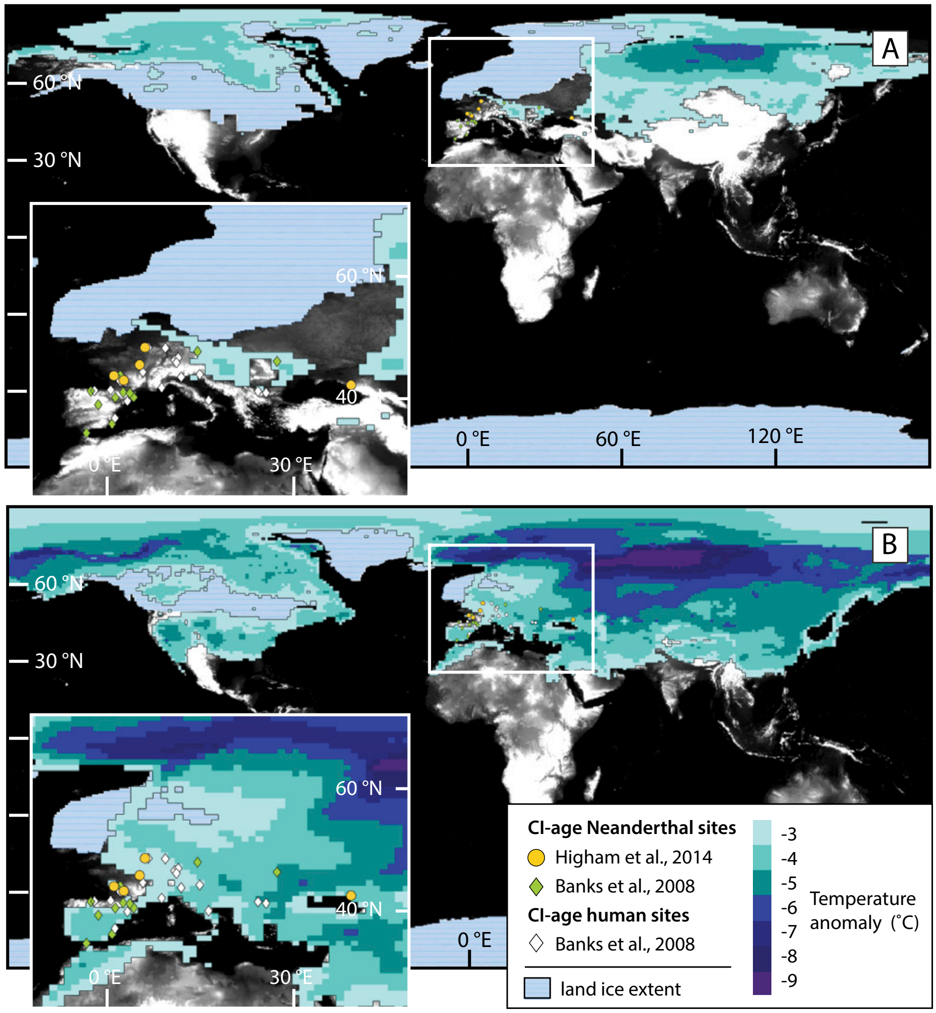

Figure 4. Annually averaged temperature anomalies in excess of 3 °C for first year after Campanian Ignimbrite (CI) eruption compared with spatial distribution of hominin sites with radiocarbon ages close to that of the eruption. A: After 50 Tg SO_2 release. B: After 200 Tg SO_2 release. Neanderthal data include Mousterian (Neanderthal) and Châtelperronian (possible Neanderthal) sites with 2s age ranges overlapping with age of CI eruption (Higham et al., 2014; Banks et al., 2008; see the Data Repository [see footnote 1]). Each map represents an ensemble average among three fully coupled simulations initialized from different starting states.

We interpret the brevity of acid deposition and the limited cooling of densely inhabited areas as evidence that the CI eruption did not trigger broad turmoil in Paleolithic societies outside of Italy. This interpretation is consistent with the archaeology of sections that include CI tephra (Lowe et al., 2012) and with previous modeling of the climate effects of the Younger Toba Tuff (Timmreck et al., 2010).

On the other hand, the available radiocarbon data suggest that at most only a few populations of Neanderthals survived until the time of the CI eruption (Higham et al., 2014). The importance of even moderate, brief cooling after the CI eruption should not be summarily discounted if Neanderthals were already teetering on the brink of extinction. Furthermore, Denisovan hominins may also have inhabited East Asia during this time (Reich et al., 2010). The impact of the CI eruption on these far-flung populations—many of which may have experienced more severe volcanic cooling—merits further investigation.

CONCLUSIONS

While the precise implications of the CI eruption for cultures and livelihoods are best understood in the context of archaeological data sets, our results quantitatively describe the magnitude and distribution of the volcanic cooling and acid deposition that ancient hominin communities experienced coincident with the final decline of the Neanderthals. In our climate simulations, the largest temperature decreases after the eruption occur in Eastern Europe and Asia, sidestepping many of the Paleolithic centers in

Western Europe. Acid deposition was intense but short lived, fading to <1% of peak levels within several years after the eruption. Based on these results, we suggest that in isolation the CI eruption was likely insufficient to cause extinction of otherwise healthy Neanderthal populations. However, though the cooling in much of Western Europe may have been limited, it was not negligible. Temperatures in Western Europe decreased by 2–4 °C on average during the year following the eruption. These unusual conditions may have directly influenced survival and day-to-day life for Neanderthals and anatomically modern humans alike, and emphasize the resilience of anatomically modern humans in the face of abrupt and adverse changes in the environment.

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