Volcanic ash layers illuminate the resilience of Neanderthals and early modern humans to natural hazards

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Marked changes in human dispersal and development during the Middle to Upper Paleolithic transition have been attributed to massive volcanic eruption and/or severe climatic deterioration. We test this concept using records of volcanic ash layers of the Campanian Ignimbrite eruption dated to *ca.* 40,000 y ago (40 ka B.P.). The distribution of the Campanian Ignimbrite has been enhanced by the discovery of cryptotephra deposits (volcanic ash layers that are not visible to the naked eye) in archaeological cave sequences. They enable us to synchronize archaeological and paleoclimatic records through the period of transition from Neanderthal to the earliest anatomically modern human populations in Europe. Our results confirm that the combined effects of a major volcanic eruption and severe climatic cooling failed to have lasting impacts on Neanderthals or early modern humans in Europe. We infer that modern humans proved a greater competitive threat to indigenous populations than natural disasters.

During the last glacial stage, between *ca.* 100 and 30 ka B.P., anatomically modern humans (AMHs) migrated from Africa to eventually reach Europe, bringing them increasingly into contact with indigenous Neanderthals (1). The latter experienced marked population decline from *ca.* 40 ka B.P. on and had largely disappeared by 30 ka B.P. (2). Over the same period, climate oscillated markedly between cold interludes—the most extreme of which are termed Heinrich Events (HEs)—and significantly warmer Interstadial periods (3). The warm transitions were particularly abrupt (within a few decades) in the North Atlantic region and Europe. Hominins were driven from large tracts of northern Europe during the cold episodes but were able to recolonize when conditions ameliorated (1). Over time, they also developed more advanced stone tool kits, created increasingly sophisticated ornamental and ritual objects, and formed closer social networks, both heralding and signaling the transition from Middle to Upper Paleolithic cultures (4). Some of these changes appear suddenly in the archaeological record, suggesting rapid assimilation of or replacement by new technologies (5). However, it remains unknown to what degree these innovations were stimulated by abrupt climatic changes that periodically tested the resiliency of hominin survival skills.

Climate is considered by some to have been the main cause of Neanderthal demise, by either progressive population attrition over several cold intervals, culminating in a terminal decline around 40 ka B.P. (6), or population collapse during a particularly severe HE at around 48 ka B.P. (7). Either way, it is assumed that AMHs had developed competitive advantages that enabled them to recolonize and survive in Europe more effectively than Neanderthals. Others, however, consider that climate change alone cannot explain Neanderthal demise, because they had already survived a long series of marked climatic oscillations. Suggested contributory factors include conflict with and displacement by invading AMHs (8) or the environmental impacts of the Campanian Ignimbrite (CI) volcanic ash, deposited at around 40 ka B.P. The CI eruption was the largest within the Mediterranean area during the last 200 ka (9). It liberated some 250–300 km^3 volcanic ash, which spread over a large sector of Central and Eastern Europe; the injection of such huge amounts of ash and volatiles (including sulfurous gases) into the atmosphere is likely to have caused a volcanic winter (10). Because this eruption occurred during the cold HE4 interval, it has led to speculation that the combination of a severe climatic downturn and widespread ash deposition either immediately drove Neanderthals out of parts of Europe, leaving the territory free for

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subsequent colonization by AMHs (11), or triggered more gradual in situ cultural and evolutionary changes, enabling AMHs to outcompete and finally, supplant the Neanderthals (12).

These hypotheses are difficult to test, however, because of chronological uncertainties that blur the precise timing of archaeological and geologic events (6). Whereas climate was capable of major swings within a human lifespan (3), it is seldom possible to link cultural and environmental responses to such abrupt shifts with similar chronological precision because of common sedimentary complications in archaeological and geologic sequences (13) and dating uncertainties that, for the period under consideration, are typically centennial to millennial in scale (14). Robust tests of proposed causal links between climate change, environmental response, and cultural adaptations during the Middle and Upper Paleolithic, therefore, require more secure dating and correlation of archaeological and geologic records. Here, we show how recent discoveries of nonvisible volcanic ash markers, termed cryptotephra, are helping to synchronize archaeological and environmental records by linking horizons of precisely the same age between widely scattered sites (15).

Results

Until recently, investigation of past volcanic eruptions has relied on the study of either proximal volcanic deposits (found close to volcanoes) or distal but visible ash layers. For example, visible ash of the CI was used to synchronize Paleolithic records from sites in southern Italy (16) and Russia (17, 18). Focusing only on visible volcanic ash layers, however, limits the number of isochrons that can be used as well as the geographic range over which they can be traced. Recent research has shown that nonvisible ash layers (Fig. 1) can also be detected in marine and terrestrial sequences (19). Consisting mainly of tiny glass particles (commonly <150 μm in size) that are recoverable in the laboratory by density separation methods, discrete layers of cryptotephra travel farther from source than their visible counterparts and frequently yield sufficient glass for analysis using geochemical fingerprinting methods (*Methods*).

Here, we report discoveries of the CI, including cryptotephra layers, detected in important archaeological sites. We have extracted CI tephra from (*i*) an ancient paludal sequence at Tenaghi Philippon, Greece; (*ii*) marine core LC21 located in the southeast Aegean Sea; (*iii*) Africa in the Haua Fteah Cave sequence in Libya; and (*iv*) four important central European archaeological cave sequences: Klissoura, Golema Pesht, Kozarnika, and Tabula Traiana (Fig. 2 and Table S1). To confirm its role as a valid, precise correlation marker, we also generated a robust dataset of the proximal chemical composition of the CI (21),

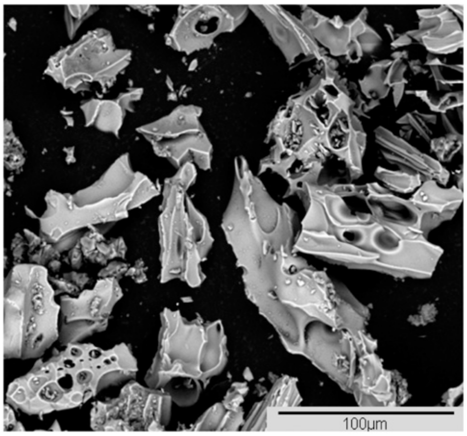

Fig. 1. Scanning electron photomicrograph of distal cryptotephra shards associated with the visible Campanian Ignimbrite layer in the Tenaghi Philippon sequence. (Photo by Suzanne MacLachlan, British Ocean Sediment Core Research Facility, National Oceanography Centre, Southampton.)

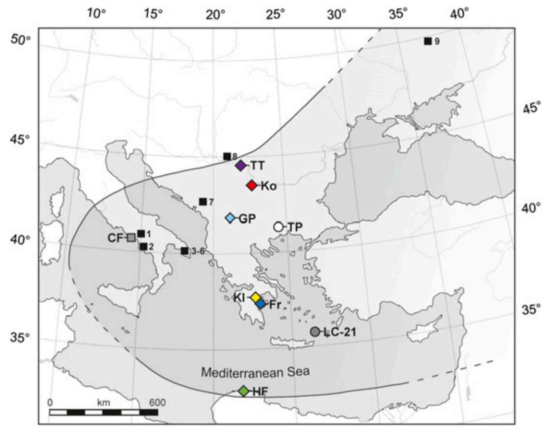

Fig. 2. Map of the preservation limits of visible layers of the CI (curved line in ref. 20), the location of its source at Campi Flegrei (CF), and positions of sites referred to in the text (symbols are explained in Fig. 3). Letters indicate sites examined within the Response of Humans to Abrupt Environmental Transitions Project: Fr, Franchthi; GP, Golema Pesht; HF, Haua Fteah; Kl, Klissoura; Ko, Kozarnika; LC-21, EC-MAST2 PALAEO-FLUX cruise 1995, "Long Core 21"; TP, Tenaghi Philippon; TT, Tabula Traiana. Numbers refer to other sequences mentioned in the text: 1, Serino; 2, Castelcivita; 3, Cavallo; 4, Uluzzo; 5, Uluzzo C; 6, Bernardini; 7, Crvena Stijina; 8, Oase; 9, Kostenki 14.

against which the chemical signatures of distal CI layers have been compared (Fig. 3 and Tables S2– S5). The results provide a secure common isochronous marker, which directly ties marine and terrestrial paleoenvironmental records with archaeological sequences over an expanded region that includes sites from both south and north of the Mediterranean.

The CI eruption occurred during the last glacial cycle, just after the onset of a millennial-scale cold stadial that encompassed HE4, a northern hemisphere-wide climatic event of extreme cold and aridity (22). We confirm this temporal relationship with identification of the CI in high-resolution paleoclimate records from the southeast Aegean Sea (core LC21) and a terrestrial sequence from Greece (Tenaghi Philippon) (7), where the climatic event is identified by increased aridity and a sharp reduction in tree pollen (Fig. 4). This area is known to be highly sensitive to cooling events triggered by northerly incursions of cold and dry continental air through gaps in the surrounding mountain ranges (23). By synchronizing the paleoclimatic and archaeological records using the CI, we find results that contradict prevailing hypotheses about the effects of volcanic activity and climate on Neanderthals and AMHs (11, 12).

Discussion

Assessment. In Europe, Upper Paleolithic (UP) industries, such as the Aurignacian, are clearly associated with modern humans and typically appear after the CI (24, 25), but some occurrences are radiocarbon-dated to older than 40 ka B.P. (26), which is the case with fossil evidence from Oase that lacks archaeological association (27). Although Neanderthals are known to postdate the CI eruption in Iberia and perhaps, elsewhere (28, 29), the terminal Middle Paleolithic (MP) industries at our studied sites in Eastern Europe all predate the CI considerably, from which they are separated by sterile or UP deposits. In Italy, UP deposits underlie the CI in at least six sites (Serino, Castelcivita, Cavallo, Uluzzo, Uluzzo C, and Bernardini) (24, 30), and AMH fossils are reportedly associated with transitional UP records at Grotta del Cavallo (31); the term transitional in this context is explained in *SI Text*. Synchronization of records using the CI, therefore, confirms that Neanderthal survival and modern human expansion were characterized by significant spatial heterogeneity (patchiness) across Europe.

Farther east, in the southern Balkans, the CI caps MP deposits at Crvena Stijena in Montenegro (32) and a nondiagnostic assemblage at Franchthi Cave in Greece (33), whereas it also caps

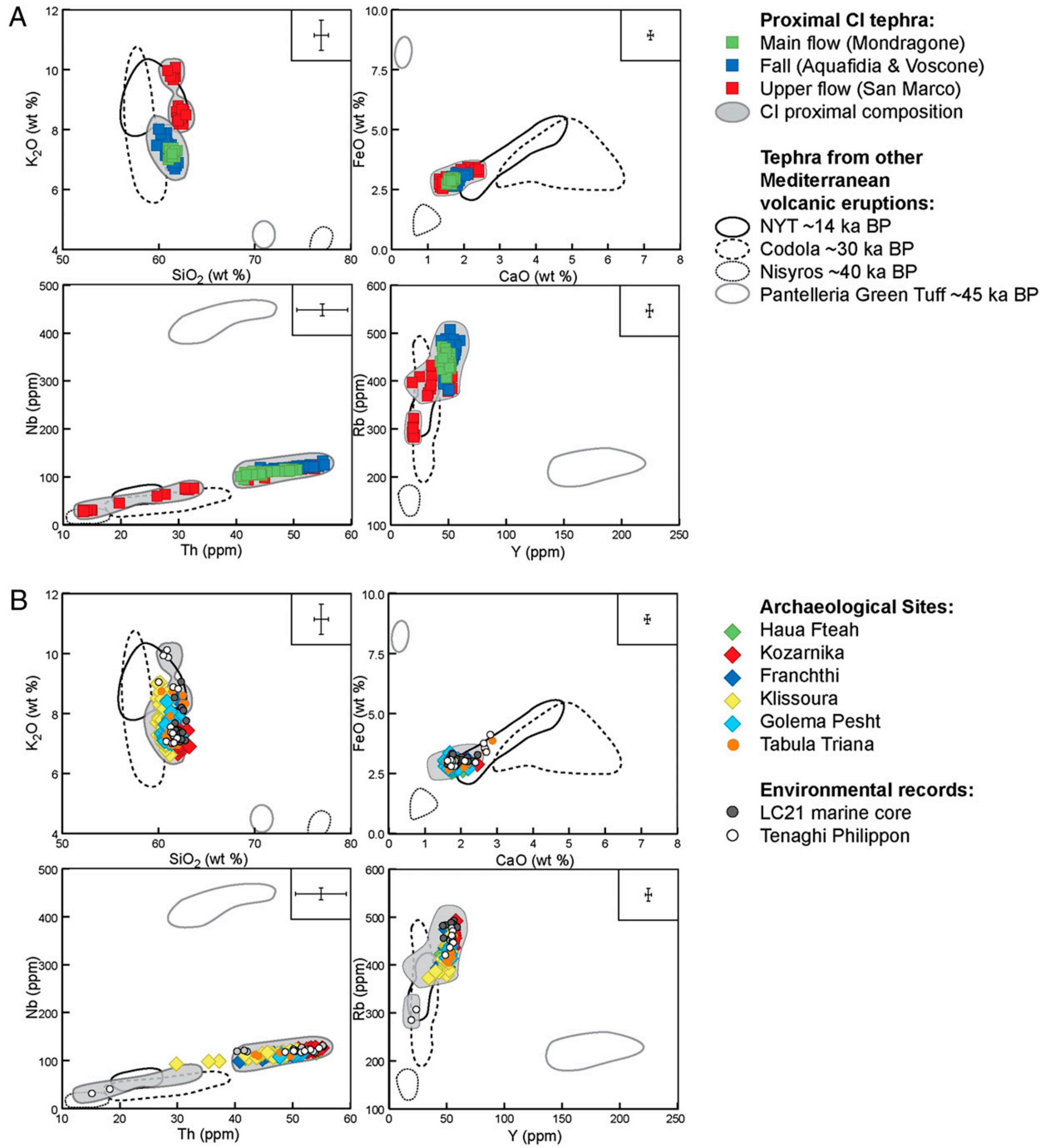

Fig. 3. (*A*) Selected major and trace element biplots with delineation of the compositional ranges of pumice matrix glasses from proximal tephra fall and flow units from the CI (gray-filled envelope) using the same discriminant source. (*B*) Compositional correlation of the distal tephra fall units from this study with the CI tephra. For comparison on all graphs, the compositional fields for four well-known Mediterranean volcanic eruptions are also plotted. The Neapolitan Yellow Tuff (NYT) is the second largest known eruption of the CF after the CI tephra. The Codola Tephra from Vesuvius, the Nisyros Island Tephra (Upper Member), and the Pantelleria Green Tuff are all found as far-traveled tephra layers and occurred within ±20 ka of the CI eruption. Representative 2σ uncertainty ranges are shown (*A*, *Upper Right* and *B*, *Upper Right*) for each biplot based on precision established from secondary standard analyses (Tables S2–S5).

a layer with transitional Uluzzian-type industry at Klissoura Cave 1, Greece (34) (Fig. 5). In contrast, the CI overlies early UP levels in Kozarnika Cave, Bulgaria (35), Tabula Traiana Cave, Serbia, and Golema Pesht Cave, Macedonia (36). In Russia, early UP layers are within or considerably below the CI at the Kostenki–Borshchevo sites, and hence, a good case can be made for AMH presence in the central Russian Plain before the CI eruption (18, 37). In most of these cases, therefore, with the exception of sites in Greece and Montenegro, modern humans and early UP demonstrably predate the CI at 40 ka B.P.

Distal CI deposits in the Haua Fteah Cave sediment sequence, Libya, allow for isochronous correlation between Paleolithic sites in Europe and Africa. At Haua Fteah, the CI is located within a continuous sequence of UP locally termed the Dabban culture, and hence, it postdates the start of the Dabban industry (38). Below the Dabban, in the same sequence, are deposits containing MP industries and two modern human jawbones, which show that modern human remains predate the CI at Haua Fteah (39). In Morocco, early modern humans have been recorded by at least 100 ka (40), and in Egypt, early modern humans have

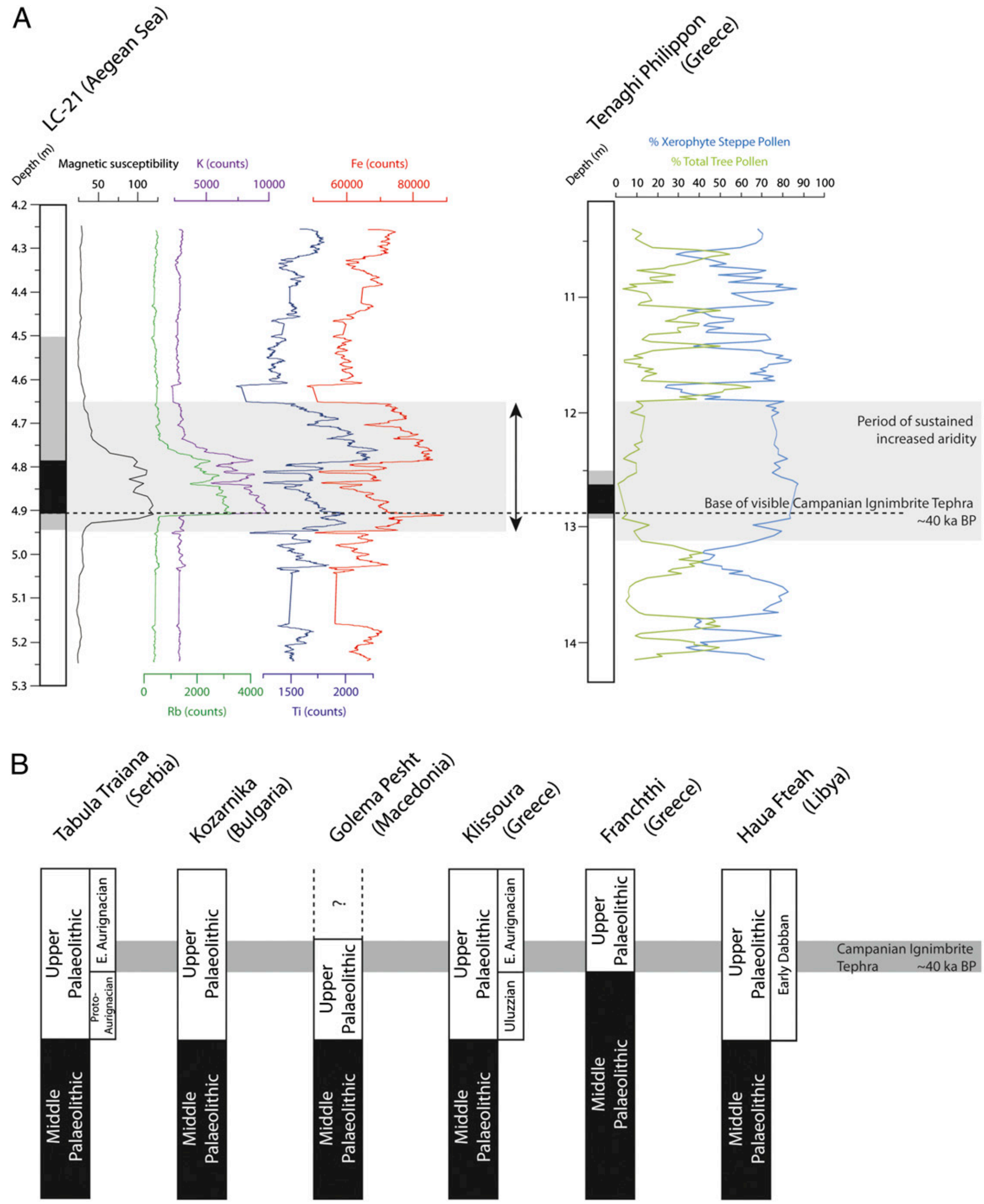

Fig. 4. (*A*) Position of the CI (black, visible glass shards; gray, cryptotephra) with respect to proxy evidence for a period of dry conditions in the eastern Mediterranean considered to approximate HE4. In core LC21, peaks in concentrations of magnetic susceptibility, Rb, and K correspond to peak CI tephra influx, whereas the longer-lasting high values for Ti and Fe reflect higher atmospheric dust influx. The marked reduction in tree pollen percentages in the Tenaghi Philippon sequence is also considered to reflect adversely dry conditions. The CI occurs early in this dry phase, which dates it to the lower part of HE4. (*B*) Schematic representation of the position of the CI with respect to the MP to UP transition in six of the archaeological sequences investigated within the Response of Humans to Abrupt Environmental Transitions Project.

been recorded by, perhaps, 60 ka (41). Thus, modern humans clearly existed in North Africa well before the CI eruption, and no adverse effects on activities since that event can be detected.

By tracing the CI ash in cryptotephra form to new sites in Eastern Europe, our results provide an unambiguous datum that reveals how the timing of the arrival of AMH industries was spatially complex in Eastern Europe, with some sites recording Aurignacian type industries much earlier than others. Recent developments in radiocarbon and luminescence dating and the routine redating of important Paleolithic sites, such as Geissenklösterle, are also revealing that AMHs were present in parts of Europe significantly earlier than considered before (42). Our method, however, now shown in two continents, provides a fixed datum against which to corroborate and test these advances. We envisage a future where the debate about major transitions in human evolution can be based on the unambiguous alignment of the stratigraphical evidence within an isochronic lattice, such as can be provided by tephra layers. Tracing the CI, as we have done here, provides an index to this future.

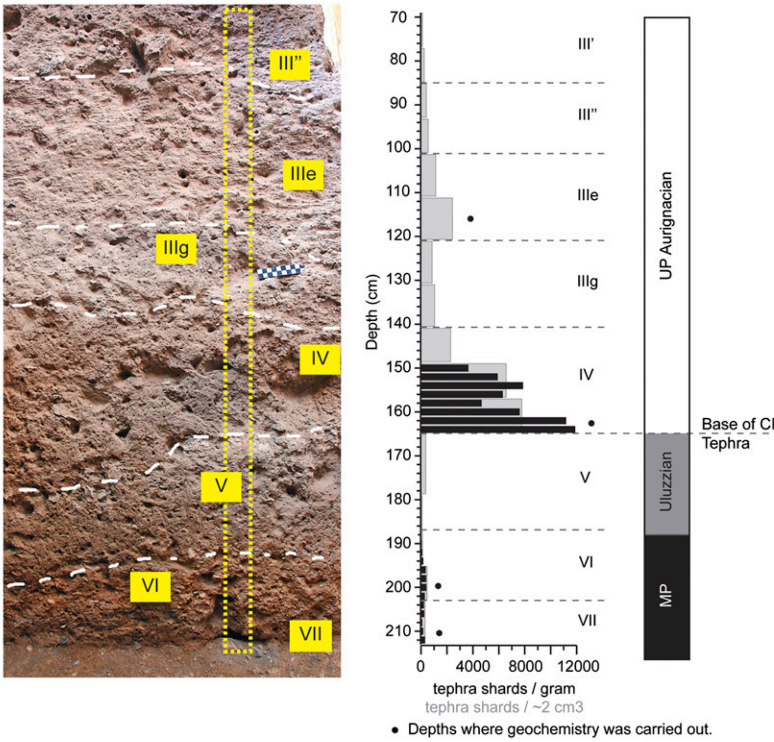

Fig. 5. The archaeological sequence in Klissoura Cave 1 in the Peloponnese of southern Greece preserves a long record of Paleolithic occupation, which is represented by Mousterian, early UP Uluzzian (layer V), Aurignacian (layers IV and III), and epipaleolithic industries (34). The dotted rectangle indicates one of the columns that was systematically investigated for tephra content, with results shown in *Right*. The CI occurs as a sharp peak at the interface of layers V and IV, which provides an important chronostratigraphic marker horizon for the Uluzzian and earliest Aurignacian levels at the site. Overlying this tephra peak, upward recirculation of CI shards through the sequence is a result of postdepositional anthropogenic and biogenic processes. A second concentration of tephra, chemically distinguished from the CI but not yet assigned to a specific source, has been identified in layer VI/VII.

Implications. The MP to UP transition began before the CI eruption in both North Africa and Europe, similar to AMH dispersal in the latter region, which implies that neither the eruption nor the HE4 cold/arid event could have been the primary driver of cultural changes and population dispersals or regional Neanderthal extinction in Northern and Eastern Europe over this period. These insights require reconsideration of the prevailing concept of straightforward, environmentally driven replacement, because both Neanderthals and early modern humans seem to have been more resilient to environmental crises than previously supposed. Although a recent assessment of Neanderthal mtDNA variation (43) indicates that Neanderthals in Eastern Europe showed overall population continuity until they became extinct, our results imply that such extinction is likely to have occurred long before the CI eruption.

With respect to the impacts on humans of the CI eruption, there must have been different outcomes in areas proximal or distal to the volcanic source. Proximal sites such as Serino, for example, located only ~50 km east of the Campi Flegrei would have felt the full impact, and it is, therefore, likely that populations here were devastated; the early Aurignacian at Serino is capped by a thick CI ash layer, with no evidence of subsequent site reoccupation. Most of our newly identified CI records, however, are from sites considerably more distal from Campania, where the effects are likely to have been less severe; here, we see no evidence of continental-scale, long-term impact on hominin species.

Our results indicate that Neanderthal extinction in Europe was not associated with the CI eruption. Furthermore, in view of the continuous records of human occupation over the MP to UP transition preserved at Klissoura, Kozarnika, Tabula Traiana, and Golema Pesht, we also question the posited scale of the impact of HE4 cooling on Neanderthal demise. AMHs also seem to have been widespread throughout much of Europe before the CI eruption; thus, Neanderthal and AMH population interactions must have occurred before 40 ka B.P. Given the spatially complex nature of the Neanderthal and AMH evidence listed here, there may have been considerable variability in the timing of such encounters across Eastern Europe and Italy. Our evidence indicates that, on a continental scale, modern humans were a greater competitive threat to indigenous populations than the largest known volcanic eruption in Europe, even if combined with the deleterious effects of climatic cooling. We propose that small population numbers and high mobility may have initially saved the Neanderthals but that they were ultimately outperformed in this capacity by AMHs.

Methods

To underpin our study, proximal CI stratigraphies were sampled for geochemical analysis, the results of which are based on unaltered juvenile clasts collected from both pyroclastic fall and flow deposits. At each site, multiple proximal samples were taken to (*i*) ensure spatial and temporal coverage and (*ii*) include any variations in vesicularity, phenocryst content, and/or color. To test for the possible presence of cryptotephra layers, which may be less than 1 mm in thickness, the full vertical interval represented at each archaeological or geologic site needed to be examined in its entirety. To test for the presence/absence of the CI tephra at archaeological cave sites, including possible cryptotephra, sediments were sampled during active excavations or from accessible standing stratigraphic sections that required minimal cleaning. Systematic sampling involved collection of small amounts (15–20 g) of in situ deposits at 2-cm consecutive and contiguous intervals along continuous vertical profiles. When possible, multiple section profiles at each site were sampled, and all samples were identified with reference to the site datum and other relevant provenience information. At each site, all sedimentary deposits dating between *ca.* 60 and 25 ka B.P. were sampled; therefore, if any tephra layers were identified, they could be directly and unambiguously associated to both other lithostratigraphic units at the site and recovered archaeological materials.

All archaeological, marine, and lake sediment sequences were investigated for the presence of cryptotephra using published protocols (44). Contiguous subsamples were analyzed, and the stratigraphic positions of cryptotephra layers were determined with a minimum depth resolution of ±1–2 cm. Details of sites referred to here, which were systematically examined for presence of CI and other tephra layers, are provided in Table S1.

Chemical characterization of single tephra shard samples was conducted in two stages using microanalytical techniques to measure the volcanic glass compositions in both proximal and distal samples (21, 45, 46). Major elements were analyzed using a Jeol JXA8600 electron probe microanalyzer with wavelength dispersive spectroscopy (EPMA-WDS) at the Research Laboratory for Archeology and the History of Art, University of Oxford. An accelerating voltage of 15 kV, 6 nA beam current, and a 10-μm beam were used. The EPMA WDS was calibrated using a suite of mineral standards (47); 9–11 elements were measured in each sample with varying count times: (Na, 10 s; Si, Al, K, Ca, Fe, and Mg, 30 s; Ti, Mn, and Cl, 40 s; P, 60 s). Trace element analysis of the same grains was carried out using laser ablation inductively coupled plasma MS with an Agilent 7500ce inductively coupled plasma MS coupled to a 193-nm Resonetics M-50 ArF (193 nm) eximer laser ablation system with a two-volume ablation cell at the Department of Earth Sciences, Royal Holloway University of London (45, 48). Laser spot sizes of 57, 34, and 25 μm were used according to the sample area available for analysis. The repetition rate was 5 Hz, and both sample and gas blank count times were 40 s. Quantification used NIST612 with ^{29}Si as the internal standard and was corrected using ^{43}Ca (full details of analytical and data reduction methods are in refs. 20 and 45). Secondary glass standards (MPI-DING Suite) were analyzed between and within EPMA WDS and laser ablation inductively coupled plasma MS analytical runs to check instrumental precision and accuracy (21, 45, 47, 48). These data are reported with the other chemical data in Tables S2–S5.

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1. Gamble C, Davies W, Pettitt P, Richards M (2004) Climate change and evolving human diversity in Europe during the last glacial. *Philos Trans R Soc Lond B Biol Sci* 359: 243–253.
2. Stringer C (2006) *Neanderthals Revisited: New Approaches and Perspectives*, eds Harvati K, Harrison T (Springer, Heidelberg), pp 315–324.
3. Andersen KK, et al. (2004) High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* 431:147–151.
4. Bar-Yosef O (2002) The Upper Paleolithic Revolution. *Annu Rev Anthropol* 31: 363–393.
5. Teyssandier N (2008) Revolution or evolution: The emergence of the upper paleolithic in Europe. *World Archaeol* 40:493–519.
6. Tzedakis PC, Hughen KA, Cacho I, Harvati K (2007) Placing late Neanderthals in a climatic context. *Nature* 449:206–208.
7. Müller UC, et al. (2011) The role of climate in the spread of modern humans into Europe. *Quat Sci Rev* 30:273–279.
8. Herrera KJ, Somarelli JA, Lowery RK, Herrera RJ (2009) To what extent did Neanderthals and modern humans interact? *Biol Rev Camb Philos Soc* 84:245–257.
9. Barberi F, et al. (1978) The campanian ignimbrite: A major prehistoric eruption in the Neapolitan area (Italy). *Bull Volcanol* 41:10–31.
10. Costa A, et al. (2012) Quantifying volcanic ash dispersal and impact of the campanian ignimbrite super-eruption. *Geophys Res Lett*, 10.1029/2012GL051605.
11. Golovanova LV, et al. (2010) Significance of ecological factors in the Middle to Upper Paleolithic Transition. *Curr Anthropol* 51:655–691.
12. Fedele FG, Giaccio B, Hajdas I (2008) Timescales and cultural process at 40,000 BP in the light of the Campanian Ignimbrite eruption, Western Eurasia. *J Hum Evol* 55: 834–857.
13. Roebroeks W (2008) Time for the Middle to Upper Paleolithic transition in Europe. *J Hum Evol* 55:918–926.
14. Blockley SPE, Ramsey CB, Higham TFG (2008) The Middle to Upper Paleolithic transition: Dating, stratigraphy, and isochronous markers. *J Hum Evol* 55:764–771.
15. Lowe D (2011) Tephrochronology and its application: A review. *Quat Geochronol* 6: 107–153.
16. de Vivo B, et al. (2001) New constraints on the pyroclastic eruptive history of the Campanian Volcanic Plain (Italy). *Contrib Mineral Petrol* 73:47–65.
17. Holliday VT, et al. (2007) Geoarchaeology of the Kostenki-Borschevo sites, Don River Valley, Russia. *Geoarchaeology* 22:181–228.
18. Hoffecker JF, et al. (2008) From the Bay of Naples to the River Don: The Campanian Ignimbrite eruption and the Middle to Upper Paleolithic transition in Eastern Europe. *J Hum Evol* 55:858–870.
19. Bourne A, et al. (2010) Tephrostratigraphical record of the last c. 105,000 years obtained from core PRAD 1-2 in the Central Adriatic Sea. *Quat Sci Rev* 29:3079–3094.
20. Fedele FG, Giaccio B, Isaia R, Orsi G (2003) *Volcanism and Earth's Atmosphere*, eds Robock A, Oppenheimer C (AGU Geophys, Washington, DC), pp 301–325.
21. Tomlinson E, et al. (2012) Geochemistry of the Phlegrean Fields (Italy) proximal sources for major Mediterranean tephras: Implications for the dispersal of Plinian and co-ignimbritic components of explosive eruptions. *Geochim Cosmochim Acta*, 10.1016/j.gcA.2012.05.043.
22. Rohling EJ, Mayewski P, Challenor P (2003) On the timing and mechanism of millennial-scale climatic variability during the last glacial cycle. *Clim Dyn* 20:257–267.
23. Rohling EJ, Mayewski P, Abu-Zied R, Casford J, Hayes A (2002) Holocene atmosphere-ocean interactions: Records from Greenland and the Aegean Sea. *Clim Dyn* 18:587–593.
24. Giaccio B, et al. (2006) *When Neanderthals and Modern Humans Met*, ed Conard NJ (Kerns Verlag, Tübingen, Germany), pp 343–375.
25. Bar-Yosef O, Zilhão J, eds (2002) Towards a definition of the Aurignacian. *Proceedings of Symposium Held in Lisbon, Portugal, June 25–30, 2002* (Instituto Português de Arqueologia, Lisbon Portugal).
26. Szmidt CC, Normand C, Burr G, Hodgins G, LaMotta S (2010) AMS ^{14}C dating the Protoaurignacian/early Aurignacian of Isturitz, France. Implications for Neanderthal-modern human interaction and the timing of technical and cultural innovations in Europe. *J Archaeol Sci* 37:758–768.
27. Zilhão J, et al. (2007) *Rethinking the Human Revolution: New Behavioural and Biological Perspectives on the Origin and Dispersal of Modern Humans*, eds Mellars P, Boyle K, Bar-Yosef O, Stringer C (McDonald Institute Archaeological Research Monographs, Cambridge, UK), pp 249–262.
28. Higham T, Ramsey CB, Karavanić I, Smith FH, Trinkaus E (2006) Revised direct radiocarbon dating of the Vindija G1 Upper Paleolithic Neandertals. *Proc Natl Acad Sci USA* 103:553–557.
29. Crevecoeur I, et al. (2010) The Spy VI child: A newly discovered Neandertal infant. *J Hum Evol* 59:641–656.
30. Mussi M (2001) *Earliest Italy: An Overview of the Italian Paleolithic and Mesolithic* (Plenum, New York).
31. Benazzi S, et al. (2011) Early dispersal of modern humans in Europe and implications for Neanderthal behaviour. *Nature* 479:525–528.
32. Morley MW, Woodward JC (2011) The Campanian Ignimbrite (Y5) tephra at Crvena Stijena Rockshelter, Montenegro. *Quat Res* 75:683–696.
33. Douka K, Perlès C, Valladas H, Vanhaeren M, Hedges REM (2011) Franchthi Cave revisited: The age of the Aurignacian in south-eastern Europe. *Antiquity* 85:1131–1150.
34. Stiner MC, Kozlowski JK, Kuhn SL, Karkanas P, Koumouzelis M (2010) Klissoura Cave 1 and the Upper Paleolithic of southern Greece in cultural and ecological context. *Eurasian Prehist* 7:309–321.
35. Sirakov N, et al. (2007) Nouveau faciès lamellaire du début de Paléolithique supérieur dans les Balkans. *Revue d'Archéologie Préhistorique, PALÉO* 19:131–144.
36. Shalamanov-Korobar L (2008) *The Palaeolithic of the Balkans*, eds Darlas A, Mihailović D (BAR International Series 1819, Oxford), pp 85–92.
37. Sinitsyn AA, Hoffecker JF (2006) Radiocarbon dating and chronology of the Early Upper Paleolithic at Kostenki. *Quat Int* 152-153:164–174.
38. Barker G, et al. (2010) The Cyrenaican Prehistory Project 2010: The fourth season of investigations of the Haua Fteah cave and its landscape, and further results from the 2007–2009 fieldwork. *Libyan Studies* 41:63–88.
39. McBurney CBM (1967) *The Haua Fteah in Cyrenaica* (Cambridge Univ Press, Cambridge, UK).
40. Hublin J-J, McPherron SP, eds (2012) *Modern Origins: A North African Perspective* (Springer, Berlin).
41. Vermeersch PM (2010) *South-Eastern Mediterranean Peoples Between 130,000 and 10,000 Years Ago*, ed Garcea EAA (Oxbow Books, Oxford), pp 66–88.
42. Higham T, et al. (2012) Testing models for the beginnings of the Aurignacian and the advent of figurative art and music: The radiocarbon chronology of Geißenklösterle. *J Hum Evol* 62:664–676.
43. Dalén L, et al. (2012) Partial genetic turnover in Neandertals: Continuity in the east and population replacement in the west. *Mol Biol Evol*, 10.1093/molbev/mss074.
44. Blockley SPE, et al. (2005) A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. *Quat Sci Rev* 24: 1952–1960.
45. Tomlinson EL, Thordarson T, Müller W, Thirlwall MF, Menzies MA (2010) Microanalysis of tephra by LA-ICP-MS—strategies, advantages and limitations assessed using the Thorsmörk Ignimbrite (Southern Iceland). *Chem Geol* 279:73–89.
46. Smith VC, Isaia R, Pearce NJG (2011) Tephrostratigraphy and glass compositions of post-15 kyr Campi Flegrei eruptions: Implications for eruption history and chronostratigraphic markers. *Quat Sci Rev* 30:3638–3660.
47. Jochum KP, et al. (2006) MPI-DING reference glasses for in situ microanalysis: New reference values for element concentrations and isotope ratios. *Geochem Geophys Geosyst*, 7:Q02008, 44 pp.
48. Müller W, Shelley M, Miller P, Broude S (2009) Initial performance metrics of a new custom designed ArF eximer LA-ICP-MS system coupled to a two-volume laser ablation cell. *J Anal At Spectrom* 24:209–214.