The Avellino 3780-yr-B.P. catastrophe as a worst-case scenario for a future eruption at Vesuvius

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Edited by George A. Thompson, Stanford University, Stanford, CA, and approved January 20, 2006 (received for review October 4, 2005)

A volcanic catastrophe even more devastating than the famous *anno Domini* 79 Pompeii eruption occurred during the Old Bronze Age at Vesuvius. The 3780-yr-B.P. Avellino plinian eruption produced an early violent pumice fallout and a late pyroclastic surge sequence that covered the volcano surroundings as far as 25 km away, burying land and villages. Here we present the reconstruction of this prehistoric catastrophe and its impact on the Bronze Age culture in Campania, drawn from an interdisciplinary volcanological and archaeoanthropological study. Evidence shows that a sudden, en masse evacuation of thousands of people occurred at the beginning of the eruption, before the last destructive plinian column collapse. Most of the fugitives likely survived, but the desertification of the total habitat due to the huge eruption size caused a social–demographic collapse and the abandonment of the entire area for centuries. Because an event of this scale is capable of devastating a broad territory that includes the present metropolitan district of Naples, it should be considered as a reference for the worst eruptive scenario at Vesuvius.

archeoanthropology | Bronze Age | volcanic catastrophe | volcanology

Plinian eruptions are highly destructive volcanic events that produce severe and long-lasting damage over thousands of squared kilometers of the territory surrounding volcanoes (1–4). Studies of the occurrence of plinian eruptions in densely populated areas reveal that most of the people who lived in the affected zones survived (3, 5). However, because of the habitat devastation and their inability to rehabilitate their homeland (5–7), many victims suffer social–economic crises and health status decline (3, 5, 8). Strong eruption precursors commonly alert the people days to months before the cataclysmic event; in the early phases of a plinian eruption, the slow escalation of the phenomena could allow them to escape from the volcano and flee beyond the lapilli fallout zone. The success of the evacuation depends mainly on its timeliness, because the early phase of a plinian eruption may not be lethal, even close to the volcano (2). Nevertheless, in most cases, the emplacement of billions of cubic meters of ash and lapilli in the form of a continuous blanket from decimeters to meters thick retards or prevents the recovery of the social–economical structure for decades to centuries, even tens of kilometers away from the vent (3, 9, 10).

An extraordinary case that sheds light on such catastrophic consequences of an eruption is the Bronze Age Avellino plinian event at Vesuvius, dated by ^{14}C to ≈3780 yr B.P. (2, 10, 11). The eruption produced ≈4 km^3 of phonolitic ash and lapilli, a large subaqueous debris-flow avalanch in the gulf of Naples (12), and was even reported to have caused a global climatic disturbance (13). This event started with a moderate-sized explosive phase followed by a plinian column that in a few hours rose to 36 km in the stratosphere and, driven by westerly winds, produced a lapilli fallout covering thousands of squared kilometers northeast of the volcano. At least six times during the eruption, conduit and column instability and magma and ground water interaction (2) caused the eruptive column to collapse, thus producing a pyroclastic flow and surge sequence. The final collapse episode occurred at the culmination of magma discharge and column growth and generated a pulsating sequence of huge pyroclastic flows and surges, which produced ≈10^9 m^3 of ash deposits (Fig. 1).

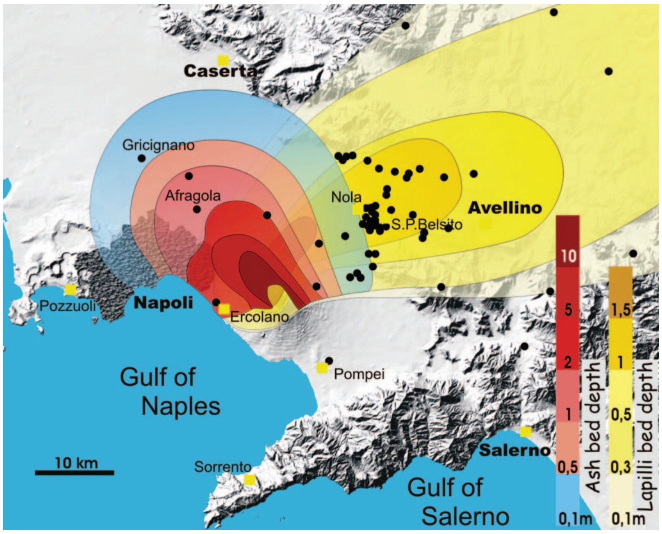

Fig. 1. The area covered by Avellino pyroclastic surge and fall deposits in the southeastern Campanian plain and surrounding uplands. Black dots indicate the identified Old Bronze Age archaeological sites buried by the products of the Avellino eruption. Because of the stratospheric winds, fallout lapilli and ash were deposited east-by-northeast of the volcano, whereas the surge clouds flowed down the volcano slopes in a prevalent NNW direction. Most sites within the fallout area (the yellow zone) were buried by a pumice lapilli blanket thicker than 30 cm, which is above the limit for roof collapse. Structures in the surge area closer than 12 km to the volcano (the dark red zone) could be swept away by the cloud impact force, whereas those at a greater distance would suffer less impact damage but still be affected by decimeters (the light red zone) to centimeters of fine ash bed or floods (the blue zone). In the present metropolitan area of Naples, the Avellino surge bed is as thick as 3 m (bar scale values are in meters).

Interdisciplinary Field and Laboratory Evidence

A detailed stratigraphic, sedimentologic, and textural study has allowed us to evaluate the impact of pyroclastic surges on the prehistoric environment. The sequence of surge clouds spread outward onto the volcano slopes and the surrounding plains reaching a maximum distance of ≈25 km in the northwest, the prevalent propagation direction, burying land and villages (2, 10, 14, 15). This phase of the eruption likely lasted no more than few

Conflict of interest statement: No conflicts declared.

This paper was submitted directly (Track II) to the PNAS office.

Abbreviation: NNW, north-by-northwest.

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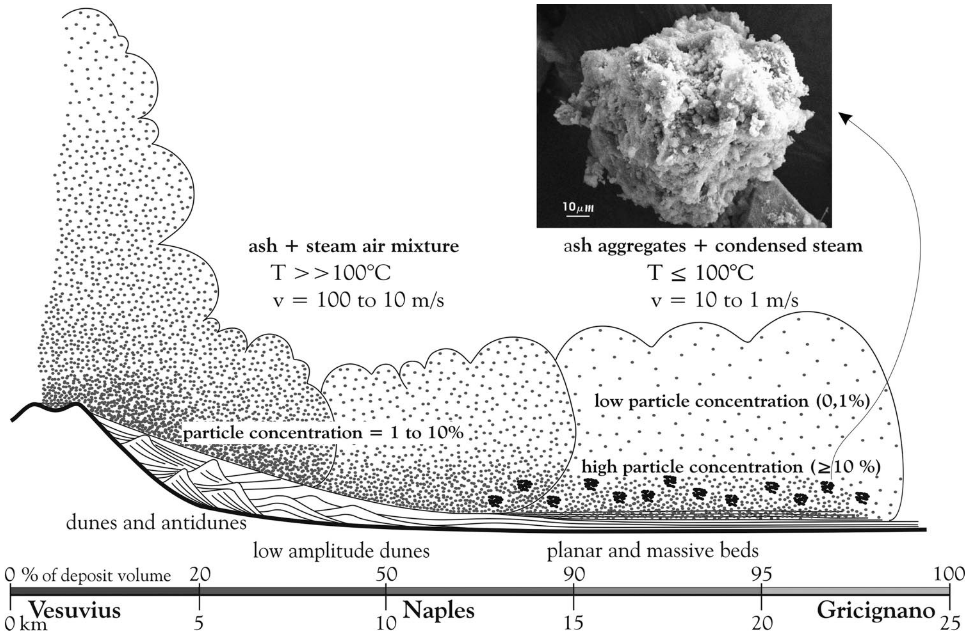

Fig. 2. Diagrammatic illustration of the transport and deposition mechanisms of the final Avellino pyroclastic surge sequence (cloud and deposit thickness are not to scale) along the prevalent northwest propagation direction. With increasing distance from the volcano, surge cloud velocity (v), temperature (T), average particle concentration, and deposit thickness decrease. In the proximal zone within 10 km of the volcano, surge clouds were highly energetic and inflated, and the nearly homogeneous dispersal of particles within a cloud with a volume fraction of 1–10% allowed the deposition of sandwave (from dunes and antidunes to low-amplitude dunes) beds. At intermediate distances between 10 and 15 km, the prevalence of gravitational settling over turbulence caused the lower part of the cloud to be denser (particle volume fraction, ≈10%) and the upper part to be dilute (particle volume fraction, <0.1%), causing low-amplitude dunes and planar beds to be formed. Within this distance, velocity ranged between 100 and 10 m/s, and temperature was ≈100°C. In distal zones from 15 to 25 km, the cloud cooled below 100°C, and deceleration (v = 10 to 1 m/s) and turbulent damping caused steam condensation, particle aggregation, and sudden settling, thus forming planar and massive beds. Within a radius of 10 km from Vesuvius, an area that includes the city of Naples, ≈50% of the entire ash and lapilli volume was deposited with a thickness decreasing from ≈20 m to ≈5 m. The photograph shows a scanning electron microscope image of a typical fine-ash aggregate of particles (≈100 μm diameter) from the distal deposits.

hours before the collapse (2), consistent with an inferred magma discharge rate of 10^5 t/s (1 t = 10^3 kg) and numerical modeling (16). Surge velocity decreased downstream from a maximum of nearly 150 m/s to <1 m/s, as indicated by our calculation of the minimum suspension velocity of particles in a dusty gas (17). This result agrees with an initial velocity that we estimated to be at least 100 m/s on the basis of the energy line model (18) by assuming a reasonable collapse height/travel distance (H/L) ratio of 0.1.

Near the vent, the pyroclastic surge temperature was a few hundred degrees, consistent with our results on the *anno Domini* 79 eruption at Herculaneum (9). While the clouds swept down the volcano flanks, they ingested air, expanded, and cooled to nearly ambient temperature, as suggested by simulation results for similar events (16). Within 10–15 km of the vent, the clouds essentially dissipated their destructive power and lost their coarser grains by gravitational settling, thus evolving from powerful dune-forming to massive and planar bed-forming fine-ash surge deposits (Fig. 2) (19, 20). Turbulent damping, steam condensation, and particle aggregation caused the cloud to deflate rapidly and deposit ash abruptly within a distance of 15–25 km. This wet surge cloud that buried the plains around Vesuvius was saturated with water steam, and where it entered rivers it generated secondary mud flows and hyperconcentrated floods that are recorded by the continuous series of ash and clay beds at the top of the volcanic sequence. Condensation of the huge amount of steam incorporated into the ash cloud as a result of magma–aquifer interaction was the main factor for the large posteruptive hydrologic catastrophe. The consequence of the eruption is a continuous layered ash bed from 15 m to a few decimeters thick that mantles the volcano slopes and surrounding plains (2).

An exceptional series of recently excavated archaeological sites provides decisive evidence for the evaluation of the effects of this prehistoric catastrophe on human settlements. Indeed, starting in the Neolithic Age, the Campanian plain experienced a spread of agriculture and growth in population that, because of technical innovations, culminated in the Bronze Age demographic explosion that is also recognized in the rest of southern Europe (21, 22). The tens of Old Bronze Age sites discovered in the area (10) clearly testify to an extensive distribution of human settlements and a widespread exploitation of land resources at the time of the eruption, as confirmed by archaeological evidence of farming and animal husbandry (10, 15). All these findings allow us to put the stages of the tragedy into the following sequence: (*i*) sudden en masse evacuation, (*ii*) widespread devastation of the land and loss of human life, (*iii*) an early sporadic and tentative reoccupation, and (*iv*) a final long-lasting abandonment of settlements.

The recent discovery of one of the world's best-preserved prehistoric villages at Nola, 15 km northeast of Vesuvius, revealed the abrupt abandonment of a human settlement at the beginning of the eruption (Fig. 3*A*) (15). Scenes of everyday life, frozen by the volcanic deposits, testify that people suddenly left the village: the moulds of four huts, with pottery and other objects left inside; skeletons of a dog and nine pregnant goat victims found in a cage; and footprints of adults, children, and cows filled by the first fallout pumice. The huts, partially collapsed from lapilli accumulation, do not show impact damage by the pyroclastic surge, which left even small objects untouched and did not erode the underlying lapilli. Imprints of hut structures, including wood beams, small spikes, and

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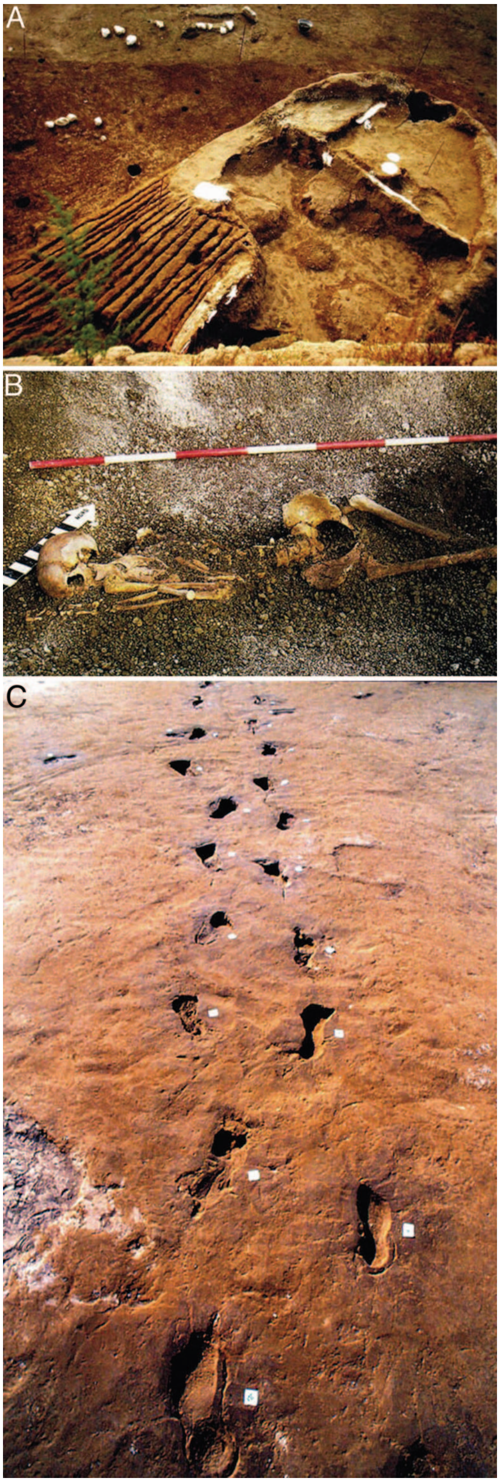

Fig. 3. Archeological evidence for the catastrophe. (*A*) The Old Bronze Age village of Nola. The mould of one of a group of huts found 15 km northeast of Vesuvius. The huts were partially buried under ≈1 m of fallout lapilli, 20 cm of planar surge, and 20–40 cm of flood deposit. The hut roof partially collapsed, but its interior, including pottery, was filled by surge ash and perfectly preserved. (*B*) One of the two human victims of the Avellino eruption found at San Paolo Belsito, near Nola. The victim, a young woman buried by 1 m of pumice lapilli, was found in a self-protecting position typical of death by suffocation. (*C*) Footprints of two fugitives in the surge ash deposit of the Avellino eruption, found ≈15 km NNW of Vesuvius. Thousands of footprints directed NNW away from the volcano testify to an en masse exodus from the devastated zone.

noncarbonized straw, as well as plant imprints at Nola and other sites clearly indicate a low emplacement temperature for the surge. These pieces of evidence suggest that the cloud lost most of its mechanical and thermal power within a distance of 15 km from vent.

One kilometer east of the village, in San Paolo Belsito, is a unique finding for the prehistory of human victims of the eruption. Here, skeletons of a man and a woman (Fig. 3*B*) dramatically testify to their unlucky escape attempt and their death due to suffocation (10, 23). These victims were buried under a 1-m-thick lapilli bed located along the main dispersion axis of the pumice fallout deposit. Dense rock fragments up to 10 cm in diameter delivered a lethal impact in this zone with a velocity of 70 m/s. However, the lack of victims' remains in other sites buried by the eruption strongly suggests that the early evacuation noted at Nola also might have occurred in most other villages.

A decisive proof of a massive exodus is the extraordinary discovery of thousands of human and animal footprints found in scattered probes within an area of a few squared kilometers in the surge deposit located about 15 km north-by-northwest (NNW) of Vesuvius and only 7 km outside metropolitan Naples (Fig. 3*C*). The common NNW travel direction away from the volcano for thousands of track paths suggests a very rapid large-scale evacuation from the devastated zone that includes the present Neapolitan district. As indicated by footprints pressed into all of the horizons in the ash bed, the evacuation occurred throughout the settling of the surge cloud. Therefore, the ash deposit had to be cool and firm enough to allow fugitives to survive, consistent with the evidence from Nola village and first-hand reports of survivors of recent eruptions with similar circumstances (24). Flood and lahar deposits overlying the surge bed also include footprints and local rain-drop imprints as well, thus testifying that the ongoing exodus occurred both during the ash fall and after the posteruption rainstorms and floods.

The huge number of track paths accounts for a massive exodus, because, before the eruption, an area of 500 km^2 around Vesuvius could sustain no more than a few tens of thousands of people. In fact, the inferred yearly production for one hectare of agricultural land would have been a few hundred kilograms of cereals, which probably is just enough for one person, as estimated on the basis of land carrying capacity and minimal need for survival (25, 26). In fact, available archaeological evidence for an extensive use of land for crops (10, 15, 21, 27), as well as paleobotanical data (28), are consistent with our paleonutritional analyses of the human victims' bones and unequivocally indicates that the local diet was mainly based on cereals.

A few posteruptive settlements located directly on top of the Avellino deposit in Nola confirm that some survivors built new huts immediately after the eruption. However, the lack of archaeological evidence at multiple stratigraphic horizons above the ash bed (28) indicates a definitive abandonment of the area a short time after reoccupation. No permanent posteruptive sites are dated earlier than 230 years after the eruption, even at sites such as Ariano Irpino, which is 70 km distant from Vesuvius (10). Although most of the fugitives were able to escape to a safe distance from the volcano before the last and most devastating plinian column collapse episode, reoccupation was likely inhibited because of environmental degradation and land desertification (5, 6, 8). The lack of access to resources and the resulting decline in health status (8) likely caused a permanent sociodemographic collapse for a large part of the Campanian Old Bronze Age communities. Such a local but long-lasting decline is a typical consequence of powerful volcanic eruptions as it is for other natural catastrophes (4, 5). In other Campanian areas and adjacent regions not directly affected by the eruption, as well as in the rest of Italy, cultural continuity is demonstrated throughout the entire Bronze Age (21). This continuous habi-

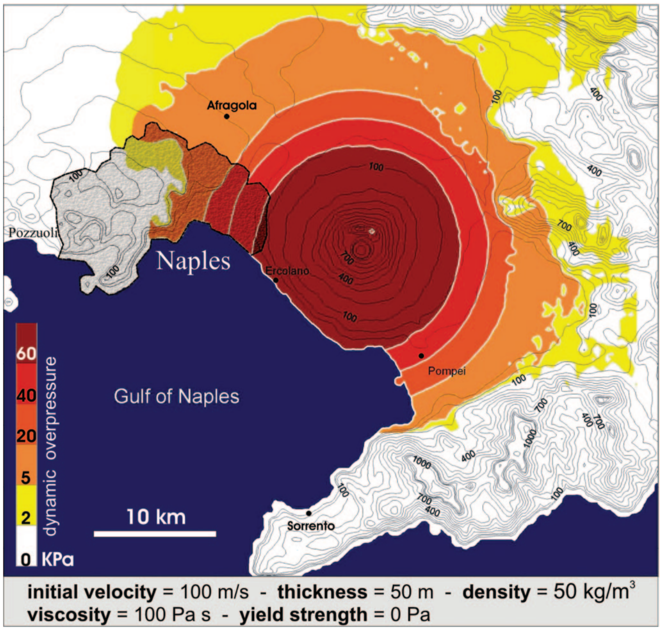

Fig. 4. Computer simulation of the areal distribution and dynamic overpressure of a pyroclastic surge cloud that is an analogue to the Avellino final surge at Vesuvius. Total devastation, corresponding to a dynamical overpressure exceeding 25 KPa, occurs within 12 km from the summit around the volcano flanks (initial velocity = 100 m/s, thickness = 50 m, density = 50 kg/m^3, viscosity = 100 Pa/s, yield strength = 0 Pa). Within the urban area of Naples, dynamic overpressure has high to moderate values, ranging from 40 to 2 KPa. Dynamic overpressure values between 10 and 25 KPa produce severe to extremely high damage to buildings and other objects. The numerical simulation is based on a simple model of a gravity-driven pyroclastic current that stops by en masse freezing.

tation is also confirmed by the discovery of ash from the Avellino deposit within the clay of the Bronze Age Apulian pot sherd, 140 km distant from Vesuvius (29).

Discussion and Conclusions

All of these joint lines of evidence provide constraints for risk assessment in Campania. An analogous catastrophe would bring extreme devastation, extending into the densely urbanized Neapolitan area that was untouched by the *anno Domini* 79 eruption that buried Pompeii, Herculaneum, and Stabiae, south-by-southeast of Vesuvius (1, 9, 11), presently with a lower total number of inhabitants. Within the city of Naples, we have identified a 3- to 0.5-m-thick pyroclastic surge deposit that was emplaced by the passage of the last and most powerful Avellino surge cloud sequence. Only the highest hills surrounding the city blocked the passage of this surge. Our numerical simulations based on a previous computer model for the movement of gravity flows at Vesuvius (14) indicate that a pyroclastic surge analogue to the Avellino event would be capable of overrunning Naples and having a destructive to moderate impact on buildings (dynamic overpressure ranging 40 to 2 KPa) (Fig. 4).

These results show that within a radius of at least 12 km from the volcano, the impact force and sedimentation rate of the pyroclastic surge would cause total devastation and mortality, because the inferred dynamic overpressure of surge clouds would exceed even the building strength (30, 31). Only beyond 15 km from the volcano would the mechanical effects drop to levels that would allow the majority of the people affected to survive. Lethal thermal effects are confined to the area within a radius of <10 km^2. The abundance of fine ash in distal zones may cause severe respiratory-tract injuries and fatalities due to acute asphyxia. Secondary floods, debris flows, and mud flows from volcano flanks also are major causes of fatalities after an eruption (32).

In contrast with fallout deposits that are generally dispersed east of the volcano by prevalent winds, field evidence from past eruptions and numerical simulations show that pyroclastic surges may propagate in all directions because of several factors: their source in the column, surge cloud thickness, and cone topography. Actually, in the present geomorphological context, the relict rim of the ancient Mount Somma volcano would channel pyroclastic clouds toward Naples. Our study suggests that this prehistoric catastrophe should be considered as a worst-case scenario for a future eruption at Vesuvius, being even more devastating than the *anno Domini* 79 event. The present emergency plan for Vesuvius, which is regularly up-graded according to new scientific knowledge, is presently based on the maximum expected event at short-term, which is a subplinian eruption.

Planning also including a relatively rare worst-case scenario is a difficult but necessary task for civil protection in areas subject to volcanic hazards. The two cases that follow are recent examples demonstrating the consequences of underestimating the maximum potential eruption in a volcanic hazard scenario. Fortunately, the volcanoes in both of these examples were not located in a densely populated urban environment like Naples. Because a volcanic crisis can start quickly, leaving only a few weeks to months for planning, it is important to use all available data to forecast the scale of potential events. We argue that the data presented here for the catastrophic Avellino eruption should now be incorporated into the hazard plan as an extreme scenario (a maximum probable event) that could impact the city of Naples and the surrounding Campanian plain in case of an eruption of Vesuvius.

Indications of renewed activity at Mount St. Helens in early 1980 prompted the U.S. Geological Survey (USGS) to create a new map to show areas of potential hazards. Their map, which defined hazard zones potentially effected by three magnitudes of events, was completed on April 1 and immediately became the main instrument for briefings and hazard planning during April and early May preceding the main eruption of May 18 (33). During this time, a USGS observation post named Coldwater II was staffed on Coldwater Ridge, located $\approx$9.5 km north of the summit and outside of the hazard zone mapped for the largest probable event. Unfortunately, the catastrophic blast of May 18, 1980 greatly exceeded official expectations and devastated a broad zone to the north of the cone extending as far as 25 km from the summit (34). This eruption essentially destroyed all life and human structures within the devastation zone; the blast removed all evidence of the USGS Coldwater II site.

Before 1991, Pinatubo was a relatively unknown, heavily forested volcano with no records of historical eruptions. At that time Clark Air Base, located $\approx$15 km east of the volcano, was the largest overseas U.S. military base in the world. In April 1991, thousands of small earthquakes at Pinatubo signaled the start of a new cycle of activity that was confirmed by strong sulfur dioxide emission beginning in early June. Preliminary hazard maps placed Clark Air Base at the east edge of pyroclastic flow hazard zones, and the base was flanked by potential mudflow hazard zones (35). Anticipating an impending hazard, the Air Force started evacuating people from Clark on June 10, and on June 12 Pinatubo started to erupt. The explosion of Pinatubo on June 15 was the second-largest volcanic eruption of the 20th century, producing an ash fall that devastated Clark and neighboring Angeles City. Pyroclastic flows that swept down the Sacobia River valley reached within 3 km northwest of housing units on Clark (35). At this point, $<1{,}000$ of the original 30,000 military personnel and employees remained at the base. By September, the U.S. Air Force had essentially evacuated the base, and in November the facility was transferred back to the Philippines.

At present, at least 3 million people live within the area destroyed by the Avellino plinian eruption. The present monitoring system can alert the authorities at least weeks before an eruption, thus allowing the evacuation plan to be activated and the people to be saved. The catastrophic effects of a plinian eruption analogue of the Avellino event, with its long-term environmental and socioeconomical implications for metropolitan, industrial, and rural areas of Campania, should be taken into account as an extreme scenario in the hazard assessment and planning for the Neapolitan area.

All of the new archaeological excavations described in the paper have been carried out under the supervision of the Soprintendenza Archeologica per le Province di Napoli e Caserta.

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