Pompeii Damaged by Volcaniclastic Debris Flows Triggered Centuries Prior to the 79 A.D. Vesuvius Eruption

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This study records that Pompeii, long before its final devastation by the 79 A.D. Vesuvius eruption in southern Italy, was damaged by several mass gravity flows. Composition of the deposits indicates that they were derived from volcaniclastic cover of carbonate highlands positioned 14 km NE of the city. Stratigraphic and petrologic analyses of sections in excavations and drill cores in and near Pompeii record the presence of three downslope-directed debris flows dated between 8th and 2nd century B.C. Some of these deposits were channelized via a stream bed that once extended from high reliefs to Pompeii. It is proposed that one of these events may have been partially responsible for urban decline during the 4th century B.C. These mass flows are interpreted as having been triggered primarily by intense rains in a manner similar to those that have occurred and destroyed towns in this region during the past 50 years. Our investigation shows that Pompeii and adjacent areas in the past, much as in recent time, have likely been most frequently susceptible to episodic damage by avalanches and mass flows of volcaniclastic material resulting from hydrological effects rather than from volcanic events, earthquake tremors, and societal disruptions such as wars. © 2013 Wiley Periodicals, Inc.

INTRODUCTION

Historical records from many cities document damage, discontinuity, and decline during their municipal development as a result of natural phenomena such as earthquakes, volcanic eruptions, floods, sediment instability, and slope failures. Pompeii, a thriving center in southern Italy until the 1st century A.D., is a distinct but by no means unique example. The present study focuses on the discovery of pre-79 A.D. volcaniclastic deposits emplaced by avalanches, slumps, and associated debris flows (secondary lahars) during volcanically quiescent phases of Mount Vesuvius volcano (Andronico & Cioni, 2002). It is postulated that such mass flows periodically damaged the city long before its major destruction by the well-documented earthquake activity in 62 A.D. and its final demise from the plinian eruption in 79 A.D. (otherwise called the Pompeii eruption; e.g., Cioni et al., 1992, 1995), and that these events likely were similar to the causes of municipal damage that have affected the Pompeii–Campania region during the past 50 years (Gurioli et al., 2005, 2007, 2010). Our geological researches in this region, largely by means of stratigraphic and petrologic analyses of sediment sequences in drill cores and excavations, have been conducted to better interpret how past natural processes have influenced the development and evolution of Pompeii before the 79 A.D. Vesuvius eruption.

Archaeological exploration at Pompeii during the past two and half centuries has emphasized this city's most recent history, that is, the period following its defeat by Rome in 89 B.C. until its demise 168 years later by the A.D. 79 Pompeii eruption. Until now, however, study of natural events affecting Pompeii during its early history has been seriously hampered by the thick (to >10 m) cover of pyroclastic deposits from the 79 A.D. eruption that almost completely buried the city (Cioni et al., 1992). At present, nearly 30% of Pompeii still remains to be excavated, and relatively little is known of pre-79 A.D. construction levels and early development of the ancient city. Moreover, to protect now-exposed and vulnerable structures at the site, excavated foundations there are reburied

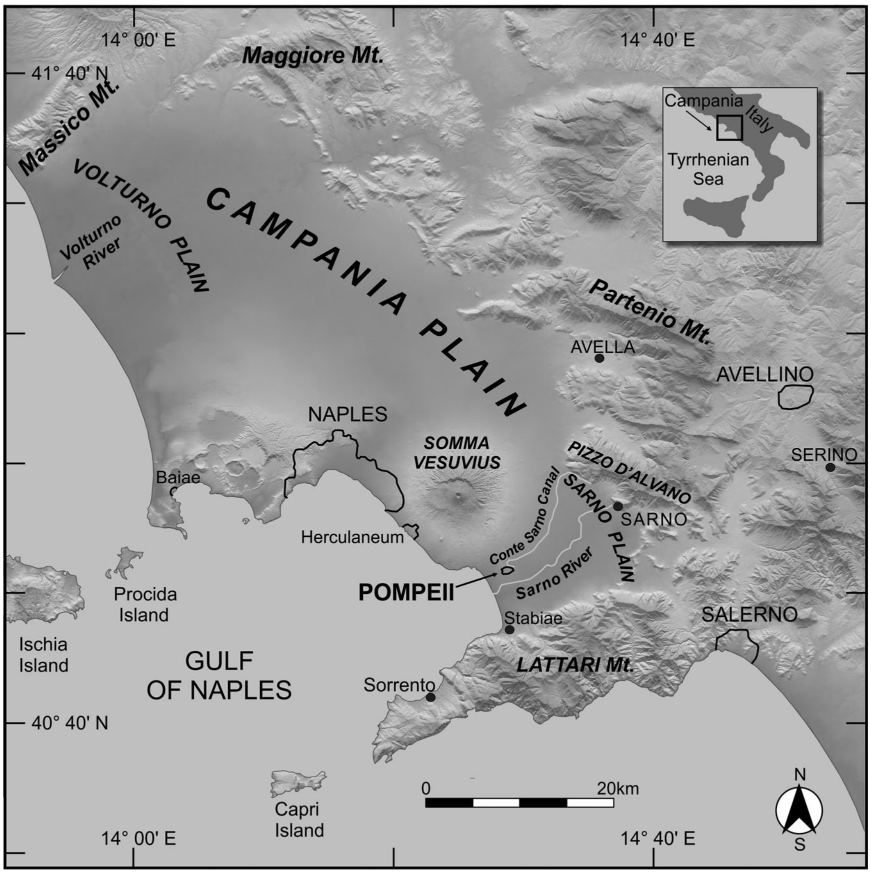

Figure 1 Map of the Campania Plain–Gulf of Naples region showing Pompeii, other population centers, and geographic features discussed in the study.

almost immediately after exposure and preliminary exploratory study.

Pompeii is situated southeast of Naples, in the Sarno Plain at the base of the Somma–Vesuvius volcano and about 2 km from the present Tyrrhenian coastline (Figure 1). The Sarno Plain is part of the Campania Plain, a broad Plio-Pleistocene graben bounded by Mesozoic and Cenozoic carbonate mountainous terrains and low areas partially filled by alluvial, pyroclastic, and marine deposits (Brocchini et al., 2001). The Late Pleistocene and Holocene volcanic activity of the Somma–Vesuvius complex is characterized by major plinian and subplinian eruptions that are followed by minor interplinian explosive activity (small-scale subplinian, violent strombolian, and vulcanian eruptions) and phases of quiescence (Arnò et al., 1987; Andronico et al., 1995; Rolandi, Petrosino, & McGeehin, 1998). The geography and development of land and population centers in the surrounding area have all been affected during this period.

After the Avellino eruption dated 3960 yr B.P. (Cioni et al., 2008), the Somma–Vesuvius remained in quiescence until 3200 yr B.P. (AP1 eruption) according to several authors (among others, Rolandi, Petrosino, & McGeehin, 1998 and Andronico & Cioni, 2002). The interplinian period between Avellino and Pompeii eruptions was characterized by several eruptions (AP1, AP2, AP3, and AP4/5) up to about 2700 yr B.P. Following this, the stratigraphy shows a tephra deposit (Vesuvian AP6) linked to a small eruption that produced a thin, only locally preserved volcanic layer according to Andronico and Cioni (2002). A written passage by the epic poet *Silius Italicus* (cf. Stothers & Rampino, 1983) indicates an age of 217 B.C. can be attributed to this last interplinian eruption (AP6) before the quiescence phase cited by Andronico and Cioni (2002).

HISTORICAL NOTES

Pompeii was founded by a population from central Italy, the Oscans, at the end of 7th century B.C. (De Caro, 1992; Guzzo & d'Ambrosio, 1998; Figure 2). The town was built on a localized elevated terrain formed by lava associated with eruptive events of the Somma–Vesuvius

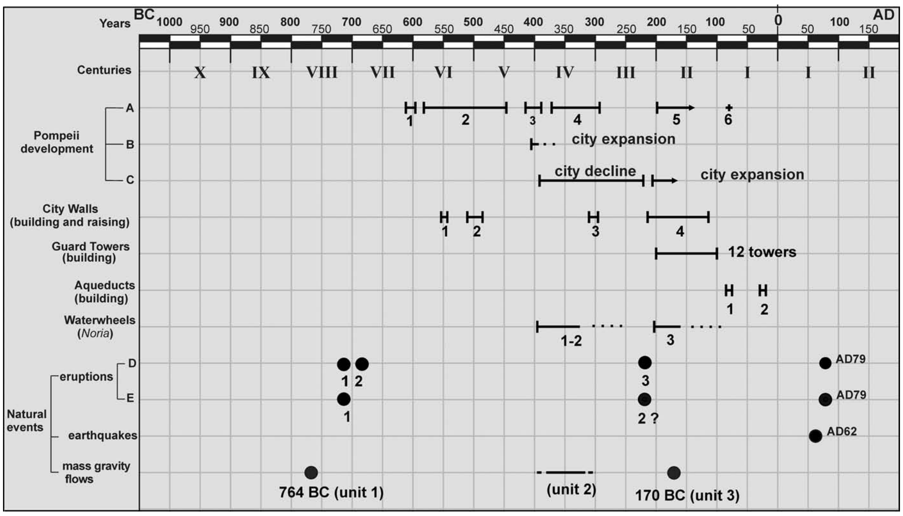

Figure 2 Synoptic framework highlighting the history of Pompeii, depicting the ages of some major archaeological structures and natural events that affected the city area from prior to its founding in the 7th century B.C. to its demise in 79 A.D. Pompeii development: (A) After De Caro (1992): 1—Pompeii foundation (end VII century B.C.); 2—Greek and Etruscan occupation (VI century and part of V century B.C.); 3—Samnitic occupation (end V century B.C.) and city expansion; 4—Samnitic immigration (IV century B.C.), city s decline and alliance with Rome (343–290 B.C.); 5—city s great prosperity; 6—Roman colony (80 B.C.); (B) After Ward-Perkins (1984); (C) After Sakai (2000–2001). City Walls: After De Caro (1985): 1—wall building (mid-VI century B.C.); 2—wall raising (about 500 B.C.); 3—wall restoration and raising (end IV century B.C.); 4—new wall restoration and raising (II century B.C.). Guard Towers: After Maiuri (1929) and Chiaramonte Trerè (1986); Aqueducts: 1—Avella (80 B.C.; Ohlig, 2001); 2—Serino (20/30 B.C.; Potenza, 2001). Waterwheels: 1–2 Stabian Baths and House of Queen of England (tannery; Maiuri, 1931); 3—Republican Baths (Oleson, 1994). Natural events: Eruptions: (D) After Andronico and Cioni (2002): 1—AP3 (2710 B.P.); 2—AP4 and AP5 (strombolian or phreatoplinian activity, no age), AP6; 3—216 B.C. (Silius Italicus); A.D. 79; E) After Rolandi, Petrosino, and McGeehin (1998): 1—Third protohistoric eruption; 2—216 B.C. (Silius Italicus); A.D. 79. Earthquakes: 62 A.D. (Seneca, Naturales quaestiones: 6, 1, 1–3, 6, 1, 106, 25, 3, 6, 30, 4–5, 6, 31, 1–3; Tacitus, Annales: 15, 22, 2); Mass gravity flows: this study.

and interpreted as the distal segment of a lava flow that remains undated. On the basis of geomorphological evidence, Cinque and Irollo (2004) interpret the elevated lava terrain as the possible remains of a separate volcano. The city was positioned in proximity to the Tyrrhenian coast and mouth of Sarno River where an active port was established (Pescatore et al., 2001). Salient events associated with the city's history and development are summarized in Figure 2.

The earliest urban nucleus of Pompeii (termed archaic city; Figure 3) occupied the southwestern part of a wider area enclosed by low walls (Maiuri, 1929; De Caro, 1985; Figure 2). The wall perimeter remained fairly constant during the city's occupation. The archaic city, covering an area of about 10 hectares, had an irregular street network delineating small city blocks and the presence of two sanctuaries. During the 6th and part of the 5th century B.C., the city was occupied by Greeks and Etruscans and, during this time, the walls were reinforced and raised (De Caro, 1985; Figure 2).

At the end of the 5th century B.C., the Samnites, a population coming from inland regions of the southern Italian peninsula conquered Pompeii. Their arrival marked the beginning of a new age for the city that was becoming an important trading centre (Figure 2). As a consequence, an increase in population led to an enlargement toward the east and north of the archaic city (Ward-Perkins, 1984; De Caro, 1992). The new quarters were laid out according to a regular orthogonal plan with rectangular blocks delineated by intersections of east-west (*decumani*) and north-south (*cardines*) streets; these were connected to the street network of the earlier urban nucleus. In the 4th century B.C., the Samnite immigration forced Pompeii to establish an alliance with Rome that accepted it as *socia* of the Roman political organization. Following this expansion and until the 3rd century B.C., the city experienced a decline (Figure 2) as no public buildings or sanctuaries can be dated prior to the 2nd century B.C. (De Caro, 1992; Sakai, 2000–2001). At the end of that century the walls were once again reinforced and eventually raised (De Caro, 1985; Figure 2).

From the first half of the 2nd century B.C., Pompeii experienced a period of considerable prosperity as recorded by homes of the wealthy, renovation and improvement of earlier public buildings, and new expansion within the perimeter of city walls. The walls were restored (De Caro, 1985; Sakai, 2000–2001) and Guard Towers were inserted along these (Maiuri, 1929; Chiaramonte

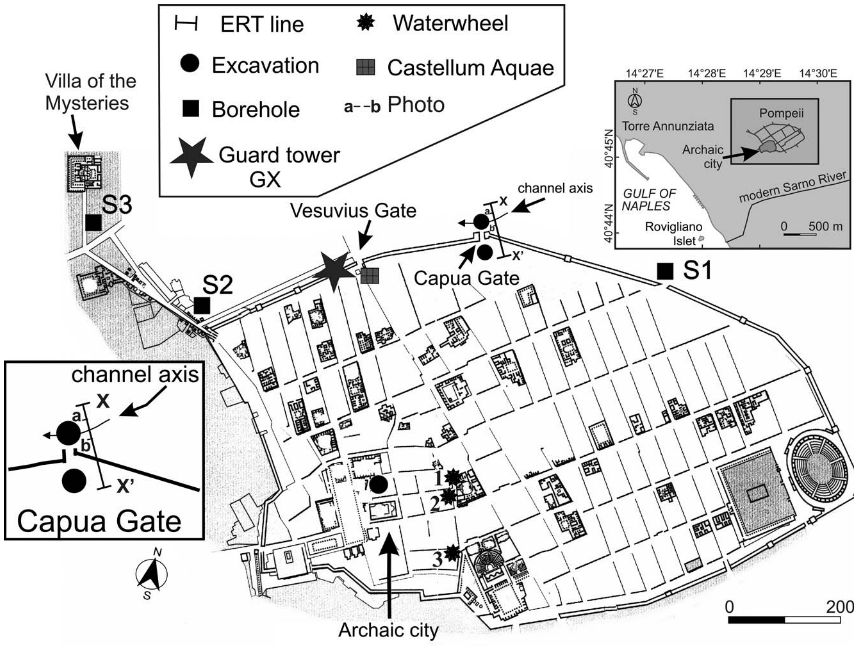

Figure 3 Map showing the archaeological area of Pompeii. The archaic sector of the city is shaded in the inset (upper right, not to scale). Position of boreholes, excavations, an ERT profile (X-X) and photograph (a–b) used in this study are depicted along with city sites and archaeological structures discussed in text (waterwheels: 1) Stabian baths; 2) tannery; 3) Republican baths).

Trerè, 1986; Figure 2). During the Social War (89–90 B.C.), Pompeii struggled against Rome to obtain political rights deriving from Roman citizenship. In April 89 B.C., the Roman army, led by Sulla, besieged Pompeii and then occupied it. A few years later (80 B.C.), the Roman colony named *Cornelia Veneria Pompeianorum* was established. By the 1st century A.D., Pompeii had become a thriving city of the Roman province, with a population that had expanded well beyond its walls.

In 62 A.D., a severe earthquake interrupted the expansion of Pompeii (Figure 2; *Seneca Naturales quaestiones: 6 1 1–3; 6 1 106 25 3; 6 30 4–5; 6 31 1–3;* and *Tacitus Annales 15 22 2*). So many buildings were seriously damaged that part of the population was obliged to abandon the city and surrounding area. After several other weak earthquakes (Cioni et al., 2000) and while still under repair from the 62 A.D. event (De Simone, 1995; Jacobelli, 1995), Pompeii was destroyed and buried by pyroclastic deposits from the devastating Vesuvius eruption of 79 A.D. (Sigurdsson et al., 1985; Giacomelli et al., 2003; Gurioli et al., 2005, 2007, 2010). The Roman emperor Titus, informed of the calamity, appointed a senatorial committee to provide aid to survivors and assess the magnitude of the damage in view of a possible reconstruction of the city. However, Pompeii had been buried by such a large volume of volcanic material that no plans or efforts were made to rebuild the city as it had been before the disaster.

After a long period of abandonment, Pompeii was rediscovered in the 16th century by the architect D. Fontana, with excavations initially made in a small area. The first systematic exploration did not begin until 1748 under the reign of Charles III, Bourbon king of Naples, and this continued to the 19th century, along with exposure and restoration of the ancient city. The archaeological site of Pompeii covers an area of approximately 66 hectares, of which about 45 have been excavated.

METHODS

The research leading to the present study has been conducted since 1995 using about 25 continuous drill cores recovered across broad area around and throughout the ancient city. The detailed stratigraphy of sediment sequences in these recent drill cores serves as a base reference with which to reinterpret about 400 logs of older drill cores that serve to reconstruct the paleolandscape of this region. The logs of older cores, recovered for different purposes since the end of the 1800s, are archived at the Pompeii Center of the "Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei." Drilling of the 25 newer cores was performed without use of circulation fluid to minimize effects of sediment reworking and better preserve sedimentary structures, textures and fabric to better interpret paleodepositional and environmental conditions.

This investigation emphasizes the results of analyses of three boreholes (S1, S2 and S3) recovered in the northern sector of the city (Figure 3). An archaeological excavation in the archaic city and one section located laterally to Guard Tower GX along the northern city walls at Vesuvius Gate were detailed (Figure 3). Moreover, a dig carried outside of Capua Gate made by the Japan Institute of Paleological Studies of Kyoto (Sakai, 2000–2001) was examined and photographed. After reburying the excavated area at Capua Gate, an electrical resistivity tomography (ERT) profile on the unexcavated dig-front was recorded (Figure 3, X-X') to obtain additional information on the subsurface stratigraphic framework. The equipment included an MAE A300E Georesistimeter with 64 electrodes along a 115-m-long profile. The Wenner–Schlumberger and dipole–dipole array methods were employed as a measure of resistance distribution; Res3DInv software was used for data interpretation. Additional information on the geoelectric equipment and settings used are available in an internal report (GTGeoTesting s.r.l., 2007).

Two samples were dated by AMS radiocarbon analysis using recovered animal bones, one from the dig in the archaic city, the other at the GX section. The base of the paleo-environmental map is an official geo-referenced topographic sheet produced at a scale of 1:5000. All boreholes used to reconstruct the compiled map were carefully positioned on this referenced topographic document. Data used for geological interpretations in the present study were obtained from studies of excavations, available sections, and sediment cores that were integrated with available archaeological information.

Macroscopic attributes of core sediment are described here. For definition of larger grain-size, granules and pebble-size clasts were measured directly using a calliper, while the size of sand grains was determined optically by using published visual comparison charts. These textural charts also served to assess clast rounding, sphericity, and sediment sorting. Sediment color was determined by means of the Munsell Color System (Munsell, 1975), and thickness of sediment units was defined according to Campbell (1967). Sediment grain size of selected samples was also measured by using the standard methodologies detailed by Folk (1968). Particles coarser than 63 μm were analyzed by sieving. The 63 μm fraction was analyzed by sedimentation-grain settling methodology. The statistical parameters of Folk and Ward (1957) were calculated and, to obtain further information on depositional environments, the textural-based method of Passega (1964) was used. A graphic stratigraphic log was plotted to summarize the sediment attributes of each drill core examined. The recent sediment cores and logs that constitute the geostratigraphic archive for the study area are archived at the Soprintendenza Laboratory of Applied Researches at Pompeii.

PRE 79 A.D. STRATIGRAPHIC SEQUENCES

Major Depositional Units

The observed sediment sequences between the basal volcanic lava underlying Pompeii and the 79 A.D. pyroclastic deposits in archaeological excavations and boreholes comprise mostly volcaniclastic deposits. The latter are dark grayish brown and olive brown in color and display variable lateral distributions, with thicknesses that range from a few centimeters to several meters. The bases of these layers are either sharply defined or irregular.

Strata to 1-m-thick tend to be massive and structureless (Figure 4A and B), while some thinner basal beds show cross- or planar lamination. A volcaniclastic matrix is prevalent, with clasts that commonly comprise rounded volcanic clasts (vol, in Figure 4A and C) and/or calcareous pebbles (cal, in Figure 4D), rounded to angular fragments of brick and ceramics (pot, in Figure 4A and E), plaster (pla, in Figure 4A), animal bone (Figure 4E) and plant matter. In most deposits, clasts are randomly distributed (Figure 4E), although locally, some larger clasts (to >10 cm) may be imbricated (Figure 4A).

Three such flow deposits, termed Units 1 to 3, from the lava base of sequence upward in three core sections (S1–S3 in Figure 5A) are identified in Pompeii and the surrounding area. Root structures observed at boundaries between the units indicate that some time elapsed between deposition of different mass flow events.

Unit 1, widespread throughout the area, has a thickness ranging between 1 and 5 m and rests directly on the lava base upon which Pompeii was built (sections S1 and S2 in Figure 5A). Radiocarbon-dated animal bone fragments recovered in this unit excavated and temporarily exposed beneath a dwelling in the archaic city (Figure 5B) provided a calibrated age (cf. Stuiver et al., 1998) of 764 years B.C. (Lab. ETH Zurich–25911; sample: N. 2, Region VII (Init 1); AMS ^{14}C age: 2530 ± 50; δ ^{13}C: −15.1 ± 1.2).

Unit *2*, identified within and outside city walls, has an average thickness of ~2 m. In the archaic city, Unit 2 incises Unit 1 and covers an older building level (shown as 1 in the circle, in Figure 5B); Unit 2 is interbedded between two construction levels at this site (shown as circled 1 and 2, Figure 5B). The older dwelling (1), built upon Unit 1, appears to have been damaged by the Unit 2 debris flow. Subsequently, a younger structure was built at a

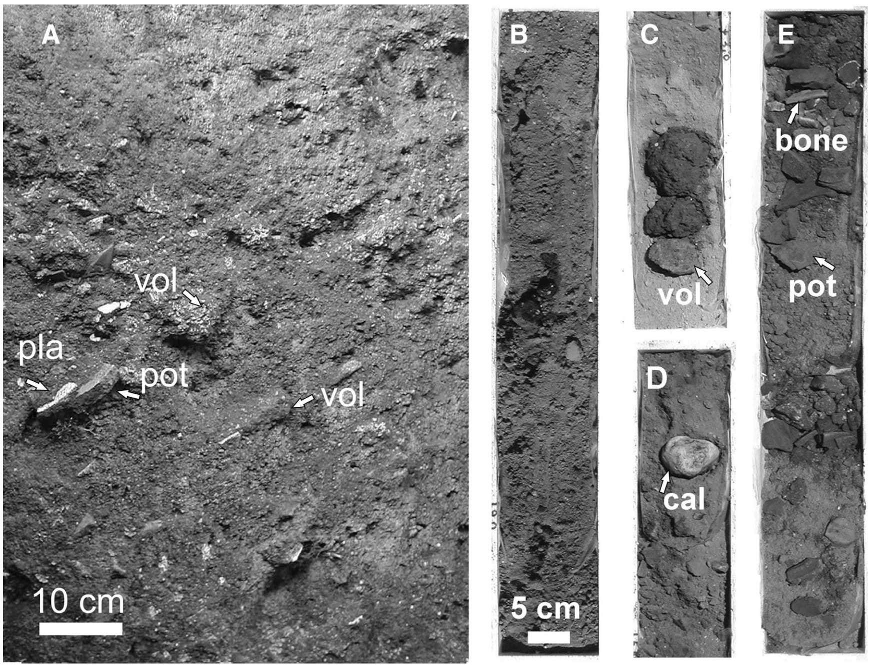

Figure 4 Examples of sediment gravity flow deposits in Pompeii (locations in Figure 3). (A) poorly sorted matrix-supported clasts in Unit 2, in the archaic city excavation. Sediment core sections: (B) volcaniclastic matrix enclosing granules and small pebbles, Unit 1 in core S2 (~8.0–8.7 m depth from core top); (C) three volcanic clasts in fine matrix, Unit 2 in S1 (~3.0–3.3 m depth); (D) rounded Mesozoic limestone pebble and potsherds in fine matrix, Unit 2 in S2 (~4.0–4.3 m); (E) angular anthropogenic debris, Unit 2 in S2 (~2.4–3.3 m). Abbreviations: cal calcareous clast; pla plaster; pot potsherd; vol volcanic clast. Horizontal bars provide size scale.

somewhat higher elevation directly upon Unit 2 (2 in the circle, Figure 5B), and this feature remained in use until its destruction by the 79 A.D. eruption.

Unit 3, with an average thickness of ~1 m, occurs along the northern city wall (boreholes S1 and S2 in Figure 5A); this layer is thicker in borehole S3 and its deposition buried an ancient road that extended from the city toward Villa of the Mysteries (S3 in Figure 5A; location in Figure 3). The core section shows that another road was subsequently built upon Unit 3 and remained in use until it, in turn, was buried by the 79 A.D. pyroclastic deposits (section S3 in Figure 5A). Guard towers were added to this city wall during the 2nd century B.C. (d'Ambrosio, 2002; Figure 2); the tower door openings at their base presently occur beneath the ground surface exposed until 79 A.D. (see road shown at position (a) in Figure 5C and D). The openings appear to have been buried by Unit 3, and became usable again after removal of Unit 3 material sometime before 79 A.D. (Figure 5D). Radiocarbon-dated animal bone in Unit 3, collected along the side of the guard tower GX door (Figures 3, 5D), yielded a calibrated age (cf. Stuiver et al., 1998) of 170 years B.C. (Lab. ETH Zurich–25912; sample: N.1, Pomerio (Unit 3); AMS ^{14}C age: 2130 ± 50; $\delta\ ^{13}$C: −16.4 ± 1.2).

The presence of the pre-79 A.D. volcaniclastic material in an excavation under a house in the archaic city (Figure 3), between below-surface construction levels (Unit 2 in Figure 5A and B), provides a means to better interpret the early evolution of Pompeii. Unit 2, exceeding 1 m in thickness, comprises mainly poorly sorted volcanic matrix of fine sand to clay size in which pebbles, animal remains, and anthropogenic debris of variable size are enclosed (matrix supported; Figures 4A–E and Figure 5B). A chaotic fabric generally prevails, although in some instances the long axes of some are oriented in a direction that parallels the transport path. The base of some layers appears erosive (between Units 1 and 2 in Figure 5A), although this attribute depends on the consistency of underlying layers (Figure 5B). It appears that some anthropogenic material in the above-described deposits originated in disposal sites and dumps proximal to ancient Pompeii (Maiuri, 1929; De Caro, 1985) prior to their being collected and displaced by the flows.

The assemblage of sedimentological attributes of these deposits indicates that mass gravity mechanisms, especially debris flows, were the dominant processes responsible for their transport. Volcaniclastic sediment with

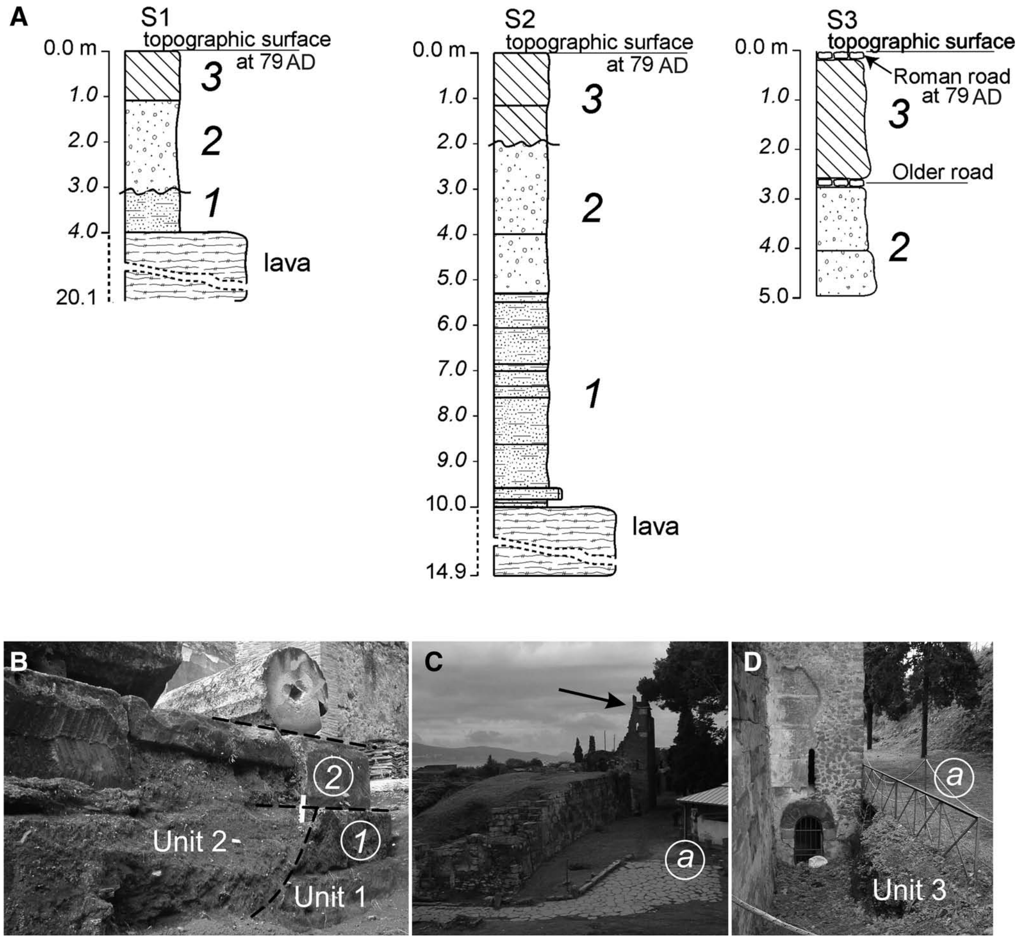

Figure 5 (A) Logs of boring S1–S3 (core sites shown in Figure 3) depicting three mass flow deposits (Units 1–3 depth in meters). Base of core sections S1 and S2 reached the layer of Pleistocene lava on which Pompeii was built. (B) Excavation beneath a dwelling in archaic Pompeii, showing: older dwelling foundation (1 in the circle) built on Unit 1; Unit 2 incises underlying Unit 1; a younger dwelling foundation (2 in the circle) is built on Unit 2 mass flow deposit (this structure was later destroyed in 79 AD). (C) Guard tower (arrow, location in Figure 1) added to city wall during the 2nd century B.C., and excavated Roman road (a in circle) used until the 79 A.D. event. (D) Door at base of guard tower was formerly covered by Unit 3; mass flow sediment was removed from the door after 170 B.C. and prior to the 79 A.D. eruption; note a road (a in circle) that functioned prior to 79 A.D.

matrix-supported clasts likely originated as slope collapse and avalanche displacement from the flanks of calcareous terrains in mountains to the NE (Pizzo D'Alvano area; Figure 1). These deposits were released from hyperconcentrated slumps and debris flows that had incorporated sediment and water during the course of downslope transport. During landslides, slumped masses of unconsolidated material can be transformed to high-concentration debris flows as has been recorded in volcanic areas elsewhere (Scott et al., 2001). Confined within downslope-trending depressions such as channels, flows can travel considerable distances to lowlands by expanding in volume during transport through a bulking mechanism that involves incorporation of additional sediment and water (Scott et al., 2005).

Capua Gate Sector and ERT

An excavation outside of Capua Gate (Figure 3) was made to examine the subsurface beneath the 79 A.D. eruption deposits to explore for an important road that had extended from Pompeii toward the north. During the course of this work, a natural feature discovered unexpectedly under the 79 A.D. pyroclastic deposits has been interpreted by us as a segment of an alluvial system (Figure 6). A channel and adjacent levee deposits were identified. The channel was oriented toward west, with its base cutting the underlying lava deposit that forms the morphologic high on which the city was founded. On the northern side of the channel, relict plough furrows were noted on the topographic surface upon which the 79 A.D. volcaniclastic products were deposited

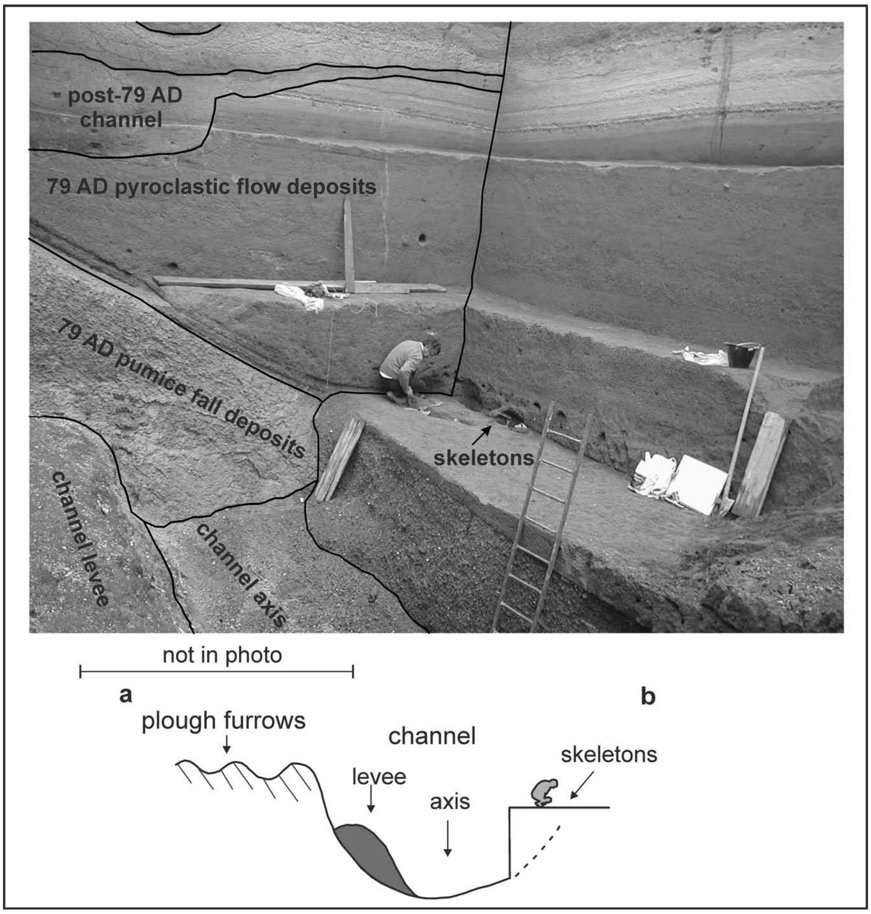

Figure 6 Photo of the excavation located outside of Capua Gate showing channel, its axis and associated levee deposits buried beneath 79 A.D. pyroclastic deposits (location in Figure 3). A schematic cross-section (a–b) is shown below (not to scale).

(Figure 6). The eruption material had completely covered these paleomorphologies. Another channel that partially eroded the top of the 79 A.D. eruption deposits indicates that channel flow became active once again following the eruption (Figure 6).

The archaeological excavation outside of Capua Gate was reburied after examination as required by the authorities. Thus, to obtain additional information on the subsurface paleogeography and sediment attributes of this sector, an ERT profile on the unexcavated dig-front was acquired. The profile orientation is NNW-SSE (X-X′ in Figure 3), with the SSE sector extending ca. 25 m inside an unexcavated section of Pompeii (Figure 7). The profile is 115 m long and reaches a depth of ~18 m below the modern topographic surface (Figure 7), that is, the depth at which the channel base in the excavation was measured. As the electrodes were placed at 5 m spacings, the profile could take into account major morphological features identified in Figure 6. Four resistivity anomalies are observed on the ERT profile. The first two (AN1 and AN2), with resistivity values ranging between 222 and 129 Ω/m (Figure 7) are interpreted, respectively, as the levee and axis of the channel shown in Figure 6. There is a close match with regards to both their position relative to electrodes and their depths beneath the present topographic surface. Resistivity values ranging between 382 and 659 Ω/m recorded at the base of profile are interpreted as the top of the lava layer on which the channel is formed and on which Pompeii was built.

Two other ERT anomalies are identified that have generally circular shapes, one of which (AN4) occurs in the archaeological area that has not yet been excavated. Anomaly AN3 positioned near the wall presents a series of concentric resistivity values that range from 129 Ω/m at the periphery to 14.6 Ω/m at the center of the feature; these values suggest the presence of sediments characterized by high humidity or, possibly, water content. The characteristics of anomaly AN3, the base of which

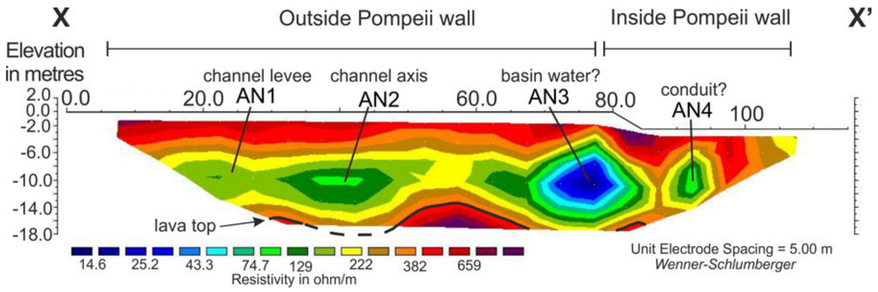

Figure 7 Electrical Resistivity Tomography (ERT) profile. Its NNW-SSE trend is shown as X-X in Figure 3. Interpretations of the four anomalies (AN1–AN4) above the lava top are discussed in text.

is at the same depth as that of the channel mapped in the excavation (Figure 6), is suggestive of an anthropogenic structure, probably one associated with water supply distribution to Pompeii. Anomaly AN4, with its narrower, circular profile and smaller size than AN3, has resistivity values at its center comparable to those of the channel (222 and 129 Ω/m). It is interpreted as a smaller channeling feature such as a duct or conduit that probably was also related to the city's water distribution system.

DISCUSSION AND IMPLICATIONS

Role of Fluvial Channel and Canal Systems

It is postulated that during their downslope transport, some flood waters and mass gravity flows would have been funneled into and channelized along stream beds, some of which extended to the immediate proximity of Pompeii such as to the northern walled margin of the city discussed above. Presently, there are no obvious river valleys or channels visible on land that would indicate how gravity flows would have reached into the walled city. Some useful information, nevertheless, is provided by focusing on what is known of Pompeii's water sources and supplies. Historians have long suggested that the city's water needs were derived from the *Sarnus* river (modern Sarno) the largest fluvial system in the region (Maiuri, 1958; Cinque & Russo, 1986). The modern Sarno channel, however, is presently positioned well to the southeast and south of Pompeii (Figures 1 and 8). On the other hand, the meandering course of the ancient Sarno river and its delta, identified by study of boreholes collected west and southwest of the Messigno area (Figure 8), was located at least 1 km south and southwest of the ancient city walls (Pescatore et al., 1999, 2001; Ciarallo, Pescatore, & Senatore, 2003; Vogel & Marker, 2010; Ciarallo, De Carolis, & Senatore, 2012).

Currently, there is a stream, named Conte Sarno Canal, extending from the base of Pizzo D'Alvano ridge (1133 m elevation) about 14 km to the NE toward Pompeii (Figure 1). On the northeastern side of the city, the stream shows a curvilinear path due to the high-relief barrier effect of the lava mound upon which Pompeii was built. The stream waters originally flowed from the Avella Mountains and which during the Samnite occupation were associated with springs located at the base of the Pizzo D'Alvano ridge (Murano, 1894). Borehole data collected N and W of the city indicate that a fluvial system reached the Pompeii outside of Capua Gate. The fluvial system is an artificial branch of the Conte Sarno Canal that was diverted toward the W and had most likely been excavated to supply the city with water (Figure 8). We postulate that it was constructed by Samnites when modifications were performed along the path of Conte Sarno Canal (Murano, 1894). Support for this hypothesis is provided by the presence of waterwheel installations to distribute water for the Stabian baths and a tannery that date to the 4th century B.C., and the Republican baths to the 2nd century B.C. (cf. Maiuri, 1931; Oleson, 1994; Figure 2). According to Oleson (1994) these waterwheels were driven by men, although our study suggests that perhaps they could also have been moved by flowing water as they are aligned in one direction at the edge of the archaic city, that is, along the southerly trending slope toward and into the city (Figure 3).

The ERT survey helps further clarify the function of the discovered artificial channel. The AN3 and AN4 anomalies on the profile (Figure 7) are linked with a probable water entry system into the city. The feature identified as the AN3 anomaly is interpreted as a water basin, and that of AN4 as a conduit that carried this water into Pompeii. Additional evidence for dispersed major water flows to Pompeii is also provided by pollen spectra examined in borings and excavations N and southeast of the city. Pollen indicate the presence of poplar and willow

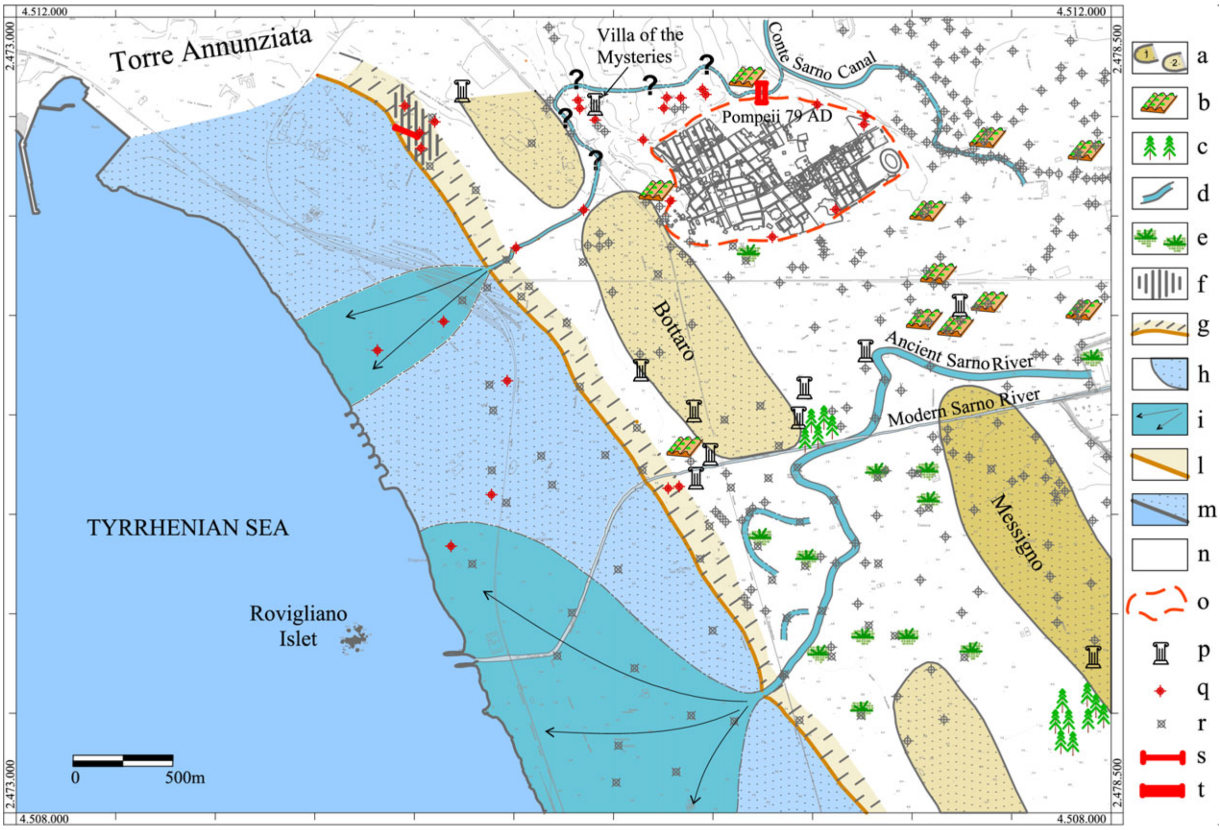

Figure 8 Paleogeographic map, based on integrated geological and archaeological analyses, depicting the Pompeii and adjacent Campania Plain–Gulf of Naples region during the period prior to the 79 A.D. Vesuvius eruption. (a) Coastal ridges: 1—Messigno (5600 yr B.P.), 2—Bottaro (3610 yr B.P.); (b) Plough furrows; (c) Poplars; (d) River channel; (e) Marsh; (f) Salt pan; (g) Emerged beach; (h) Submerged coastal margin; (i) Submerged delta; (l) 79 A.D. coastline; (m) Present day coastline; (n) No data; (o) Edge of Pompeii excavations; (p) 79 A.D. archaeological structures; (q) Boreholes between 1996 and 2007; (r) Boreholes before 1996; (s) GPR profile; (t) ERT profile. Note course of two separate fluvial systems: the branch of the Conte Sarno Canal that flowed to north and SW of Pompeii, and the Sarno River at some distance to the SE and south. Some mass gravity flow deposits of volcaniclastics reaching Pompeii prior to 79 A.D. were transported downslope via the channel of the fluvial system that reached to the north of the city. An artificial branch of this fluvial system that entered Pompeii for water distribution purposes and that was buried by 79 A.D. pyroclastic deposits was discovered by the present borehole and excavation survey. Progradational and aggradational sedimentary processes active mainly at the time of the Vesuvius eruptions and some volcano-tectonic uplift caused seaward migration by 1 km of the coastline (light blue area) since 79 A.D.

(Figure 8) as well as cultivated plants, associated with evidence of plough furrows (Figures 6 and 8), all of which indicate the need for an adequate supply of water (Ciarallo, 2001–2002). In summary, dense sediment slurries originating in highlands to the NE of the city flowed downslope, along depressions such as the Conte Sarno Canal and its excavated channel (Figures 1 and 8), and likely reached the city by way of one or more gated passages and/or a breach in the northern wall. It was along its western and southwestern paths that the channel likely collected the city's wastewater that was then discharged further downslope in a delta once positioned along the coastal margin SW of Pompeii (Figure 8).

Floods and Mass Gravity Flows into Pompeii

It appears that at times of unusually high rainfall and flood, the sediment-charged flows that could not be contained within channels and ducts likely overflowed and rushed into and across Pompeii. These flood waters and denser slurries were dispersed primarily in SSE and SE directions, on the prevailing slopes of the city, streaming along streets between buildings before reaching exit drains and gates placed at the town's lower elevations.

Rounded calcareous clasts of diverse size (cal, in Figure 4D) indicate that the three mass flows were derived from high-relief limestone terrains NE of the Sarno plain, that were partially covered (to ca. 5 m in thickness) with volcaniclastic deposits. Unit 1 was widely deposited prior to the founding of the early population center at Pompeii. Coarse debris flow Unit 2 appears to have been particularly destructive, blanketing the city with a mud-rich deposit of highly irregular thickness. While generally similar in lithology to Units 1 and 3, this deposit contains much higher amounts of anthropogenic debris (Figure 4A and E). Unit 2, although not radiocarbon dated, accumulated between the 5th and 3rd century B.C., quite possibly during the 4th century B.C., a period when according to historians the town remained in decline for some time and major public edifices were not built (Figure 2; Sakai, 2000–2001).

The wall surrounding the city is a source of useful information pertaining to deposition of Unit 2. A first wall, much lower than the one observed today, was constructed during the second half of the 6th century B.C. The wall was reinforced and elevated at the beginning of the 5th century B.C., and then was raised to an even higher level in the 4th century B.C. (Lorenzoni et al., 2001). We suggest that these alterations were made not only to protect the city against hostile attack (Sakai, 2000–2001), but also as a buffer against effects of natural hazards, such as debris flow Unit 2, that had caused damage and decline in city development prior to the 2nd century B.C. A considerable time after the Unit 2 event, building activity resumed, and the wall was again reinforced and a broad internal embankment was emplaced at the end of the 3rd century B.C. The city flourished during the 2nd century B.C. (Figures 2 and 5B).

Twelve massive guard towers were added to the wall in the 2nd century B.C. in preparation for battle between inhabitants of Pompeii and Roman aggressors (d'Ambrosio, 2002). Our study indicates that tower construction was completed before deposition of mass flow Unit 3 in 170 B.C. This material buried the base of wall towers, including their doors (Figure 5C and D). Moreover, borehole S3 (Figure 5A) reveals the presence of a road that had been built on Unit 2, and then was subsequently buried by Unit *3*. A new road built on top of Unit *3* was used from ca. 170 B.C. until the city's final destruction in 79 A.D. This sequence of events is confirmed by recent excavations beneath the 79 A.D. volcanic horizon elsewhere within the city walls in Pompeii's northern area. These exposures reveal at least 80 cm of sediment thickness (Bourdial, 2004), some of which comprise Unit 3 of mass gravity flow origin.

Archaeologists of the Japan Institute of Paleological Studies in Kyoto also excavated inside the city close to Capua Gate that exposed an archaeological structure (Figure 3). Sakai (2000–2001) suggested that the structure was probably part of a Guard Tower, but noted that its building style, having only one entrance, was older than that of other Guard Towers. This opening was not used before the 79 A.D. eruption as indicated by the excavation record showing sediment of Unit 3 piled against the entrance, thus preventing its access. Moreover, a duct extending from outside the walls into the city was discovered under the first floor of the building, and this feature was filled with sediment. The AN4 anomaly on the ERT profile may represent a conduit to this duct found below the excavated structure inside the city close to Capua Gate (Sakai, 2000–2001). According to our core data, the sediments found inside of the duct and those piled against the door of the structure are comparable to, and thus interpreted as, those of Unit 3. At the time of the 79 A.D. eruption neither duct nor structure were in use. It appears that after the mass gravity flood event that deposited Unit 3, the water distribution system at Capua Gate had to be abandoned because its position posed a risk to the city. A new method of supplying water was thus installed at a different locality, the Vesuvius Gate (Figure 3). Capua and Vesuvius gates are both positioned at sites of Pompeii's highest elevation and, therefore, they occupy strategic points for distribution of the city's water supply. It was from here that water entering into the city, discharged by gravity flow, was able to activate three waterwheels (Maiuri 1931; Oleson, 1994) located at the edge of the archaic city (Figures 2 and 3).

A circular water basin at Vesuvius Gate was probably built ca. 80 B.C. and connected to the Avella aqueduct according to Ohlig (2001). The aqueduct extended from mountains northeast of Avella, a town distant about 25 km from Pompeii (Figure 1). This water basin was subaerially exposed and constructed without a regulating device to control water flow (Ohlig, 2001). The structure was eventually covered and, in 20 B.C., connected to the new Serino Aqueduct (Nappo, 1996; Potenza, 2001; Matsui et al., 2009) when it attained its final form as presently observed (*Castellum aquae*, Figure 3). The city's water distribution system connected with aqueducts became safer and more reliable as it provided a more constant supply. These engineered changes also helped reduce the danger of episodic mass flows from directly entering Pompeii.

CONCLUSIONS

Evidence of eruptive Somma–Vesuvius volcanic activity is not recorded in the study area during the 7th century period prior to 79 A.D. examined here. However, we find that slope instability and failure, slumps, and associated downslope transformed sediment gravity flows are events that periodically affected Pompeii long before its demise in 79 A.D. There is also independent evidence that such gravitative and associated mass flows of volcaniclastic material have continued to plague the city during the past 19 centuries since burial of the city, including a series of such events that affected the surrounding region between 79 and 472 A.D. (Lirer et al., 2001). Moreover, destructive mass flows of the type recorded in pre-79 A.D. Pompeii and its vicinity have also been documented in recent time over wide areas of the Vesuvian-Gulf of Naples region (Orsi et al., 2003; Perrotta et al., 2006; Favalli, Pareschi, & Zanchetta, 2006).

It is of note that most of these recent volcaniclastic depositional events have not been directly associated with phases of volcanic eruptions, although we do not exclude the possibility of seismotectonic tremors that periodically affect this region (Marturano et al., 2009) as triggers of some mass flows that reached Pompeii during its early history. Other factors are also critical for periodic release of large landslide-associated mass gravity sediment flows of volcaniclastic sediment deposited at Pompeii and that continue to prevail in this high-risk sector of Italy (Guzzetti, 2000; Pareschi et al., 2000). These include primarily periodical high rainfall events (especially in the fall and spring), widespread distribution of an unstable water-saturated volcaniclastic sediment cover on proximal moderate to steep highland slopes, and much intensified terrain modification by human activity that lead to further slope instability.

Altered climatic conditions involving increased rain storm activity that occurred during cool-humid phases in southern Italy from the 5th to the 3rd century B.C. (Boenzi et al., 2001) may have been a major factor in periodic destruction of Pompeii by mass flows. A modern example in this respect are the destructive avalanche flows on 5 May 1998 released in this region after about 30 hours of strong continuous rainfall (reaching 100–180 mm). In that instance, rain-triggered landslides of water-saturated tephra-rich colluvium, including boulders, were suddenly released from the surrounding calcareous highlands and displaced downslope at a rate of ca. 50 km/h (Del Prete, Guadagno, & Hawkins, 1998; Pareschi et al., 2000; Revellino, Guadagno, & Hungr, 2008). During their downslope transport, slumps evolved to hyperconcentrated flows that incorporated remobilized volcaniclastic sediment along with carbonate debris that were discharged on the Sarno plain. Petrologically, these deposits closely resemble those that we describe in this study of pre-79 A.D. Pompeii sequences. The recent 1998 high-density mass flows cited here as possible modern analogues of those we interpret at Pompeii killed more than 150 persons, destroyed numerous dwellings and other structures, and thickly blanketed the streets of the town of Sarno about 14 km northeast of ancient Pompeii (Figure 1).

In summary, this geoarchaeological study indicates that Pompeii's phases of episodic growth and decline, including periods of adverse social and cultural consequences, may have been partial responses to the recurring, large-scale natural hydrographic phenomena of the type described here, especially when occurring during stressful periods of wars and other societal pressures. Merging results of lithostratigraphic and petrologic analyses with paleoclimatological investigations and findings from archaeological exploration of the pre-79 A.D. period at Pompeii will assist in further deciphering the still poorly documented early history and evolution of this famous site.

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REFERENCES

Andronico, D., Calderoni, G., Cioni R., Sbrana, A., Sulpizio, R., & Santacroce, R. (1995). Geological map of Somma Vesuvius volcano. Periodico di Mineralogia, 64, 77–78.

Andronico, D., & Cioni, R. (2002). Contrasting styles of Mount Vesuvius activity in the period between the Avellino and Pompeii Plinian eruptions, and some implications for assessment of future hazards. Bulletin of Volcanology, 64, 372–391.

Arnò, V., Principe, C., Rosi, M., Santacroce, R., Sbrana, A., & Sheridan, M.F. (1987). Somma-Vesuvius eruptive history. CNR, Quaderni della Ricerca Scientifica, 13, 53–103.

Boenzi, F., Caldara, M., & Pennetta, L. (2001). L'influenza delle variazioni climatiche e dei processi storico-sociali sull'evoluzione delle forme del rilievo del Mezzogiorno. In F. Macchia, (Ed.), Territorio e società nelle aree meridionali (pp. 7–34). Bari: Mario Adda Editore.

Brocchini, D., Principe, C., Castratori, D., Laurenzi, M.A., & Gorla, L. (2001). Quaternary evolution of the southern sector of the Campanian Plain and early Somma-Vesuvius activity: Insights from the Trecase 1 well. Mineralogy and Petrology, 73, 67–91.

Bourdial, I. (2004). Il existait une Pompei avant Pompei Science & Vie, no.1037, p. 56–61.

Campbell, C.V. (1967). Lamina, laminaset, bed and bedset. Sedimentology, 8, 7–26.

Chiaramonte Trerè, C. (1986). Nuovi contributi sulle fortificazioni pompeiane. In Quaderni di Acme, 6 (pp. 1–144). Università di Milano: Cisalpino Editore.

Ciarallo, A. (2001–2002). Colture ed habitat del territorio vesuviano nel 79 d.C. Rivista di Studi Pompeiani, Naples, L'Erma di Bretschneider, 12–13, 167–176.

Ciarallo, A., Pescatore, T., & Senatore, M.R. (2003). Su di un antico corso d'acqua a nord di Pompei. Dati preliminari. Rivista di Studi Pompeiani, L'Erma di Bretsheneider, 14, 274–283.

Ciarallo, A., De Carolis, E., & Senatore, M.R. (2012). Water supply and water circulation in ancient Pompeii: Resource management and catastrophic events in the past as in the present. Rendiconti Online, Società Geologica Italiana, 21, 738–740.

Cinque, A., & Russo, F. (1986). La linea di costa del 79 d.C. fra Oplonti e Stabiae nel quadro dell'evoluzione olocenica della Piana del Sarno (Campania). Bollettino della Società Geologica Italiana, 105, 111–121.

Cinque, A., & Irollo, G. (2004). Il vulcano di Pompei: Nuovi dati geomorfologici e stratigrafici. Il Quaternario, Italian Journal of Quaternary Sciences, 17, 101–116.

Cioni, R., Marianelli, P., & Sbrana, A. (1992). Dynamics of the AD 79 eruption: Stratigraphic sedimentological and geochemical data on the successions from the Somma–Vesuvius southern and eastern sectors. Acta Vulcanologica, 2, 109–124.

Cioni, R., Civetta, L., Marianelli, P., Métrich, N., Santacroce, R., & Sbrana, A. (1995). Compositional layering and syneruptive mixing of a periodically refilled shallow magma chamber: The AD 79 Plinian eruption of Vesuvius. Journal of Petrology, 36, 739–776.

Cioni, R., Guiroli, L., Sbrana A., & Vougloukalakis, G. (2000). Precursors to the Plinian eruptions of Thera (Late Bronze Age) and Vesuvius (AD 79): Data from archaeological areas. Physics and Chemistry of the Earth (A), 25, 719–724.

Cioni, R., Bertagnini, A., Santacroce, R., & Andronico, D. (2008). Explosive activity and eruption scenarios at Somma–Vesuvius (Italy): Towards a new classification scheme. Journal of Volcanology and Geothermal Research, 178, 331–346.

d'Ambrosio, A. (2002). Mura di cinta. In A. d'Ambrosio, (Ed.), Pompei, gli scavi dal 1748 al 1860 (pp. 92–93). Milano: Electa.

De Caro, S. (1985). Nuove indagini sulle fortificazioni di Pompei. Annali Istituto Orientale, Napoli, 7, 75–114.

De Caro, S. (1992). Lo sviluppo urbanistico di Pompei. Atti della Società della Magna Grecia, 1, 67–90.

De Simone, A. (1995). I terremoti precedenti l'eruzione. Nuove attestazioni da recenti scavi. In Archäologie und Seismologie, La regione vesuviana dal 62 al 79 d.C. Problemi archeologici e sismologici, Colloquium, Boscoreale 26–27 November 1993 (pp. 37–43). Munich: Biering & Brinkmann Verlag.

Del Prete, M., Guadagno, F.M., & Hawkins, A.B. (1998). Preliminary report on the landslides of 5 May 1998, Campania, southern Italy. Bulletin of Engineering Geology and the Environment, 57, 113–129.

Favalli M., Pareschi M.T., & Zanchetta G. (2006). Simulation of syn-eruptive floods in circumvesuvian plain (southern Italy). Bulletin of Volcanology, 68, 349–362.

Folk, R.L. (1968). Petrology of Sedimentary Rocks. In University of Texas Publication (pp. 1–170). Austin, Texas: Hemphill Publishing Co.

Folk, R.L., & Ward, W.C. (1957). Brazos river bar: A study in the significance of grain size parameters. Journal Sedimentary Petrology, 27, 3–26.

Giacomelli, L., Perrotta, A., Scandone, R., & Scarpati, C. (2003). The eruption of Vesuvius of 79 AD and its impact on human environment in Pompeii. Episodes, 26, 235–238.

Gurioli, L., Pareschi, MT., Zanella, E., Lanza, R., Deluca, E., & Bisson, M. (2005). Interaction of pyroclastic currents with human settlements: Evidences from ancient Pompeii. Geology, 33, 441–444.

Gurioli, L., Zanella, E., Pareschi, MT., & Lanza, R., (2007). Influences of urban fabric on pyroclastic density currents at Pompeii (Italy) I: Flow direction and deposition. Journal of Geophysical Research, B: Solid Earth, 112, B05213.

Gurioli, L., Sulpizio, R., Cioni, R., Sbrana, A., Santacroce, R., Luperini, W., & Andronico, D. (2010). Pyroclastic flow hazard assessment at Somma–Vesuvius based on the geological record. Bulletin of Volcanology, 72, 1021–1038.

Guzzetti, F. (2000). Landslide fatalities and the evaluation of landslide risk in Italy. Engineering Geology, 58, 89–107.

GTGeotesting s.r.l. (2007). Esecuzione di indagini geofisiche area archeologica di Pompei (NA). Relazione tecnica, profili tomografici geoelettrici, carotaggi esplorativi a distruzione, DVD videoispezioni (pp. 1–21). Pozzuoli (NA).

Guzzo, P.G., & d'Ambrosio, A. (1998). Pompei. L'Erma di Bretschneider (pp. 1–160). Naples: Electa.

Jacobelli, L. (1995). I terremoti fra il 62 e il 79 d.C. nell'area Vesuviana: Le ragioni di un convegno. In Archologie und Seismologie, La regione vesuviana dal 62 al 79 d.C. Problemi archeologici e sismologici, Colloquium, Boscoreale 26–27 November 1993 (pp. 17–21). Munich: Biering & Brinkmann Verlag.

Lirer, L., Vinci, A., Alberico, I., Gifuni, T., Bellucci, F., Petrosino, P., & Interri, R. (2001). Occurrence of inter-eruption debris flows and hyperconcentrated flood-flow deposits on Vesuvio volcano, Italy. Sedimentary Geology, 139, 151–167.

Lorenzoni, S., Zanettin, E., & Casella, A.C. (2001). La più antica cinta muraria di Pompei. Studio petro-archeometrico. Rassegna di Archeologia, 18B, 35–49.

Maiuri, A. (1929). Studi e ricerche sulla fortificazione di Pompei. Rendiconti Accademia Nazionale Lincei, Monumenti antichi, 33, 8–286.

Maiuri, A. (1931). Pozzi e condutture d'acqua nell'antica città. Scoperta di un antico pozzo presso "Porta Vesuvio". Notizie degli Scavi di Antichità, Accademia Nazionale dei Lincei, Roma, 546–576.

Maiuri, A. (1958). Pompeii. Scientific American, 198, 68–78.

Marturano, A., Aiello, G., Barra, D., Fedele, L., Grifa, C., Morra, V., Berg, R., & Varone, A. (2009). Evidence for Holocenic uplift at Somma-Vesuvius. Journal of Volcanology and Geothermal Research, 184, 451–461.

Matsui, S., Sorrentino, L., Sakai, S., Shimizu, Y., & Iorio, V. (2009). La provenienza dell'acqua potabile nell'antica Pompei: un'ipotesi basata sull'analisi chimica dei residui calcarei degli impianti idrici. Fast Online, Documents & Research, 162.pdf.

Munsell, A. (1975). Soil Colour Charts. Macbeth Division of Kallmorgen Corporation, Baltimore, Maryland 21218.

Murano, D. (1894). Pompei. Donde venivano le acque potabili ai castelli acquari. Napoli, Tipografia Cav. A. Morano & E. Veraldi, pp. 1–147.

Nappo, S.C. (1996). L'impianto idrico di Pompei. Nuovi dati. In N. de Haan & G.C.M. Jansen (Eds.), Cura Aquarum in Campania, Proceedings of the Ninth International Congress on the History of Water Management and Hydraulic Engineering in the Mediterranean Region Pompeii, 1–8 October 1994 (pp. 37–45). Leuven, Belgium: Peeters Publishers.

Ohlig, C. (2001). De aquis Pompeiorum. Das Castellum Aquae in Pompeji: Herkunft zuleitung, Verteilung des Wassers. In J.A.K.E. De Waele & E.M. Moormann (Eds.), Circumvesuviana 4 (pp. 1–483). Nijmegen: Books on Demand, Norderstedt.

Oleson, J.P. (1994). Water-lifting devices at Herculaneum and Pompeii in the context of Roman technology. In N. de Haan & G.C.M. Jansen (Eds.), Cura Aquarum in Campania, Proceedings of the Ninth International Congress on the History of Water Management and Hydraulic Engineering in the Mediterranean Region Pompeii, 1–8 October 1994 (pp. 67–75). Leuven, Belgium: Peeters Publishers.

Orsi, G., de Vita, S., Di Vito, M. A., Isaia, R., Vane, R., & Heiken, G. (2003). Facing volcanic and related hazards in the Neapolitan area. In G. Heiken, R. Fakundiny, & J. Sutter (Eds.), A. Reader, Earth Science in the City (pp. 121–170). Washington D.C.: American Geophysical Union, doi:10.1029/SP056p0121.

Pareschi, M.T., Favalli, M., Giannini, F., Sulpizio, R., Zanchetta, G., & Santacroce, R. (2000). May 5, 1998, debris flows in circum-Vesuvian areas (southern Italy): Insights for hazard assessment. Geology, 28, 639–642.

Passega, R. (1964). Grain size representation by CM patterns as a geological tool. Journal Sedimentary Petrology, 34, 830–847.

Perrotta, A., Scarpati, C., Luongo, G., & Aoyagi, M. (2006). Burial of Emperor Augustus' villa at Somma Vesuviana (Italy) by post-79 AD Vesuvius eruptions and reworked (lahars and stream flow) deposits. Journal of Volcanology and Geothermal Research, 158, 445–466.

Pescatore, T., Senatore, M.R., Capretto, G., & Lerro, G. (2001). Holocene coastal environments near Pompeii before the AD 79 eruption of Mount Vesuvius, Italy. Quaternary Research, 55, 77–85.

Pescatore, T., Senatore, M.R., Capretto, G., Lerro, G., & Patricelli, G. (1999). Ricostruzione paleogeografia delle aree circostanti l'antica città di Pompei (Campania, Italia) al tempo dell'eruzione del Vesuvio del 79 d.C. Bollettino della Società Geologica Italiana, 118, 243–254.

Potenza, U. (2001). Gli Acquedotti Romani di Serino. Azienda Municipalizzata Acquedotto di Napoli (AMAN), pp. 1–22.

Revellino, P., Guadagno, F.M., & Hungr, O. (2008). Morphological methods and dynamic modelling in landslide hazard assessment of the Campania Apennine carbonate slope. Landslide, 5, 59–70.

Rolandi, G., Petrosino, P., & McGeehin, J. (1998). The interplinian activity at Somma–Vesuvius in the last 3500 years. Journal of Volcanology and Geothermal Research, 82, 19–52.

Sakai, S. (2000–2001). La storia sotto il suolo del 79 d.C. Considerazioni sui dati provenienti dalle attività archeologiche svolte sulle fortificazioni di Pompei. Opuscula Pompeiana, 10, 87–100.

Scott, K.M., Macias, J.L., Naranjo, J.A., Rodriguez, S., & McGeehin, J.P. (2001). Catastrophic debris flows transformed from landslides in volcanic terrains: Mobility, hazard assessment, and mitigation strategies. U.S. Geological Survey Professional Paper 1630, Reston, Virginia, 1–59.

Scott, K.M., Vallance, J.W., Kerle, N., Macias, J.L., Strauch, J.L., & Devoli, G. (2005). Catastrophic precipitation-triggered lahar at Casita volcano, Nicaragua: Occurrence, bulking and transformation. Earth Surface Processes and Landforms, 30, 59–79.

Sigurdsson, H., Carey, S., Cornell, W., & Pescatore, T. (1985). The eruption of Vesuvius in AD 79. National Geographic Research and Exploration, 1, 332–387.

Stothers, R.B., & Rampino, M.R. (1983). Volcanic eruptions in the Mediterranean before A.D. 630 from written and archaeological sources. Journal Geophysical Research, 88, 6357–6371.

Stuiver, M., Reimer, P.J., Bard, E., Beek, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., Plicht, J., & Spurk, M. (1998). INTCAL98 radiocarbon age calibration, 24,000-0 cal. B.P. Radiocarbon, 40, 1041–1083.

Vogel, S., & Marker, M. (2010). Reconstructing the Roman topography and environmental features of the Sarno River Plain (Italy) before the AD 79 eruption of Somma–Vesuvius. Geomorphology, 115, 67–77.

Ward-Perkins, J.B. (1984). Note di topografia e urbanistica. In F. Zevi (Ed.), Raccolta di studi per il 19° centenario dell'eruzione vesuviana Pompei 79 (pp. 25–39). Napoli: Soprintendenza Archeologica Pompei.

