The Eruption of Vesuvius in A.D. 79: Reconstruction from Historical and Volcanological Evidence*

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(Pl. 4)

Abstract

Reinterpretation of the volcanological and historical evidence shows that the eruption of Vesuvius in A.D. 79 consisted of two main phases. The initial 18 to 20-hour Plinian phase caused extensive pumice-fall south of the volcano, resulting in the slow accumulation of a pumice layer up to 2.8 m. thick over Pompeii and other regions to the south. Much of the population fled the area during this non-lethal phase. On the second day of activity the Peléan phase occurred, when a series of nuées ardentes or hot ash-avalanches swept down the south and west flanks of the volcano, affecting the region as far as Misenum, 30 km. to the west. The first of two nuées ardentes which inundated Pompeii overwhelmed and asphyxiated those who remained above ground in the city and their bodies were immediately interred in the fine-grained deposit. The effects of the Peléan activity were even more severe west and northwest of Pompeii, resulting in burial of the cities of Oplontis and Herculaneum by a series of nuée ardente deposits.

The interment of Pompeii, Oplontis and Herculaneum during the eruption of Vesuvius in A.D. 79 has beautifully preserved the art, industry and architecture of three Roman cities as well as a unique record of the everyday way of life some 1900 years ago. While Herculaneum, with an estimated population of four to five thousand, and Pompeii, with a population of approximately 20,000,[1] have been systematically mined for their art treasures, there has been little attempt to reconstruct the sequence of events during the natural disaster. Fortunately, much of the evidence still remains intact and can be read from the stratigraphy of the volcanic deposits of A.D. 79 and in the contemporary letters of Pliny the Younger.

This article presents new information on the stratigraphy and offers a new interpretation of the timing and nature of the volcanic disaster which overtook the cities of Vesuvius on 24 and 25 August, A.D. 79. Advances in the science of volcanology in the 1970s[2] allow us to extract much more information from volcanic deposits, particularly regarding mode of transport of the material from the volcano to the site of deposition. Here we argue that the eruption consisted of two main phases: a Plinian air-fall phase and a Peléan nuée ardente, or glowing avalanche phase, and that the main destruction of life and property took place during the second phase. Both Rittmann[3] and Maiuri[4] have maintained that the burial of Pompeii and the general loss of life occurred entirely during a rapid accumulation of air-fall pumice and ash. This view has been echoed widely in the general literature as well as in volcanology texts.[5] The idea that Pompeii was affected by nuées ardentes is not, however, new, but was tentatively suggested by Helprin and Merrill[6]

* The reconstruction expressed in this article was presented in a lecture at the Pompeii Colloquium, University of Rhode Island, on 29 March 1979. The results presented here on stratigraphic studies are part of a broader investigation of the deposits of Vesuvius being made in cooperation with Prof. T. Pescatore of Naples University. His collaboration in the field is gratefully acknowledged. We are also grateful to Lawrence Richardson, Jr., to R. Ross Holloway and to Professor F. Zevi (Soprintendente alle Antichità della Campania). Fieldwork was funded by grants from the National Science Foundation and NATO.

[1] A. Maiuri, "Pompeii," *Scientific American* 198.4 (1958) 70; A. Maiuri, *Herculaneum* (Rome 1977) 13.

[2] S.R.J. Sparks and G.P.L. Walker, "The Ground Surge Deposit: a Third Type of Pyroclastic Rock," *Nature* 241 (1973) 62–64; S.R.J. Sparks, S. Self and G.P.L. Walker, *Geology* 1 (1973) 115–18; S.R.J. Sparks, "Dusts of Destruction," *New Scientist* (1973) 134–36.

[3] A. Rittmann, *Vulkane und ihre Tätigkeit* (Stuttgart 1960) 48.

[4] Maiuri 1958 (supra n. 1) 69.

[5] G.A. Macdonald, *Volcanoes* (Englewood Cliffs 1972) 234; F.M. Bullard, *Volcanoes of the Earth* (Austin 1976) 200; P. Francis, *Volcanoes* (New York 1976) 63.

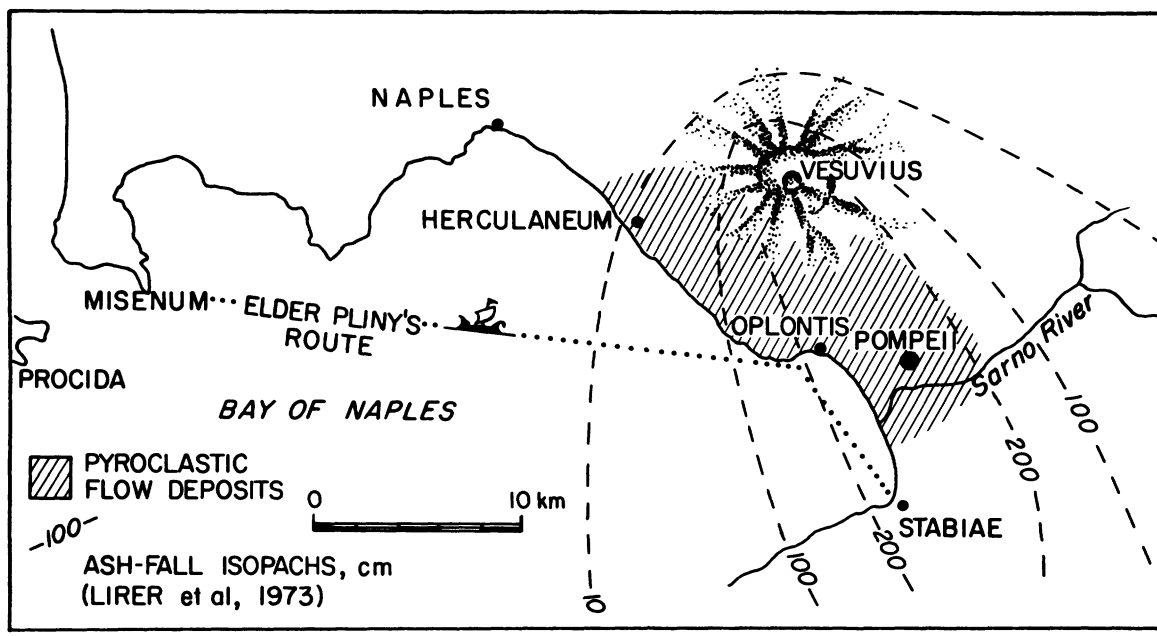
[6] A. Helprin, *Mont Pelée and the Tragedy of Martinique* (New York 1903) 120; E.T. Merrill, "Notes on the Eruption of Vesuvius in 79 A.D.," *AJA* 22 (1918) 304–309; E.T. Merrill, "Further Note on the Eruption of Vesuvius in 79 A.D.," *AJA* 24 (1920) 262–68.

after the disastrous nuée ardente eruption of Mt. Pelée in 1902, and later revived by Sparks and Walker,[7] and Lirer et al.[8]

VOLCANOLOGICAL EVIDENCE

Products of the eruption of Vesuvius in A.D. 79 form distinct deposits on the southwestern and southern slopes of the volcano and on the Sarno plain as far south as Castellammare (ill. 1). We have studied these deposits in the excavations at Pompeii, Herculaneum, Oplontis (now Torre Annunziata) and in the excavations of Villa Ariadne and Villa di Varano near Castellammare (formerly Stabiae). The deposits are entirely pyroclastic rocks, i.e. fragmentary volcanic rocks consisting predominantly of pumice and volcanic ash. Three main types of pyroclastic deposits are recognized, reflecting three different modes of transportation from the crater of Vesuvius to the site of deposition.

Air-fall pumice is the most widely spread type of deposit, resulting from fall-out of pumice and ash from a high eruption cloud downwind from the crater. Air-fall deposits accumulate gradually during the explosive phase of a volcanic eruption and characteristically mantle the topography with a well-bedded, uniform pumice layer which shows an exponential decrease in thickness with increasing distance from the volcano. Their distribution is entirely controlled by the effect of the prevailing wind direction on the vertical eruption column, which may reach a height of tens of kilometers above the volcano. The air-fall phase of explosive eruptions and the resulting pumice deposits are referred to in the volcanological literature as the Plinian phase and the Plinian layers, respectively, in honor of Pliny the Younger, who provided the first written eyewitness account of this type of activity in his description of the A.D. 79 eruption.



Ill. 1. Map of the Vesuvius region and Bay of Naples, showing the extent of the area affected by pyroclastic flows during the eruption of A.D. 79. Broken lines are isopachs of the pumice fall during the Plinian phase

Pyroclastic flows or ignimbrites form a second type of deposit. They occur as hot, chaotic avalanches of pumice, ash and gases flow down the flanks of a volcano. Pyroclastic flows can move at high speeds along the ground and pass over substantial obstacles. Their distribution is, however,

[7] Sparks and Walker (supra n. 2) 62–64.

[8] L. Lirer, T. Pescatore, B. Booth and G.P.L. Walker, "Two Plinian Pumice-fall Deposits from Somma-Vesuvius, Italy," *Bulletin of the Geological Society of America* 84 (1973) 759.

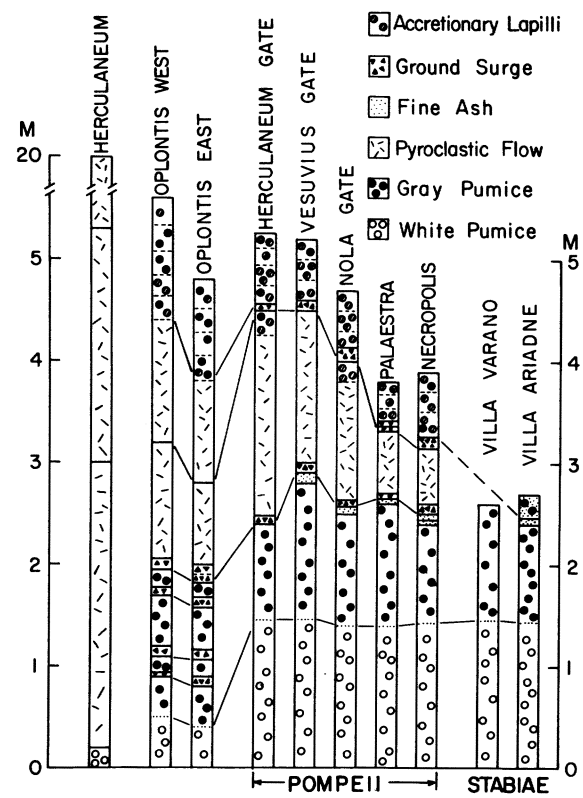
strongly controlled by topography as they generally are guided by the principal valleys from a volcano and form localized, unbedded deposits which may be tens of meters in thickness, filling valleys and depressions. Pyroclastic flows come to rest in depressions or on the lowlands around the volcano and are absent from the steep volcanic flanks.

The third type is the ground surge deposit. It is generally thin, well-bedded, often rich in dense, angular rock fragments and more widely distributed than pyroclastic flow deposits, although not as widespread as air-fall pumice layers. The ground surge is a turbulent cloud of volcanic ash and hot gases, which hugs the ground and travels at speeds often exceeding 100 km. per hour. It probably precedes pyroclastic flows, in many cases by only a few seconds. A well known example of a ground surge occurred in the classic eruption of Mt. Pelée on Martinique in 1902. During this eruption, the surge, composed of pumice, ash, dense rock fragments and hot gases, descended the western flank of the volcano towards the city of St. Pierre. The ground surge swept widely over the terrain, traveling at speeds of over 100 km. per hour down the slopes of the volcano and over the city of St. Pierre, and almost instantly killed all but two of its 28,000 inhabitants.[9] The surge left a deposit of only 20 to 30 cm. in thickness, yet caused spectacular destruction, flattening many stone buildings.

The deposits from ground surges are usually thin and inconspicuous, yet they represent the most destructive style of volcanic activity known. Only in the last few years have systematic studies of the deposits provided reliable criteria for their recognition. From this work it is now apparent that many volcanoes show deposits of the Pelée type, including Vesuvius. The origin of ground surges is still controversial. One possibility, which is the theory usually espoused, is that the ground surge accompanies or precedes by a short time a dense pyroclastic flow. The flow and surge are thus two effects of the same volcanic process, as suggested by the common intimate association of the distinctive flow and surge deposits. Although a great deal of research remains to be done on the origin of surges, there is no doubt about their lethal effects and on their common occurrence.

Typical cross-sections through the deposit of A.D. 79 in the region of Campania are shown in ill. 2. In most of the sections near Vesuvius the three types of pyroclastic deposits are encountered, with an air-fall pumice layer at the base, overlain by a succession of ground surge and pyroclastic flow deposits.

The air-fall pumice layer near Pompeii is a very coarse, homogeneous deposit with particles having a mean diameter of about one centimeter. The characteristics and distribution of this layer have been studied in detail by Lirer et al.[10] Their work shows that the air-fall pumice was dispersed to the southeast of the volcano by the prevailing wind direction during the eruption (ill. 1). The deposit can be traced along the southwest coast of Italy as far as Agropoli, 72 km. from Vesuvius. The extent of the area subject to fall-out of air-fall pumice during the eruption, however, extended much farther south, since recent oceanographic studies on deep-sea sedi-



Ill. 2. Stratigraphy of the deposits of A.D. 79 in excavations west and south of Vesuvius

[9] A. Lacroix, *La Montagne Pelée et ses éruptions* (Paris 1904).

[10] Lirer et al. (supra n. 8) 759–72.

ments show that the pumice from Pompeii also fell in the Ionian Sea.[11] Dio Cassius,[12] writing a century and a half after the eruption, reports that the wind carried the ash from Vesuvius as far as the north coast of Africa and the Levant. To the south of Vesuvius, in the region of Pompeii and Stabiae, the air-fall layer is everywhere thicker than 200 cm. (ill. 1) and up to 280 cm. at the Vesuvius Gate of Pompeii. The main axis of the fall-out thus lies over Pompeii and the deposit thins rapidly east and west of the city, to 180 cm. at Oplontis and less than 20 cm. at Herculaneum, for example. Between 75 and 90% of the air-fall deposit is lightweight porous pumice,[13] ranging in density from 0.6 to 1.0 g. $cm.^{-3}$. The largest pumice fragments which fell on Pompeii are approximately 20 cm. in diameter, whereas pumice lumps up to 36 cm. long have been found in the Oplontis air-fall layer.

In the lower half of the deposit the pumice is white in color, changing abruptly to a greenish-gray color in the upper part. The color change is an expression of a change in the chemical composition of the erupted material, reflecting the progressive emptying of a compositionally zoned magma reservoir under the volcano.

The air-fall layer also contains dense fragments of limestone and old volcanic rocks, ripped off the walls of the volcanic pipe of Vesuvius during the explosive eruption. These rock fragments make up approximately 12% of the lower half of the pumice layer, but increase to 20% in the upper gray part. The rock fragments rarely exceed 12 cm. in length. The increase in pumice diameter and proportion of rock fragments in the upper gray part of the pumice deposit, together with a wider dispersal of the gray pumice layer, have led Lirer et al.[14] to propose that the climax of the Plinian phase of the eruption was reached during ejection of the gray pumice. Wilson et al.[15] have interpreted these features in the Vesuvius pumice deposit as the result of eruption column height increasing with time, reflecting an increase in discharge rate. In their explanation, erosion of the Vesuvius conduit as the eruption progressed allowed increasing rate of escape of magma from within the volcano (i.e. increasing intensity). The total volume of the pumice deposit is estimated as 2.6 $km.^3$.

In Pompeii and Oplontis the air-fall pumice layer is overlain by a thin (5 to 20 cm.) ground surge deposit which mantles the topography. This well sorted layer contains abundant fragments of limestone and dense volcanic rocks up to 3 cm. in diameter together with rounded pumices in a sandy crystal-rich matrix. This deposit is in many respects similar to the lithic-rich ground surge deposit found in St. Pierre, Martinique, which was the result of the nuée on 8 May 1902. The presence of roof tiles in this layer in Pompeii (e.g. in the Vesuvius Gate section, pl. 4, fig. 1) lends strong support to the interpretation that it was deposited from a nuée ardente during the Peléan phase of the eruption. Near the Vesuvius Gate section (pl. 4, fig. 1) abundant bricks and roof tiles from the walls and towers occur at this level, suggesting major collapse. The 280 cm. pumice deposit could not have caused such damage. The devastating effects of a Pelée-style nuée are believed responsible.

In Pompeii the ground surge deposit occurs only above the air-fall pumice layer. At Oplontis, on the other hand, there are three ground surge deposits interbedded with the gray air-fall pumice layer, in addition to a fourth ground surge layer on top of the air-fall (ill. 2). The stratigraphic evidence thus indicates that at Oplontis the accumulation of gray air-fall pumice was interrupted at least three times by ground surge activity, while at Pompeii, 4 km. to the east, the air-fall accumulation continued uninterrupted. The three minor ground surges which advanced into Oplontis thus did not reach Pompeii. The fourth and largest of the ground surges extended over both Oplontis and Pompeii after the pumice air-fall had ceased. The extent of the ground surge beyond Pompeii is not yet known. The deposit is absent in sections in the villas near Stabiae, and the ground surge probably did not extend beyond the Sarno River which flows to the sea south of Pompeii.

In Pompeii and Oplontis the ground surge layer is overlain by a massive, fine-grained pyroclastic flow deposit. This layer is of variable thickness,

[11] Personal communication from D. Ninkovich, Lamont-Doherty Geological Observatory.

[12] Dio Cassius, *Epitome*, 66.23.

[13] Lirer et al. (supra n. 8) 768.

[14] Lirer et al. (supra n. 8) 771.

[15] L. Wilson, S.R.J. Sparks and G.P.L. Walker, "Explosive Volcanic Eruptions IV: The Control of Magma Chamber Properties and Conduit Geometry on Eruption Column Dynamics," *Geophysical Journal of the Royal Astronomical Society* (in press).

being thick in depressions and thin over elevations. Its upper surface is everywhere flat and nearly horizontal, characteristics well exhibited in the Oplontis excavations. In Pompeii, the pyroclastic flow deposit ranges in thickness from 60 cm. in the Palestra and the Necropolis southeast of the city (pl. 4, fig. 2) to 180 cm. in sections at the Vesuvius and Herculaneum Gates north and northwest of the city walls. The deposit is homogeneous and poorly sorted, but shows faint internal laminations, and occasionally shows minor cross-bedding and long-wave length dune structures at the base. At Oplontis the deposit lacks the faint internal laminations. These structures are best seen in the Oplontis excavations at the base of the deposit. The deposit is everywhere fine-grained and poorly sorted, consisting predominantly of fine ash (less than 4 mm.) which is partly consolidated. This fine compacted ash has preserved the detailed casts of bodies and garments of the Pompeians probably killed by the nuée ardente which gave rise to the ground surge. The pyroclastic flow clearly followed the surge very closely, and was probably part of the same eruptive phenomenon. It contains minor rock fragments and occasional bricks and other debris from buildings, as well as carbonized wood. At Oplontis a 30 cm. wide tree withstood the force of the three earlier ground surges, but was broken down by the pyroclastic flow (pl. 4, fig. 3). The vertical trunk now protrudes 70 cm. up into the pyroclastic flow deposit, with the broken but attached upper part pointing away from Vesuvius, in the direction of the flow. The destructive force of the pyroclastic flow and the preceding ground surge has also left its mark on the walls in Oplontis, where a 5 m. high wall has been rebuilt to its original form. The lower 3 m. of the wall remained intact, protruding 1 m. into the pyroclastic flow deposit, but above this level the wall was knocked down by the blast of the nuée ardente.

Only one pyroclastic flow was deposited in Pompeii. This layer is, however, overlain by a second 10 to 20 cm. ground surge deposit which is very rich in fragments of limestone and dense volcanic rocks. Thus, a second nuée ardente must have reached the city, although not sufficiently intense to leave a pyroclastic flow deposit. At Oplontis a second pyroclastic flow deposit occurs, overlying the first one. This layer may have been deposited from the same nuée ardente which laid down the upper ground surge in Pompeii.

The city of Herculaneum, only 7 km. west of the crater of Vesuvius, was buried under 20 m. of pyroclastic deposits during the eruption. The prevailing wind direction during the Plinian phase of the eruption reduced air-fall accumulation to a minimum (20 cm.), but the city was inundated by a series of thick pyroclastic flows because of its exposed position and proximity to Vesuvius. The origin of the deposits which buried Herculaneum has been a source of controversy. Some workers have interpreted them as mudflows, resulting from remobilization of ash and pumice deposits on the slopes of Vesuvius by heavy rains during the eruption.[16] Others have regarded them as pyroclastic flow deposits.[17] The 20 m. succession contains six gray to greenish-gray main flow units, 2 to 3 m. thick. Each unit is homogeneous and unstratified, consisting of a highly consolidated mixture of ash and pumice with minor angular fragments of older volcanic rocks and limestone. The presence of charcoal within the deposit and the prevalence of carbonized wood in the buried houses of Herculaneum are strong evidence that the city was buried by hot pyroclastic flows. All wood in Herculaneum has been converted to carbon, a substantial indication that the deposits were largely the products of hot flows. Studies of carbon from Herculaneum by Maury[18] have demonstrated that the wood was heated up to at least 400°C. When thermal degradation of wood occurs, characteristic structural and chemical changes occur with rising temperature which can be found by infrared spectrometry, reflectance and analysis. Maury has calibrated these changes with temperature. The deposits at Herculaneum are largely ignimbrites (pyroclastic flow deposits), although some may, however, represent mudflows, generated by remobilization of other deposits. Such association of mudflows and ignimbrites is very common and the two types of deposits are difficult to distinguish. Another feature characteristic of hot flow deposits is the oc-

[16] Maiuri 1977 (supra n. 1) 7; E.C.C. Corti, *Untergang und Aufstehung von Pompeji und Herculaneum* (Munich 1940) 92; R. Etienne, *Pompeji: Das Leben in einer antiken Stadt* (Stuttgart 1974) 35; A. Mau, *Pompeii: Its Life and Art* (tr. F. Kelsey 1899) 20.

[17] Sparks and Walker (supra n. 2) 62–64; Sparks (supra n. 2) 134–36; Helprin (supra n. 6) 120; Merill 1918 (supra n. 6) 304–09; Merill 1920 (supra n. 6) 262–68.

[18] R.C. Maury, "Evolution à haute température des materiaux organiques dans les formations volcaniques ou à leur contact," *Bulletin de Centre Recherche Pau-SNPA* 10 (1976) 289–300.

currence of gas pipes. These are vertical pipes in the deposit where streaming gases have removed fine ash and concentrated heavy coarse fragments. Such pipes are abundant in the lowermost deposits at Herculaneum. The highly consolidated nature of the deposit may also indicate that the temperature of the flow was locally high enough to cause incipient welding or to sinter together hot plastic ash fragments in the layer.

The pyroclastic flow deposits at Oplontis and Pompeii are regarded as lateral equivalents of the lower deposits at Herculaneum. The upper pyroclastic deposits at Herculaneum are derived from later and more localized nuées ardentes which did not extend to the southern region.

The final explosive activity of Vesuvius in A.D. 79 produced a fine-grained ash deposit which overlies the uppermost ground surge layer in Pompeii. The gray-colored layer is 60 to 70 cm. thick and consists of consolidated very fine-grained ash and pea-sized accretionary lapilli. It is made up of well-bedded 10 to 20 cm. thick units. Accretionary lapilli are spherical pellets which consist of concentric shells of fine ash. They form in the eruption cloud as ash particles aggregate onto falling water droplets and can grow to several centimeters before falling to ground. Accretionary lapilli are tell-tale signs of the presence of water, and well-bedded fine-grained ash layers rich in accretionary lapilli are generally regarded as products of explosions where water has entered the volcanic vent or explosions accompanied by heavy rainfall at any rate. Accretionary lapilli also occur in the topmost part of the pyroclastic flow deposit in Pompeii.

THE HISTORICAL RECORD

Pliny the Younger (*Epistles* 4.16 and 20) recorded his own observations from Misenum and those of informants with his uncle who died at Stabiae. The reports from Stabiae came mostly from the town, with a few from ships in the bay. Although Pliny the Younger might have exaggerated some of the phenomena witnessed at Misenum, his reports agree with the geological record and we consider them generally reliable. Also, there are sufficient chronological references in the two letters to allow events to be synchronized with moderate precision. Thus, there is a time-scale to which the geological record has been related in the Table.

Two sets of facts in these reports are especially informative: (1) Stabiae was subjected to a fall of pumice (sometimes mixed with ash) throughout the afternoon of August 24, the following night, and probably into the next morning. No casualties are reported from this fall, and the Stabians, although afraid, did not panic. On the morning of the second day an event occurred at Vesuvius which caused them to flee; (2) although Misenum was not subjected to a fall of pumice or ash during the first day or night, a volcanic event occurred on the morning of the second day which caused the residents to flee. Within a short time fall of ash (but no pumice) occurred.

These facts indicate that the eruption consisted of two major phases, the first characterized primarily by fall of pumice and lasting in excess of 18 hours (Plinian phase), the second not characterized by fall of pumice but involving fine ash and having a much shorter duration (Peléan phase).

The Report from Stabiae

Pliny the Elder cannot have reached Stabiae from Misenum before late afternoon of the first day. The eruption column was witnessed at Misenum during the early afternoon, around 1:00 (*hora fere septima*, 16.4). He was delayed in departing because his initial preparations for a scientific mission to study the eruption had to be altered after the arrival of a message from a friend (Rectina) who lived under Vesuvius and requested aid in escaping by sea. This caused Pliny to call out quadriremes of the fleet under his command for a rescue mission (16.8–9; 4). It is thus unlikely that he could have set out before 2:00, probably later. As his ship approached the coast west of Vesuvius, fall (*ruina*) from the eruption and floating rafts of pumice prevented putting in. The text suggests that he came fairly close to shore (*iam vadum subitum*) before changing course for Stabiae.[19] Pliny the Younger does not

[19] "*Vadum subitum*" could mean that Pliny the Elder's ship "approached the shallows", i.e. "suddenly they were in shallow water" (B. Radice, *The Letters of Younger Pliny* [New York 1963] 167), or it could mean "the shallows approached" (or "sprang up"), as preferred by R.M. Haywood (*Classical Weekly* 49.1 [1952] 2) and others. If the latter translation is correct, then Pliny found himself in shallow water sooner than expected. But this need not be due to a "rise of the bottom of the bay and the

state the location of Rectina's villa and Pliny's destination. Circumstantial evidence does, however, indicate that he approached land well south of Herculaneum and perhaps nearer to Oplontis (see RECONSTRUCTION OF EVENTS infra). Finding access to shore impossible, he changed course and proceeded parallel to the coast in a southerly direction to Stabiae (16.12). If he was heading towards Oplontis, he would have covered a distance of 28 km. from Misenum before changing course for Stabiae, 8 km. farther to the south. Given the probable maximum speed of a quadrireme as 8 knots,[20] the voyage from Misenum to Stabiae would require about 5 hours, so he cannot have reached Stabiae before 7 P.M. The text indicates that there was no difficulty putting in at Stabiae.

When he reached Stabiae, "danger was not yet near but obvious, and since it was growing, would be most near," so the residents would have fled by sea if the wind were not contrary (16.12). Despite the figurative language, the text indicates that "*periculum*" refers to the accumulation of volcanic material in progress at Stabiae. The text does not imply that the Stabians were witnessing the danger in areas closer to Vesuvius and fearing that it would eventually reach them, but rather that fall at Stabiae was increasing in thickness, and since it was growing (*cum cresceret*), they would eventually be in danger.

Therefore, fall on Stabiae was in progress during the afternoon and was continuing, and accumulation was gradual enough to cause fear but not panic. Since the Stabians could not leave by sea, they remained rather than attempt flight overland. Although this portion of the text does not mention the nature of the fall, it is likely that the previous description of the fall on the ships in the bay of hot ash (*cinis*) and "pumice and even dark stones burned and broken by fire" would apply to the afternoon fall at Stabiae too (16.11).

Textual evidence indicates that during the night fall continued to accumulate gradually. At an unspecified point, since the build-up of pumice and ash (*cinere mixtisque pumicibus oppleta*) threatened to block the door of the cubiculum in which Pliny the Elder was sleeping, he was aroused (16.14).

Around the same time tremors became more frequent and larger (*crebris vastisque tremoribus*). From fear of falling structures the Stabians decided to spend the rest of the night in the open, protecting their heads from falling pumice (16.15–16). This is described as "light and porous" (*levium exesorumque*, 16.16). There is no mention of ash. After commenting on how they protected their heads, Pliny the Younger in the next sentence speaks of daybreak.

It is clear that seismic activity increased sometime during the night. The fall was now predominantly pumice and the accumulation was at least high enough to obstruct a door. But still the fall was gradual, and there is no indication of panic on the part of the Stabians.

The text is not decisive as to whether pumice fall continued until or beyond daybreak. But the manner of description suggests the probability that pumice was still falling at daybreak: although there was now daylight elsewhere (*iam dies alibi*), at Stabiae there was still darkness, "blacker and thicker than all nights" (16.17), which necessitated the use of lamps and torches. Even allowing for rhetorical exaggeration, it is unlikely that suspended matter from previous fall would have led to such a description. "*Nigrior*" implies the virtually total obstruction of sunlight, and "*densior*" seems to be a direct reference to the nature of the obstructing material figuratively transferred to the darkness (*nox*) itself, typical of the author's writing style. It is improbable that the text would describe daybreak in this way if the informants had not told Pliny the Younger that there was still a steady fall of pumice. But nothing in the text allows us to infer whether there was a cessation or decrease in fall between daybreak and the time when the next volcanic event was witnessed.

Around daybreak the Stabians tried again to leave, but the still contrary wind and rough sea

consequent shallowness of the water" (Haywood). Although it is possible that seismic activity had produced an uplift of the seafloor, it is more likely that fall of pumice had created a carpet of pumice on the surface, as the rest of the line ("*ruinaque montis litora obstantia*") suggests. This is sufficient to account for "*vadum subitum*." (See RECONSTRUCTION OF EVENTS infra).

[20] The maximum speed of Roman warships under oar and with the most favorable conditions has been calculated by Lionel Casson (*Ships and Seamanship in the Ancient World* [Princeton 1971] 281) as 8 knots. This is with all oars manned and all men pulling at maximum strength, a situation which could only prevail for short periods of time. It is not likely that Pliny's quadriremes would average as much as 8 knots between Misenum and Stabiae.

prevented it (16.17–18). The text does not make clear how much time elapsed between this attempt at daybreak and the next reported event, but the connective "*deinde*" suggests that the latter did not happen immediately after the former. Probably there was at least a small interval of time. At this time a volcanic event was witnessed by the Stabians which caused them to take flight.

From the perspective of those at Stabiae, this event was perceived as "fires and the smell of sulphur forewarning of fires" (*flammae flammarumque praenuntius odor sulpuris*, 16.18–19). Whatever happened that caused them to see "*flammae*" and smell an odor interpreted as sulphur was clearly a new volcanic event. Although on the previous night they had seen burning in the area around Vesuvius (16.13), previous volcanic activity as experienced at Stabiae was described as either fall of pumice (and ash) or tremors. This event was frightening enough to send them into flight—presumably overland, since there is no indication that the wind had changed. Pliny the Elder tried to escape too, but his health prevented it (16.19).

Whatever the Stabians witnessed from the direction of Vesuvius on the morning of 25 August, it was sufficient to send into flight a population who had withstood at least 18 hours of pumice fall. This implies a major change in the nature of the volcanic activity. As a whole, the report from Stabiae indicates that the eruption occurred in two major phases: the first consisting of the fall and gradual accumulation of pumice (sometimes mixed with ash) over a period of not less than 18 hours (reckoning from the earliest report of the eruption time as around 1:00 P.M. to daybreak the next day—roughly assumed to be around 6:00 A.M.), the second and more terrifying part introduced at Stabiae by sulphurous odor and sight of "fires"—with the clear implication that these fires will reach Stabiae—and occurring sometime during the morning of the second day.

The Report from Misenum

The phenomena experienced at Misenum differ from those at Stabiae, but they are consistent with and support the supposition that the eruption consisted of two major phases, the second on the morning of the second day. Pliny the Younger himself was the observer.

Apart from the sight of the distant eruption column and a mention of previous tremors (16.10; 20.3), no volcanic phenomena are reported as witnessed from Misenum until sometime during the night (24–25 August). Clearly Misenum experienced no fall on the first day, nor is there reference to fall during the night. Although Pliny the Younger probably exaggerated his nonchalance concerning the events around Vesuvius, it is clear that Misenum felt little effect from the volcanic events of the first day. Certainly if there had been any fall, it would have been mentioned.

The first abnormal event to affect Misenum came during the night in the form of increased tremors, strong enough that things seemed to be "not only moving but turning over" (20.3–4). These, which separately but simultaneously aroused Pliny and his mother from bed, are surely the same set of tremors which caused the Stabians to remain outside for the rest of the night, so it appears that they were stronger at Stabiae than Misenum. There is no evidence on which to base an estimate of the time of these tremors, but their probable simultaneity on either side of the bay is important in synchronizing the two sets of reports. Although there was now some consternation at Misenum, there is no evidence that anyone felt the need to flee. Pliny and his mother remained indoors (20.4–5). The text does not indicate whether the night tremors subsided before violent shocks began the next morning. They were strong enough to send people to areas away from buildings; vehicles did not remain in place even with rocks scotched around their wheels; the sea retreated, stranding marine animals (20.7–9). It is apparent that this seismic activity was far more severe than that of the previous night. This implies a major event at Vesuvius on the morning of the second day.

Within a very short time after these shocks began, Misenum was first subjected to volcanic ash. The following sentence speaks of a "dark cloud (*nubes atra*) from the other direction," lightning-charged (20.9.13–16). This sight sent some into immediate flight. Very shortly (*nec multo post*) this cloud reached the promontory of Cape Misenum, descending over the ground there, and also out toward Capri (20.10–11). Pliny and his mother argued as to whether he should flee while she remained, and without any informative temporal connective, Pliny says ash (*cinis*) began to fall (20.12–13). This was light (*rarus*) at first, then so heavy that he describes

it as "night" (*nox*), not merely moonless and foggy but like night in an enclosed room when lights are out (20.14). After a brief return of light (*reluxit*)—according to Pliny, due to fire (*ignis*) in the cloud—the fall of ash was so heavy (*multus et gravis*) that they had to shake it off to prevent being covered (20.16). Eventually (*tandem*)—we cannot know how much time elapsed—the cloud disappeared and they returned home. The ash is described as "deep, like snow" (*altoque cinere, tamquam nive*, 20.19).

An important feature about this activity is the apparent rapidity with which the first cloud of ash reached areas as distant from Vesuvius as Misenum (around 32 km.) and Capri. It was immediately after Pliny described the most severe shocks that he refers to this cloud appearing from the other direction. It is clear that the shocks and the ash-cloud are parts of the same volcanic event. These phenomena witnessed at Misenum were so different from previous phenomena that they are probably the result of a major change in the nature of the eruption.

Except for continuing tremors, no further volcanic activity is reported. It is apparent that no major volcanic events followed those which sent the second ash-cloud over Misenum on the morning of the second day.

Comparison of the Two Reports

Experiences undergone at Stabiae and Misenum are different but complementary.

1. While at Stabiae there was gradual fall and accumulation of ash and pumice throughout the afternoon, at Misenum there was no fall.
2. While at Stabiae there was gradual fall of pumice during the night, at Misenum there was no fall.
3. At both places there was an increase in seismic activity sometime during the night, probably stronger at Stabiae than Misenum. At neither place were these tremors formidable enough to cause flight overland.
4. Sometime after daybreak on the second day, while at Stabiae there were the sight and fear of approaching "fires" and a sulphurous odor, at Misenum there were violent shocks followed quickly by two advancing ash clouds. These different experiences were formidable enough to cause the inhabitants of both places to take flight.

Both the differences and the similarities between these respective synchronous experiences can be accounted for by reference to the geological record.

RECONSTRUCTION OF EVENTS OF THE ERUPTION

The volcanological interpretation of the deposits and the historical evidence presented in Pliny's letters provide a firm framework for reconstruction of the eruption in A.D. 79.

Premonitory symptoms of the outbreak went unheeded by the people of Campania, probably because of their ignorance of the true volcanic nature of Mt. Vesuvius. Early historians such as Diodorus Siculus (45 B.C.) and Strabo (30 B.C.) had, however, recognized that Vesuvius was a volcano. Recent studies show that Vesuvius had had a series of explosive eruptions prior to A.D. 79.[21] The last major eruption occurred, however, in the Bronze Age or approximately 1200 B.C. and deposited a thick layer of pumice and ashes to the east.[22]

The first sign of the coming activity was a strong local earthquake in February, A.D. 62, documented by Tacitus and Seneca.[23] The damage was so severe in Pompeii and Herculaneum that repair work had not been completed seventeen years later. The earthquake of 62 was probably due to the initial movement of magma toward the surface and fracturing of the edifice of Vesuvius. On 20 August A.D. 79 tremors were again felt in the region and in increasing frequency during the next four days as magma forced its way up the feeder pipe of the volcano. Many springs also dried up around the volcano.

At around 1 P.M. on 24 August Vesuvius burst into life. An eruption column laden with pumice and ash rose vertically above the crater. The Plinian phase of the eruption, which was to prevail for the next 18 hours, had now commenced. During this period the volcano produced about 2.6 km.^{3} of pumice[24] at an average rate of 40,000 m.^{3} sec^{-1}. The distribution and grain size characteristics of the Plinian pumice layer in A.D. 79[25] are consistent with a 20 km. high eruption column, given a wind blowing from the northwest at 20 m. sec^{-1}. The dense erup-

[21] P. Di Girolamo, "Petrografia del Sommo-Vesuvio: le serie piroclastiche," *Acad. Sci. Fis. e Nat. Napoli* (1968) 35.

[22] Lirer et al. (supra n. 8) 763.

[23] Tacitus, *Annals* 15.22–23; Seneca, *Natural Questions* 6.1 and 27.

[24] Lirer et al. (supra n. 8) 770.

[25] Lirer et al. (supra n. 8) 771.

tion cloud eclipsed the mid-day sun and must have brought on total darkness in Pompeii and other towns beneath the southerly drifting eruption cloud. The wind direction resulted in only minor pumice fall on Herculaneum. Pliny the Elder's ships suffered a heavy fall of pumice as they approached the shoreline near Rectina's villa. So Pliny the Elder must have sailed towards land well south of Herculaneum in order to come within the pumice fall-out. We therefore infer that Rectina's villa was south of Herculaneum and perhaps nearer to Oplontis.[26]

The Pompeii pumice had a terminal velocity of approximately 10 m. sec^{-1}. Given an eruption cloud height of 20 km., then the major pumice fall would have started in the city about 30 minutes after the onset of the eruption. During the next 18 hours a uniform pumice layer 280 cm. thick was deposited on the city's streets, roofs and gardens, accumulating at an average rate of 15 cm. per hour. The accumulation of air-fall pumice must have presented two types of problems in Pompeii. First, many flat roofs must have caved in under the weight of the pumice. In the excavations of the villa at Oplontis there is good evidence for roof collapse during the Plinian air-fall phase. Here the portico roof in the western part of the garden has collapsed, with columns lying horizontally within the pumice layer (pl. 4, fig. 4). Secondly, the accumulation made it difficult to get about outdoors, as pedestrians had to wade in loose pumice in total darkness. It is unlikely, however, that the Plinian air-fall phase claimed many victims. On the contrary, it is more likely, in fact, that the 18 hour period of pumice-fall alarmed the Pompeians and gave the majority of the population opportunity to flee the city before the main disaster struck. While the low density pumice (0.6 to 0.8 g. $cm.^{-3}$) will not have caused bodily harm, the fall of dense fragments of limestone and old volcanic rock (2 to 2.8 g. $cm.^{-3}$) could have been lethal to some. These rock fragments range from 9 to 11 cm. in diameter in Pompeii, but their low abundance in the deposit shows that the chances of being struck down by such dangerous projectiles was relatively small.

The Plinian phase was witnessed by Pliny the Elder as his quadriremes approached the coastline west of Vesuvius in the late afternoon on 24 August. His rescue mission had to be abandoned, however, because the low-density pumice had formed a massive floating carpet on the sea near Vesuvius.[27] Pliny the Elder changed course at this point, running with the wind to the south, and made landfall at Stabiae.

Although 17 km. from the volcano, Stabiae lies on the main axis of the pumice fall-out. During the night the pumice accumulation, which reached a final thickness of 250 cm., was so heavy that Pliny and his friend Pomponianus decided to move outdoors rather than risk being trapped inside by pumice or falling buildings. During the night increased earthquake activity was noted both by Pliny the Younger at Misenum and by the Stabians. It is likely that this build-up corresponds to the eruption of the gray upper part of the pumice layer, derived from deeper levels in the Vesuvius magma chamber.[28]

The pumice fall lasted throughout the night at Stabiae and continued into the morning hours. Pliny's informants at Stabiae reported that, while daylight was seen elsewhere, conditions there were "blacker and thicker than all nights." The situation at Pompeii must have been comparable on the morning of 25 August.

At Misenum the earthquake activity reached a climax shortly after daybreak on 25 August, corresponding to the climax of the Plinian phase. Pliny the Younger gives a vivid description of a prelude to a tsunami or seismic tidal wave accompanying the earthquakes, where the sea surges back upon itself "as though forced back by the tremors of the earth," leaving marine animals stranded. Tsunamis commonly accompany great volcanic eruptions, and may result from large-scale displacements of the sea-floor or, more likely in this case, from slumping of sea-

[26] The popular belief that Pliny was heading toward Herculaneum is based on the now rejected reading of *Rectinae* in 16.8 as *Retinae* (= Resina, the town presently occupying the site of Herculaneum). See R. Hanslik, "Plinius der Jungere," *Jahresbericht Bursian* 282 (1943) 65–66; R. Hanslik on Cn. Pedius Cascus in *ÖJh* 16 (1954) 159.

[27] Supra n. 19. Floating pumice rafts are a common phenomenon in explosive eruptions. They were observed near the South Sandwich Islands in 1962 (I.G. Gass, P.G. Harris and M.W. Holdgate, "Pumice Eruption in the Area of the South Sandwich Islands," *Geological Magazine* 100 [1963] 321–30) and more recently near the Tonga Islands in May 1979 where pumice blocks up to 0.5 m. floated on the ocean, and in the 1883 Krakatoa eruption the pumice rafts were up to 3 m. thick and impassable to ships (J.W. Judd, "The Eruption of Krakatoa and Subsequent Phenomena," *Royal Society of London* 1888, 56).

[28] Lirer et al. (supra n. 8) 770.

floor sediments mobilized by earthquake activity in the area.

During the morning a major change occurred in the style of the eruption, marking the beginning of the Peléan phase. The change in activity was observed at Misenum as a black cloud which descended to earth and covered the sea, and at Stabiae where Pliny the Elder was aroused by "fires and the smell of sulphur, forewarning of flames," which caused his companions to flee.[29] The black cloud marked the appearance of the first of several nuées ardentes which swept down the southwest slopes of Vesuvius during the next few hours, devastating the region from Pompeii in the south to Herculaneum in the west.

The mechanisms which generate nuées ardentes are still poorly understood. Hypotheses concerning their origin are based partly on the characteristics of the deposits and partly on direct observations, which clearly are difficult to make. Examination of many stratigraphic sections through the products of explosive volcanic eruptions shows that the deposits of the Plinian phase are generally overlain by deposits of the Peléan phase. This systematic relationship suggests that the deposits and their modes of eruption reflect vertical variations in gas content of the magma reservoir,[30] with gas-rich magmas from the upper part ejected to great height above the volcano to form a Plinian eruption column with low-density frothy pumice, whereas gas-poor magmas from the deeper part of the magma reservoir are erupted with much less vigor and merely boil over the crater rim as a hot mixture of relatively dense pumice, ash and volcanic gases which descends the flanks of the volcano as a nuée ardente.

The ground surge deposit overlying the pumice layer at 250 to 280 cm. above street level marks the beginning of the Peléan phase in Pompeii. The black cloud which Pliny saw sweep down the flank of the volcano and out to sea was the first major nuée ardente or glowing avalanche of the eruption. There is evidence in the Oplontis sections, however (ill. 2), that three minor nuées ardentes were discharged down the southwest flank of Vesuvius in the night, during the accumulation of the gray pumice, but none of these reached Pompeii. The first nuée ardente in Pompeii swept over a city which was already partly buried by pumice. Protruding above the pumice layer were the second storeys of buildings, roofs, trees and upper portions of colonnades and walls. Many roofs had already collapsed under the weight of the pumice. The great majority of the population had fled during the preceding 18 hours of pumice air-fall. Those who remained were either huddled indoors or in the process of fleeing across the desert-like landscape. Historical nuées ardentes such as those from Mt. Pelée in Martinique in 1902 and from Mt. Lamington in Papua-New Guinea in 1951 travel at velocities in excess of 100 km. per hour.[31] Those who remained within the city had no chance of escape during the 5 to 6 minute period which the black cloud took to cover the distance from the crater rim. The main bulk of the nuée ardente was preceded by the ground surge, which left a deposit of only 10 to 20 cm. The relatively unimpressive deposit carries a significance which is much greater than implied by its thickness. The ground surge from Mt. Pelée in 1902 was sufficiently forceful to capsize a steam ship in the harbor of St. Pierre, to cut off smokestacks and masts of other vessels, blow down masonry walls 1 m. thick and carry a 3-ton statue a distance of 16 m.[32] The victims of nuées ardentes are not, however, killed by the force of the blast, but rather by asphyxiation from the heat of gases in the dust-laden cloud. Many of the bodies in the excavation of Pompeii are indeed found lying on top of the ground surge deposit.

The ground surge was immediately followed by the pyroclastic flow, the second component of the nuée ardente, which deposited a layer ranging in thickness from 200 cm. at the north wall of the city to 50 cm. in the Necropolis area south of Pompeii. This hot dense mixture of fine ash and gases instantly buried the victims of the ground surge and suffocated any survivors. The excellent preservation of bodies in Pompeii is entirely due to the fine-grained powdery nature of the pyroclastic flow deposit. The coarse-grained air-fall pumice layer could not of course preserve any of the fine detail

[29] The smell of sulphur is consistent with nuée ardente activity and consequent increased concentration of volcanic gases in the atmosphere near ground level. Volcanic gases during the Plinian phase are dispersed high in the atmosphere, whereas in the Peléan phase much of the gases are transported at lower levels with the nuée ardente.

[30] Sparks, Self and Walker (supra n. 2) 118.

[31] G.A. Taylor, "The 1951 Eruption of Mt. Lamington, Papua," *Bulletin of the Bureau of Mineral Resources of Australia* 38 (1958) 117.

[32] Macdonald (supra n. 5) 145.

that is exhibited by the many human plaster casts that have been obtained by the Fiorelli technique since 1863, and we may safely conclude that all these casts were of people who succumbed to the nuée ardente.[33]

The blast of the nuée ardente on the morning of 25 August must have severely damaged most structures protruding above the pumice layer in Pompeii. The presence of roof tiles and bricks (pl. 4, fig. 1) within the ground surge and pyroclastic flow deposits indicates that roofs were stripped off houses, fatally exposing those who had sought shelter from the hot dust cloud.

Pliny the Younger found himself at the periphery of the nuée ardente which swept over Pompeii, Oplontis and Herculaneum on the morning of 25 August. As he quickened the pace with his mother on the flight from Misenum, presumably heading north, he was followed by a threatening thick cloud which poured over the land "in the manner of a torrent," resulting in light fall of ash. It enveloped them in total darkness. We can infer from this description that the dilute leading edge of the nuée ardente extended 30 km. west from Vesuvius. The ash cloud enveloping Pliny cleared up a little later and light returned.

Shortly thereafter there was darkness again and heavy ash fall until the cloud "dispersed into smoke or fog." Pliny is clearly describing here the effects of a second nuée ardente from Vesuvius and again he is fortunate enough to be at the very periphery of the ground surge cloud. There are no deposits of A.D. 79 known at Misenum today, which is not surprising in view of the low resistance of such ash layers to erosion. It is probable that this nuée formed the second pyroclastic flow deposit at Oplontis, 3 to 4 m. above ground level, and the 10 to 20 cm. thick upper ground surge deposit in Pompeii at 3.5 to 4.5 m. above street level. There are no deposits at Stabiae which can be related to the nuée ardente activity. Fine ash clouds of the sort that engulfed Pliny the Younger at Misenum must, however, have reached Stabiae, and the approach of the first of those dust clouds probably caused the flight of the companions of Pliny the Elder.

Pliny the Younger's account of the eruption ends on 25 August, as the ash-cloud disperses and he returns to Misenum in pale sunshine. We therefore have to rely on the stratigraphic evidence of the deposits in order to reconstruct the final stages of activity. The uppermost deposit from the eruption of A.D. 79 is a fine-grained well-bedded ash layer containing abundant accretionary lapilli. The layer thins with distance from the volcano, ranging from 100 cm. at Oplontis and 70 cm. in Pompeii to about 20 cm. near Stabiae. The presence of accretionary lapilli and the uniform fine-grained character of this layer are features typical of deposits formed during phreatomagmatic explosive eruptions, i.e. explosions generated by the interaction of magma and water. The closing stages of the eruption therefore consisted mainly of a series of moderate vertical explosions, throwing out fine ash which was carried with the prevailing wind and deposited south of Vesuvius.

CONCLUSIONS

Correlation of the historical and geological evidence indicates that the eruption of Vesuvius in A.D. 79 consisted of two main phases. The initial Plinian phase affected the region to the southeast of the volcano, depositing up to 280 cm. of air-fall pumice over Pompeii at a rate of 15 cm. per hour, during an 18-hour period. The Peléan phase began on the morning of 25 August, as nuées ardentes swept down the south and west flanks of the volcano, over Herculaneum, Oplontis, Pompeii and presumably also over the cities of Taurania, Tora, Sora, Cossa and Leucoptera, which still remain to be discovered. The initial blast of the nuée ardente in Pompeii was a hot, dust-laden ground surge cloud, which overwhelmed and asphyxiated those who remained above ground level in the city. Their bodies were immediately interred in the following

[33] The stratigraphic position of most of the bodies in the volcanic deposits was generally not documented by the early excavators at Pompeii. Maiuri recognizes human remains at two levels in the volcanic deposits ("Last Moments of the Pompeians," *National Geographic Magazine* 120 [1961] 655): skeletal remains at the base of the Plinian layer ("gravel-like lapilli") and well-preserved body molds in the pyroclastic flow ("upper layer of ash"). It is from the latter that plaster casts have been made. Recent discoveries of bodies from well-documented excavations are at this level, e.g. Maiuri's discovery of many bodies near the Nuceria Gate, unearthed from the pyroclastic flow deposit. It is also known that in Murat's excavations in 1812 numerous bodies were found more than 3 m. above ground level (personal communication from Lawrence Richardson, Jr.).

pyroclastic flow. The good preservation of the victims of this disaster is entirely attributable to the fine grain size of the pyroclastic flow deposit.

Of a total estimated population of 20,000 there have been approximately 2,000 victims accounted for within the excavated region of Pompeii. It thus appears that the vast majority of the population had fled the city during the preceding 18-hour period of air-fall pumice accumulation. Only further excavations will tell whether they fled to safety or if they were overtaken by the nuées ardentes outside the city walls.

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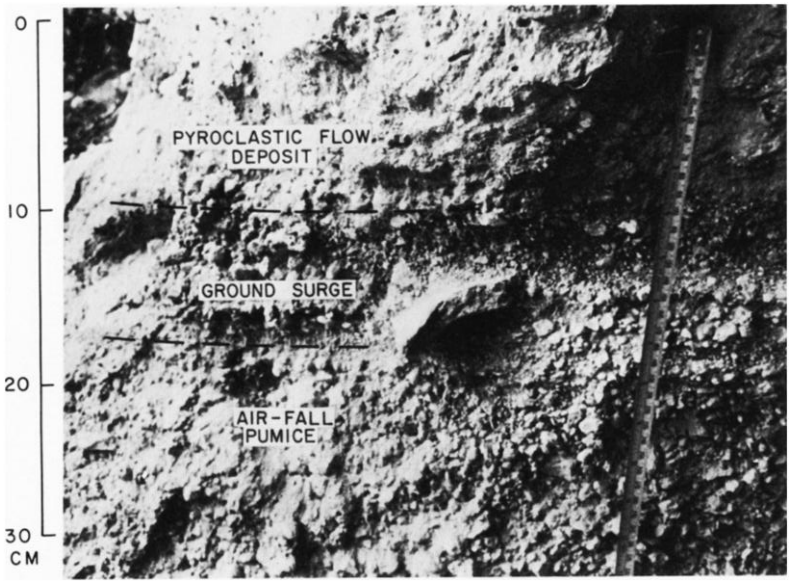

FIG. 1. Roof-tile in ground-surge layer near Vesuvius Gate in Pompeii

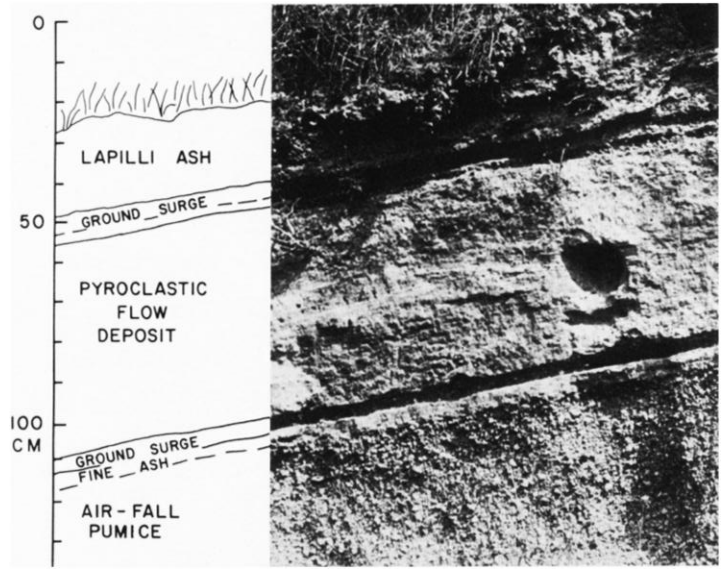

FIG. 2. Section of the deposit of A.D. 79 in the Necropolis south of Pompeii. Lower homogeneous layer is pumice from the Plinian air-fall phase; upper layers are ground-surges (thin) and pyroclastic flow deposit from the Pelean phase of the eruption

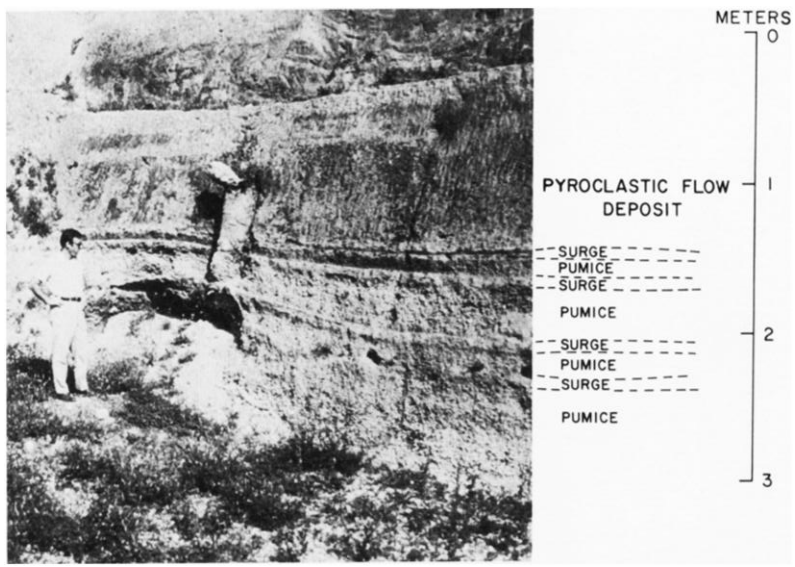

FIG. 3. Section of the deposit of A.D. 79 at Oplontis. Note the tree-trunk which protrudes up through the pumice layer, but is broken within the pyroclastic flow deposit

FIG. 4. Oplontis, portico roof collapsed under load of pumice accumulating during Plinian phase, with columns falling within the pumice deposit