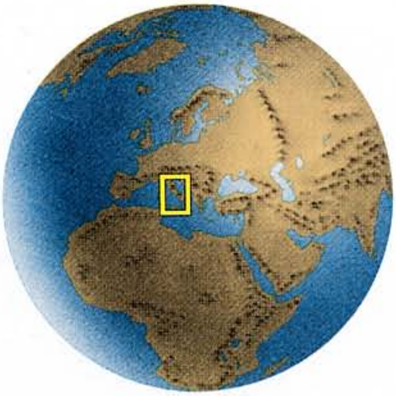
*Haraldur Sigurdsson, Steven Carey, Winton Cornell, and Tullio Pescatore*

# The Eruption of Vesuvius in A.D. 79



*The stratigraphy of volcanic deposits is described and related to the eyewitness accounts of Pliny the Younger in chronologically reconstructing events of the A.D. 79 eruption of Vesuvius. Initial activity was a small phreatomagmatic explosion that resulted in ashfall on the volcano and to the east, probably early on 24 August. The subsequent Plinian eruption began shortly after noon. It resulted in fall of white pumice over districts south of the volcano for about seven hours. Following this, the continuing Plinian eruption tapped magma of more primitive composition, producing gray pumice-fall; prevailing stratospheric winds restricted this to southeastern districts. At about 1 a.m. on 25 August the first pyroclastic surge was generated. During the next seven hours the Plinian eruption was interrupted six times by surges and pyroclastic flows. The first surge overwhelmed Herculaneum where it killed all remaining residents. Later surges were of progressively greater extent, with the fourth surge reaching Pompeii at about 7 a.m. on 25 August. Shortly thereafter the two largest surges were produced, which affected Stabiae and Misenum. The intermittent generation of surges and pyroclastic flows during the Plinian eruption of the gray pumice is attributed to collapse of the eruption column, triggered by increasing mass eruption rate and density and decreasing volatile content of the magma. Structural change in the volcanic edifice, such as caldera collapse, is the most likely cause of increased mass eruption rate. The dynamics of the Plinian eruption are attributed to exsolution of a vapor phase from the magma. Final activity, on the other hand, produced fall and surge layers rich in accretionary lapilli which probably were produced by phreatomagmatic explosive activity, resulting from interaction of meteoric water and magma in the conduit.*

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Explosive volcanic eruptions, one of the earth's major natural hazards, have claimed 240 000 lives in the past 380 years. During this period, some fatalities have occurred in 5% of all volcanic eruptions; one of six active volcanoes has caused deaths (Simkin et al. 1981). One style of volcanic activity is particularly lethal — explosive eruptions that generate catastrophic nuées ardentes (glowing avalanches of tephra and hot gases), surges, and pyroclastic flows. In this century four eruptions have shown dramatically the physical processes that operate during this style of activity and have underscored the lethal effects of the pyroclastic surge. The eruptions of Mont Pelée (1902), Mount Lamington (1951), Mount St. Helens (1980), and El Chichon (1982) generated blastlike surge clouds that totally devastated areas as far as 25 km from the volca-


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noes and claimed about 35 000 lives within the surge zones.

Destructive as they are, surge clouds often leave only very thin deposits. Thus the surge from the 1982 eruption of El Chichon left only a 3-cm-thick deposit in the town of Naranjo, 8 km from the crater, but the town was completely devastated by the high velocity and high temperatures in the surge cloud. Surge deposits can also be easily overlooked or misinterpreted in the geologic record because they often appear nondescript and may resemble reworked, cross-bedded volcaniclastic deposits. Thus the cross-bedding in the surge layers in Pompeii from the A.D. 79 eruption of

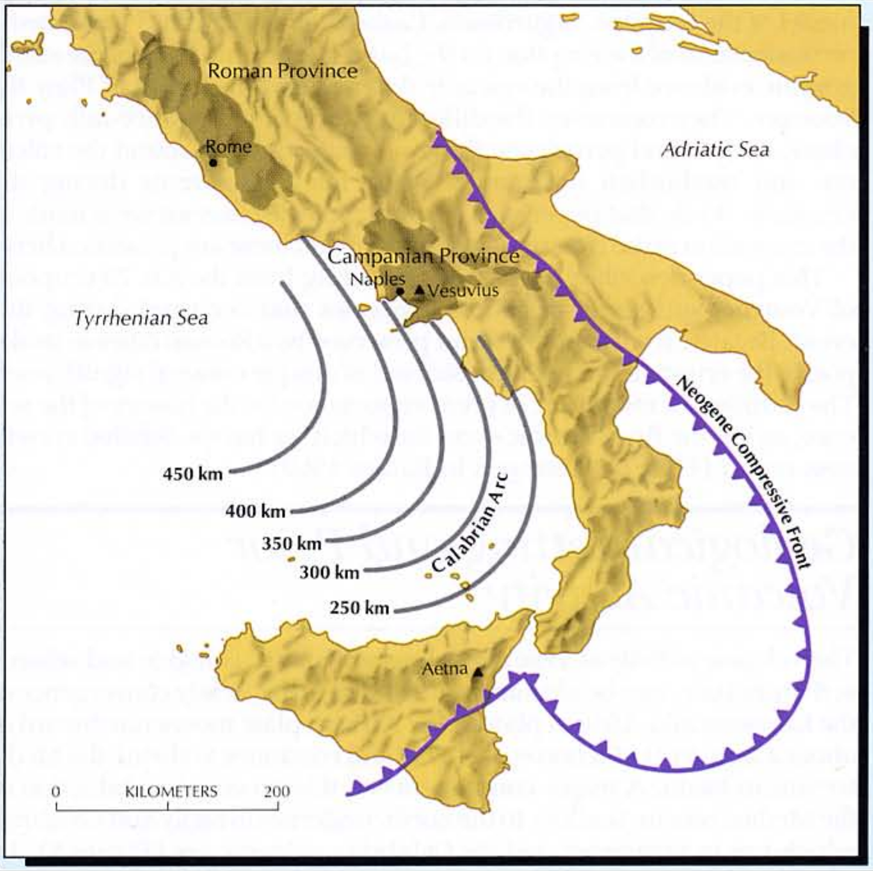


*Figure 1. Structural setting of Vesuvius and other volcanic provinces in Italy (after Gasparini et al. 1982). Isopleths show the form of the curved, 250- to 450-km-deep Benioff zone.*

Vesuvius led Rittmann (1950) to conclude that these layers were ashfalls that had become cross-bedded by ancient quarrying.

The concept of surges as ground-hugging clouds that travel away from an explosion source at high velocity was first formulated during nuclear tests in 1947 (Brinkley et al. 1950). Deposits resulting from this process during volcanic explosions were subsequently identified from phreatomagmatic explosions (Moore 1967) and later from explosive eruptions in general. Since their discovery, pyroclastic surges have been shown to be an important lithologic component of many volcanoes.

The destruction of Pompeii and Herculaneum during the A.D. 79 eruption has been much studied in the past, beginning with the visit of Dolomieu to Herculaneum in the 18th century. In early studies, for example Ippolito's (1950), the fate of the cities was attributed to very heavy and rapid fall of pumice and ash in the case of Pompeii and inundation by mudflows in the case of Herculaneum. This view was held by Rittmann (1950) and echoed widely in the geological literature. Following the recognition of nuées ardentes in the 1902 eruption of Mont Pelée, some geologists began to see the Vesuvius eruption in a new light (Lacroix 1908). In two particularly perceptive papers, Merrill (1918, 1920) proposed that the eruption had produced nuées ardentes and made several observations that supported his case. Merrill's work went unnoticed, however, and Rittmann's view prevailed (Maiuri 1977). When the first theoretical models of eruption column behavior had been developed (Wilson 1976), it became obvious that the A.D. 79 eruption had involved both pyroclastic surges and pyroclastic flows (Lirer et al. 1973, Sparks & Walker 1973). Sheridan et al. (1981) identified surges and pyroclastic flows in the lower sequence in Herculaneum but still proposed mudflows and lahars for the upper layers as part of a phreatomagmatic model of the eruption. Sigurdsson, Cashdollar et al. (1982) presented a reconstruction of the eruption on the basis of a combination of the stratigraphic evidence from the volcanic deposits and the letters of Pliny the Younger. They contrasted the different effects of the pumice-fall, pyroclastic surges, and pyroclastic flows on communities around the volcano, and established a chronology for the main events during the eruption. While that paper was in press, new discoveries were made at the excavation of the Herculaneum waterfront; these are presented here.

This paper describes the deposits resulting from the A.D. 79 eruption of Vesuvius and reconstructs the processes that occurred during this event. Because it encapsulated and preserved two Roman cities in its deposits, the eruption has been considered of unique cultural significance. The eruption is, moreover, of great importance for the history of the science, as it is the first volcanic event for which we have a detailed eyewitness report (Pliny the Younger, in Radice 1969).

## *Geological Setting and Prior Volcanic Activity*

The volcanic activity of Vesuvius, along with other volcanic and seismic activity in Italy, can be ultimately attributed to the steady convergence of the Eurasian and African plates. The African plate moves northward at about 2.3 cm/yr (LePichon et al. 1973) and continues to shrink the Mediterranean basin. A major consequence of this process is subduction of the Mediterranean seafloor to the north, underneath Sicily and Calabria, which has in turn generated the Calabrian volcanic arc (Figure 1). To the north, however, most of the region of Calabria, eastern Sicily, the southern Tyrrhenian basin, and southwestern Italy is underlain by a northwesterly dipping Benioff zone as the trace of subduction curves under the Appennine mountain chain (Gasparini et al. 1982). This trend also continues underneath the Campanian and Roman volcanic provinces (Civetta et al. 1978). The tectonic picture is further complicated by the Tyrrhenian basin, which has been opening since the late Miocene, perhaps in response to the subduction process.

The Vesuvius region is thus located between the opening Tyrrhenian basin to the west and the westward-migrating Appennine compressive front to the east. The tectonic relations indicate subduction of the continental lithosphere to the west, underneath the Appennine nappes, generating a westward-dipping Benioff zone, some 300 km deep under Vesuvius (Gasparini et al. 1982). The nearest volcanoes to Vesuvius are the Phlegrean Fields caldera 30 km to the west, the volcanic islands of Ischia and Procida at the mouth of the Bay of Naples, Roccamonfina 60 km to the northwest, and Vulture 100 km to the east.

The products of Vesuvius are dominantly basic, silica-undersaturated, potassic magmas, ranging in composition from tephrites to leucitites. Most of the activity of Vesuvius has consisted of numerous small eruptions of lavas, accompanied by minor pyroclastic eruptions which have built up the ancestral Somma stratovolcano. The age of the ancestral Somma volcano is not known, but a K–Ar age of 0.3 m.y. was obtained from a lava sample from a 1345-m-deep well drilled near the volcano (Principe et al. 1982).

About 17 000 years ago a major Plinian explosive eruption occurred which deposited a widespread layer known as the "basal pumice" (Delibrias et al. 1979). This event is generally regarded as marking the termination of Monte Somma's activity and the birth of Vesuvius. Now, Somma Vesuviana is a composite central volcano consisting of the older Monte Somma and the younger cone of Vesuvius (Figure 2). The huge explosive eruption of the basal pumice 17 000 years ago may have collapsed the summit of Monte Somma and formed the caldera-like structure in which the modern cone of Vesuvius is nested. The Monte Somma caldera wall has restricted the spread of lava flows from Vesuvius; consequently lava flows younger than 17 000 years are not found on the north flank of Monte Somma. Similarly, the caldera rim influenced the northward distribution of pyroclastic flows and surges in A.D. 79.

O. Louis Mazzatenta

*Figure 2. A view of Vesuvius from the air showing the modern cone and, in the foreground, the caldera rim of the older Monte Somma.*

The eruption of the basal pumice was the first of Vesuvius' eight major explosive eruptions in the past 17 000 years. These were mainly highly explosive phonolitic eruptions that produced Plinian pumice-fall deposits, often associated with pyroclastic flows and surges. Delibrias et al. (1979) studied their general stratigraphy and chronology, and determined radiocarbon ages of these explosive events. Typically, a 400- to 4000-year period of volcanic quiescence has preceded each Plinian ex-

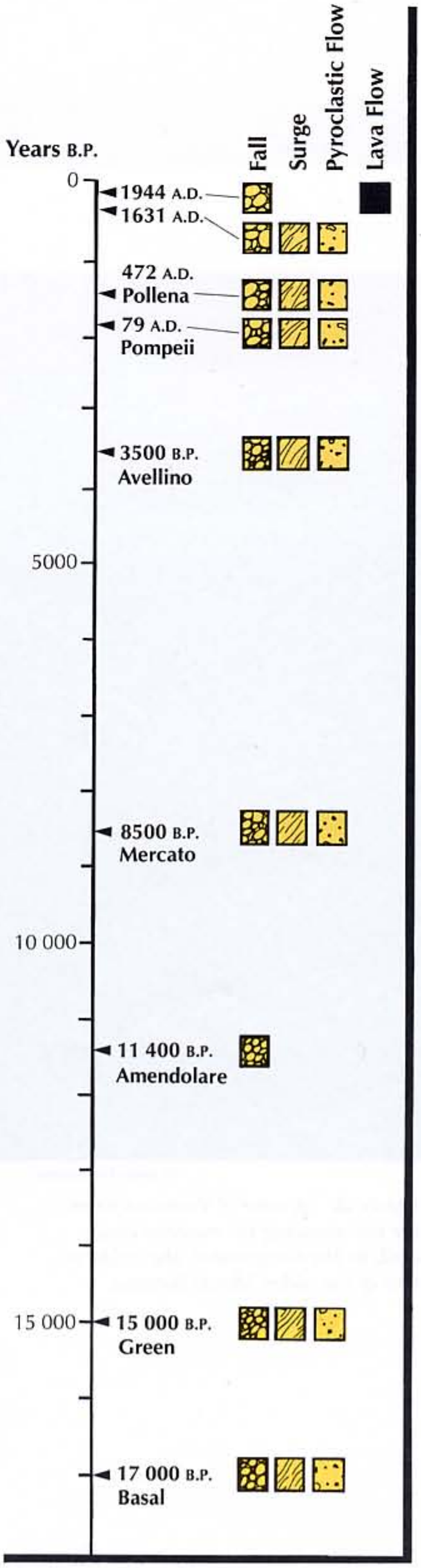


*Figure 3. Generalized volcanic stratigraphy of Vesuvius, showing the timing and types of deposits of the eight major explosive eruptions and the latest eruption in 1944 (after Delibrias et al. 1979).*

plosive event, as marked by well-developed paleosols under the Plinian deposits (Figure 3). Each Plinian eruption is regarded as the beginning of a new eruptive cycle. The major volcanic cycle that preceded the A.D. 79 eruption was the fifth cycle of Vesuvius' activity and began with the Plinian eruption of the Avellino pumice, which was deposited on a thick paleosol radiocarbon dated as 3760 ± 70 B.P. Lirer et al. (1973) studied the ash- and pumice-fall deposit from the Avellino eruption in detail, and established that fallout occurred primarily to the east and east-northeast of the volcano during this event. This eruption was very similar in magnitude, composition, and extent to that of A.D. 79, and also produced pyroclastic flows and surges in the final stages of the event.

Many historians writing in the Augustan age (31 B.C. to A.D. 14), including Diodorus Siculus, Vitruvius, and Strabo, recognized Vesuvius' volcanic character. Strabo describes the summit as barren and ash-colored. Before the large A.D. 79 eruption, Vesuvius is generally believed to have been a single truncated cone. The idea that Vesuvius had a single peak before A.D. 79 stems mainly from Strabo's first century B.C. descriptions: "The summit of Vesuvius is in large part flat." Similarly, Dio, writing in the third century A.D., states that "once Vesuvius was equally high at all points." A wall painting in the House of Centenary in Pompeii shows a mountain with a single peak; this has generally been taken as the appearance of Vesuvius prior to the A.D. 79 eruption. Other Roman wall paintings of a twin-peaked mountain have however been described from Herculaneum (Stothers & Rampino 1983) and thus the matter remains open. It is clear nevertheless that the Monte Somma ridge influenced the distribution of the deposits of the A.D. 79 eruption and therefore caldera collapse must have occurred either before or in the early stages of this eruption.

## *Volcanic Processes and Field Characteristics of the A.D. 79 Deposits*

Field studies of the volcanic deposits of the A.D. 79 eruption indicate that a variety of processes operated during the event. The nature and timing of these processes can be inferred from the physical properties and relative stratigraphic position of different eruptive units.

Fallout of tephra from a tall column was an important process during most of the eruption, particularly at the beginning. This so-called Plinian phase, named in honor of Pliny the Younger, produced a widespread deposit, mantling the local topography and decreasing in thickness downwind from Vesuvius (Figure 4). Typically the fall deposit is well sorted, grain size decreasing systematically with distance from the source (Lirer et al. 1973). An exception to this is the basal ashfall layer of the A.D. 79 sequence, a deposit that remains fine-grained even close to source, despite having dispersal characteristics unequivocally related to tephra fallout. This is typical of deposits formed by phreatomagmatic eruptions in which magma fragmentation is enhanced by the interaction of nonjuvenile water, and deposition is modified by premature fallout as accretionary lapilli (Self & Sparks 1978).

In Oplontis, Boscoreale, and many other sites south of the volcano, layers of thin, dark gray, fine-grained but poorly sorted ash occur within the upper part of the pumice-fall deposit. These layers contain fragments of roof tiles and other building material, as well as carbonized wood (Figure 5) and in some cases human skeletons. The occurrence of cross-bedding and dune structures in some of the layers indicates transport of

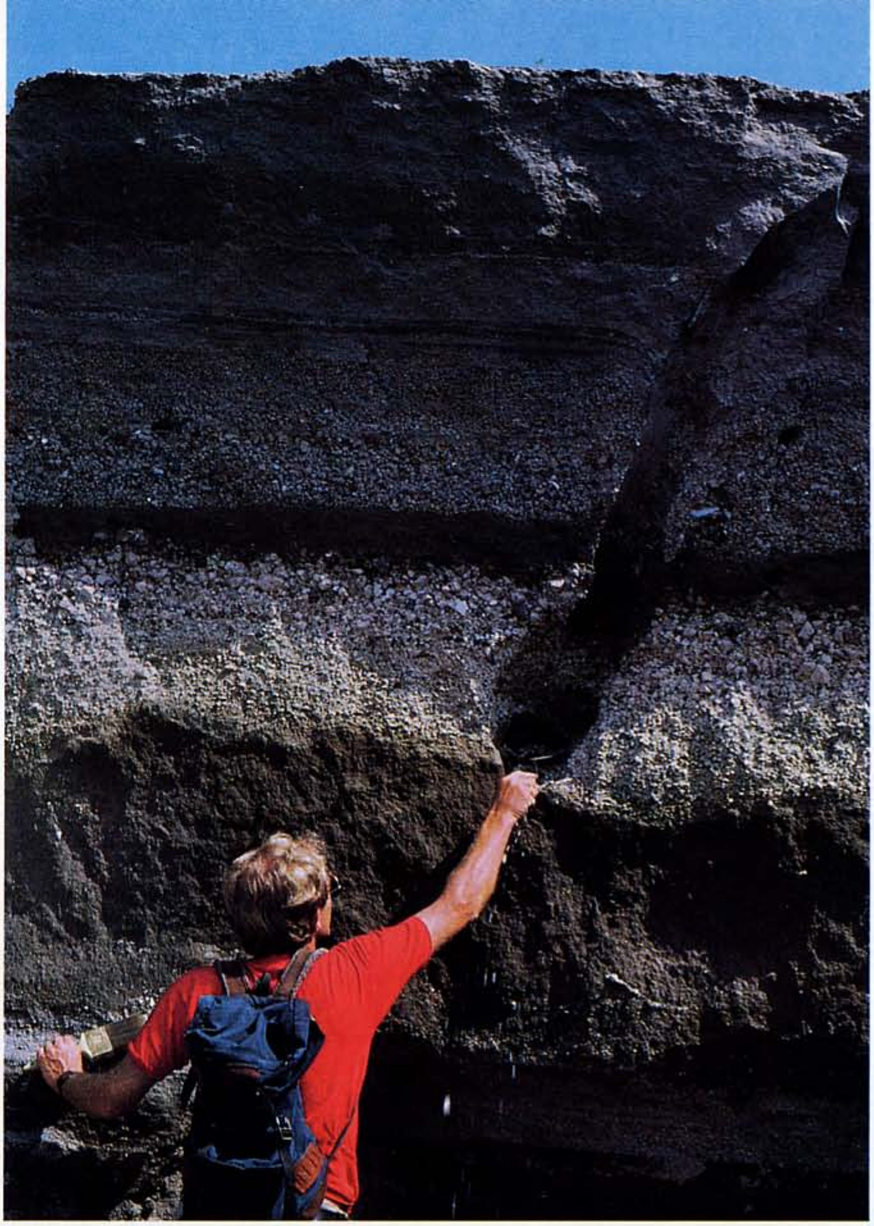

*Figure* **4** (left). *Typical view of the stratigraphy of the* A.D. *79 volcanic deposit near Terzigno, resting on dark brown soil. A tree has left its hollow impression in the deposit. Immediately above the soil is a thin (4 cm) gray layer of initial ashfall (A-1), overlain by thick, coarse white pumice-fall (A-2). This is in turn overlain by the dark gray surge S-2, gray pumice-fall, and several other surge layers. Figure* **18** *(page 349) shows a stratigraphic section of this locality.* **5** (above). *Surge layer with abundant carbonized vegetation, sandwiched between pumice-fall units (S-2 surge at Terzigno). Note the sharp upper surface and more irregular lower surface of the massive surge.*

a bed-load by traction and saltation, and rules out fallout of tephra. Following studies of the deposit in Pompeii, it was proposed that these distinctive layers were the products of pyroclastic surges (Sigurdsson, Cashdollar et al. 1982). These deposits thus are more informative than surge deposits of most other volcanoes, as they contain abundant examples of the effects of surges on buildings and common objects, providing evidence of the type and magnitude of the physical processes involved.

In Herculaneum, Oplontis, and several other regions around Vesuvius, the surge layers are associated with pyroclastic flow deposits. They are thick and massive layers of partly indurated, very poorly sorted tephra (Figure 6), generally lacking building fragments and other artifacts, but clearly deposited at high temperature (Kent et al. 1981). Each pyroclastic flow is underlain by a surge layer, but the latter has a much more extensive distribution radially around the volcano. The pyroclastic flows, on the other hand, form localized valley fills and fans and their distribution is clearly controlled by the local topography.

Juxtapositions in the field indicate that flows and surges are closely related and that they were probably generated during the same event. The origin of pyroclastic flows and pyroclastic surges during the A.D. 79 eruption of Vesuvius is best accounted for by collapse of the eruption column (Sparks & Wilson 1976).

Such nuées ardentes and their lethal effects are well known from studies of the eruptions of Mont Pelée in 1902 (Lacroix 1904), Mount Lamington in 1951 (Taylor 1958), and El Chichon in 1982 (Sigurdsson, Carey et al. 1984). The highly inflated and turbulent nuée ardente rapidly segregates by differential settling of large, dense clasts into a lower high-concentration flow at ground level and an overlying fine-grained suspension. The lower (high-concentration) component forms pyroclastic flows that are strongly controlled by topography, because of high concentration of particles, high density, and laminar flow behavior.

*Figure **6.** A massive, pumice-rich pyroclastic flow from the A.D. 79 eruption in a quarry near Cava Montone, 5 km west-northwest of the Vesuvius crater. At base is brown soil, overlain by about a 1-m-thick surge layer (S-2). A band of lithics and pumice blocks occurs in the upper part of the flow, which is overlain by light brown surges. The succession is capped by the dark lava flow of 1872.*

The upper (low-concentration) component of the nuée ardente is very turbulent, suffers much less drag and internal friction, and consequently surges ahead of the pyroclastic flow and forms a pyroclastic surge. Because of its internal turbulence and low density, the pyroclastic surge can spread radially from the crater with little regard for topography. The deposit remaining on the ground after the passage of a surge may be very thin (1 to 15 cm) as a consequence of the small bed-load or particle concentration in the active surge cloud. Both pyroclastic flows and surges are hot during transport, because the nuée ardente ingests a relatively small volume of air. Pyroclastic surges contain a much larger fraction of air than pyroclastic flows, and are therefore generally cooler.

The uppermost layers of the deposit from the A.D. 79 eruption are dark gray, silty-sandy beds that rarely extend more than 15 km from the volcano. They are characterized by abundant accretionary lapilli and many show cross-bedding or dune structures. The presence of accretionary lapilli is good evidence of deposition from water-rich eruption clouds; these layers can be interpreted as products of phreatomagmatic explosions that generated wet surges and ashfall. Condensation of water in these clouds enhanced aggregation of fine ash particles and led to formation of accretionary lapilli.

Since the total deposit from the A.D. 79 eruption of Vesuvius is a complex, multilayer deposit, an alphanumeric scheme is used to identify the various layers. Thus the fallout layers are numbered sequentially from A-1 (the basal fine ash) to A-9. Similarly, the pyroclastic surge layers are numbered from S-1 to S-7. Pyroclastic flow deposits are labeled F-1 to F-6, from lowermost to topmost flow. Correlated phreatomagmatic accretionary lapilli beds from the final stage of the eruption are designated C-1, etc., although most have not yet been differentiated into units that can be mapped.

## *Distal Stratigraphy*

In the region of Campania around Vesuvius the Roman soil is a dark brown, humus-rich layer, 0.5 to 1 m thick, and easily identified because of its high content of artifacts and its peculiar undulating surface.

Near Terzigno (Figure 4) for instance, undulations have an amplitude of 20 to 30 cm and a wavelength of about 1 to 2 m. They are caused by low, conical mounds, which often contain a hollow, vertical pipe, 2 to 10 cm in diameter. The mounds are so widespread and uniform that they can only be products of Roman cultivation and most likely are analogous to the mounds of soil piled up around the base of vines in the vineyards of Campania today.

Shortly after midday on 24 August in A.D. 79 a rain of ash and pumice began, which gradually buried the vineyards, estates, and towns south and southeast of Vesuvius. On land, this deposit can be traced as far as Agropoli, 74 km southeast of Vesuvius. Much of the distal ashfall has been eroded, however; accounts written shortly after the eruption tell of much more extensive ashfall. Cassius Dio, writing in about A.D. 150, notes that ashfall occurred in North Africa, Egypt, Palestine, and elsewhere in the Levant following the eruption (Cary 1915). Long-range dispersal of the ash was therefore very similar to the easterly dispersal of the Campanian tephra from the great explosive eruption of the Phlegrean Fields caldera, about 35 000 B.P. (Cornell et al. 1983). Most of the fallout deposit is coarse pumice. It is underlain by a thin grayish-to-pink, fine-ash layer east of the volcano (layer A-1), which is a product of fallout from the first explosive phase of this eruption. This layer is exposed around the villas at Terzigno to the east and Cava Montone, northwest of Vesuvius. It consists of vesicular to poorly vesicular glass and crystal fragments (Figure 7). The layer is fine-grained throughout, with a median diameter of 25 μm at 6 km from source. The presence of small accretionary lapilli, the high degree of fragmentation, and the variable vesicularity of the tephra indicate a phreatomagmatic explosion. The distribution of fallout of the A-1 layer (Figure 8) is almost due east of the crater. This is clearly quite different from the dispersal of the subsequent pumice fallout A-2 to A-6, and indicates that the initial explosion, which generated the A-1 ash, produced a low eruption column, which was dispersed easterly by low-level local winds and was not subject to stratospheric winds. The total volume of the layer is only $7 \times 10^6$ m$^3$ of tephra.

The main features of the overlying pumice-fall (A-2 to A-6) have been described by Lirer et al. (1973). Their study was, however, of the deposit

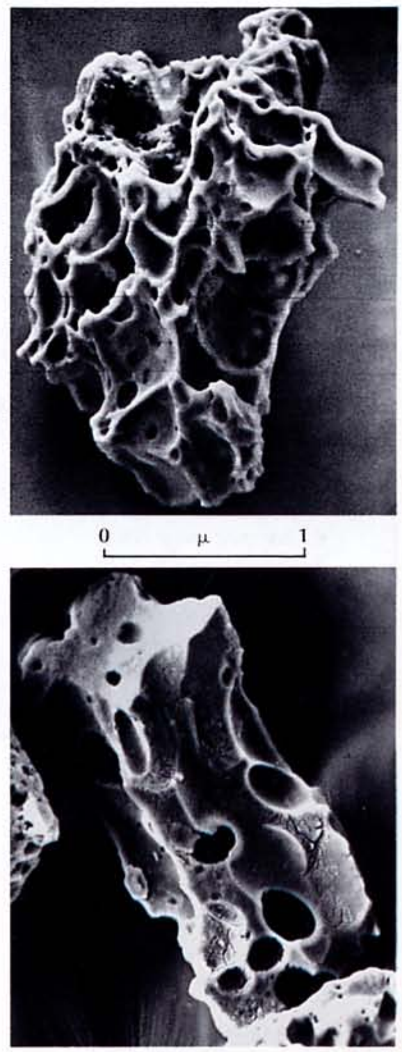


*Figure 7. Scanning electron micrographs of tephra from the ashfall layer A-1.* Upper: *vesicular glass fragment.* Lower: *poorly vesicular glass fragment.*

south of Vesuvius, whereas the present study adds many new datum points nearer to source, west, north, and east of the crater, and restudies the southern fallout deposit.

The pumice-fall deposit is relatively coarse, with a distinct color change in the middle, from a lower white part to an upper greenish gray part (Figure 9). The color change is the result of a change in composition of the erupting magma, and thus reflects the compositional gradient in the volcano's reservoir. The fallout stage of the eruption can therefore be divided into two phases: the earlier white pumice and the later gray

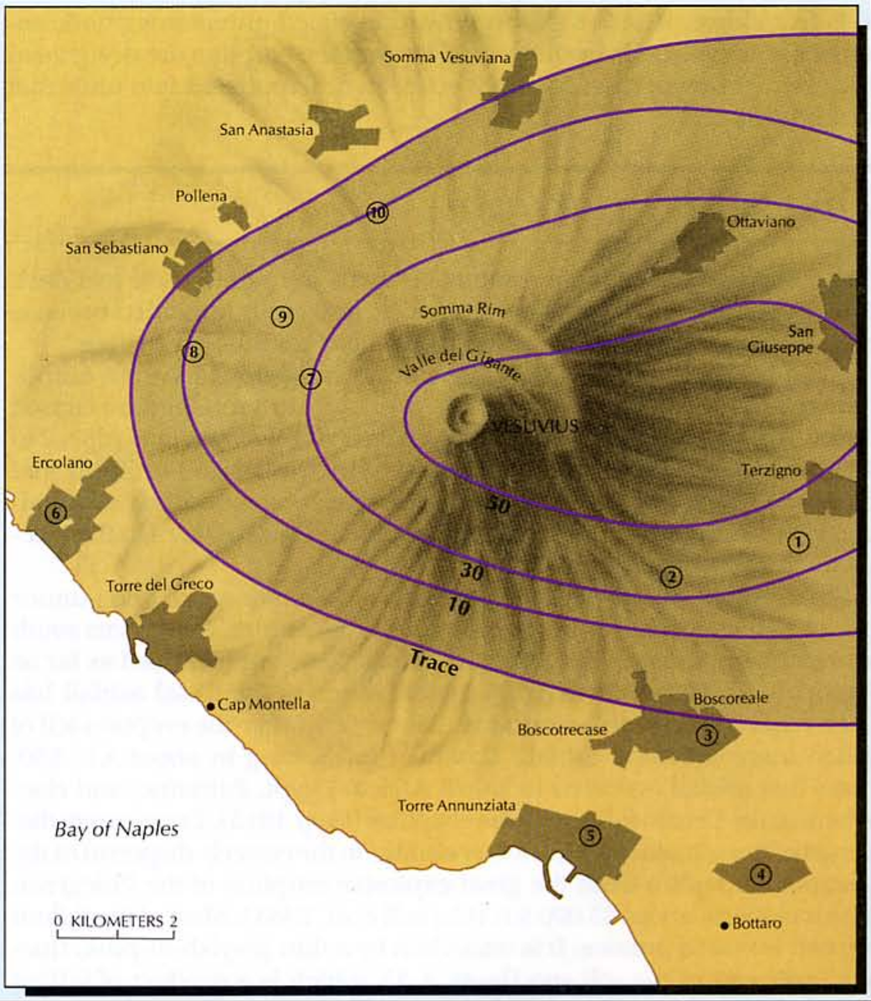


*Figure 8. Isopach map of the ash-fall layer A-1, showing easterly dispersal from the crater (contours in millimeters). Discussion of the sites (numbered on the map south and clockwise around the volcano) begins on the indicated page:*

1. *Terzigno (page 344)*
2. *Pozzelle (page 347)*
3. *Boscoreale (page 349)*
4. *Pompeii (page 350)*
5. *Oplontis (page 353)*
6. *Herculaneum (page 357)*
7. *Observatory Hill (page 371)*
8. *Cava Montone (page 371)*
9. *Casa Baroni (page 372)*
10. *Monte del Vente (page 373)*

pumice. This compositional change in the fallout deposit also corresponds to an important change in density of the tephra. In the white pumice layer, tephra density ranges from 0.5 to 0.6 g/cm$^3$, but increases in the gray pumice to a maximum of about 0.9 g/cm$^3$ in the middle of the gray fallout layer. This density variation may have influenced the eruption column behavior. The axis of fallout of both gray and white pumice layers is to the southeast (Figure 10). The isopach fallout axes are remarkably close, trending 155° for the gray and 140° for the white pumice. This may indicate either a slight shift of the stratospheric wind direction during the eruption, or slightly different wind direction at the stratospheric level where the gray pumice was being transported.

In general Plinian fallout deposits thicken toward the source. The A.D. 79 pumice deposit is an exception to this rule, however, as seen in Figure 10. Both the gray and the white pumice deposit bulge just south of Pompeii (10 to 15 km from the crater) and consequently the pumice deposit becomes thinner northward, from a maximum of about 280 cm in Pompeii to about 180 cm in the saddle north of Pompeii (about 5 km from the crater). During the A.D. 79 eruption, the maximum thickness of the pumice fallout was thus attained 10 to 15 km from the source (Figure 11). A similar condition prevailed during the great Taupo eruption in New Zealand, where the maximum thickness of the pumice-fall deposit was 20 km from source (Walker 1980).

The thickness of the fallout deposit along the dispersal axis downwind

*Figure 9. The A.D. 79 pumice-fall deposit near Stabiae, with lower white pumice (A-2) and upper gray pumice layers (A-3 to A-6).*

of the volcano is shown in Figure 12 for both the white and the gray pumice layers. This illustrates the area of maximum thickness over Pompeii, and serves as a comparison with thickness of fallout deposits from several major Plinian eruptions. The volume of the white and the gray pumice fallout deposits has been determined on the basis of the isopach map (Figure 10), by the method of Rose et al. (1983). In these calculations the observed isopach area per thickness trends has been extrapolated to the 1-μm level, giving 6.4 $km^3$ and 2.5 $km^3$ tephra volume for the gray and the white pumice layers, respectively, corresponding to 2.6 $km^3$ and 1 $km^3$ dense-rock-equivalent volume, assuming a density of 1.0 $g/cm^3$ for the deposit and 2.5 $g/cm^3$ for the magma. Total volume is estimated at more than three times the earlier estimate of Lirer et al. (1973).

The grain size of fallout deposits is a useful indicator of the energetics of the eruption column and atmospheric transport. The maximum diameter of pumice and lithics fragments has been determined in the gray and the white fallout deposits at many localities. The results are shown on the isopleth maps (Figures 13 & 14) based on the average of the maximum diameters of the five largest pumice and lithics fragments found in a 1-$m^2$ area at each locality. Lithics, which comprise 10 to 15% of the deposit, are more representative of transport dynamics, since they do not break upon impact. Pumice isopleths are, on the other hand, conservative because they do break. These isopach maps of pumice and lithics for the southern or distal area are in general agreement with the work of

Lirer et al. (1973). Figures 15 and 16 show new data on pumice and lithics isopleths for the proximal fallout.

The isopleth maps of pumice and lithics show that the largest fragments fell near the vent, and decrease with distance from source; thus these maps show no eccentric features analogous to the secondary thickness maximum of the isopach maps. This indicates that the secondary thickness maximum must be linked to both the size frequency distribution of pyroclasts produced by magma fragmentation and the lateral transport by upper-level winds. The high accumulation at the secondary

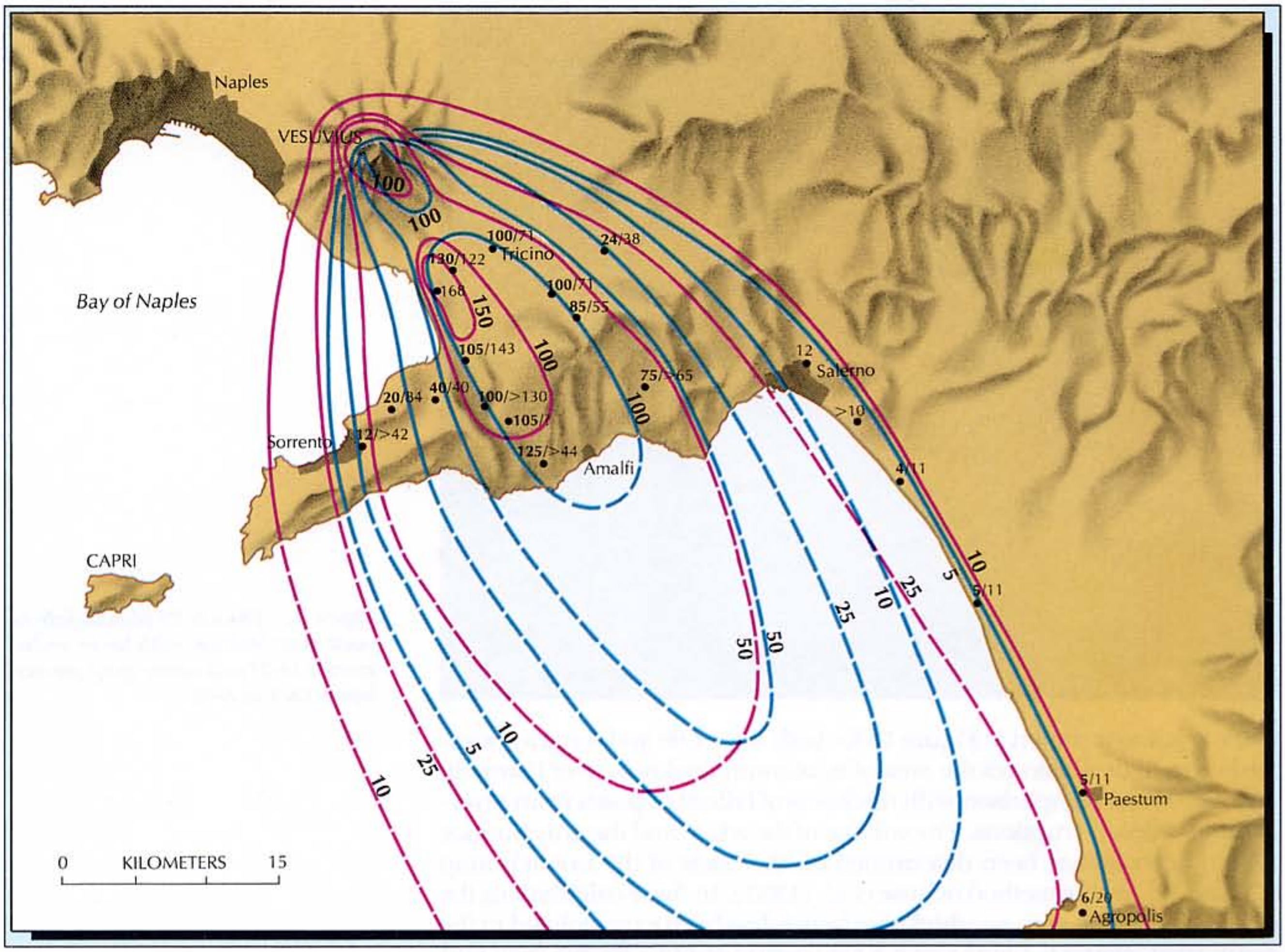


*Figure **10**. Extent (in centimeters) of pumice-fall. Numbers on the isopachous lines (red for gray and blue for white pumice-fall) were extrapolated from values at datum points (regular type for gray and bold type for white pumice-fall).*

thickness maximum results from deposition of the coarse pyroclasts that were produced quite abundantly by fragmentation but were transported downwind from the crater as a result of their high-altitude ejection and subsequent fallout through the atmospheric wind field.

It is evident from Figures 15 and 16 that equivalent isopleths for pumice and lithics in the later gray fallout are much more extensive than in the earlier white fallout layer. This was also observed by Lirer et al. (1973) who used the greater dispersal of gray ejecta as evidence for a higher eruption column. On the basis of the total volume of gray and white tephra erupted during the Plinian phase and the duration of each event (as estimated from the relative thickness of each layer and a total duration of 19 hours), the height of the eruption column has been calculated from the plume equation of Morton et al. (1956) as modified for volcanic eruptions (Wilson et al. 1978). Accordingly, with a duration of seven hours for the white pumice fallout (Plinian stage) (Figure 47) and

12 hours for the gray pumice fallout, eruption columns would be 27 km and 33 km, respectively.

## *Proximal Stratigraphy*

The best evidence of volcanic processes during the A.D. 79 eruption comes from study of the volcanic deposits in the archaeological sites near the volcano (Figure 8). The following description of the important proximal sites begins at Terzigno, east of Vesuvius, and proceeds clockwise around the volcano.

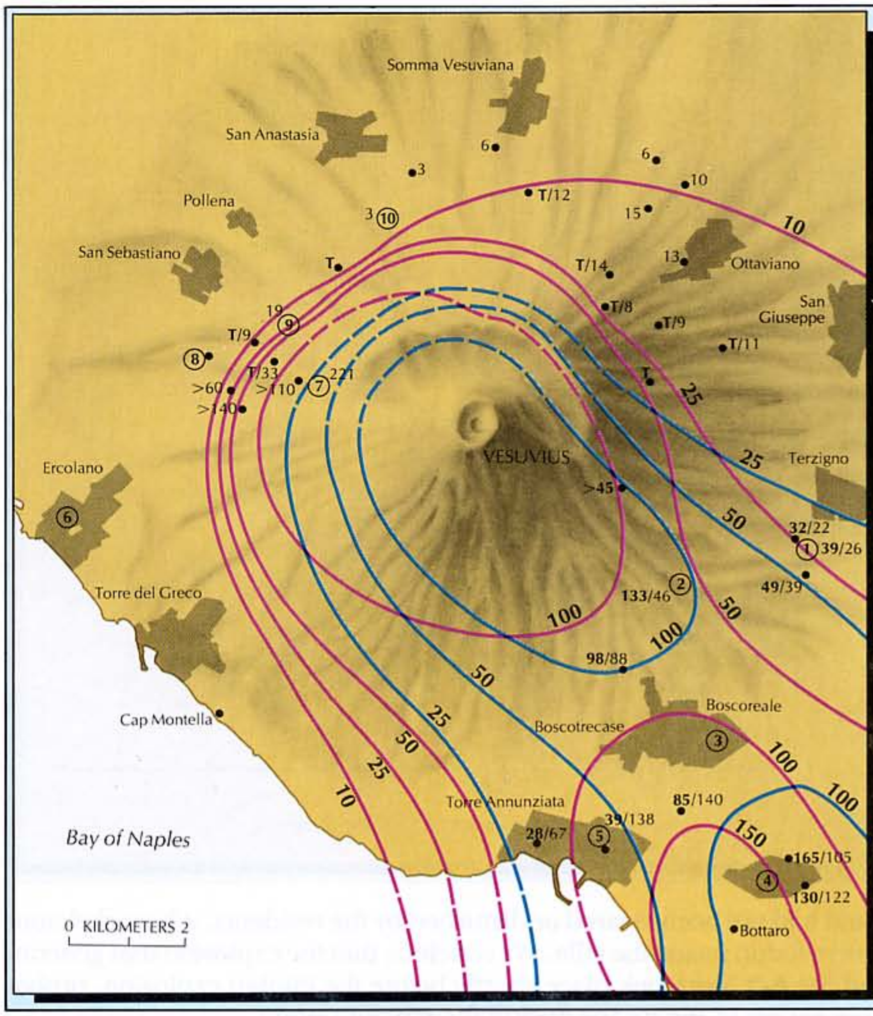


*Figure* **11.** *Extent (in centimeters) of pumice-fall near Vesuvius. Numbers on the isopachous lines (red for gray and blue for white pumice-fall) were extrapolated from values at datum points (regular type for gray and bold type for white pumice-fall). See Figure* **8** *for the key to site numbers.*

### Terzigno and Pozzelle Quarries

In the spring of 1981 a new Roman archaeological site was discovered in a large quarry south of Terzigno, only 6 km east of the crater of Vesuvius. Shortly thereafter another site was discovered in an adjacent quarry, 1 km to the north. These sites are currently under excavation by Elena Menotti, who has shown that they represent *villae rusticae,* wine-growing estates, that were destroyed during the A.D. 79 eruption. In this area the deposits from the eruption are overlain by about 10 m of ejecta from later eruptions and capped by the lava flow of 1834. The A.D. 79 deposit, which can be traced throughout the Terzigno quarries, overlies a rich brown soil with the characteristic hummocks of the Roman vineyards.

*Terzigno*

A stratigraphic section of the A.D. 79 volcanic deposits is shown in Figure 18. At Terzigno the first products to be deposited consisted of light gray, silty ash to a thickness of between 3 and 6 cm (layer A-1). The A-1 layer is well preserved in all localities and there is no sign of its weathering or erosion before deposition of the pumice-fall. Evidence from the excavation of the northern villa rustica in the Terzigno quarry indicates that the pumice-fall may have rapidly followed the deposition of the A-1 ash layer. Here the fine ash layer lies in the doorway and courtyard of the villa and had not been cleared or disturbed by the residents, whose skeletons were found inside the villa. We conclude that the explosion that generated the A-1 layer took place shortly before the Plinian explosion, probably earlier in the day or during the previous night.

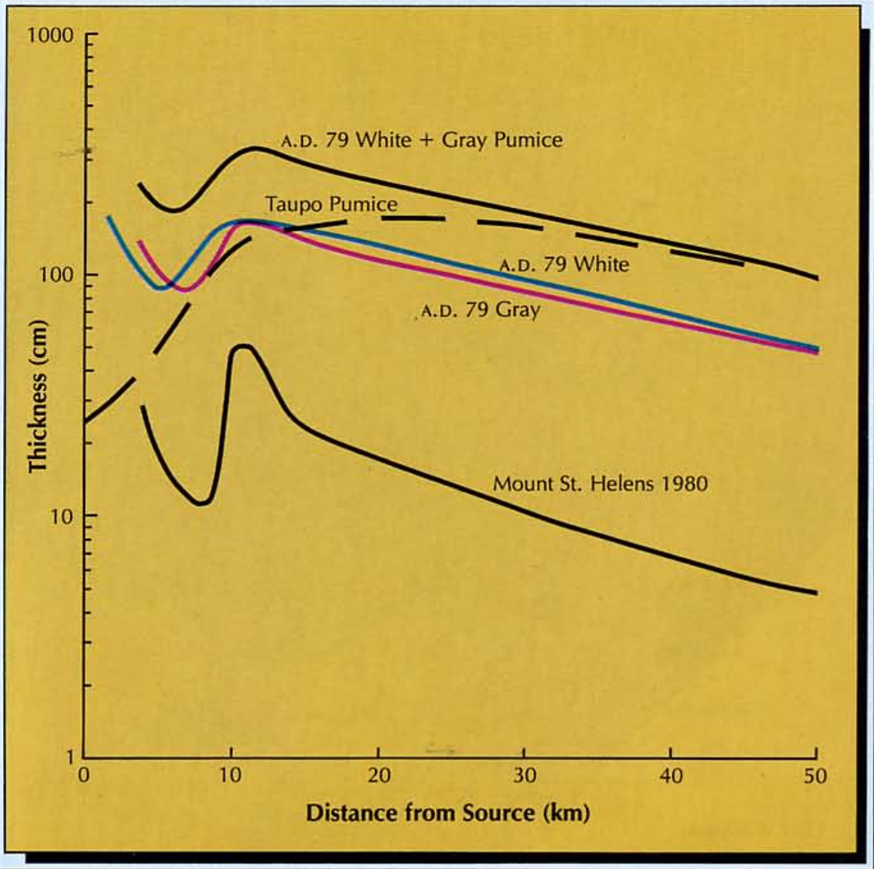


*Figure* **12.** *Variation in thickness of the A.D. 79 pumice-fall deposit with distance from source, along the dispersal axis. Data for the gray (red) and white (blue) pumice layers and the total fall of the A.D. 79 eruption are shown, together with data from Taupo, New Zealand (Walker 1980) and Mount St. Helens, Washington (Carey & Sigurdsson 1985).*

The evidence of volcanic activity before the noontime explosion may explain one of the major puzzles raised by Pliny's letters — the message from his friend Rectina. As he was about to leave Misenum on a voyage toward Vesuvius to study the natural phenomenon, Pliny the Elder received a message and a plea for help from Rectina, a woman who lived near the volcano. Pliny subsequently changed his research expedition into a rescue mission and called out part of the Roman fleet to accompany him. A message sent from a villa near Vesuvius during the great noontime explosion could not possibly have reached Pliny the Elder at Misenum before his departure in the early afternoon. Rectina's messenger must therefore have set off from Vesuvius on the 40-km land journey well before the noon explosion and Rectina's fear of danger from the volcano was most likely due to an event earlier that day or the previous night, namely the small explosion that deposited layer A-1.

Following the deposition of layer A-1, continuous fallout of coarse pumice deposited layers A-2, A-3, and A-4. Near the southern villa rustica a total of 58 cm of pumice-fall accumulated during this phase as opposed to only 35 cm near the northern villa. The contrast in thickness demonstrates the rapid thinning of the pumice-fall deposit to the northeast of the volcano.

Fallout of pumice was interrupted by the emplacement of the first surge to affect the Terzigno area (S-2). This surge damaged the villae rusticae as evidenced by the occurrence of minor building fragments in the deposit. Transport of building fragments was limited, however, to about 5 m downwind, suggesting a relatively low destructive capacity. Passage of the surge laid down a predominantly massive, sandy layer, 7 to 24 cm thick, with some faint stratification, and occasional dune structures. In this and other areas around the volcano the S-2 surge is split into two units by a 0.5-cm-thick, sandy, well-sorted lens.

A deposit from the first surge generated by the eruption (S-1) is not found in the Terzigno area, indicating that it was weaker and less extensive than the second surge east of the volcano. The second and more powerful surge cloud swept over an area already blanketed by the previous pumice-fall. In the southern villa rustica the 58-cm accumulation of pumice had collapsed roofs and the villa had been abandoned. In the northern villa the roof had withstood the 35-cm pumice accumulation, and was therefore still inhabited when the surge struck, as evidenced by two skeletons found inside.

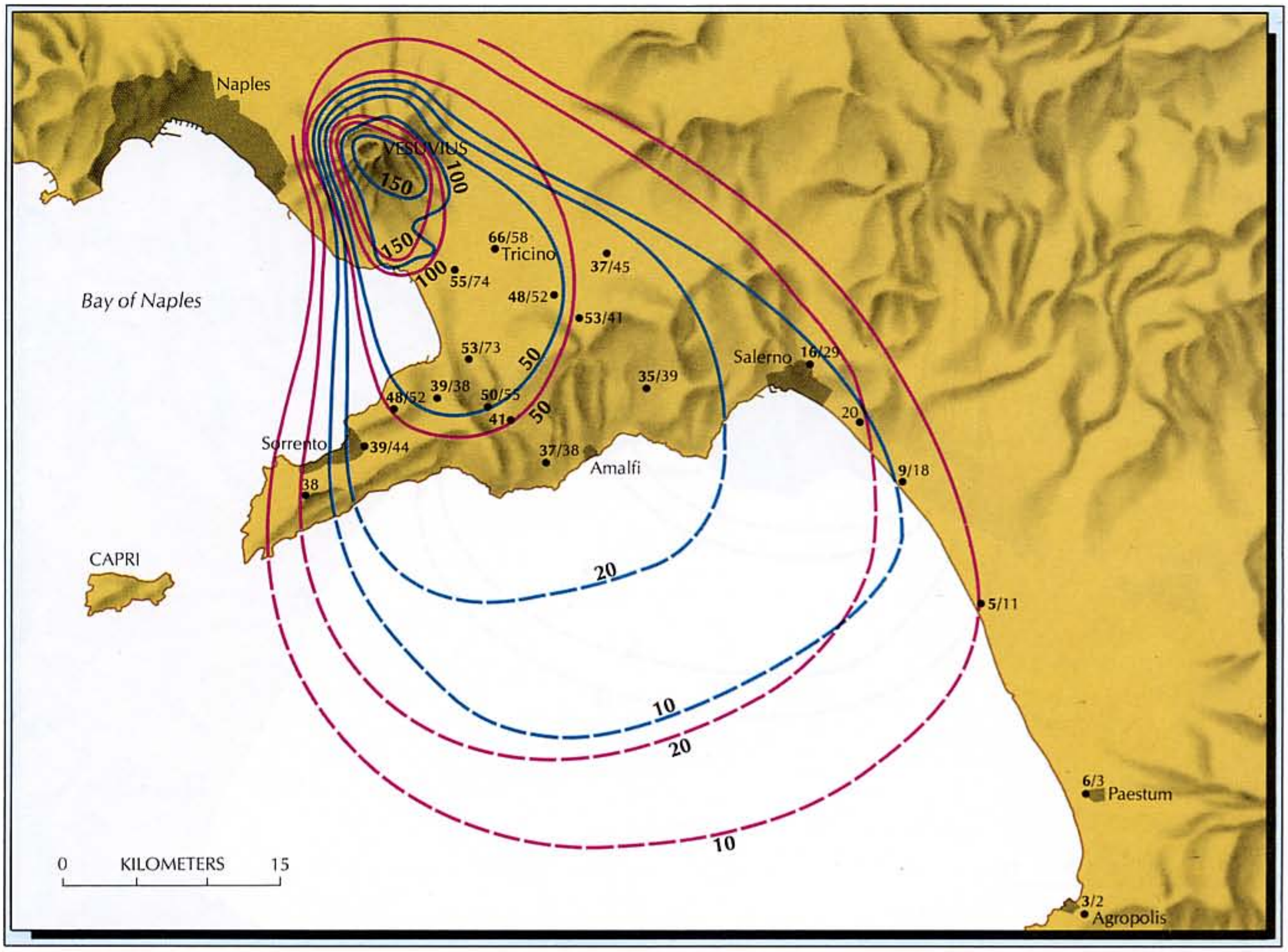


*Figure **13**. Isopleth map of the distribution of maximum diameters (in millimeters) of pumice in the fall deposit. Each datum point (regular type for gray and bold type for white pumice) is the average of the maximum diameter of the five largest clasts found in a 1-m² area of the layer at each locality. Distal diameters noted on the contour lines (red for gray and blue for white pumice-fall) were extrapolated from values at the datum points.*

Gray pumice continued to fall after the S-2 surge emplacement but with a significantly coarser grain size (layer A-5), indicating an increase in the height of the eruption column (Figure 17). Another surge (S-3) swept through the Terzigno area, leveling the remaining structures and depositing 1 to 6 cm of poorly sorted, silty-sandy ash with common, rounded, gray pumice.

The rain of gray pumice continued to mantle the area with a 4- to 6-cm thickness of pumice and lithics (layer A-6). A surge once again descended the east flanks of Vesuvius and inundated the Terzigno area, deposit-

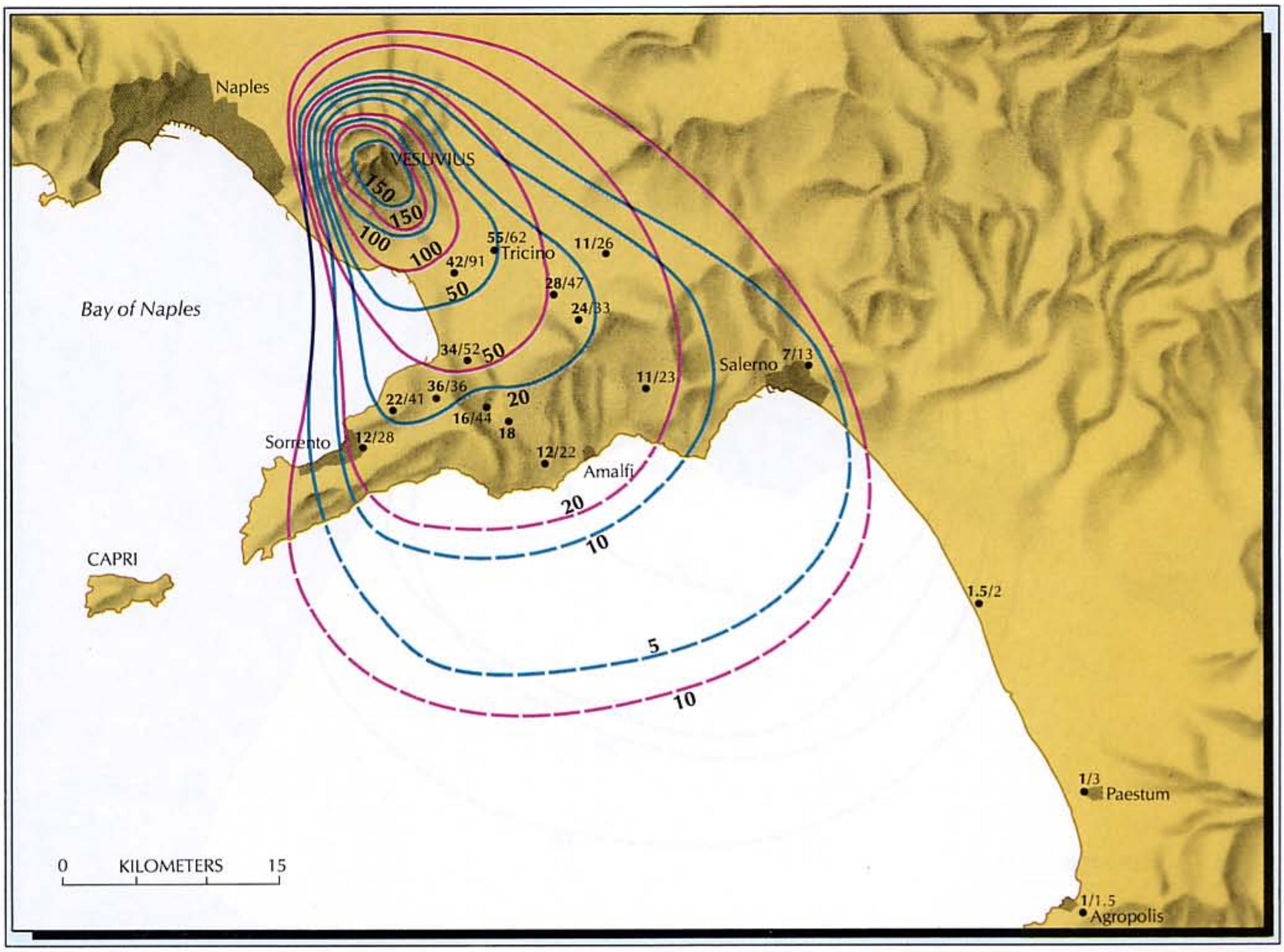


*Figure **14**. Isopleth map of the lithics (in millimeters) in the pumice-fall deposit (red for gray and blue for white pumice-fall). Numbers (regular type for gray and bold type for white pumice-fall) indicate datum points from which the numbers on the distal contours were extrapolated.*

ing a thick (11 to 30 cm) sandy cross-bedded layer with a lower part relatively rich in rounded pumice which grades upward into a lithic-rich top part (S-4). This surge activity was followed by fallout of a significantly different character than the preceding pumice-fall (A-6). The shower consisted of abundant lithic fragments with common carbonate rock fragments and only minor darker gray, juvenile pumice. The smaller thickness and grain size of the layer (A-7) suggest a short duration and a greatly diminished eruption column. More surge activity immediately followed this new fallout phase, laying down two separate dark gray, sandy, lithic-rich deposits with a total thickness of 60 to 140 cm (S-5, S-6). The upper part is generally stratified and cross-bedded while the base is often massive with lenses of rounded pumice, and grades locally into facies that resemble a pyroclastic flow deposit.

Overlying surges S-5 and S-6, is a 7- to 13-cm-thick, poorly sorted, massive ash layer with 5 to 12 mm of accretionary lapilli. This layer and overlying deposits represent a new phase in the activity of the eruption. Above this level are many interbedded minor surges and massive accretionary lapilli beds, with occasional lithic-rich fall layers. All are virtually free of pumice and probably are the result of numerous phreatomagmatic explosions. At Terzigno these layers are ≤ 2 m.

*Pozzelle*

Only 2 km west-southwest of Terzigno is the quarry of Pozzelle which is cut by the lava flow of 1794. Despite its proximity to Terzigno, the section

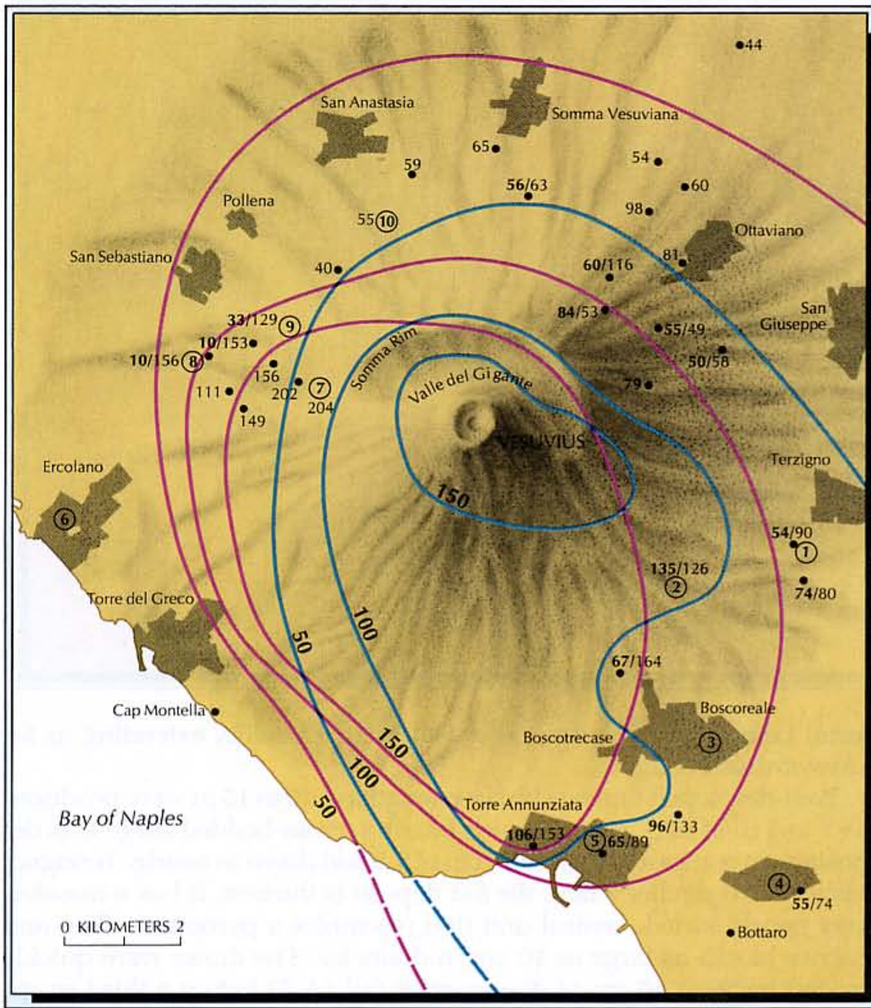


*Figure **15**. Isopleth map of maximum diameters (in millimeters) of pumice (red for gray and blue for white pumice-fall) near Vesuvius. Distal diameters were extrapolated from values at datum points (regular type for gray and bold type for white pumice-fall). See Figure **8** for the key to site numbers.*

of A.D. 79 deposits demonstrates rapid lateral facies variations in the pyroclastic deposits (Figure 19). The A-1 fall layer is continuous through the Pozzelle area and the occurrence of accretionary lapilli supports the suggestion that the initial phase of activity was phreatomagmatic.

Pumice-fall layer A-2 is about twice the thickness as in nearby Terzigno, indicating closer proximity to the main fallout axis. At Pozzelle the A-2 pumice-fall was, however, interrupted by the emplacement of the first surge in the A.D. 79 sequence (S-1), which deposited a 4- to 13-cm-thick layer frequently divided into a lower silty unit with angular white pumice and an upper, sandy, cross-bedded unit with rounded gray pumice. The shift to gray pumice-fall apparently occurred close to the generation of S-1, although in general other stratigraphic sections indicate that some gray pumice-fall occurred before S-1 was emplaced. Deposition of gray pumice mantled the S-1 layer with 10 to 16 cm of ma-

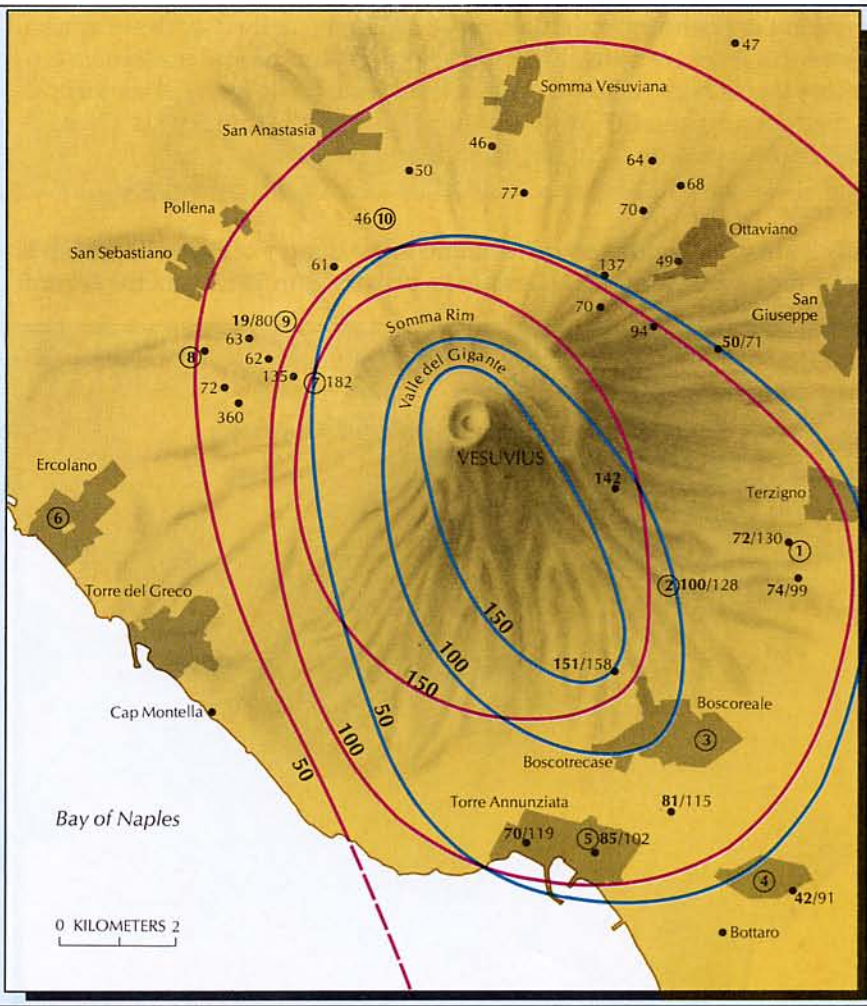


Figure **16.** Isopleth map of maximum diameter (in millimeters) of lithics near Vesuvius. Numbers on contour lines (red for gray and blue for white pumice-fall) were extrapolated from valves at datum points (regular type for gray and bold type for white pumice-fall). See Figure **8** for the key to site numbers.

Figure **17.** Section through the lower part of the A.D. 79 volcanic deposit in the northern part of the Terzigno quarry, showing the stratigraphic succession illustrated in Figure **18.** The scale is 1 m long. Note light gray ashfall A-1 at base, overlying hummocky soil. The top 15 cm of the scale are at the level of the S-5 surge.

terial before the S-2 surge passed through Pozzelle, extending as far eastward as Terzigno.

Well-developed dunes with wavelengths of 10 to 15 m were produced as 1 to 5 m of dark gray, pumice-bearing, cross-bedded surge was deposited, in contrast to the 5 to 24 cm of S-2 laid down in nearby Terzigno. Locally at Pozzelle, where the S-2 deposit is thickest, it has a massive, very poorly sorted, central unit that resembles a pyroclastic flow and carries blocks as large as 20 cm in diameter. The dunes were quickly buried by 36 to 40 cm of gray pumice-fall (A-5) before a third surge, roughly similar in magnitude to S-2, laid down an additional 1.5 to 2 m of cross-bedded dunes with characteristics very similar to those of S-2.

After deposition of the S-3 surge, a significant event in the evolution of the eruptive sequence is exhibited at Pozzelle. Directly overlying the S-3 surge is a massive, pyroclastic debris-flow deposit, 8 m thick in places, consisting of angular lava blocks, mostly 0.5 to 1 m in diameter, but occasionally 3 m (Figure 20). Carbonate blocks as large as 1 m are also present. The blocks are supported by a sandy, dark gray, poorly sorted matrix with minor gray pumice. In general the deposit is normally graded, with most blocks concentrated in the middle of the flow.

This is the first known occurrence of a debris flow in the succession of deposits from the A.D. 79 eruption. It represents the breakup of part of the older structure of the volcanic cone, perhaps during widening of the vent or collapse of the Monte Somma caldera rim. Pozzelle is situated in one of the major topographic depressions on the south flank of Vesuvius and directly below the southern termination of the Monte Somma ridge. The debris flow may have been channeled to this area by the topographic barrier of the Somma ridge. The occurrence of topographically controlled pyroclastic flows at Pozzelle also supports the idea that this area was a major valley through which the more concentrated flows of the eruption were directed.

Following the inundation of the valley by the debris flow, each of four surges deposited 18 to 20 cm of pumice-free, sandy ash. Deposition of accretionary lapilli layers then began, heralding the final phase of phreatomagmatic activity that included both wet fall and surge emplacement. The topmost succession of sandy and accretionary lapilli layers on top of the debris flow must correlate with the deposits on top of the S-6 surge at Terzigno (Figure 18). Since further detailed correlations of the upper stratigraphic sequence at Pozzelle are not yet possible, the stratigraphic position of the debris flow can only be inferred. It is most likely contemporaneous with the S-6 surge, and probably eroded off the missing lower deposits of the S-4 and S-5 surges present at Terzigno.

## Boscoreale

Villa Regina at Boscoreale was discovered during excavations for the foundation of an apartment building in 1977. This villa rustica has now been fully excavated and restored, and the high banks of volcanic deposits surrounding the villa provide excellent sections of the deposits from the eruption of A.D. 79. This locality offers one of the most complete sections of the volcanic deposits and serves as a benchmark for stratigraphic designation of surge events (Figure 21).

Unlike Terzigno and Pozzelle, the initial fall of fine ash (A-1) did not occur at the Villa Regina. Instead, coarse pumice-fall was the first eruptive product to reach the area. The first surge that overran the villa deposited 5 cm of ash (S-1). Useful information about the relative flow intensity of surge clouds can be obtained from in situ plaster casts of trees found in the volcanic deposit (Jashemski 1979). Branches of a tree were broken but not detached and now lie at the level of the first surge pointing away from the volcano in the direction of flow. Extensive building damage is not evident, indicating that S-1 was not particularly destructive although potentially lethal to the residents. This first surge is absent from Pompeii, and apparently did not extend much farther south than Boscoreale.

Fall of gray pumice and lithics continued, depositing a reversely graded 20-cm fall layer (A-4), reflecting a gradual increase in the eruption column height. A second surge spread over Boscoreale, depositing an 8-cm-thick layer (S-2) which is subdivided into two units. The two surge units are separated by a 1-cm well-sorted pumice- and lithic-fall unit. This splitting of the S-2 surge layer is a distinctive feature which is useful in correlating the volcanic stratigraphy elsewhere around the volcano. The thin fall layer suggests that the S-2 layer was produced by two surge events in rapid succession. The surge extended to the villae rusticae at Terzigno and to Oplontis, but not to Pompeii to the south.

The second phase of surge emplacement was followed by an extended period of gray pumice fallout (A-5). The size of pyroclasts systematically decreased with time during this period, indicating a gradual reduction in the height of the eruption column. The pumice-fall was briefly interrupted by the emplacement of a relatively small surge (S-3). Although thin at Boscoreale, this surge apparently had substantial mobility, as it is the first surge to have extended as far southeast as Pompeii.

Another 13 cm of gray pumice-fall (A-6) accumulated before the

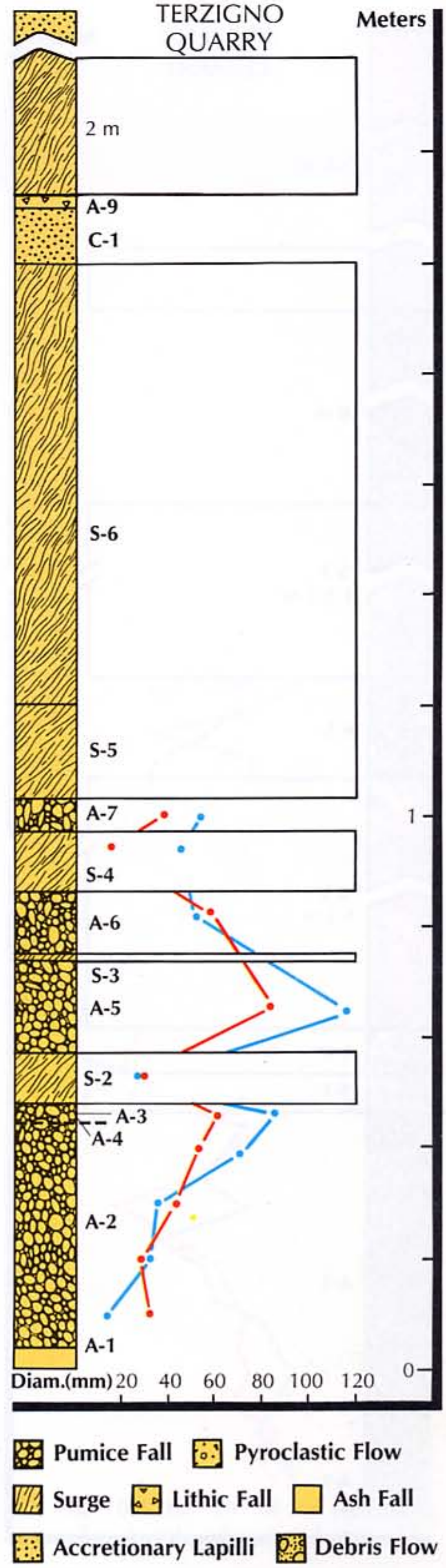


*Figure 18. Stratigraphic section in northern part of the Terzigno quarry, showing fall and surge deposits, and variation in the maximum diameter of pumice (red) and lithics (blue) through the deposit.*

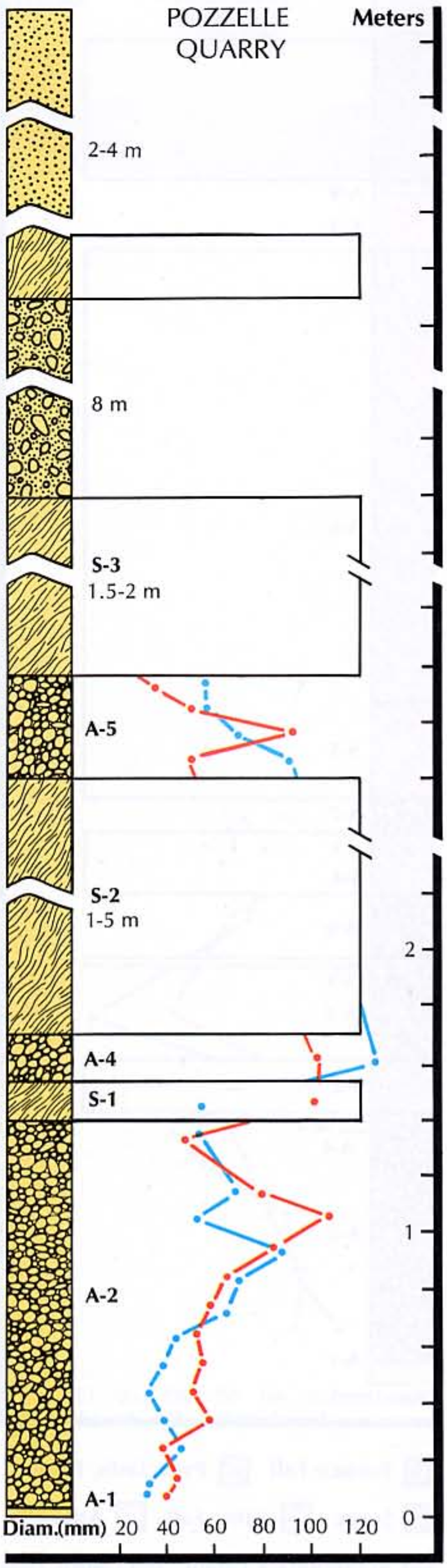


*Figure **19.** Stratigraphic section of the A.D. 79 deposit at the Pozzelle quarry. Note 8-m-thick debris flow on top of surge S-3. Also shown is the variation in maximum pumice (red) and lithics (blue) diameters in the fall deposits. For key to deposit types, see page 349.*

fourth surge (S-4) passed through Boscoreale and again extended as far south as Pompeii where it was the first surge to overwhelm the city. A very brief period of lithic-rich, gray pumice-fall (A-7) then followed before the fifth and significantly more powerful surge (S-5). At this level in the deposit, trees as large as 20 cm in diameter were sheared off and the masonry walls of the villa, which had resisted the early surges, were similarly truncated near the roof level. Dunes with amplitudes of at least 35 cm were produced during this event, and in sections to the north (Campanariello) this deposit thickens to over 2 m and takes on the appearance of a pyroclastic flow.

Minor lithic-rich ashfall (A-8) preceded the emplacement of the thickest and probably the most destructive surge to pass through the Boscoreale area (S-6). Up to 170 cm of dune-bedded, sandy surge with a massive lower part was laid down. The presence of building material and lack of trees protruding into this unit attest to its destructiveness. Toward the north, near Campanariello, a similar thickening and transition to pyroclastic flow occurs as was observed for S-5. Overlying S-6 is the first appearance of accretionary lapilli (C-1), indicating the transition to phreatomagmatic activity; it can be traced to other sections at Boscotrecase and Campanariello where it maintains a similar thickness.

The upper, widespread lithic-rich fall layer (A-9) rests on the accretionary lapilli bed, indicating a brief period of relatively dry, fall deposition. Above this layer is a total thickness of 125 cm comprised of eight successive layers. They are all pumice-free, sandy to silty, alternating lapilli layers and surges.

## Pompeii

In the Middle Ages the region south of Vesuvius, near the Sarno River, was known by the mythical name la Citta, the City. In 1594 the architect Domenico Fontana supervised the digging of a tunnel through this area to divert water from the Sarno River to Count Muzzio Tuttavilla's weapons factory in Torre Annunziata. During the tunneling, the workmen came across ancient painted walls and inscriptions, including one that contained the words *"decurio Pompeiis."* But not until 1637 did the German scholar Holstenius propose that la Citta was indeed the site of ancient Pompeii. Excavations began in earnest in 1748 under King Charles of Bourbon and have continued to the present (Bowersock 1980).

The volcanic deposit has been removed from most of Pompeii or is inaccessible for study, but there are excellent sections just outside the city walls, at Herculaneum Gate to the west, eastward to Vesuvius Gate, Nola Gate, and in the Necropolis near Nocera Gate (Figure 22). These localities provide a composite section through the deposit, and give a picture of the advance of surges over the city.

The citizens of Pompeii became directly aware of Vesuvius' eruption sometime in the early afternoon of 24 August as coarse pumice-fall began to plunge the city into darkness. No trace remains of the initial fine ashfall that affected areas to the north and east farther up the slopes of the volcano. The initial explosive phase of the eruption (A-1) may have been witnessed from Pompeii — an excellent view of the summit — but without direct consequences; it probably only generated curiosity.

Pumice and lithics rained continuously from early afternoon on 24 August to early the next morning, according to accounts of Pliny the Younger. During this time 130 to 140 cm of white pumice (A-2) accumulated, on top of which another 110 to 130 cm of gray pumice was laid down (A-3 to A-5). Although the pumice layer appears relatively homogeneous, the diameter of lithics and pumice varies throughout (Figure

23), reflecting variations in height of the eruption column during the Plinian phase. For example, relatively large, dense pieces of pumice are concentrated about 10 cm above the base of the gray pumice layer.

Pompeii happened to be located on the secondary thickness maximum of the fallout deposit, and thus received the thickest accumulation of pumice- and lithic-fall. Roofs probably collapsed about halfway through the deposition of white pumice (some 40 cm). With most structures unsafe for habitation, an exodus from the city is likely to have begun. Escape of most of Pompeii's residents can thus be attributed to the extended yet comparatively innocuous Plinian fallout phase.

*Figure **20**. Debris-flow deposit from the A.D. 79 eruption as seen in the Pozzelle quarry, south of Vesuvius. The flow, which rests on surge S-3, contains matrix-supported angular blocks of lava ≤ 3 m in diameter, and minor carbonate blocks. On top are pyroclastic flows and surges of later eruptions. Note man for scale.*

The first surge to reach Pompeii swept against the north wall of the city in the early morning of 24 August, depositing dark gray ash near the Herculaneum Gate (S-3). Neither Vesuvius Gate, 200 m to the east, nor other sites in the Pompeii area evidence this surge. Therefore it is possible that the surge cloud did not extend inside the city walls but flowed just west of Pompeii over the Villa dei Misteri and Villa Diomede. The surge must have caused alarm and almost unbearable conditions in the city. Evidence from Mount St. Helens in 1980 and El Chichon in 1982 indicates a peripheral zone of high heat associated with the distal ends of surge clouds (Moore & Sisson 1981; Sigurdsson, Carey et al. 1984). The first surges of the eruption (S-1 and S-2), which form a characteristic doublet in the middle of the pumice-fall at Boscoreale and Oplontis, did not reach as far southeast as Pompeii.

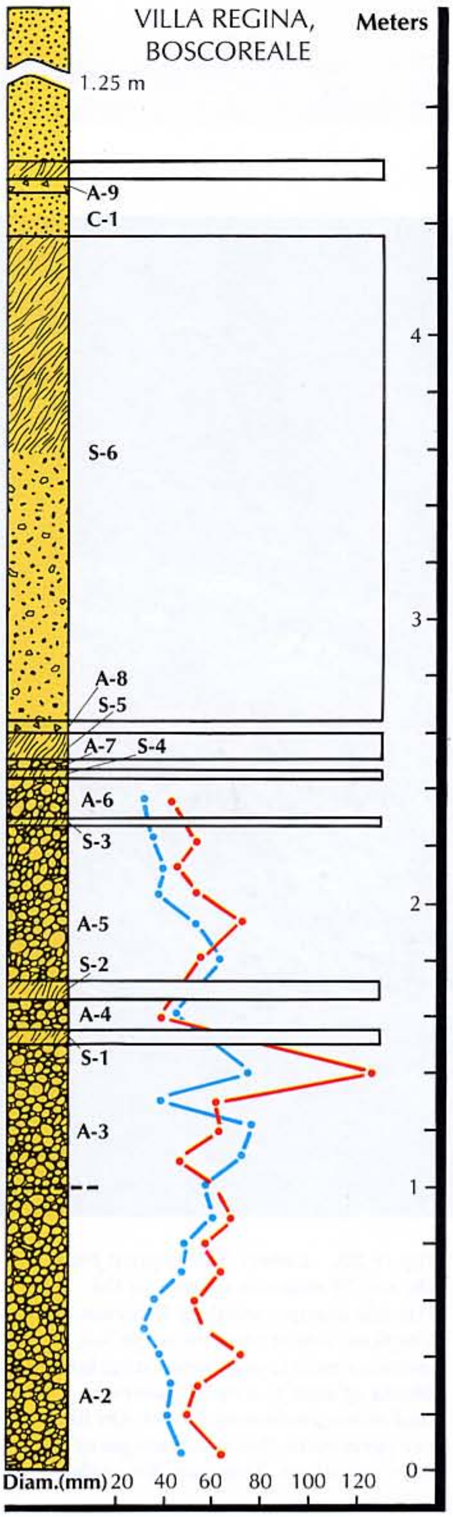


*Figure **21.** Stratigraphic section at Villa Regina, Boscoreale. Also shown is the variation of maximum diameters of pumice (red) and lithics (blue) in the fall deposit. For key to deposit types, see page 349.*

Within the city, 3 cm of pumice- and lithic-fall (A-6) accumulated before the next surge (S-4) overwhelmed the city. This surge also extended to Bottaro, 1 km south of Pompeii (Figure 8), and to Tricino, 3 km east of Pompeii (Figure 10).

The majority of human remains discovered in the excavations have been found on top of the pumice-fall layer, lying within surge deposits S-4 and S-5, but principally buried by the thick S-6 surge (Figure 24). Because of their fine-grained, silty nature, the surges have preserved accurate molds of the victims including details of facial expressions and sometimes clothing. With time, the soft tissues have decayed, leaving only bones in the hollow cavities. In 1860 Giuseppe Fiorelli developed the ingenious technique of making plaster casts of these impressions before the surrounding surge deposit is disturbed (Figure 25). Many hundreds of casts of the dead in Pompeii have since been made in this manner. In 1966, for example, casts of 13 victims were made in the Garden of the Fugitives, where they fell in various groups of adults and children on top of the pumice-fall deposit. Thus evidence is compelling that the S-4 surge was the lethal event in Pompeii. Since detailed stratigraphic studies of the deposit have not yet been feasible inside Pompeii, the extent of building damage resulting from the S-4 surge cannot be judged. By this time the ground-floor levels of buildings had already been buried and only the upper stories protruded from the pumice blanket.

A brief period of gray pumice- and lithic-fall (A-7) blanketed the surge deposit. This deposit is present near Herculaneum Gate and Vesuvius Gate but is missing in other sections, presumably due to erosion by the following surges. The next surge (S-5) extended over the entire city leaving 0.5 to 11 cm of cross-bedded ash. Since the A-7 fall is often missing, the S-5 surge lies directly on top of the S-4 surge layer in some sections, producing a distinctive doublet. This surge extended to Tricino, 3 km east-northeast of Pompeii, but it did not reach Bottaro, directly south of Pompeii (Winkes 1982).

Fall of pumice on the city continued but from an eruption column of diminished altitude and with an increasing content of lithic fragments (A-8). Only 2.5 to 4.5 cm of fall accumulated before the invasion of the major surge cloud over Pompeii, leaving up to 180 cm of material in its wake (S-6). The deposit consists of distinct lower and upper units. The lower unit is relatively massive and flowlike and contains a higher proportion of pumice in a brown silty-to-sandy matrix. This poorly sorted unit also contains tiles and other building fragments, evidence of its destructive force. The upper unit is pumice-poor, cross-bedded, and finer grained and contains dune structures of 1.2- to 1.5-m wavelength and 10- to 30-cm amplitude.

The S-6 surge was the agent of major destruction in Pompeii. It toppled the walls of most buildings that protruded above the level of the volcanic deposit, and transported building fragments some distance. Finally, the bodies of victims killed by the earlier S-4 surge were largely buried by the thick S-6 surge layer. The S-6 surge extended at least as far east as Tricino, where it deposited a 39-cm-thick layer, and to Bottaro in the south where the deposit is 32 cm thick. Pliny the Elder was at the distal edge of the largest surge (S-6) when he died at Stabiae on the morning of 25 August (Sigurdsson, Cashdollar et al. 1982). In excavations of the Villa Ariadne near Stabiae the 2-m pumice-fall deposit is overlain by a 1-cm surgelike layer, which may be the distal facies of the S-6 surge, but further work is required to establish its southern limit.

After the deposition of the S-6 surge, the ground surface in Pompeii and elsewhere around Vesuvius was characterized by low dunes. These dunes were buried by dark gray ash with common accretionary lapilli (C-1). The layer's relatively uniform thickness and distribution suggest an origin in fallout; it represents the transition to the phreatomagmatic phase of the eruption. Two brief periods of relatively dry lithic-fall (A-9 and A-10), with abundant lava and carbonate fragments, directly followed deposition of C-1, but a minor surge (S-7) was emplaced between these falls. These layers are overlain by a total of 60- to 80-cm-thick, undifferentiated accretionary lapilli layers and thin silty-to-sandy surges from the final stages of the A.D. 79 eruption.

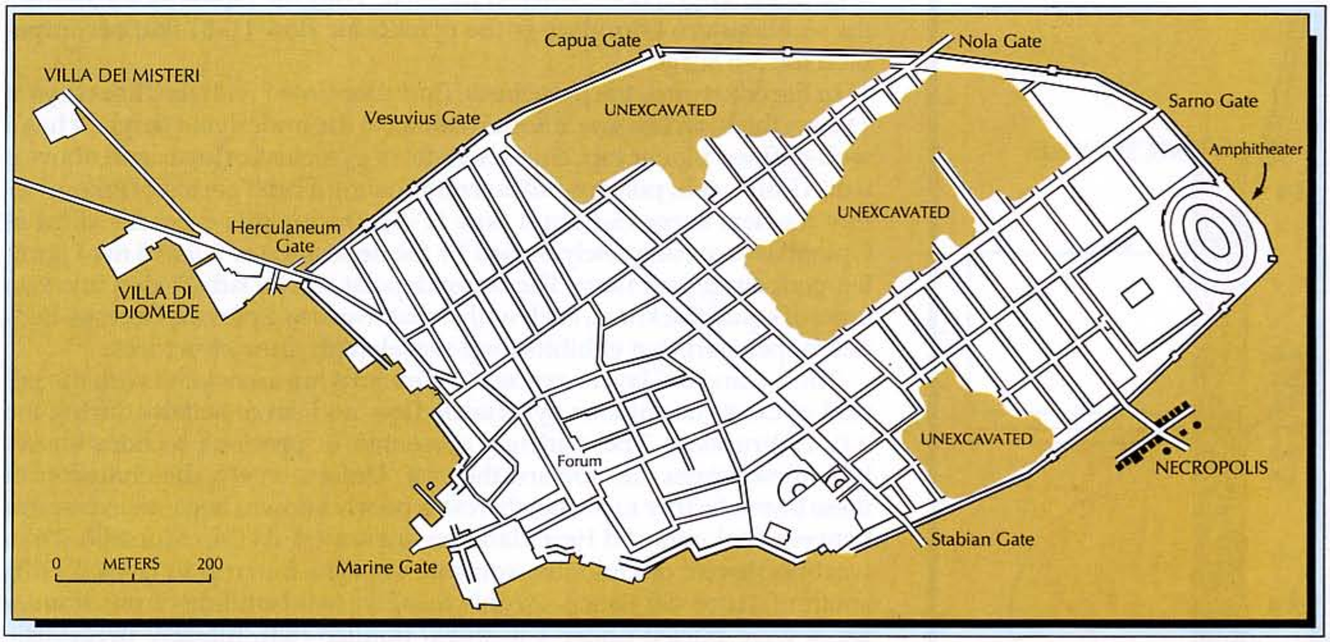


*Figure 22. Pompeii, excavated and unexcavated. The first surge to reach the city swept against the north wall, but evidence of this surge is not found in the eastern part of Pompeii.*

## Oplontis

In 1967 a large Roman villa was discovered near the munitions factory in Torre Annunziata. The villa is believed to have been at or near Oplontis (Figure 26), a town known from Roman times at this site; Oplontis appears on the Tabula Peutingeriana map from the third century A.D. A number of amphorae found in the villa contain the inscription *"Poppaea Libertus,"* and it has consequently been inferred that the villa belonged to Poppaea Sabina, Emperor Nero's second wife, who was known to have owned a villa in the region (D'Arms 1970). Judging from the size and lavish decoration, the villa would indeed have been suitable for an imperial household. About 0.5 km farther east, another excavation has unearthed more buildings, now known to be the Villa Crassus Tertius. A third archaeological site in Torre Annunziata is found at Via Marconi, number 58, where part of a Roman villa is exposed. Excellent sections of the A.D. 79 volcanic deposit can be found at the three sites (Figure 28). The succession of volcanic deposits at Oplontis is in general very similar to that at Boscoreale, until emplacement of the S-5 surge, when pyroclastic flows affected the Oplontis area. Excavation of the portico of the Oplontis villa shows that the colonnade and roof over the portico collapsed during the deposition of the gray pumice (A-3); this may have triggered evacuation of the villa. Shortly thereafter, the first surge (S-1) descended upon Oplontis, damaging buildings and destroying vegetation. This layer is also recognized at the waterfront section at Via Marconi 58 in Torre Annunziata, indicating that the surge cloud reached the coast and undoubtedly spread out over the water.

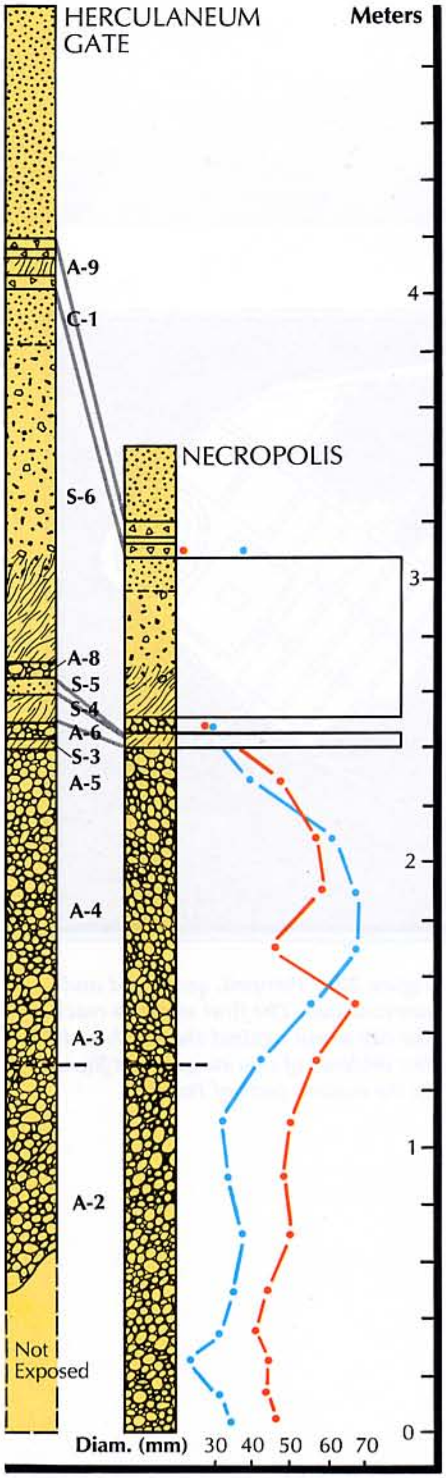


*Figure* **23.** *Stratigraphic sections of the A.D. 79 deposit near Pompeii, showing the variation in the deposit between a section at the Herculaneum Gate, northwest of the city, and at the Necropolis, southeast of the city. Note that the S-3 surge pinches out, and the S-4 and S-5 surges merge at the Necropolis. Also shown is the variation of maximum diameter of pumice (red) and lithics (blue) in the fall deposits. For key to deposit types,* *see page 349.*

At Oplontis the lithic-rich A-7 fall was interrupted by the emplacement of a powerful surge (S-5), followed almost immediately by inundation of the villa by pyroclastic flows. The fifth surge (S-5) swept over all of the Oplontis area, greatly damaging the buildings. In the process it deposited cross-bedded ash and lapilli with prominent alternating lenses of well-rounded pumice and sandy ash. Unlike the surge, the associated pyroclastic flow was influenced by local topography and was confined to the large courtyard, open toward Vesuvius. Buildings on the southeast side of the courtyard dammed the flow and prevented its spread to the area of the large pool farther to the east. Thus the Oplontis site defines the southeastern boundary of the pyroclastic flow (F-5) that accompanied the S-5 surge.

In the courtyard, the pyroclastic flow associated with the fifth surge is 110 cm thick, with a gradational contact to the underlying surge. It has a well-defined planar top, characteristic of pyroclastic flows, and above it a thin lithic-rich, pumice-fall layer indicating a brief period of fallout before the next surge (S-6) and flow (F-6). During this event the villas at Oplontis were completely buried by the deposition of 2.5 to 3 m of pumice-poor surge and flow. The surge deposit can be subdivided into two units of equal thickness, each with a massive lower part and a cross-bedded upper part that exhibits long-wavelength dune structures.

The S-5 and S-6 layers exposed at Oplontis are associated with the period of most voluminous pyroclastic flow and surge activity during the A.D. 79 eruption. The evidence presented in previous sections shows how these layers thin toward the east. Unfortunately, the character of these layers farther to the northwest is poorly known, because exposures between Oplontis and Herculaneum are scarce. At Cap Montella, 7 km west-northwest of Oplontis, volcanic deposits outcrop in coastal cliffs south of Torre del Greco. At this locality, two buildings from Roman times were buried under 4-m-thick, pumice-rich, massive pyroclastic flow, overlain by a sequence of gray surges ≤ 3 m thick, bearing accretionary lapilli. The base of this succession is not exposed, but the authors propose that the massive flow correlates with the F-5 or F-6 pyroclastic flows at Oplontis. The Cap Montella locality (Figure 8) helps define the Roman shoreline as it was before Vesuvius' A.D. 79 eruption, and it provides further evidence of widespread distribution of thick pyroclastic flows and surges west of the volcano.

At Oplontis as elsewhere around Vesuvius, the S-6 layer is capped by a bed rich in accretionary lapilli, indicating the shift to phreatomagmatic activity. Overlying the accretionary lapilli beds (C-1) are ≤ 240 cm of alternating surges and accretionary lapilli layers, formed during the waning phreatomagmatic phase of the eruption.

### *The Pool*

Near the villa at Oplontis is a *piscina,* a large outdoor swimming pool, comparable in size to the large pools in the Villa dei Papyri and the *palestra*, a large park, in Herculaneum. The Oplontis pool is 17 m wide and about 50 m long, with depths between 135 and 142 cm. During excavations in 1984, the volcanic stratigraphy in the pool was well exposed: Some details are strikingly different from the stratigraphy elsewhere in Oplontis, but these differences can be attributed to the presence of water in the pool during the eruption (Figures 27 & 29).

The lowermost layer (A-2) consists of very well-sorted lithic-rich (50%), white pumice-fall. In the center of this layer is a 3- to 5-cm-thick lens which consists of at least 70% lithics. Although the A-2 layer in the pool contains some white pumice, it is clearly very different from the normal A-2 white pumice-fall, in being thinner and much higher in lithics content. The second layer is gray pumice-fall mixed with 10 to 15% white pumice and minor lithics.

Silty-to-sandy pumice-rich surge (S-1), with common gray pumice and minor white pumice forms the third layer. The surge is normally graded, but very poorly sorted. The upper part is markedly vesicular, indicating that hot tephra caused the water to boil. Roof tiles and other building fragments are common in the surge. The pumice in a 20-cm-thick zone under the S-1 surge has a silty coating. The deposit between the first two surges (S-1 and S-2) in the pool is a complex layer (A-4), composed of four lithologic units. The lowermost unit is gray pumice-fall, with minor white pumice (10%) and lithics. Pumice fragments in the lower part of this unit have a coating of silty, vesicular ash. The second unit consists of white angular, very well-sorted pumice. This local inversion may be attributed to the floating of the low-density, white pumice in the pool, and to the settling of the denser, gray pumice. The third unit is gray pumice-fall, mixed with equal proportions of white floating pumice. The uppermost unit is a lens of white, well-sorted pumice float, lithic-free, with a minor coating of silty ash in the upper part.

*Figure* **24** (above). *Upper part of the Necropolis section. The coarse pumice-fall is overlain by the thin S-4 and S-5 surges. The main S-6 surge shows cross-bedding and dune structures and contains bricks and other building material. It is overlain by a massive accretionary lapilli bed, followed by two lithic-rich, thin, fall layers.* **25** (left). *Cast of a victim of the eruption, made by pouring thin plaster of Paris into the cavity left by the body in the compacted surge deposit.*

The second surge (S-2) is split into two units by a pumice-rich lens. Each unit of the surge is normally graded, with a vesicular top. Pockets of white pumice were trapped underneath several of the concave roof tiles contained within the surge. This is clear evidence that the tiles and other material in the surge settled through a body of water covered by floating white pumice. The layer on top of the second surge consists of two units. A lens of white pumice forms the lower unit. It is well-sorted, lithic-free, and normally graded, with tree casts and remains of planks of uncarbonized wood. This unit represents the last raft of floating white

After the passage and deposition of the S-2 surge, a 20- to 30-cm-thick raft of white pumice still remained on top of the pool. This was most likely a spongy mass of grain-supported pumice, and water was only present as interstitial fluid. The deposition of the gray pumice-fall (A-5) on this surface was therefore analogous to deposition on dry land.

## Herculaneum

According to legend recounted by Dionysius of Halicarnassus, when Hercules returned from Iberia he founded a town bearing his name on the Bay of Naples. The first mention of the city is in Theophrastus (314 B.C.) under the name Heracleion. Like Naples, or Neapolis, Herculaneum was a Greek city by origin but fell to the Samnites toward the end of the fifth century B.C. In Roman times Herculaneum was a prosperous and luxurious seaside resort (Figure 30) with a population of 4500 to 5000, including such notable Romans as Nonius Balbus, one-time governor of Crete and Libya, and Calpurnius Caesonius Piso, Julius Caesar's father-in-law, who owned the patrician Villa dei Papyri on the northern outskirts of Herculaneum. Being situated on the Via Antiniana, which connected the major cities around the Crater (the Roman name for the Bay of Naples), Herculaneum was frequented by many patricians and officials. A graffito proves that Apollinaris, Emperor Titus' physician, was in Herculaneum less than a month before the eruption of A.D. 79, and therefore perhaps also the emperor himself (D'Arms 1970).

Previous reconstructions of the physiography of Herculaneum in Roman times picture a city situated on a high bluff overlooking a broad, flat coastline (Maiuri 1977, Pistolesi 1836) with the beach about 300 m west of the city. The recent excavations indicate that major revision of this picture is required, although they support the idea that the city was situated on a bluff about 15 to 20 m above sea level, with a splendid view of the Bay of Naples to the west and the cone of Vesuvius to the east. The discovery of a beach at the very foot of this bluff during the excavations in 1982 indicates, however, that the city was not separated from the ocean by a low stretch of land, but was situated on a hill or headland with the ocean waves lapping at its base (Figure 31).

Early in its history the ocean front of the city was fortified by a massive wall that covered the rocky outcrops of the bluff from sea level to street level in the city. Later this wall was no longer required for defense, and the open waterfront beyond the wall was developed by the construction of the luxurious Suburban Thermae and the Sacred Area.

This development was at the water's edge and therefore required foundations that could take the pounding of the waves. The problem was solved by constructing a series of arches, which form the base of the Sacred Area, along the waterfront. Ten arches have been uncovered so far, five on either side of the long flight of steps leading from sea level to the city's Marine Gate, but many probably remain to be discovered in the unexcavated area to the northwest. Each arch forms a vault or chamber, 3.75 m high, 3.15 m wide, and 3.85 m deep. In these chambers, many residents of Herculaneum sought shelter when their city was overwhelmed by the first pyroclastic surge during the A.D. 79 eruption.

On the southern part of the waterfront, the magnificent Suburban Thermae were also constructed outside the city wall (Figure 32). The entrance to the Thermae is through a hanging garden, bearing the statue of Nonius Balbus. The Thermae were not supported by arches, but were built directly on the waterfront, so that bathers only had to descend a short flight of steps to the small beach and the ocean. This convenience meant that the Thermae were fully exposed to the waves, and therefore

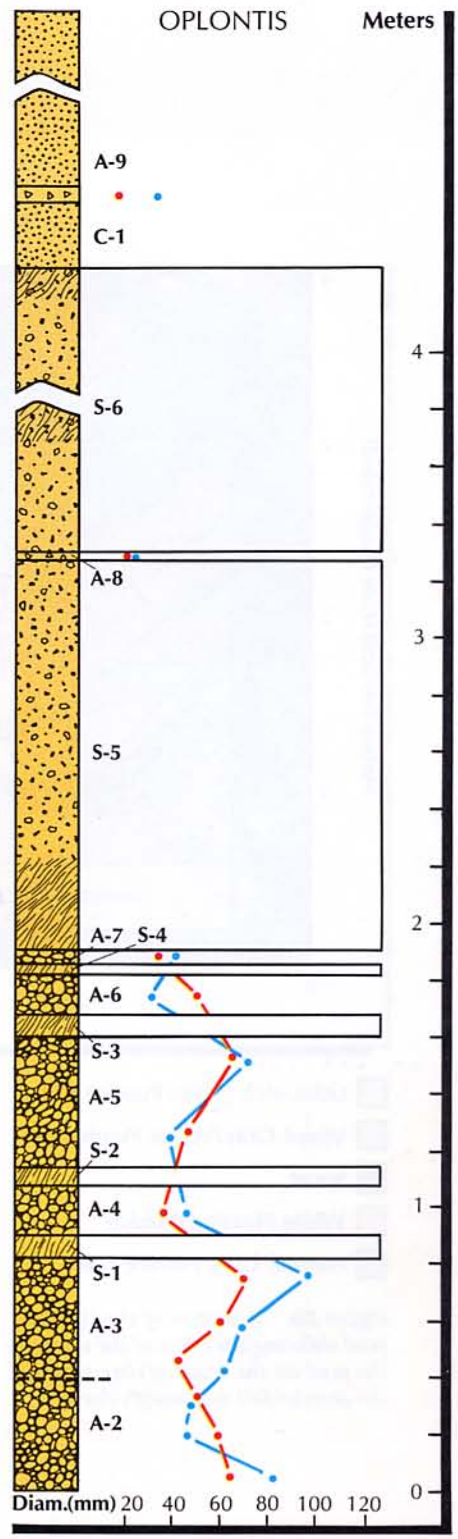


*Figure 28. Stratigraphic section of the A.D. 79 deposit at Oplontis. Note the pyroclastic flow layers on top of S-5 and S-6 and the variation in the diameter of pumice (red) and lithics (blue) through the deposit. For key to deposit types, see page 349.*

the builder cleverly designed a lip or ledge on the exterior walls about 4 m above sea level to deflect the spray from the breaking waves away from the large windows of the bathhouse.

*The Beach in Roman Times*

The beach and shoreline of Herculaneum prior to the A.D. 79 eruption can be reconstructed from exposures in the new excavations (Figure 33). The beach consists of three deposits: tuff, black beach sand, and gravel. The oldest is massive, consolidated tuff which forms bedrock in

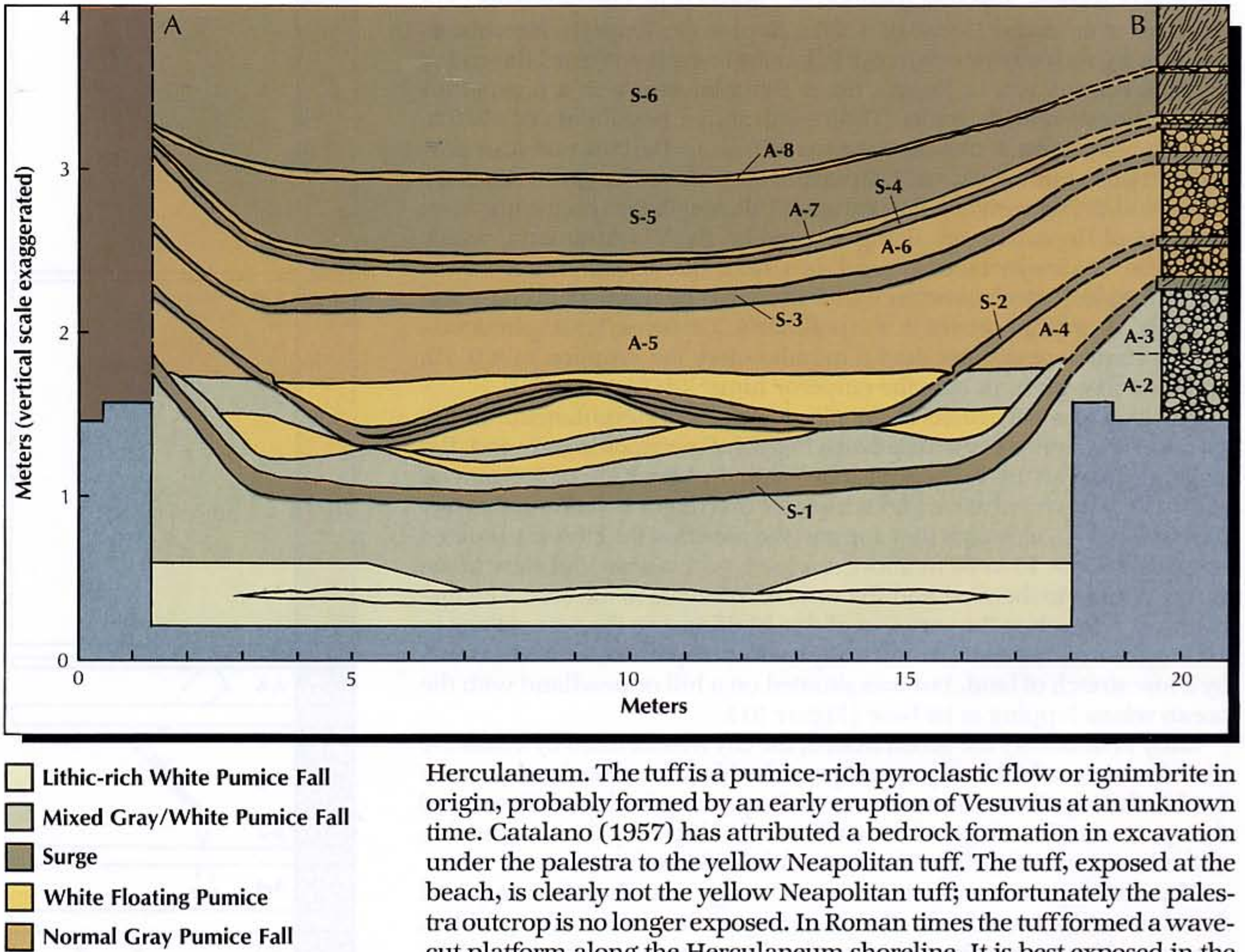


*Figure 29. A section of the Oplontis pool showing the effect of the water in the pool on the mode of deposition of the pumice-fall and surge layers.*

Herculaneum. The tuff is a pumice-rich pyroclastic flow or ignimbrite in origin, probably formed by an early eruption of Vesuvius at an unknown time. Catalano (1957) has attributed a bedrock formation in excavation under the palestra to the yellow Neapolitan tuff. The tuff, exposed at the beach, is clearly not the yellow Neapolitan tuff; unfortunately the palestra outcrop is no longer exposed. In Roman times the tuff formed a wave-cut platform along the Herculaneum shoreline. It is best exposed in the floor of a recent (1982) tunnel that trends away from the Roman beach and toward the area directly underneath the new Herculaneum Museum. The tunnel section shows that the tuff formed a reef 10 to 20 m offshore, which was probably exposed at low tide. The surface of the tuff has been worked and fashioned to provide a slip-way for large boats. A 3-m-long keel-groove and holes for supporting beams are exposed on the tuff surface in the tunnel, indicating that the larger vessels were pulled up here for maintenance on the reef.

Black beach sand is the second deposit on the Herculaneum shoreline and overlies the tuff. The beach sand is derived from erosion of volcanic rocks. It is thickest (0.5 m) in front of the Suburban Thermae and the chambers, and thins rapidly away from shore, pinching out completely some 10 m from the waterfront.

The youngest deposit on the Herculaneum beach, before the A.D. 79

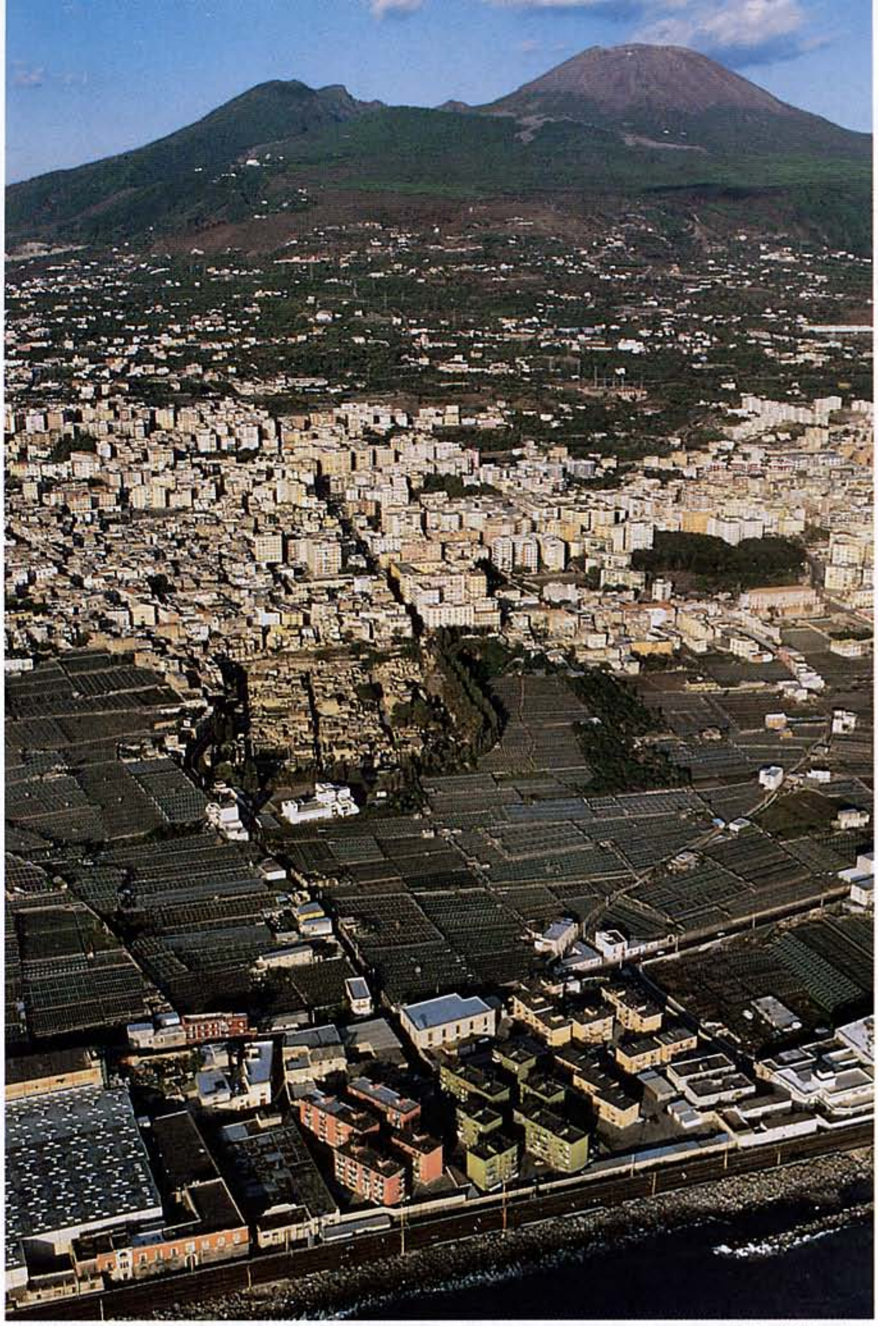

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*Figure **30.** Herculaneum surrounded by the modern city of Ercolano; Vesuvius is on the horizon. The modern shore is in the near foreground, with the ancient shore now occupied by greenhouses.*

eruption, is a gravel layer. It is thickest (0.6 m) in front of the Thermae, thins gradually along the waterfront in front of the chambers, and pinches out to the north of the Marine Gate steps. The gravel is composed primarily of rounded pebbles of limestone, lava, and rubbish (fragments of pottery, tiles, stucco, broken glass, bones, seashells) in a matrix of black sand. The degree of rounding of fragments varies systematically in the gravel within the area. The upper part of the deposit (in front of the Thermae) consists of angular fragments, whereas rounded fragments dominate where the deposit is exposed at lower levels. The transition from rounded to angular fragments occurs at about 1 m. (All reported elevations in the Herculaneum excavation are relative and refer to the datum of the local survey network for the excavations, and not present sea level. The zero reference level of the excavation survey network is about 5 m below present sea level.)

The boundary between rounded and angular fragments in the gravel is significant because it provides evidence of sea level in Herculaneum at the time of the A.D. 79 eruption. Clearly this deposit results from dumping building rubble and other rubbish on top of the black beach sand. Some of the material was within reach of the wave action of the surf, resulting in rounding of the fragments, while upper parts of the deposit were above sea level and escaped rounding. Preeruption sea level was at the boundary between angular and rounded material; this is about 1 m above the survey datum or about 4 m below present sea level. Herculaneum has thus undergone major subsidence in the 1900 years since the eruption. This subsidence may have occurred rapidly after the eruption, due to deflation of the magma reservoir under the volcano — such deflations are a common consequence of large eruptions. Alternatively, the subsidence may be part of regional tectonic tilting and long-term structural events in the Bay of Naples.

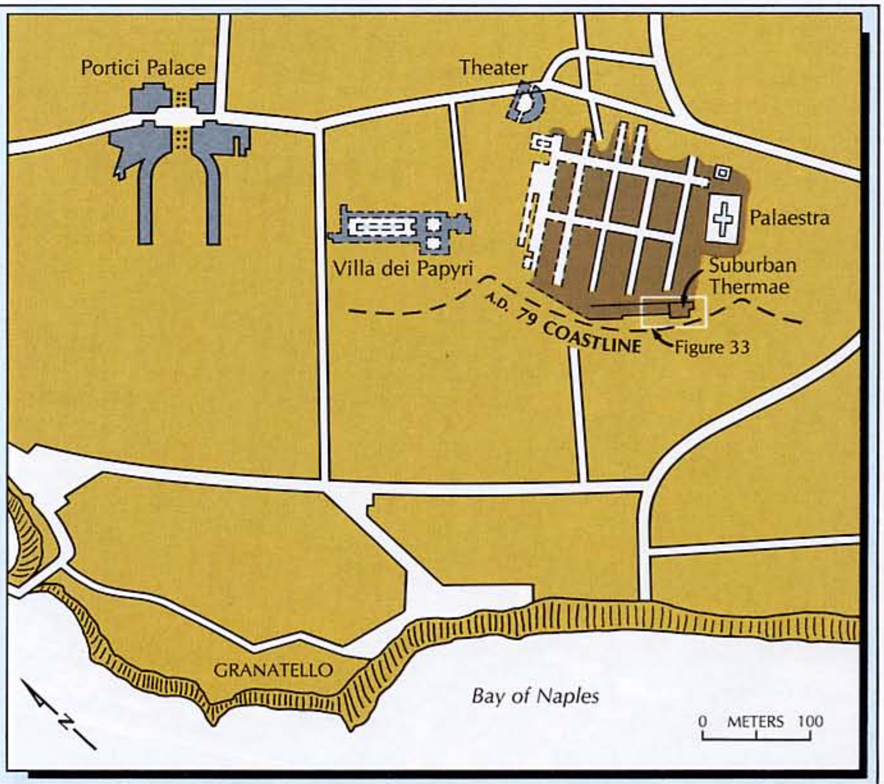


*Figure **31.** The Herculaneum area. This map shows the present coast and the coast in Roman times, based on the recent excavation of the waterfront. Location of Villa dei Papyri is after Pistolesi (1836), and the theater after Maiuri (1958).*

The gravel shows that part of the Herculaneum beach was a rubbish dump in A.D. 79. This is surprising since the dump was located in front of the Suburban Thermae, the most elegant club in town. There are however some indications that the rubbish dump may have been a very recent feature on the Herculaneum beach at the time of the eruption. The rubbish-derived gravel rests on black beach sand, as stated above. The normal beach environment thus was characterized by a wave-cut rock platform of tuff, with lenses of black beach sand at the waterfront. The large protruding masonry lip at 4.6-m elevation on the exterior walls of the Suburban Thermae indicates that surf would pound the waterfront during storms. This surf-lip would presumably help deflect sea spray from the windows of the Suburban Thermae. At the time of deposition of the black beach sand, the beach appears to have been exposed and active, with surf up to the buildings at the waterfront. The overlying gravel, on the other hand, suggests that activity of the surf may have decreased, as shown by the angular character of the fragments that constitute the upper part of the deposit.

This suggests that surf was not active along the entire beach at this time. The decrease in surf action may be due to shallowing of the beach, i.e., uplift. It is possible that the Herculaneum area, and indeed all of the Vesuvius region, underwent inflation some months or years before the A.D. 79 eruption, either when magma rose to higher levels in the earth's crust or when the magma chamber rose under the volcano. Such inflation or bradyseism would lead to uplift and a drop in sea level at Herculaneum, reducing surf action around the rubbish tip in front of the Suburban Thermae. Such uplift was probably no more than 0.5 to 1 m, but the population must have noticed it, and if it was accompanied by

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*Figure* **32.** *The excavation of the Herculaneum waterfront, looking northeast. This photo was taken from the gray wall of pyroclastic flows, 23 m thick, that buried the city. The Suburban Thermae are at the right. The shack (lower right) encloses the boat (Figure* **36***). The arched chambers are in the foreground.*

earthquake activity, it must have caused unrest in the town as in Pozzuoli today. A major earthquake struck the Vesuvius area on 5 February 62 (Cassius Dio, in Cary 1915). Buildings were seriously damaged in Herculaneum, calling for radical restoration or complete rebuilding. An inscription records, for example, the restoration of the temple of the Mater Deum, financed by Emperor Vespasian. The gravel formation on the Herculaneum beach may well date from this catastrophe and represent building rubble cleared out of the city after the earthquake.

The morphology of the 79 beach is shown in Figure 33. It was 2 to 4 m wide in front of the steps to the Suburban Thermae, narrowing to less than 1 m in front of the chambers. The sea was very shallow off the shore of Herculaneum. Within the area exposed by the current excavations, the maximum depth of water was 0.5 to 0.7 m which occurred in the region from the Marine Gate steps to the new tunnel. The shallow nature of the harbor suggests that wooden jetties or wharfs were probably constructed, as often depicted in contemporary wall paintings of real or imaginary Roman harbors. An obvious place for such a jetty would have been in line with the steps to the Marine Gate, toward the tunnel. The extraordinary amount of planks and timber found in the first surge layer on the waterfront may be evidence of a former jetty.

*Volcanic Stratigraphy*

Following its rediscovery in 1709, workers explored Herculaneum by underground tunnels for the Bourbon kings of Naples until 1765. When excavations resumed in 1828, workers began completely removing the thick volcanic overburden for the first time. Since then, an area of about

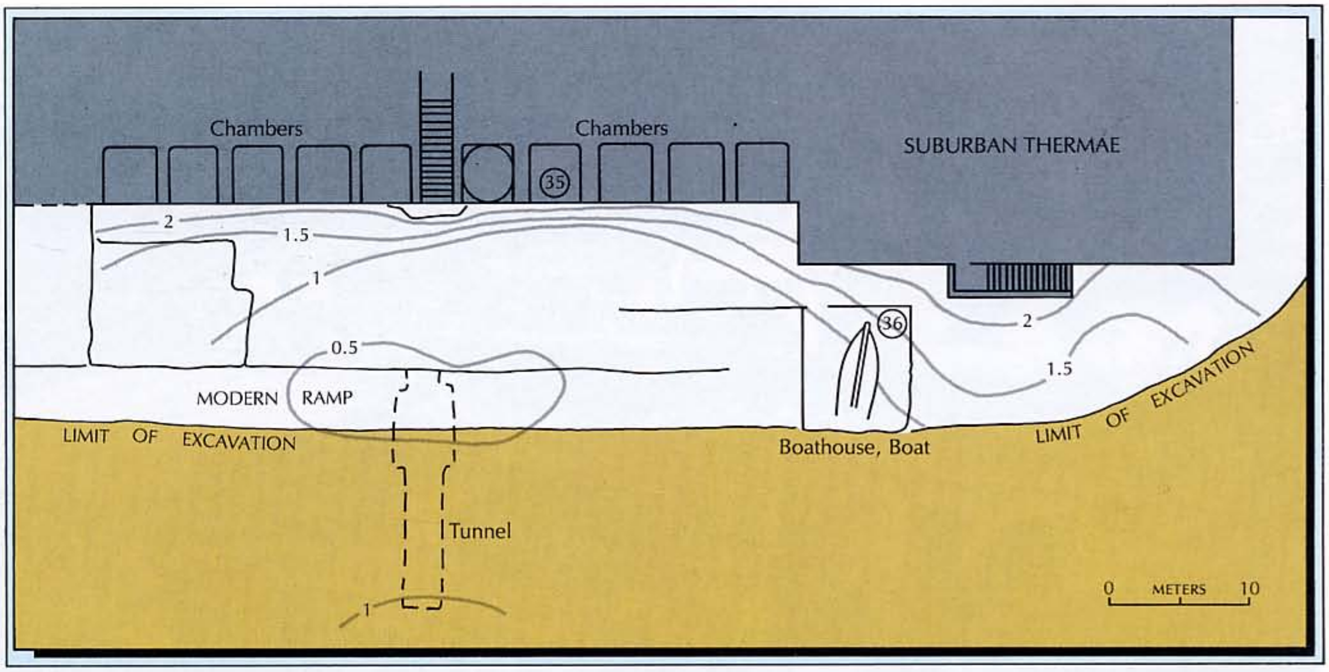


*Figure* ***33.*** *A plan of the Roman beach in Herculaneum. Contours show the morphology of the beach prior to the eruption. Contour lines (in meters) refer to the relative datum elevation. Zero reference level of this datum is about 5 m below present sea level. Roman sea level was at about 1 m, contour level; i.e., the coast has subsided about 4 m since the eruption. Circled numbers refer to photographs taken at those locations.*

40 000 $m^2$ has been fully cleared, resulting in partial to complete exposure of eight city blocks (*insulae*); further expansion of the excavations to the north and east is hindered by the overlying city of Ercolano.

The nucleus of Herculaneum, which has been fully cleared, is surrounded by a 10- to 23-m-high, nearly vertical bank of the volcanic deposit from the A.D. 79 eruption. The best exposure is in the 23-m-high wall of deposits overlying the beach, which forms the type section for this locality and is described in detail below. Other good exposures can be found in the network of tunnels in the palestra in the southeastern part of the city. Previous estimates of < 20 cm of accumulated ash- and pumice-fall during the initial phase of the eruption (Sigurdsson, Cashdollar et al. 1982) proved much too high. Later studies showed that the entire fallout was probably around 1 cm. The insignificant thickness of this layer contrasts sharply with the > 1-m-thick layer of pumice-fall that accumulated south of the volcano during the same period. In most parts of Herculaneum the ashfall layer is absent, presumably because of erosion by the overlying surge.

Generally the first deposit from the eruption is therefore an unconsolidated gray surge layer (S-1). It ranges in thickness from 35 to 50 cm on the beach and is 60 cm at the mouth of the chambers, but thickens to 150 cm at the inner end of the chambers. The layer is poorly sorted and silty, with massive lower and cross-bedded upper parts. Tile fragments and lithics are also present. The surge layer contains a high proportion of wood, especially in the lower part, including both carbonized and uncarbonized logs. Possibly the former were dry, seasoned wood, while the latter were green wood, more resistant to carbonization. Most of the wood is trimmed and worked and includes large beams, over 4 m long and 10 x 20 cm in section. In areas below 1-m elevation, i.e., below the preeruption sea level, the S-1 surge layer is underlain by an 8- to 10-cm well-sorted, sandy, and cross-bedded gray to dark gray layer that contains fragments of charcoal and roof tiles, some 15 cm long. This is likely to have been associated with the entrance of the surge into the water.

Elsewhere on the beach, this basal unit grades laterally into a 5- to 15-cm unit composed mostly of carbonized thatch and other vegetation.

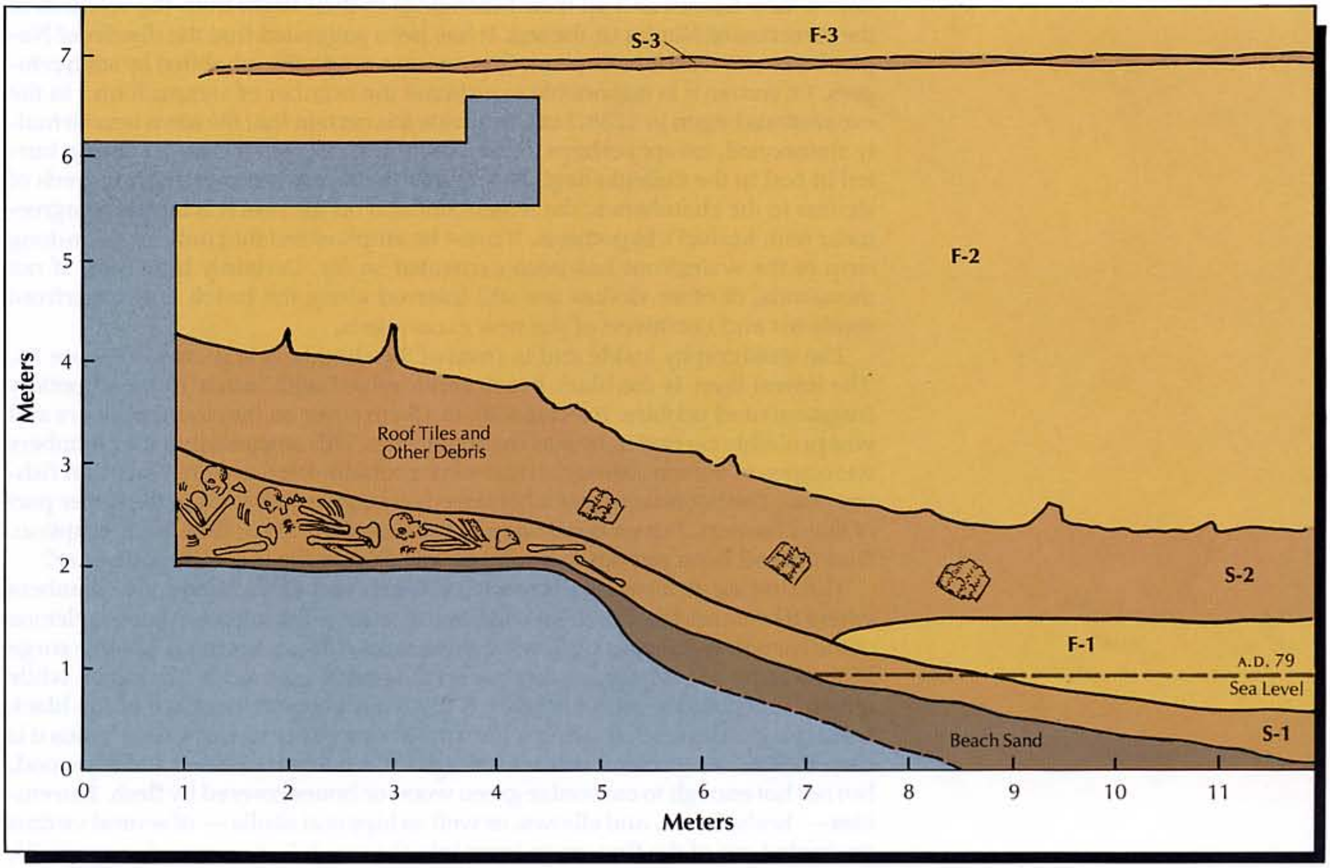


*Figure 34. The Herculaneum beach and one of the chambers, showing the sequence of the A.D. 79 volcanic deposits and position of the victims in the S-1 surge. Roman sea level is at 1 m, datum.*

This unit also contains a high proportion of logs and timber $\leq$ 10 cm in diameter. The thatch consists mostly of 5- to 10-cm-long and 0.5- to 1-cm-diameter twigs of carbonized vines in a sandy surge matrix. The thatch layer is thickest (15 cm) in front of the Suburban Thermae. It may have been stripped off the vineyards on flanks of the volcano, transported in the head of the surge, and deposited immediately before the main surge layer was laid down. The wood planks and other timber associated with the thatch layer were also stripped off structures in the town and on the flanks of the volcano and transported in the head of the surge cloud. A thin well-sorted layer of dark gray sand rests on top of the S-1 layer in the tunnel and in front of the chambers. This may be ashfall from phreatic explosions caused by the hot surge entering seawater.

### *The Victims*

The S-1 surge layer deposited on the beach above sea level in front of the chambers and the Thermae, contains many human skeletons. Inside the chambers, the layer is virtually crammed with more skeletons. This dramatic discovery of hundreds of victims of the eruption during excavations of the waterfront in 1982 throws new light on the demise of the population of Herculaneum during the eruption. Before 1982, only about 10 victims of the A.D. 79 eruption had been found during the excavation of Herculaneum. They include a skeleton found on the upper floor of the House of Scheletro in 1831, two skeletons (a man and a woman) in the dressing room (*apodyterium*) of the men's Thermae, a carbonized skeleton of a man lying face down on a bed in the Collegio degli Augustali, an infant in a cradle in the House of the Gem, and a skeleton of a boy in bed in the House of the Gem-cutter. Amedeo Maiuri, who was in charge of the excavation from 1927 to 1961, comments specifically on the lack of human victims in the excavation. The scarcity of remains of human victims in a town with a population of 4500 led Maiuri (1977) to the conclusion that the Herculaneans abandoned their houses and all their belongings in their flight from the volcano, in the direction of Naples or the sea. It has been suggested that the district of Naples known as the Herculaneum Quarter was originally inhabited by such refugees. Of course it is impossible to estimate the number of victims found in the excavations begun in 1738, but at any rate it is certain that the town was virtually abandoned, except perhaps for the sick and the aged, such as the person buried in bed in the Collegio degli Augustali. The recent discovery of hundreds of victims in the chambers at the waterfront and on the beach is largely in agreement with Maiuri's hypothesis. It must be emphasized that only an 85-m-long strip of the waterfront has been excavated so far. Certainly hundreds, if not thousands, of other victims are still interred along the beach and waterfront southeast and northwest of the new excavations.

The stratigraphy inside and in front of the chambers is shown in Figure 34. The lowest layer is the black beach sand, mixed with minor rounded pottery fragments and pebbles. It forms a 10- to 15-cm cover on the chamber floors and was probably carried in by surf during storms. This suggests that the chambers were open to the sea although some were probably used to store boats and fishing gear. The boats were probably stored on large crossbeams in the upper part of the chambers. But no boats were in the chambers at the time of the eruption. Had they all been put out to sea by people fleeing the impending disaster?

The first surge layer (S-1) covers the beach and extends into the chambers where it becomes finer grained with few or no large fragments. All the skeletons of the human victims, as well as the skeleton of a horse, occur within this surge layer (Figure 35). Many rest directly on the beach, covered by the surge, while others lie within the surge deposit, 5 to 15 cm above the surface of the black beach sand. All skeletons lying within the S-1 surge are uncarbonized; thus it is clear that this surge cloud was hot enough to carbonize seasoned and dry wood, but not hot enough to carbonize green wood or bones covered by flesh. Extremities — heels, knees, and elbows, as well as hips and skulls — of several victims protruded out of the first surge layer into the much hotter second surge (S-2); these parts of the skeletons are carbonized.

The highest concentration of victims occurs inside the chambers: Each contains 15 to 40 skeletons, i.e., $> 3/m^2$. Groups of victims also occur immediately in front of the chambers, particularly on the northwestern part of the beach. The great majority of these lie with the head toward the chamber. Similarly, skeletons inside the chambers are generally oriented with the head toward the end-wall or the south corner of the chamber. Most victims seem to be in a natural position, huddled together, curled up, embracing, or with hands and arms over the face. A thorough study of the position of the skeletons has not been undertaken, but preliminary analysis indicates that most victims lie on the side (47%), while others lie face-down (37%) or, more rarely, on the back (16%). The horse is in the mouth of one of the chambers and partly on top of human skeletons. Its death struggle may have been the longest.

The stratigraphic evidence shows clearly that these people were killed by the effects of the first surge. This is not surprising considering the physical environment inside a surge cloud like the one that invaded Herculaneum. A number of studies of recent eruptions indicate that surge clouds travel at high speed (100 to 300 km/hr) and that they are extremely turbulent (Kieffer 1981, Rosenbaum & Waitt 1981). Consequently fragments of rocks, building material, tiles, etc. are hurled along in the cloud as lethal projectiles. Secondly, surge clouds can have temperatures of 100 to 400°C. The Mount St. Helens surge cloud, for example,

singed hair (120°C) and melted plastics (350°C). Thirdly, the surge cloud is probably low in free oxygen content and may carry harmful volcanic gases in toxic concentration. Autopsies of 26 of the 67 known fatalities of the 1980 Mount St. Helens surge blast show that 18, or the great majority, died of asphyxiation, while five died of thermal effects and three of injuries (Eisele et al. 1981). The asphyxiation was caused by an occlusive plug of volcanic ash, mixed with mucus in the larynx, trachea, and upper airway. Some of the victims had little or no ash in the airway and were diagnosed as having died by thermal shock. They were not burnt, but rather baked or cooked in the hot deposit, resulting in mummification of hands and feet and desiccation and shrinking of internal organs. The tympanic membranes in the Mount St. Helens victims were all intact (Eisele et al. 1981), indicating that the pressure wave associated with the surge was not sufficient to cause injury, i.e., $< 0.1$ to 0.5 bars. The three victims who died from injuries were struck by flying rocks or falling trees. Chemical analyses of blood from the victims did not show any evidence of high content of toxic gases in the surge cloud. Most of the surge victims in Herculaneum, Pompeii, and elsewhere around Vesuvius must have suffered a similar fate. It is likely that the surge cloud was not hot enough to cause thermal shock. Once engulfed in the cloud, the people would gasp for air and soon choke on ash lining the trachea, dying of asphyxia within one or two minutes.

The preservation of victims' remains in Herculaneum is, at first sight, very different from that in Pompeii. In Herculaneum the remains are skeletons embedded in relatively soft, wet volcanic ash (surge S-1) and no hollows of the soft tissue remain. In Pompeii, on the other hand, the victims formed hollow cavities in the deposit, where the soft tissues have decayed, leaving a perfect impression of the body at the time of death, while the skeleton remains inside the cavity

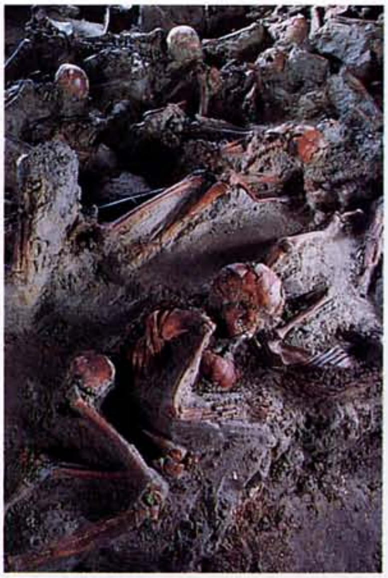

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**Figure 35.** Upper: *embracing couple shown in the foreground of the lower photo.* Lower: *remains of victims in one of the chambers, partly excavated out of the gray silty S-1 layer.*

(Figure 25). The different states of preservation in the two cities does not in any way reflect different processes during the eruption, since the populations in both cities were killed by surge activity. The different preservation reflects, on the other hand, the level of the groundwater table in the two cities after the eruption. In Herculaneum the bodies were buried at a level below the posteruption groundwater table. The deposit consequently remained soft and plastic. As the soft tissue decayed, the surrounding deposit, under the weight of the 20-cm-thick layers, gradually enclosed the skeleton. In Pompeii, on the other hand, the victims were buried in the surge layer about 2.5 m above street level, on top of the porous pumice-fall deposit. The bodies were therefore well above the groundwater table and covered by only 2 m of overburden. The fine ash of the surge deposit hardened quickly around the body before decay of the soft tissues became advanced, forming a perfect cast of the body. The deposit was well drained through the underlying pumice and did not become waterlogged.

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In Herculaneum the passage of the first surge must have been a sudden event and the surge cloud probably dispersed within minutes. On the beach this surge is overlain by a pyroclastic flow (F-1). Such a sequence of surge overlain by pyroclastic flow is typical of ignimbrite deposits (Sparks, Self et al. 1973). The F-1 flow is a massive, consolidated deposit that contains some charcoal, but fragments of tiles and other building material are generally few. F-1 is < 1.5 m thick but thins northward along the beach and pinches out near the new tunnel. The layer reappears in the tunnel and persists to the west.

The basal surge layer (S-1) and the first pyroclastic flow (F-1) are intimately related in the field and it is proposed that they are two components derived from a single nuée ardente. The highly inflated surge cloud would engulf the area and sweep over all the surrounding terrain on its route radially from the crater. It would probably reach Herculaneum two to five minutes after the collapse of the eruption column. The pyroclastic flow, although generated simultaneously, would follow topography and flow along riverbeds and valleys. Herculaneum was situated on a low hill, with shallow valleys to north and south (Pistolesi 1836). F-1 flowed around the hill and emerged onto the beach from the valley south of the town, but did not flood the town except the palestra, as discussed later. The first surge (S-1), on the other hand, swept through the town and over the beach, some minutes before the flow arrived at the coast. The flow then advanced into the sea, at least 40 m beyond the former coastline, as shown by sections in the new tunnel, and formed a new shoreline. A shallow moat or inlet was formed between the chambers and the flow, about 10 m wide.

O. Louis Mazzatenta

*Figure **36.** Richard Steffy (of Texas A&M) studies the Roman boat excavated from the volcanic deposit. The boat is protected inside a metal shed.*

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### *The Boat*

A boat (Figure 36) about 8 m long was discovered in the first pyroclastic flow on the beach in front of the Thermae. The stern of the boat is about 5 m from the Thermae wall. The boat is overturned and trends almost perpendicular to the waterfront (Figure 33). The stern is largely intact, whereas the main part of the hull has been partly flattened by the overburden. The bow has not been fully excavated but is clearly more distorted and broken.

From the stratigraphic position of the boat, as determined in exploratory pits dug alongside the hull (Figure 37), it is clear that the boat does not rest on the Roman beach. It is between 0.5 and 2 m above the beach, and is separated from the beach by the thatch layer and the S-1 deposit. The lowermost exposed part of the hull is the wale, which is 65 cm above the Roman sea level. The gunwale, which is not exposed, was probably about 10 to 25 cm wide (Richard Steffy personal communication). The gunwale would then rest directly on the surface of the S-1 layer, whereas the sternpost penetrated the S-1 layer. Most of the hull is encased in the F-1 pyroclastic flow which has carbonized most of the planks.

The rest of the hull and the keel of the overturned boat were blasted and buried by the second surge (S-2) and the second pyroclastic flow (F-2).

On the basis of these observations it can be deduced that the boat was not in the water at the time of the eruption, as the boat is in fact above the Roman sea level. It is also clear that the boat was not on this part of the beach when the eruption began, or it would have been buried by the first surge (S-1). Instead, the boat rests on top of this surge. It can be inferred that the boat was transported to its present position after deposition of the first surge. Perhaps the boat was on dry land for repairs on the beach south of the Thermae. It was not carried any great distance by the first surge, but the F-1 pyroclastic flow engulfed the boat and carried it west around the corner of the Thermae to its present position. As it was bulldozed along in the pyroclastic flow, the boat may have been overturned, which could account for the damaged bow section. The heat of the flow subsequently carbonized the hull. The remaining exposed section of the hull and keel, protruding out of the F-1 flow, were then sandblasted by the S-2 surge and finally buried completely by the accompanying F-2 pyroclastic flow. The skeleton of a male (so-called "helmsman") found lying on his back near the stern of the boat was within the S-1 surge layer and not within the flow. It is therefore likely that the boat and this skeleton are unrelated, but that this person perished on the beach before the boat was transported to its present position by the pyroclastic flow.

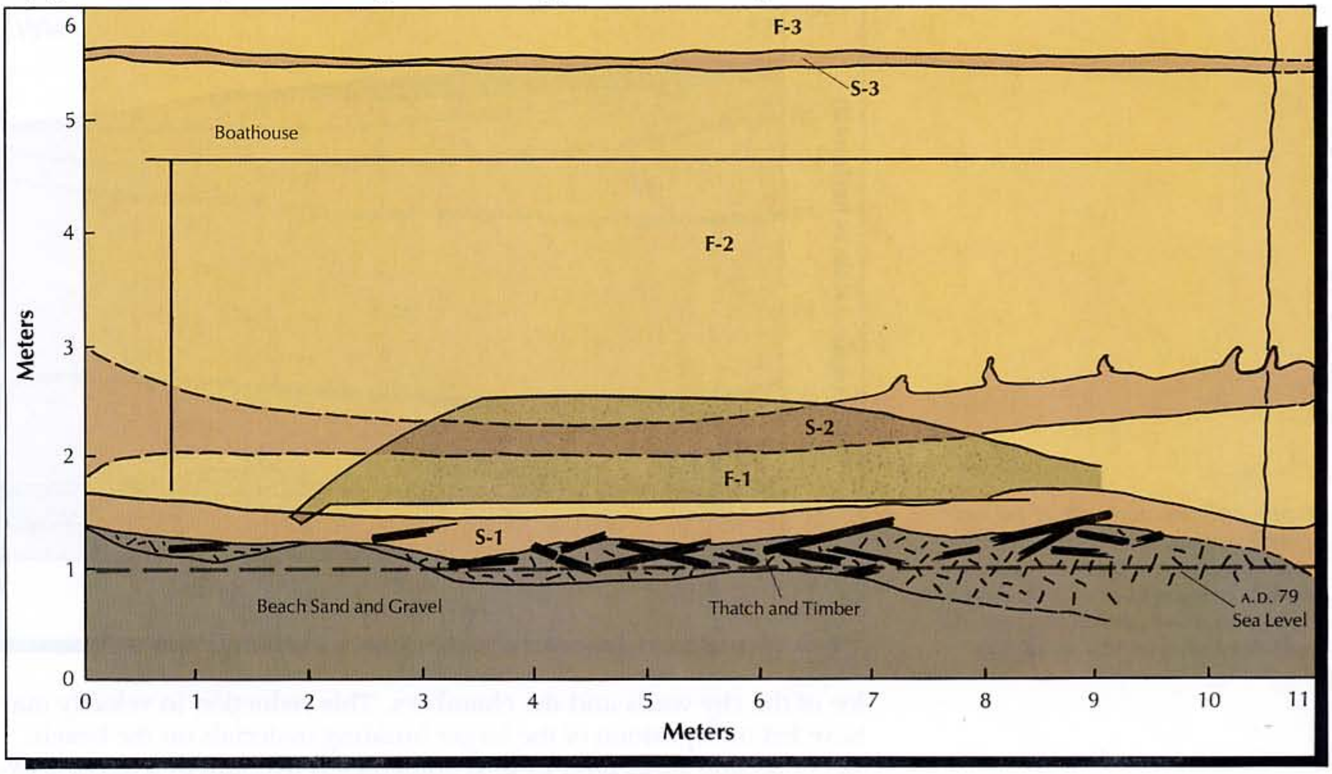


*Figure* **37.** *Stratigraphic position of the boat. At base is beach sand and gravel, overlain by thatch and timber. The boat lies largely within the first pyroclastic flow (F-1), and is covered by the S-2 and F-2 layers.*

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The third layer deposited on the Herculaneum waterfront is a pyroclastic surge (S-2). This distinctive layer is generally poorly consolidated, dark gray, and relatively coarse-grained with pumice fragments ≤ 20 cm. Its most distinctive feature is the high content of building material, including bricks, roof tiles, stucco, column parts, and wall portions. The largest components of this type are two wall fragments, each about 1 m long and weighing about 500 kg, which were transported at least 10 m. The S-2 layer is ≤ 1.5 m thick and slightly normally graded, with faint stratification and long-wavelength cross-bedding. Charcoal fragments are common in this layer, but uncarbonized wood is absent, unlike in the S-1 surge. This surge also thins regularly to the southeast and is only 10 cm thick at the south corner of the Suburban Thermae.

The presence of large wall fragments and coarser grain size is evidence that the S-2 surge cloud had greater carrying capacity and was more violent than the earlier surge cloud. The second surge was clearly responsible for widespread destruction of masonry in the city and carries a particularly large load of terra-cotta roof tiles. Similarly, the presence of charcoal and absence of uncarbonized wood also indicate that the 2 surge cloud was hotter than the S-1 cloud. The velocity of the S-2 surge cloud was probably checked somewhat at the waterfront, in the

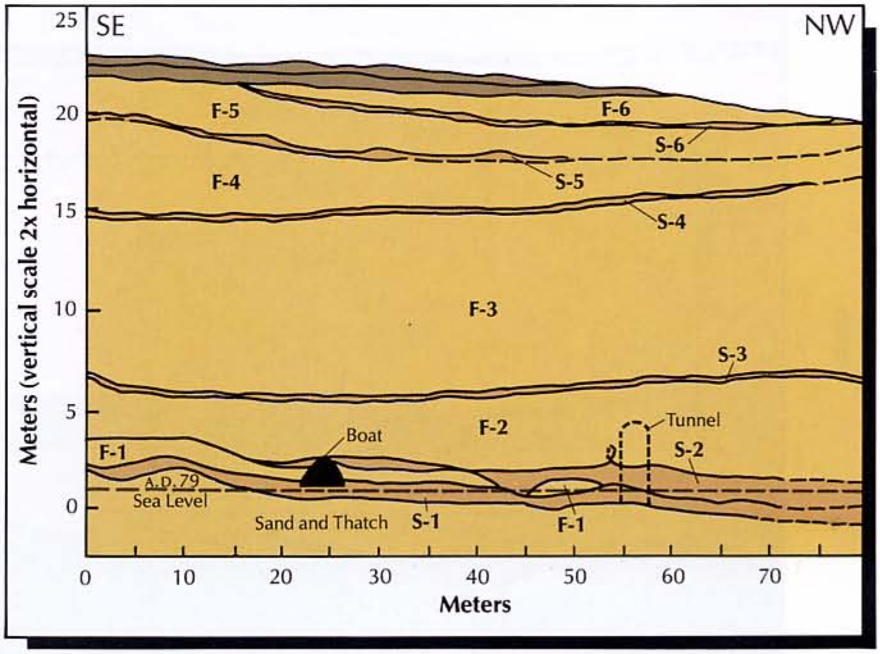


*Figure **38.** Stratigraphy of the A.D. 79 volcanic deposits on the Herculaneum beach. Note that the vertical scale is based on datum that originates 5 m below present sea level. Roman sea level was at 1 m, datum.*

lee of the city walls and the chambers. This reduction in velocity may have led to deposition of the larger building materials on the beach.

The second surge layer (S-2) is immediately overlain by a massive pyroclastic flow (F-2) (Figure 38), ≤ 5 m thick, consolidated, pumice-rich, and devoid of internal structures, except steam pipes. It carried some building fragments near the base. The contact between F-2 and S-2 is indistinct in places and the two layers were probably deposited in very rapid succession.

The pyroclastic flow (F-2) is thinnest in front of the Thermae and thickens to southeast and northwest, indicating that the flow advanced as two lobes, one on either side of the city, and that the lobes coalesced on the beach. The F-2 flow swamped the waterfront and filled in the chambers completely. This thick blanket of dense, hot pyroclastic flow boiled the underlying water and caused explosive rise of steam. Such steam expulsion gave rise to numerous vertical steam pipes in the lower part of the pyroclastic flow.

In the great bank of deposits revealed by excavation of the waterfront, the F-2 pyroclastic flow is overlain by a 10-cm-thick sandy surge layer (S-3). This is in turn overlain by a third massive pyroclastic flow, ≤ 10 m thick; it is pumice-rich and contains a higher concentration of lithics than flow F-2. Its upper surface slopes gently from northwest to southeast, indicating flow from north of the city. About 3 m above its base the pyroclastic flow contains a lens rich in 10- to 20-cm lithic fragments of lava and carbonate. Samples of these lithics have yielded important information on the emplacement temperature of the flow (Kent et al.

1981), which in turn has contributed to determining the origin of the massive layers that buried the city.

The origin of the deposits that buried Herculaneum has been a source of controversy for many years. It has previously been proposed (Sigurdsson, Cashdollar et al. 1982), and supported by later work, that the city was buried by the products of nuées ardentes, depositing thin surge layers and thick pyroclastic flows. Previous workers — Corti (1964), Etienne (1974), Maiuri (1977), and Mau (1899) — have interpreted the Herculaneum deposits as mudflows. Sheridan et al. (1981) have also proposed that the upper section of the Herculaneum deposits are mudflows (lahars), but recognized that the lower deposits were surges and pyroclastic flows. Several features of these deposits support a pyroclastic flow origin and high emplacement temperatures. The flows have common vertical lithic-rich and fines-depleted pipes (degassing structures or steam pipes). The typical association of a fine-grained, thin, basal surge layer at the base of each flow is also evidence for an origin in pyroclastic flow (Sparks, Self et al. 1973). Direct measurements of the flow emplacement temperature have also been made. First, Maury's (1976) studies of the common carbonized wood fragments in Herculaneum have demonstrated that the wood was heated to at least 400°C. His results have been further supported by paleomagnetic studies of the deposits by Kent et al. (1981) who have studied the remnant magnetism of lithics, bricks, and pumice from the F-3 pyroclastic flow. It is clear from this work that after emplacement, the lithic clasts became partially remagnetized at 350 to 400°C in the pyroclastic flows.

The third flow is overlain by a surge layer 15 to 60 cm thick (S-4). The fourth flow (F-4) is a massive, pumice-rich pyroclastic flow, ranging from 2 to 3 m in thickness. This flow and other flows in the waterfront exposure are well-consolidated deposits, whereas the overlying flows and outcrops of pyroclastic flows in the high-lying parts of Herculaneum are relatively poorly consolidated. The consolidation is thus local and cannot be attributed to welding, but is probably related to cementation and crystallization on grain boundaries from a vapor phase rising from the underlying beach and surges, soaked in seawater. The fourth flow, overlain by a sandy, cross-bedded surge (S-5), is dune-bedded and varies in thickness from 10 to 120 cm. The fifth pyroclastic flow (F-5) is 2- to 3-m-thick, poorly consolidated pumice-flow. It is covered by a thin (8 cm) cross-bedded surge (S-6) which is typically richer in sand-sized lithics than lower surges. The topmost pyroclastic flow (F-6) has a maximum thickness of 1 m, but pinches out to the south. The section is capped by a 60-cm-thick sequence of dark gray, silty surges.

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### *The Palestra*

Some of the layers that make up the volcanic stratigraphy of the waterfront can be traced in the banks of deposits north and south of the excavated city (Figure 39). Because of Herculaneum's elevated position the first two pyroclastic flows did not enter the nucleus of the city and were diverted along valleys to the north and south, whereas all the surges swept through Herculaneum. These relationships can be inferred from studies of the deposits overlying the palestra (eastern Herculaneum) — a magnificent rectangular park, about 50 x 80 m, surrounded by porticos, and used for gymnastic exercises, sports, and games. In the center of the park is a cross-shaped, 1.2-m-deep swimming pool with a serpentlike fountain in its center. The palestra has not yet been excavated, but can be explored by means of a network of tunnels (Figure 40) where the stratigraphy gives evidence of the effects of the eruption on the eastern outskirts of the town.

The first significant deposit in the palestra is the surge layer S-1 (Figure 41). Underneath it are local remnants of the ashfall ≤ 7 mm thick, which sprinkled

Herculaneum in the first stage of the eruption. The S-1 surge thickens locally to 1.4 m where it incorporates the rubble of the collapsed portico and other buildings around the palestra. It consists generally of two units. The lower unit is massive and poorly sorted and contains abundant building fragments, columns, roof tiles, charcoal, and pumice in a sandy matrix. The upper unit is moderately sorted and stratified and consists of sandy-to-silty beds that show low-amplitude cross-bedding. The upper unit is persistent throughout the palestra, whereas the lower unit, dominated by building rubble, is discontinuous and pinches and swells depending on the availability of building material. This first surge was powerful enough to cause widespread damage to buildings but

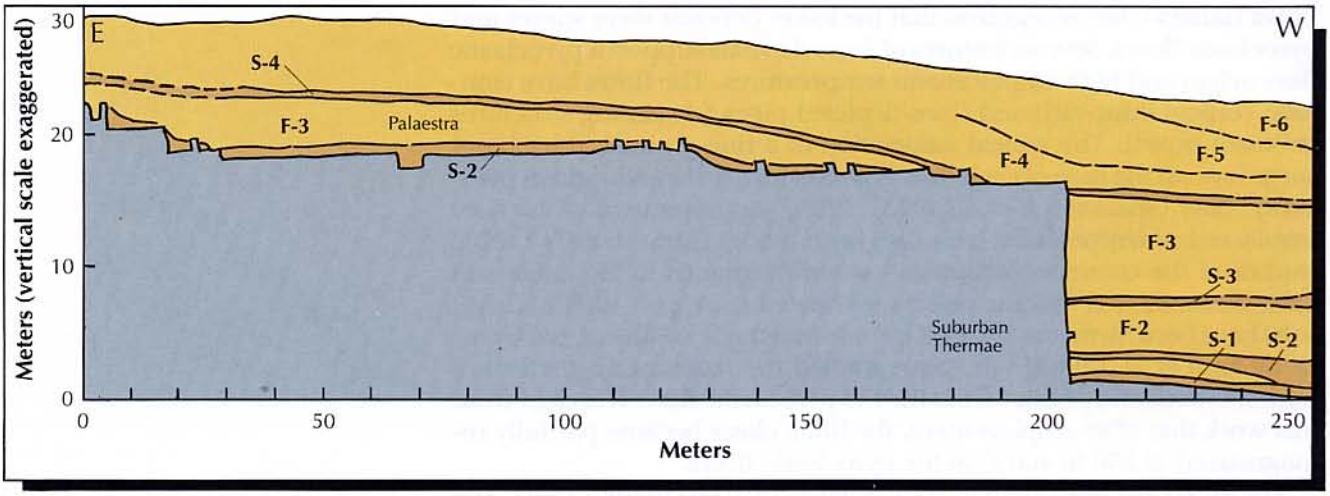


*Figure 39. Schematic section through the volcanic deposits in Herculaneum, from east to west.*

was not powerful enough to transport the rubble more than a few meters.

The first surge is overlain by a massive pyroclastic flow, which partly filled the pool as it flowed from the east or southeast onto the palestra (Figure 41). The flow pinches out completely to the west and northwest and clearly did not flow into Herculaneum. It did however flow down the valley to the south of the Suburban Thermae and emerge on the beach.

The second surge, which is exposed in the upper parts of the exploration tunnels of the palestra, is very rich in building material. Tiles, pieces of pumice, and building fragments are often 15 to 20 cm, some ≤ 60 cm long; charcoal is present. It slopes down toward the north, across the pool where it rests directly on F-1, and onto the northwest half of the palestra where it rests directly on top of S-1. It was inferred from the study of sections in the beach area that the S-2 surge was much more powerful than the S-1. This is supported by exposures in the palestra where the S-2 surge forms a continuous rubble layer.

The second surge (S-2) is overlain by a pyroclastic flow in the palestra, which can be traced west, past the House with the Relief of Telephus, to the waterfront where it correlates with F-3. It is therefore clear that the second pyroclastic flow (F-2) neither covered the palestra nor traveled along the valley southeast of the city, but flowed down the valley to the northwest past the Herculaneum Theater. This contention is supported by the fact that the F-2 flow thins out from northwest to southeast along the beach section. The topmost major deposit in the palestra is a massive pyroclastic flow, ≤ 10 m thick. It contains lithic-rich lenses and rests on a 30- to 60-cm surge layer (S-4).

### *Herculaneum Theater*

Outcrops in front of the Collegio degli Augustali and along Decumanus Maximus show that the northeastern part of the city was also not affected by the first two pyroclastic flows. The section of the deposit has a 1.4-m-thick, poorly consolidated surge at base, tentatively correlated with S-2. The surge is overlain by pyroclastic flows F-3 and F-4, separated by the S-4 surge. These outcrops are within 100 m of the Herculaneum Theater, and provide a basis for correlating the layers that cover this majestic building. The Herculaneum Theater is located about 100 m north of the excavated part of the city, but is still 27 to 30 m underground (Figure 31). The theater was rediscovered in 1709; it can be explored by an intricate network of tunnels and shafts. Built on top of a hill, overlooking a valley to the northwest, the 106-m-wide theater seated 2500 to 3000 people. Inside is a 50-cm-thick surge layer at the base, rich in building rubble (S-2). This deposit is overlain by a 2.4-m massive pyroclastic flow (F-3) in the stage area. A second surge (S-4) overlies the flow, which is in turn overlain by a second 3-m-thick pyroclastic flow (F-4).

Outside the theater, on the steep slope that drops off to the northwest, the lowermost exposed layer is a pyroclastic flow, below the level of the theater interior (F-2). This is overlain by an 80-cm surge, rich in building fragments.

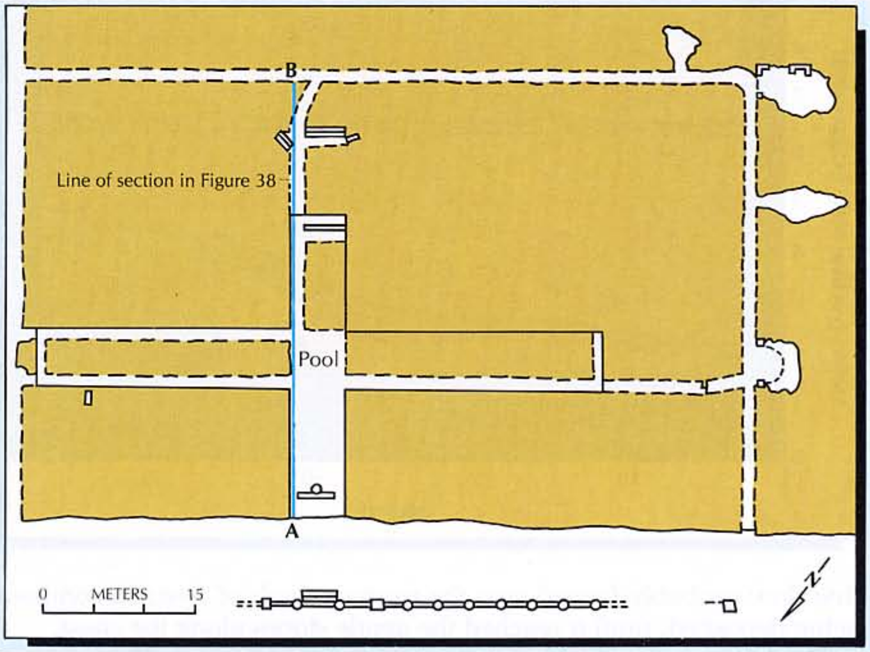


*Figure* **40.** *Plan of the palestra showing 18th-century exploration tunnels and the cross-shaped pool.*

## West and North Flanks of Vesuvius

Until recently, only small, scattered outcrops of the A.D. 79 deposit existed on the western and northern flank of the volcano. Recent construction has improved the situation and new outcrops of the deposits are now exposed in numerous quarries, such as Cava Montone and Pollena, which have cut deep into the A.D. 79 deposit and below it. With the exception of a few proximal outcrops, sections on the west and north flank are more difficult to interpret and correlate because of the lack of a thick well-developed pumice-fall sequence, such as occurs southeast of Vesuvius.

### *West Flank*

An outcrop at the junction of the main Vesuvius road and the road leading up the hill to the Volcanological Observatory is the most proximal section studied and serves as an important reference to the stratigraphy of the A.D. 79 deposits to the west (Figures 42 & 43). Despite the steepness of the surface on which it rests, the section is remarkably complete, containing all but three of the fall and surge layers present at the stratigraphic type locality at Boscoreale (Figure 21). At the Observatory Hill outcrop the A-1 ashfall forms the basal layer, which is generally present on the west flank of Vesuvius, and can be traced as far as Cava Montone, 3 km northeast of Herculaneum. At Casa Baroni, farther north, the A-2 and A-3 pumice-falls form a 20-cm layer, but are absent farther to the west, e.g., at Cava Montone, because the pumice-fall thins to the west and because the later surges were severely erosive.

The first surge at Observatory Hill (S-1) can be traced down the west flank to the quarries at San Giorgio and Cava Montone. The remains of a villa rustica, destroyed by the first surge, were discovered in 1983 in the Cava Montone quarry. Here the S-1 surge is discontinuous because of erosion by the second surge, but is best preserved in the rubble of building material of the destroyed villa (Figure 44). The first surge was clearly much less erosive and did not greatly disturb the underlying A-1 ashfall layer. A layer equivalent to the first pyroclastic flow in Herculaneum (F-1) has only been observed in one of the quarries (Lava Channel), where it forms a 20- to 50-cm massive layer on top of the S-1 surge. The

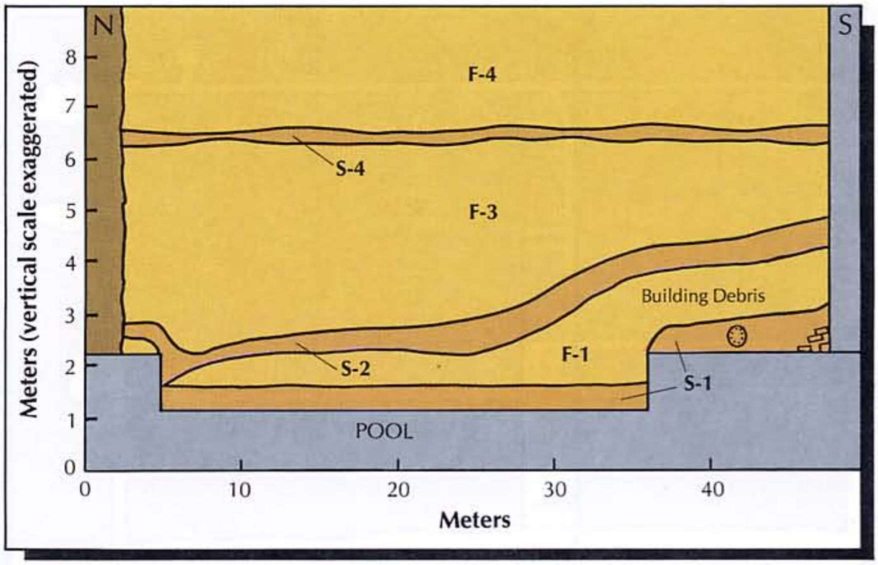


*Figure* **41.** *Stratigraphic section through the* A.D. *79 deposits in the palestra. Note that the F-1 pyroclastic flow terminates in the pool.*

first flow probably passed over the western flank of Vesuvius without being deposited, until it reached the gentle slopes along the coast.

The S-2 surge was highly erosive, and stripped the soil off some topographic features facing the volcano. This is a highly distinctive layer on the west flank of Vesuvius. It consists of two units: a lower massive, coarse, poorly-sorted, fines-depleted unit with abundant lava and carbonate lithics of $\leq 25$ cm in diameter; and an upper, poorly-sorted, pumice-rich, fine-grained, cross-bedded unit with well-developed dune bedding. On ridges and hills only the upper unit is present, whereas both units are generally present in the valley and the plain to the west.

In lithology, the lower massive unit clearly resembles the S-2 surge layer at the Herculaneum waterfront. Elsewhere around the volcano, only the upper cross-bedded unit of the S-2 surge is present, with the exception of the Ottaviano area northeast of Vesuvius. The two-unit S-2 layer is remarkably similar in many respects to the pyroclastic surge layer deposited by the 18 May 1980 blast of Mount St. Helens (Moore & Sisson 1981), which also consists of a lower, coarse unit and a finer stratified upper unit. It is significant that the coarse basal unit shows some topographic control in both eruptions, whereas the finer upper units are more widespread. In Cava Montone and adjacent quarries the upper S-2 surge unit grades upward into a pumice-rich pyroclastic flow (F-2). In the easternmost quarry, where the preeruption surface is steeper, the F-2 flow and later pyroclastic flows pass laterally into cross-bedded surges several meters thick.

*Figure* **42.** *Lower part of the outcrop at Observatory Hill, shown in Figure* **43.** *The thick and coarse gray pumice layer is A-5, overlain by the S-3 surge.*

The distribution of surges and flows west of Vesuvius shows evidence of strong topographic control. On the hills and ridges, such as Observatory Hill and Casa Baroni, the surges are well represented, but pyroclastic flows are absent, whereas the flows are thick on valley floors. The valley between Observatory Hill to the south, and Casa Baroni to the north appears to have directed the course of pyroclastic flows and, to some extent, the associated surges. This valley is a continuation of Valle del Gigante (Figure 8), which separates the main core of Vesuvius from Monte Somma and has been a conduit of many of the volcano's lava flows onto the lowlands to the west and northwest for the past 400 years.

Above S-2 at Observatory Hill, the section shows that a long interval of pumice-fall (A-5) before the third surge (S-3) was generated. After S-3 the gray pumice-fall was again interrupted twice by surges assigned to S-4 and S-5, respectively (Figure 43). But to the west, for example in Cava Montone, the succession above S-2 consists of dune-bedded surges with associated pyroclastic flows and little interbedded fall (Figure 45). In none of the outcrops is there a complete sequence of the six flows and surges deposited at the Herculaneum waterfront. This indicates that some of the Herculaneum flows did not pass down the Valle del Gigante but traveled other routes farther to the south. Unfortunately most of the west flank is covered by younger lava flows, but exposures near Capella Palomba, 300 to 400 m above Torre del Greco, show that A.D. 79 pyroclastic flows and surges also traveled west and southwest from the crater; these could have spread to Herculaneum.

*North Flank*

Deposits from the A.D. 79 eruption extend over a very limited area on the north flank of Vesuvius and are generally not found outside a 7-km radius from the present crater. The deposits are thin, rarely exceeding 1 to 2 m in thickness. Three important exceptions occur in the valleys or drainage basins above Pollena, Santa Anastasia, and Somma Vesuviana (Figure 8), where the surges thicken and are accompanied by localized pyroclastic flows. The initial ashfall (A-1) is generally present at base, and white pumice is commonly impacted into the ashfall, representing the A-2 pumice-fall layer. In the valleys above Ottaviano and above Somma Vesuviana the ashfall is overlain by a thin surge layer—most probably the S-1 surge. These two lobes of the S-1 surge were funneled down the valleys or drainage basins, whereas the main surge spread to the south and west. In most areas of the north flank the A-1 ashfall is overlain by a pumice-fall layer (A-4). The pumice-fall layer is overlain by a sequence of two to four thin surges on the north flank. The surge succession is capped by a ubiquitous 3- to 10-cm dark gray, silty layer, rich in accretionary lapilli, which is overlain by 5- to 10-cm-thick sandy, moderately sorted black ash.

At Monte del Vente, south of Santa Anastasia, the ruins of a villa rustica are found in the A.D. 79 deposit. This villa, situated on a scenic ridge, was apparently an olive-growing estate, judging from implements found at the site. The stratigraphy of the deposits (Figure 46) shows that after minor ashfall (A-1), two surges toppled the villa's 40-cm-thick walls. Likely they correspond to the first two surges of the eruption, and the intervening pumice-fall (A-4) was eroded by the second surge.

Pyroclastic flows from the eruption are well exposed in four localities on the volcano's north flank, where they are being quarried for building materials. One of these is the Pollena quarry, where at least two pyroclastic flows are exposed. In quarries above Santa Anastasia, e.g., Edil Cava Sud, a similar section is exposed, with at least two pyroclastic flows. In the nearby Primavera quarry a pyroclastic flow lies directly on the first surge above of the A-4 pumice-fall. The easternmost pyroclastic flows are exposed at Torretta Scozia, south of Somma Vesuviana where they rest on a surge. The common association of the basal pyroclastic

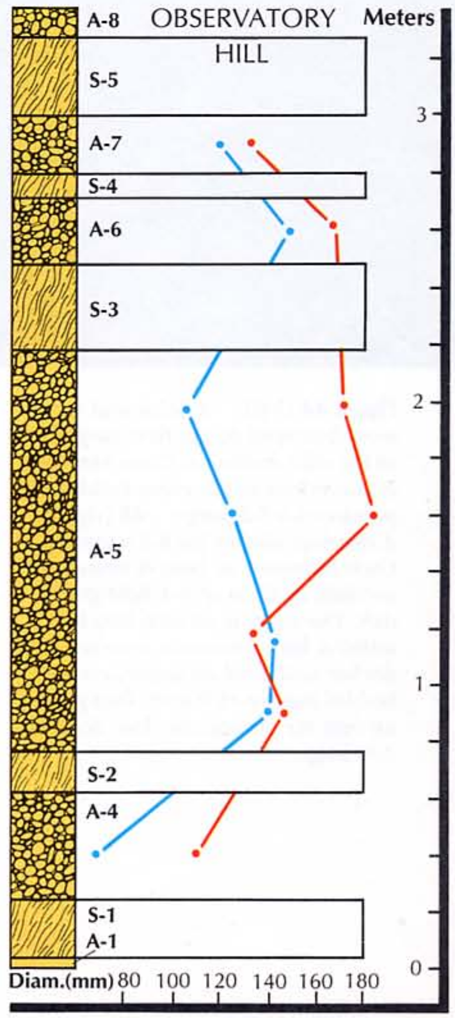


*Figure 43. Stratigraphic section of the A.D. 79 deposits on Observatory Hill, 2.5 km from the Vesuvius crater. This locality is at the junction of the road to the crater and the road to the observatory. Variation in the diameter of pumice is shown in red and of lithics is shown in blue. For key to deposit types, see page 349.*

flow with the first major surge (S-2) is taken as an indication that they were generated from the same event.

The stratigraphic evidence indicates that as many as five surges and at least three pyroclastic flows descended the north flank of the volcano during the A.D. 79 eruption. These deposits are however thinner and not as abundant as at comparable distances from the crater on western and southern sectors of the volcano. The high, semicircular ridge of Monte Somma can therefore be inferred to have posed a significant topographic barrier that limited the northward flow of surges.

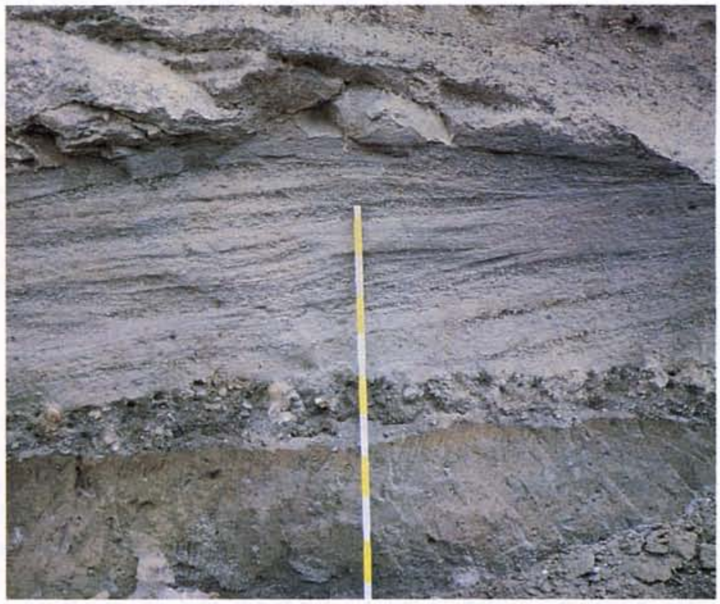

*Figure* **44** (left). *A brick and tile oven destroyed by the first surge (S-1) in the villa rustica at Cava Montone. It is overlain by the cross-bedded pumice-rich S-2 surge.* **45** (right). *A close-up view of the S-2 surge at Cava Montone. At base is brown soil, overlain by 6 cm of A-1 light gray ash. The surge is divided into two units: a lower, massive, coarser, and darker unit; and an upper, cross-bedded pumice-rich unit, that grades up into the pyroclastic flow. Scale is 1 m long.*

# Discussion

## Course of the Eruption

### *Precursors*

Historical accounts describe two events cited as precursors of the A.D. 79 eruption (Seneca, in Cary 1915). The first is the great earthquake of 5 February in A.D. 62 that caused major damage in Pompeii and Herculaneum and also affected Naples. It is likely, therefore, that the source of this earthquake was located close to Vesuvius, but proposals of a connection between the earthquake and the eruption 17 years later remain speculative. Possibly the earthquake was not of volcanic origin, since earthquakes related to regional tectonics are common in this area of Italy. Also, 17 years between a precursor earthquake and an eruption is an unusually long period for related volcanic events. Second, the historian Seneca states that flocks of several hundred sheep were poisoned on the volcano as they wandered into areas where toxic fumes were seeping from the mountain at the time of the A.D. 62 earthquake; perhaps Vesuvius was awakening. Thus it is possible that the earthquake was associated with the rise of magma under Vesuvius, accompanied by fracturing of the overlying crust and local emission of volcanic gases.

Although the indications of geographic upheaval — the dumping of building rubble on the beach in Herculaneum possibly after the A.D. 62 earthquake, and the receding sea level perhaps caused by inflation of the volcano (bradyseism) and adjacent coastline before the eruption — are poorly constrained, they do give some idea of the type of phenomena the populations of Pompeii and Herculaneum may have experienced before the eruption. Unlike these speculations about the precursor activity, the subsequent eruption sequence can be accurately reconstructed on the basis of volcanic stratigraphy and the letters of Pliny the Younger. In his first letter (Radice 1969), Pliny notes the appearance of the Plinian eruption cloud above Vesuvius, as seen from Misenum. This phenomenon was first noted around the seventh hour (*hora fere septima*). In Roman time the first hour occurred at sunrise and the 12th hour at sunset, irrespective of the time of year. Thus the sixth hour was at noon, and the beginning of the Plinian eruption at the seventh hour would thus have occurred about 1 p.m. While this event marks the beginning of the eruption of the white pumice, which started to accumulate as the A-2 pumice layer over Pompeii a few minutes later, it does not mark the first event in the eruption. This occurred when lower-level explosions generated the A-1 ashfall deposit, which may have taken place earlier that morning or the previous night.

The chronologic scheme proposed herein (Figure 47) is based on four assumptions: First, the beginning of the Plinian phase and subsequent A-2 pumice-fall is taken as at hora fere septima or 1 p.m. Second, the most widespread surge (S-6) is taken to correspond to the surge or "black cloud" which Pliny the Younger watched spread across the Bay of Naples and which set him in flight from Misenum shortly after daybreak (near 8 a.m.) on the second day of the eruption. Third, using the relative thickness of the eight pumice-fall layers at Boscoreale as a measure of duration of the Plinian events, the rate of accumulation is assumed to have been uniform during these events. Fourth, the surges are regarded as instantaneous events, and surge thickness is excluded from this time scale. On the basis of this chronology, the change from white to gray pumice-fall occurred around 9 p.m. on 24 August, and the first surge was generated at about 1 a.m. on 25 August.

*Figure* **46.** *Volcanic deposits in the villa rustica at Monte del Vente, on the north slope of Vesuvius. A wall remnant cuts diagonally across the field of view. At the base is the first surge (S-1), dark gray and overlain by the 5-cm-thick A-4 pumice-fall, which is generally prominent on the north flank. This is overlain by a thick, cross-bedded light gray surge, which is probably S-2.*

### *Ashfall Begins*

The first eruptive activity of Vesuvius in A.D. 79 was a phreatomagmatic explosion that generated a low eruption cloud. Drifting with the prevailing westerly onshore wind, the ash plume spread to the east, resulting in deposition of ashfall layer A-1 on the flanks of the volcano and the area east of Vesuvius (Figure 8). The ash fell on the villae rusticae on the slopes of the volcano, but apparently did not extend to the cities or the coastline to the west and south. The ashfall was at most a few centimeters of light gray, fine ash, and therefore although not harmful, probably alarming. It is possible that Rectina's plea for help, sent to Pliny the Elder at Misenum from her villa "under the mountain," was triggered by this event, i.e., that Rectina's villa was within the A-1 ashfall. The presence of accretionary lapilli and the fine-grained character of this layer indicate that ashfall occurred from a "wet" eruption cloud, and that the explosion induced a high degree of fragmentation. A small explosion of this type would probably not have drawn the attention of the Plinys at Misenum, 30 km west of the volcano; if noted, it would have been simply dismissed as a weather cloud over the mountain, and therefore we have no eyewitness evidence of the timing of this event. However evidence from the volcanic deposit at the villae rusticae at Terzigno indicates that this explosion probably occurred shortly before the main Plinian event. At Terzigno, the A-1 ashfall layer in front of the inhabitated northern villa rustica is undisturbed in the doorway. This suggests that the ash fell on the morning of 24 August or during the previous night, because if it had fallen much earlier, it would have been disturbed by the residents.

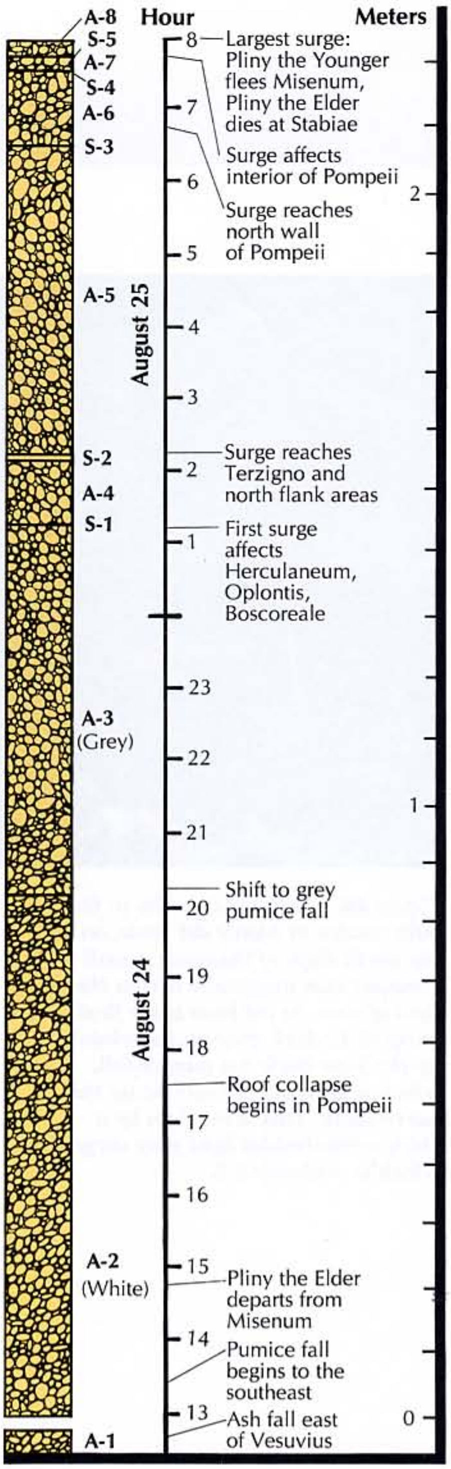


*Figure 47. Chronology of the A.D. 79 eruption, based on correlation of events described in the letters of Pliny the Younger with the volcanic stratigraphy at Villa Regina, Boscoreale. The stratigraphic section (left) shows the thickness of the fall layers as a measure of duration. The thickness of the surge layers is omitted from this column, as surges are considered to be nearly instantaneous events.*

*Pumice-fall Begins*

The high eruption column, which the Plinys observed from Misenum at about 1 p.m. on 24 August, marks the beginning of the Plinian phase. During the next 12 hours, a 27-km-high and later a 33-km-high eruption cloud was sustained over the volcano, ejecting pumice and ash into the stratosphere. It is clear from Pliny's description that the top of the eruption column mushroomed into a very broad cloud, connected to Vesuvius by a long trunk, thus resembling a Mediterranean pine. Preliminary modeling of the eruption column indicated an initial height of 27 km during eruption of the white pumice. Because of the stratospheric wind-shear, the cloud was drawn into an elongated plume to the southeast, resulting in the fall of coarse pumice near the volcano and fine ash at greater distance. During the first seven hours of activity, Vesuvius erupted white pumice, which was deposited downwind over the regions southeast of the volcano as the pumice-fall layer A-2. The location of maximum pumice-fall accumulation was displaced downwind, to the area of Pompeii, because of stratospheric wind-shear on the eruption column and the fragmentation characteristics of the magma.

The southeasterly trend of the fallout, which reflects the stratospheric wind direction prevailing during the eruption, is unusual for Vesuvius' tephra fallout. More typical is the fallout pattern of the Avellino pumice (3500 B.P.) (Lirer et al. 1973) and the 1906 pumice (Rosi et al. 1981), which have fallout axes trending east-northeast of Vesuvius. These trends are in agreement with the average wind direction in the stratosphere for September to May above southern Italy, which has an azimuth near 260° or just south of west (Cornell et al. 1983). In summer however the stratospheric winds are from the east. The A.D. 79 eruption occurred at a time when the stratospheric winds were shifting from their summer to autumn pattern, and the rather anomalous southeasterly fallout direction may thus result from the eruption occurring during a transitional period of the stratospheric winds. This was an unfortunate coincidence for Pompeii and other districts to the southeast of Vesuvius, because they lay in the area of maximum pumice-fall, with accumulation rates of 12 to 15 cm/hr.

People in Pompeii, Oplontis, and elsewhere in the zone of heavy pumice-fall were faced with two problems during the afternoon of 24 August. First, the pumice-fall was accompanied by fall of dense lithic fragments, some fist-sized. These lithics, falling at terminal velocities of over 50 m/s, were dangerous projectiles, and surely injured or killed some people outdoors. Fortunately, pyroclastics of this type were only 10% of the total fall. Calculations, using the mean size of pyroclasts at Pompeii, the average accumulation rate, and an assumed 40% porosity in the fall deposit, show that the frequency of lithic-fall with diameters of 1.5 cm or larger was roughly 70 fragments/min/m$^2$. Second, the weight of accumulating pumice would have collapsed roofs in Pompeii during the afternoon, probably after two or three hours of pumice-fall. This must have led to widespread evacuation of buildings and exodus from the city. Pompeii and other areas southeast of Vesuvius were however in darkness at this time, caused by the dense eruption plume overhead.

During the evening, after seven hours of white pumice-fall (A-2), the composition of the erupting magma changed, and gray pumice was now produced. As the gray pumice erupted, the height of the eruption column increased significantly. This is shown, for example, by the marked increase in diameter of lithics within the fall deposit across the white–gray boundary at Pompeii (Figure 23). The Plinian eruption of gray tephra continued for five hours, depositing layer A-3 to the southeast of the volcano where ≤ 150 cm of pumice had accumulated by this time.

*Surge S-1 and Flow F-1*

During the first 12 hours of activity the heavy pumice-fall mainly affected an area southeast of Vesuvius, bounded by Terzigno to the east and Oplontis to the west. Other areas around the volcano were relatively unaffected, except for minor pumice-fall on the upper slopes and light dusting of ashfall in Herculaneum. Around 1 a.m. on 25 August the style of activity changed as Vesuvius produced the first of six pyroclastic

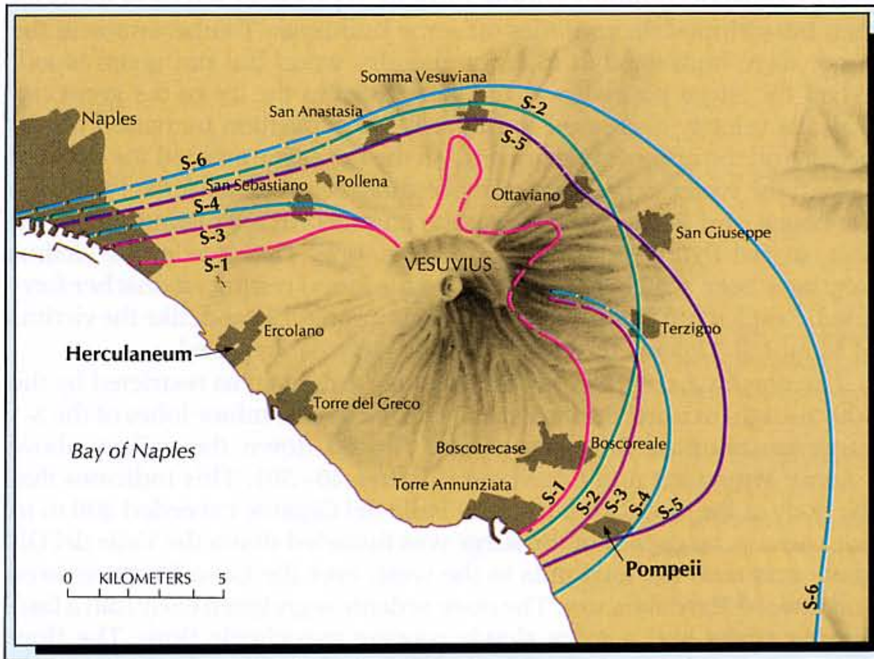


*Figure 48. Distribution of the six surge layers from the A.D. 79 Vesuvius eruption.*

surges and flows, which were to interrupt the pumice-fall during the next seven hours, killing people within a 7- to 10-km radius from the crater. The first surge (S-1) spread over the south and west flank of Vesuvius, overwhelming Villa Regina at Boscoreale, Oplontis, and all the west coast to Herculaneum (Figure 48). Small tongues of this surge extended down the valleys above Somma Vesuviana and Ottaviano on the north and northeast flank. This first and smallest of the surges did not however reach the villae rusticae at Terzigno nor the city of Pompeii. The effects of this surge were remarkably similar to the effects of the surges of the 1982 eruption of El Chichon in Mexico, which devastated nine towns and villages (Sigurdsson, Carey et al. 1984). The effects of the S-1 surge are best studied and most dramatic in Herculaneum. During the preceding 12-hour period of activity, the city had only received a light sprinkling of ashfall, less than 1 cm thick. With the erupting volcano in full view, and being only 7 km from the crater, the population must have been uneasy. Many Herculaneans must have left their city during this period, and fled toward safety in Naples to the north where these lucky refugees became permanent residents of the Herculaneum Quarter.

People remaining in Herculaneum may have seen the precursor of the surge as a nuée ardente sweeping down the cone of the volcano. During the 1980 Mount St. Helens eruption, the main surge moved at 60 to 250 m/s (Moore & Rice 1984). The S-1 surge is however much finer grained and of smaller extent, and probably more similar to the southern Mount St. Helens surge, which traveled at only 30 m/s. Even at this lower velocity, the surge would have taken no more than four minutes to reach Herculaneum. People in the city were without doubt on the alert that night, and probably in the streets watching the spectacle of the ominous eruption column, with its lower trunk glowing from incandescent tephra, and its upper part illuminated by flashes of lightning. The cascade of the nuée ardente down the flank would have been immediately noticed and recognized as a threat. Flight from the eruption to the waterfront and along the coast toward Naples is the most obvious solution.

At about 1 a.m. the first surge cloud swept into Herculaneum at sufficient velocity to topple the colonnade and portico around the palestra and to transport building rubble 2 to 4 m. It probably left most walls intact, but stripped the roof tiles off some buildings. Temperatures in the surge were high enough to carbonize dry wood but not green wood. When the surge poured over the waterfront in the lee of the great city wall, its velocity decreased locally, so that deposition increased on the beach and the adjacent chambers. As the hot surge entered the ocean it caused the water to boil and give off small steam explosions. People on the beach and in the chambers were engulfed in a swirling ash-cloud that carried flying roof tiles and other debris. Thus one of the victims may have been struck down by the red tile found resting against her forehead. Respiration in the surge cloud was impossible and, like the victims of Mount St. Helens, the Herculaneans were asphyxiated.

The northward spread of the first nuée ardente was restricted by the 300-m-high arcuate Monte Somma rim. Only two minor lobes of the S-1 surge surmounted this barrier and flowed down the valleys above Somma Vesuviana and Ottaviano (Figures 48–50). This indicates that the body of the nuée ardente in the Valle del Gigante exceeded 300 m in thickness. A large part of the surge was funneled down the Valle del Gigante and onto the lowlands to the west, over the Cava Montone area and toward Herculaneum. The nuée ardente segregated early into a fast-moving surge and a more slowly moving pyroclastic flow. The flow reached Herculaneum shortly after the surge, and came into the city from the east, flowing into the palestra where it filled the large cross-shaped swimming pool. The flow did not advance through the city, but rather down a valley along its southern edge and onto the beach in front of the Suburban Thermae. Here the pyroclastic flow (F-1) engulfed and carbonized a large boat on the beach and advanced into the ocean before coming to rest. Where exposed on the waterfront, the F-1 flow rests directly on top of the S-1 surge. Here the flow contains gas pipes, produced by the escape of steam expelled from the underlying surge, which by now had become soaked by seawater.

*Surge S-2 and Flow F-2*

Fall of gray pumice continued as before, following the emplacement of the first surge and flow, and led to accumulation of pumice-fall layer A-4, during one hour, south of the volcano. Elsewhere, the new desertlike surface created by the first surge remained bare, with protruding, smoking carbonized tree trunks and steam rising from rivers and the coast. One hour later, near 2 a.m., the second nuée ardente was generated from the crater, and formed a surge with a volume about three times that of the first event. The surge cloud spilled out of the Valle del Gigante and over the Somma rim to the north, devastating all the north flank of Vesuvius within 7 km of the crater (Figures 48–50). It destroyed the villae rusticae at Terzigno beyond the reach of the first surge, but ran its course south of Boscoreale before reaching Pompeii.

On the west flank the surge left a deposit similar to that of the 18 May 1980 Mount St. Helens blast, and was probably moving at 100 to 200 m/s. In Herculaneum, where its effects were particularly severe, it struck with sufficient force to break down the masonry walls and roofs unaffected by the first surge. The surge was closely followed by the pyroclastic flow F-2, which flowed north of Herculaneum and onto the beach. Flows also advanced down valleys on the north flank leading to Pollena, Santa Anastasia, and Somma Vesuviana, but no pyroclastic flows are known to have affected the south flank at this time. In many southern outcrops, the S-2 surge is split by a thin pumice-fall layer, from which the surge can be inferred to have come in two rapid pulses to the south.

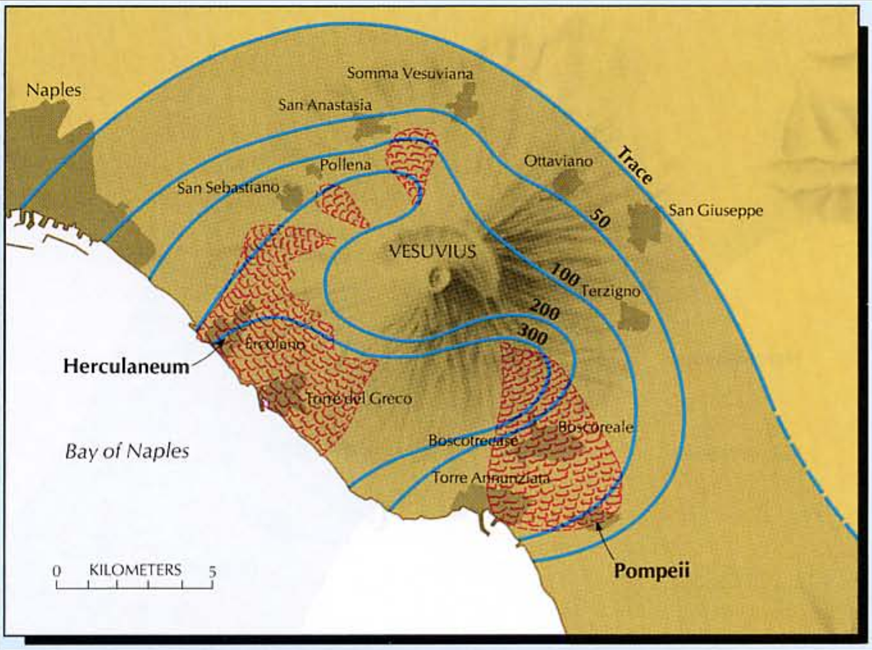


*Figure **49**. The thickness of the total surge deposits (in meters), with isopachous lines. Distribution of pyroclastic flows (red) is also shown.*

Pumice-fall continued after passage of the great S-2 surge, and the A-5 gray pumice layer accumulated during about four hours, until about 6 a.m. During this Plinian phase a larger proportion of lithics was erupted than before, probably indicating increased erosion of the vent. These included both lavas and fragments from the carbonate basement. Around 6:30 a.m. the third surge was generated, with similar distribution, as S-2. It extended even farther south, running up against the northern city wall of Pompeii but not entering the city. The surge was followed by a pyroclastic flow in the northwest, which flowed directly over the remains of Herculaneum and completely buried the city so that only the theater protruded. This and subsequent flows extended the new coastline an additional 400 m to the west of the Herculaneum waterfront.

*Surge S-4*

The pumice-fall was now darker and more lithic-rich. It continued for about an hour, until 7:30 a.m., forming layer A-6. Subsequently a fourth surge was generated (S-4), which followed the previous pattern and spread even farther south, this time overwhelming Pompeii and Bottaro. As the surge cloud came over the northern city wall of Pompeii, it rolled over an area already blanketed by 2.4 m of pumice-fall. Most roofs had collapsed, and only the walls of two- and three-story buildings stood above the bleak wasteland. Most of the inhabitants had abandoned the city to escape the collapsing roofs, but a surprising number of people were moving about on top of the pumice-fall when the lethal fourth surge struck at about 7:30 a.m. About 2000 people, or 10% of Pompeii's population, are estimated to have become victims of the fourth surge inside the city walls (Maiuri 1958). Their deaths are tragically recaptured in the plaster casts of hollows in the deposits (Figure 25). They were asphyxiated in the surge cloud, which tore through the city, removing roofs and collapsing many walls.

*Surge S-5*

The fourth surge was followed by the fifth surge a few minutes later. Even larger, it was accompanied by a pyroclastic flow in many areas to

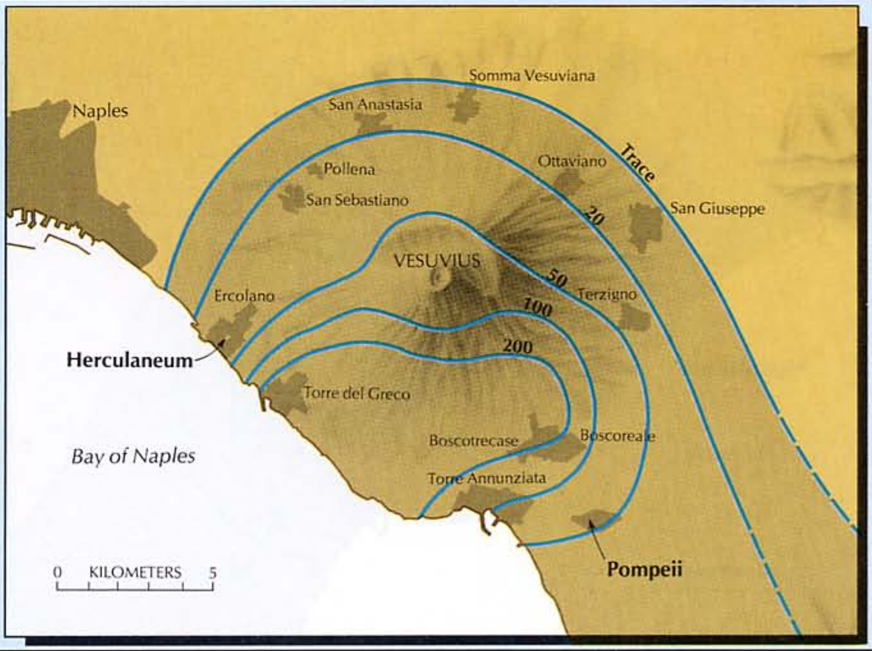


*Figure* ***50.*** *Distribution and thickness (in centimeters) of accretionary lapilli beds (falls and surges).*

the south, such as Oplontis. At this time Pliny the Elder was marooned at the house of his friend Pomponianus at Stabiae, 14 km south of the crater. The previous afternoon Pliny had abandoned his plans of making landfall on the southwest coast under the volcano, because of very heavy fall of hot pumice and lithics on his ships and because sailing near the coast was made impossible by thick floating rafts of pumice. He therefore gave up his rescue mission and headed for the comparative safety of Stabiae to the south. Judging from the stratigraphic section at the Villa Ariadne (Sigurdsson, Cashdollar et al. 1982), nearly 2 m of pumice-fall accumulated at Stabiae during the eruption. It is not surprising, as Pliny the Younger states, that his uncle had difficulty opening his door the next morning, because of the thick pumice layer in the courtyard:

> They debated whether to stay indoors or take their chance in the open, for the buildings were now shaking with violent shocks, and seemed to be swaying to and fro, as if they were torn from their foundations. Outside, on the other hand, there was the danger of falling pumice-stones, even though they were light and porous; however, after comparing the risks they chose the latter (Radice 1969:168).

The black eruption plume overhead caused darkness at Stabiae "blacker and denser than any ordinary night," but they could see daylight underneath the cloud, probably to the northeast and west.

*Surge S-6*

"Then the flames and smell of sulfur which gave warning of the approaching fire drove the others to take flight" (Radice 1969:168). This event must represent the advance of the sixth and largest surge over the south flank toward Stabiae at about 8 a.m. on 25 August. At Villa Ariadne the surge deposited a 2-cm layer on top of the pumice-fall and thus clearly affected Stabiae. By his nephew's admission, Pliny the Elder was an overweight man with a weak constitution and he did not take flight with the others, but collapsed in the arms of his two slaves as he choked in the dusty surge cloud. Near the volcano the sixth surge left a major deposit, which is often 0.5 to 1 m thick in outcrops. It grades upward into a pyroclastic flow, e.g., at Oplontis and Boscoreale; thicker parts of this deposit at Pompeii also resemble pyroclastic flow.

Severe earth tremors also threatened Pliny the Younger and his mother that morning at Misenum and they decided to abandon the tottering buildings and leave town. En route they witnessed a tidal wave and over the volcano "a fearful black cloud was rent by forked and quivering bursts of flame, and parted to reveal great tongues of fire, like flashes of lightning magnified in size" (Radice 1969:171). They were witnessing the great nuée ardente that generated the sixth surge about 8 a.m., and took the life of Pliny the Elder. "Soon afterwards the cloud sank down to earth and covered the sea; it had already blotted out Capri and hidden the promontory of Misenum from sight" (Radice 1969:171). Both are about 30 km from Vesuvius. Pliny the Younger then describes their experience as they fled the surge cloud rolling across the Bay of Naples:

> Ashes were already falling, not as yet very thickly. I looked around: A dense black cloud was coming up behind us, spreading over the earth like a flood. . . . Darkness fell and ashes began to fall again, this time in heavy showers. We rose from time to time and shook them off. . . . At last the darkness thinned and dispersed into smoke or cloud; then there was genuine daylight, and the sun actually shone out (Radice 1969:172).

There can be no doubt that the surge traveled across the Bay of Naples and reached Misenum, where fine ash from the turbulent surge cloud settled. It must have cooled on its long path, because Pliny mentions no heat. The deposit left by the surge at Misenum was probably only a few centimeters and soon eroded away, because no deposit remains today. The passage of a surge cloud over a long distance across water was also documented in the 1883 Krakatau eruption in Indonesia, where surge clouds from the volcano engulfed islands and settlements on the south coast of Sumatra (Simkin & Fiske 1983).

*Post Surge S-6*

The activity of Vesuvius following the sixth and largest surge is not chronicled by Pliny, but the deposits bear evidence of continued eruption. Within 10 km of the volcano this later activity laid down surges and accretionary lapilli beds consisting of at least 20 units (Figures 49 & 50). Many of these beds are pumice-free and mostly composed of lithics, thus indicating the small role of juvenile magma at this stage. These deposits were probably formed by a large number of small phreatic or phreatomagmatic explosions, resulting from interaction of groundwater and magma remaining in the volcano's conduit (Sheridan et al. 1981). This activity may have persisted for days or weeks.

When the eruption came to an end, pyroclastic surges that left a deposit of 0.23 $km^3$ dense rock equivalent (DRE) had totally devastated 300 $km^2$ around Vesuvius. By comparison, the volcano produced about 0.14 $km^3$ DRE of pyroclastic flows during the eruption and 0.16 $km^3$ DRE of accretionary lapilli beds during the final phreatomagmatic phase. These figures do not take into account the unknown volumes of tephra that entered the Bay of Naples. Including 2.6 $km^3$ DRE of gray pumice and

1 $km^3$ DRE of white pumice, the total deposit produced by the eruption is thus about 4 $km^3$ DRE; about 90% was juvenile material.

## Eruptive Mechanisms

The variation in eruptive style during the A.D. 79 eruption of Vesuvius, as revealed in the volcanic stratigraphy of the deposits, can be related to a model of magma discharge that integrates various physical properties of the magma, the geometry of the vent system, and the size and location of the magma reservoir beneath the volcano. Prior to the eruption, a large body of compositionally zoned phonolitic magma (minimum 3.5 $km^3$) accumulated in a high-level, crustal magma chamber at a depth of $\geq 3$ km (Barberi et al. 1981). Evolved magma from this reservoir gradually ascended into the volcanic edifice until it interacted with meteoric water, resulting in phreatomagmatic explosions that marked the beginning of the A.D. 79 eruptive sequence. With a free path to the surface, eruption of magma at a high rate from the reservoir began shortly thereafter. The pressure gradient necessary to drive magma out of the reservoir at about a 3-km depth cannot have been induced by volatile saturation within the reservoir (e.g., Blake 1984), since preliminary studies of volatile content in glass inclusions in phenocrysts indicate that the magma would become water-saturated at 1.7 to 2.4 km depth. More likely, magma flow resulted from the density contrast between the magma and surrounding crustal rocks (Wilson et al. 1980).

### *Eruption Column*

Fragmentation of the magma into pumice and ash and the rapid acceleration of this material in the conduit was caused by the exsolution and expansion of juvenile volatiles dissolved in the phonolitic melt. Discharge of the mixture of gas and pyroclasts generated a high-altitude eruption column as sufficient thermal energy was transferred to entrained atmospheric air in order to sustain buoyantly convective conditions (Wilson 1976). The lower part of the column consisted of a momentum jet, extending perhaps 3 km above the crater, and an upper convective portion that was as much as 90% of the total column height (Wilson et al. 1978). During the first seven hours of this phase, 1 $km^3$ of phonolitic magma erupted and was distributed predominantly to the southeast of Vesuvius as white pumice-fall. The mass eruption rate was $10^8$ kg/s, based on a magma density of 2.5 $g/cm^3$, or about five times the mass eruption rate of the 18 May 1980 Plinian eruption of Mount St. Helens (Carey & Sigurdsson 1985).

Wilson et al. (1978) and Settle (1978) have shown that the height of an eruption column during an explosive event is determined primarily by the rate at which magma is erupted. Using the equation for eruption cloud height from Wilson et al. (1978), a mass eruption rate of $10^8$ kg/s would yield a column 27 km high. Field data show however that during fall of the white pumice and lithics, the size of the pyroclasts increased as the eruption progressed. Because this type of variation was also observed at distal sites, the increase in pyroclast size must be attributed to an increase in eruption column height, which ultimately controls the height attained by particles and thus their maximum lateral distribution (Wilson et al. 1980). It follows, therefore, that the mass eruption rate was also increased during this period.

For explosive eruptions that are driven solely by a buoyancy force, the mass eruption rate can be expressed as,

$$MER = \rho_m (\rho_c - \rho_m) g / 8h$$

where r is the conduit radius, $\rho_m$ is the magma density, $\rho_c$ is the density of the surrounding crustal rocks, g is the acceleration of gravity, and h is the magma viscosity (Wilson et al. 1980). It can be seen that small variations of r can have a large effect on the mass eruption rate. Thus the increasing mass eruption rate during ejection of the white pumice is likely to merely reflect a continually enlarging conduit, brought about by erosion of the rock of the conduit's wall.

After 1 $km^3$ of evolved phonolite was erupted, gray, less-evolved phonolitic pumice began to be discharged with no apparent break in the fall succession. During the next 12 hours the Plinian eruption deposited a layer of gray pumice-fall with a volume of 2.6 $km^3$ DRE, equivalent to a mass eruption rate of $1.5 \times 10^8$ kg/s. Significant compositional discontinuities between the white and gray pumice indicate the tapping of an important physicochemical boundary within the magma chamber (Cornell & Sigurdsson 1984). Because of lower volatile content and therefore lower vesicularity, the gray pumice is also denser. As with the white pumice, discharge of gray pumice generated a tall eruption column (33 km), but the field evidence indicates an even larger increase in column height than occurred during eruption of the white pumice. This increase is attributed to vent erosion on an accelerated scale with a corresponding rise in the mass eruption rate. The first major shift in activity occurred roughly five hours after gray pumice began to erupt, when the first of a series of pyroclastic surges and flows was generated.

*Convecting Versus Collapsing Eruption Column*

On the basis of a theoretical model, Sparks & Wilson (1976) presented the critical combinations of vent radius, exit velocity, and mass eruption rate that define the transition from convecting eruption columns, which produce only ash and pumice fall, to collapsing columns, which generate pyroclastic surges and flows (Figure 51). In order to bring about a shift from convecting to collapsing columns either the vent radius and mass eruption rate must increase, or the exit velocity and volatile content must decrease. At the point of the first surge and flow generation, the eruptive sequence had evolved toward the former conditions. Some preliminary data on the contrast in volatile content between white and gray pumice suggest that the latter condition was also satisfied (Figure 51). The volatile content and mass eruption rates for the white and gray pumice phases both plot in the convective field of Figure 51. These points are however the average values for these parameters during the two phases. The important feature at this point is that the gray pumice is shifted significantly toward the transition boundary. We are currently investigating the variation of these parameters in more detail using experimental phase equilibria and computer simulation of eruption column dynamics. On the basis of these initial data, we propose that the shift from fallout to surge and flow activity resulted from an increasing mass eruption rate and the tapping of a relatively volatile-depleted portion of the magma body. It is important to realize that it is only the jet phase that collapses during such events, and not the entire eruption column, which in fact continues to rise.

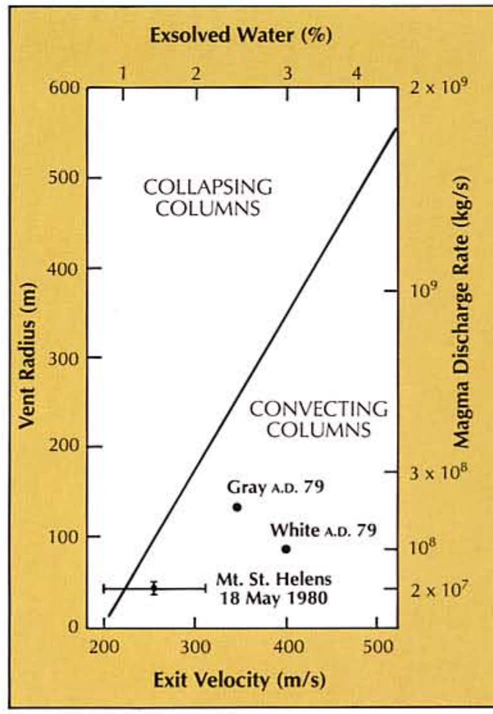


*Figure 51. The combinations of vent radius, exsolved water content, mass eruption rate, and exit velocity that define the regions of convecting and collapsing eruption columns (Wilson et al. 1980). Because of higher water content (estimated from microprobe analysis of glass inclusions in phenocrysts) and relatively low mass eruption rate, the eruption column during eruption of the white pumice was wholly within the convecting column field. Because of higher mass eruption rate and lower water content, the eruption column for the gray pumice is closer to the boundary of column collapse.*

*Surge and Flow Activity*

Four more periods of surge and flow generation occurred in association with gray ash- and pumice-fall. The oscillation between surge and flow, and fall during this period reflects minor variations in the eruptive parameters that shifted across the boundary defined by Sparks & Wilson (1976). This type of oscillation has also been inferred for the

18 May 1980 eruption of Mount St. Helens (Carey & Sigurdsson 1985).

Throughout the period of alternating surge–flow and fall activity the field data show that the amount of lithic fragments was increasing and that the height of the eruption column reached a maximum and then began to subside. At this stage of the eruption, the extent of magma evacuation from the chamber may have led to collapse of roof-rocks as underlying support was diminished. Collapse may have occurred along inwardly inclined ring fractures so that the location of the conduit system to the surface remained somewhat fixed (Druitt & Sparks 1984). It is possible that the Somma ridge was accentuated at this time, leading to the further diversion of pyroclastic flows and surges as suggested by the distribution of the deposits (Figure 48). The increase in lithic fragments thus represents increasing disruption of the upper parts of the reservoir and conduit system. Associated with this trend is the gradual exhaustion of volatile-rich magma available for eruption and the consequent decrease in the mass eruption rate. Although volumetrically important near the volcano, the surge and pyroclastic flow deposits are a minor component of the eruption as a whole (Figures 49 & 50).

After the emplacement of the sixth, lithic-rich surge, a new phase of activity began to dominate. Lithic-rich, fine-ash beds containing abundant accretionary lapilli overlie S-6; they indicate a shift to phreatomagmatic activity. A thick sequence of interbedded accretionary lapilli beds and finely stratified, lithic-rich surge deposits was laid down during this final phase of activity (Figures 49 & 50). At this stage, the ascent rate of magma was probably very low, and water from the hydrologic system of the volcano's edifice poured into the open conduit, in contact with stagnant magma. This led to a series of vulcanian explosions, which generated small water-rich eruption clouds.

*Magma–Water Interactions*

Sheridan et al. (1981) have also presented a model for the A.D. 79 eruption of Vesuvius which is in some respects similar to the one presented here. Their model however emphasizes the interaction between meteoric water and magma as a mechanism to widen the vent and increase the "explosivity" during eruption of the gray pumice. Surge layers at Oplontis and the general increase in lithic fragments in the gray fall layers are cited as support for this hypothesis. They also call upon hydromagmatic explosions to provide the necessary fragmentation for the production of pyroclastic flows.

The model presented here differs from the model presented by Sheridan et al. in the extent to which external water has influenced various stages of the eruption. Clearly, at the time of the S-6 surge, the interaction between external water and the remaining magma was a major factor controlling the dynamics and style of the eruption, as Sheridan et al. suggest. Nevertheless it is not necessary to call upon significant magma–water interaction at any point before this stage except during the initial phreatomagmatic explosion which produced the ashfall layer A-1. As shown, the increase in mass eruption rate, shift to surge and flow activity, and increase in lithic fragments can all be accounted for using only juvenile magmatic volatiles and variations in certain other eruptive parameters. Furthermore, pyroclastic flows have occurred during eruptions without any evidence of magma–water interaction and thus the availability of meteoric water does not appear to be a valid limiting condition for this style of activity. Fragmentation of magma by exsolution of juvenile volatiles is likely to be sufficient to generate the observed size distribution of flow material.

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