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Journal of Volcanology and Geothermal Research 126 (2003) 201–223

Journal of volcanology and geothermal research

www.elsevier.com/locate/jvolgeores

Impact of the AD 79 explosive eruption on Pompeii, I. Relations amongst the depositional mechanisms of the pyroclastic products, the framework of the buildings and the associated destructive events

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Received 26 February 2002; accepted 24 April 2003

Abstract

A quantitative and qualitative evaluation of the damage caused by the products of explosive eruptions to buildings provides an excellent contribution to the understanding of the various eruptive processes during such dramatic events. To this end, the impact of the products of the two main phases (pumice fallout and pyroclastic density currents) of the Vesuvius AD 79 explosive eruption onto the Pompeii buildings has been evaluated. Based on different sources of data, such as photographs and documents referring to the archaeological excavations of Pompeii, the stratigraphy of the pyroclastic deposits, and in situ inspection of the damage suffered by the buildings, the present study has enabled the reconstruction of the events that occurred inside the city when the eruption was in progress. In particular, we present new data related to the C.J. Polibius' house, a large building located inside Pompeii. From a comparison of all of the above data sets, it has been possible to reconstruct, in considerable detail, the stratigraphy of the pyroclastic deposits accumulated in the city, to understand the direction of collapse of the destroyed walls, and to evaluate the stratigraphic level at which the walls collapsed. Finally, the distribution and style of the damage allow us to discuss how the emplacement mechanisms of the pyroclastic currents are influenced by their interaction with the urban centre. All the data suggest that both structure and shape of the town buildings affected the transport and deposition of the erupted products. For instance, sloping roofs 'drained' a huge amount of fall pumice into the 'impluvia' (a rectangular basin in the centre of the hall with the function to collect the rain water coming from a hole in the centre of the roof), thus producing anomalous deposit thicknesses. On the other hand, flat and low-sloping roofs collapsed under the weight of the pyroclastic material produced during the first phase of the eruption (pumice fall). In addition, it is evident that the walls that happened to be parallel to the direction of the pyroclastic density currents produced during the second eruptive phase were minimally damaged in comparison to those walls oriented perpendicular to the flow direction. We suggest that the lower depositional parts of the pyroclastic currents were partially blocked (locally reflected) and slowed down because of recurring encounters with the closely spaced walls within buildings. Locally, the percentage of demolished walls decreases down-current, which has been interpreted as a loss in kinetic energy within the depositional system of the flow. However, it seems that the upper transport system by-passed these obstacles, then supplied new pyroclasts to the depositional system that restored its physical

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0377-0273/03/$ – see front matter
doi:10.1016/S0377-0273(03)00146-X

characteristics and restored enough kinetic energy to demolish the next walls and buildings further along its path.

Keywords: Vesuvius; AD 79 eruption; Pompeii; damage to buildings; destructive impact; Polibius; emplacement mechanisms

1. Introduction

The impact of explosive eruptions on densely inhabited regions is without a doubt one of the central themes in modern volcanology. The objective of these studies is to develope short- and long-term strategies aimed at reducing the risks associated with various styles of explosive eruptions. An accurate evaluation of the volcanic risk is, nevertheless, not an easily achievable goal, as it depends not only on the exposed development, but also on the cumulative knowledge of the physical behaviour and the past eruptive history of the volcano.

This paper relates the emplacement of pyroclastic products associated with the well-known Vesuvius AD 79 explosive eruption to the destructive events in the city of Pompeii; it is aimed at understanding the impact of the eruption on the urban centres located around the volcano. The study examines the role of the buildings in affecting the deposition and resultant distribution of the pyroclastic products, including a large-scale study of the effects of the eruption on the city buildings and an extremely detailed investigation in the C.J. Polibius' house, a large mansion located in the city centre. The studied building was chosen for the following reasons: (1) the nearby presence of adjacent outcrops of the pyroclastic deposits of the AD 79 eruption; (2) the relatively recent age of the excavation, assuring excellent preservation of the effects of the eruption; (3) the availability of excavation reports containing stratigraphic data and information about the state of the building, including the restoration techniques adopted; (4) the availability of clear, comprehensive photographic coverage, together with several drawings and watercolour paintings, documenting the main phases of the excavation.

This research was performed applying a typical volcanological approach (stratigraphy and lithofacies definition, reconstruction of the emplacement mechanisms) to the study of these archived photographs, paintings and documents. This enabled a detailed analysis of the behaviour of these urban constructions as they were exposed to extreme mechanical and thermal conditions associated with the eruption, as well as evaluated the extent to which the buildings affected the distribution and dispersion of the pyroclastic products. In particular, a model for the interaction between the urban structures and the depositional system of the pyroclastic density currents (PDCs) is presented. A reconstruction of the sequence of events in Polibius' house is also proposed. Finally, a general model of the effects of the AD 79 eruption on the city of Pompeii is discussed.

2. The Vesuvius AD 79 eruption

The AD 79 eruption that destroyed Pompeii and Herculaneum has been widely studied in the last twenty years and several interpretations of its dynamics have been proposed (e.g. Lirer et al., 1973; Sigurdsson et al., 1985; Carey and Sigurdsson, 1987; Cioni et al., 1990, 1992, 1996; Yokoyama and Marturano, 1997; Mastrolorenzo et al., 2001). The letters, written by Plinius the Younger to the historian Tacitus, reporting the dramatic events formed the starting point for all of them, even the most recent ones.

The eruption was preceded by several earthquakes. The strongest of them, which severely affected the city of Pompeii, occurred in AD 62 and is considered to be directly related to the AD 79 event (Luongo et al., 1995). The eruption lasted 19 h, from 1.00 p.m. of August 24 to 8.00 a.m. of August 25. It began with a weak phreatomagmatic explosion covering the volcano with an ash deposit. Next, a pumice lapilli fall from a Plinian column 14–32 km high (Carey and Sigurdsson, 1987) covered a large area south of the volcano (Lirer et al., 1973). Pumices are white at the base and grey towards the top of the deposit, reflecting a change in chemical composition and density of the tapped magma (Civetta et al., 1991). The maximum thickness of the fall deposit (2.8 m) was reached 10 km south of the volcano in the city of Pompeii (Sigurdsson et al., 1985). Several PDCs were produced immediately before, during and after the fallout phase of the grey pumices; they flowed mainly to the north, west and south. Cities such as Herculaneum, that were little, if at all, affected by the pumice lapilli fallout, were reached by PDCs the emplacement temperature of which was as high as 400°C (Kent et al., 1981; Capasso et al., 2000; Mastrolorenzo et al., 2001). The development of a syn-eruptive caldera structure is possibly evident by the presence, only to the volcano slopes, of lithic-enriched, valley ponding flow deposits (Cioni et al., 1992, 1996). The role of phreatomagmatism during the course of the eruption is debated. The beginning of magma–water interaction is related to the first PDC after the fall phase (Barberi et al., 1989; Cioni et al., 1996) or, more probably, to the last stage of the eruption (Sigurdsson et al., 1985), as testified by the abundant accretionary lapilli and the high degree of fragmentation of the particles forming the final stratified ash deposit. The emplacement of the PDCs during this latter stage was not continuous, as is shown by the presence of three lithic-rich fall layers easily distinguishable in the upper part of the phreatomagmatic sequence.

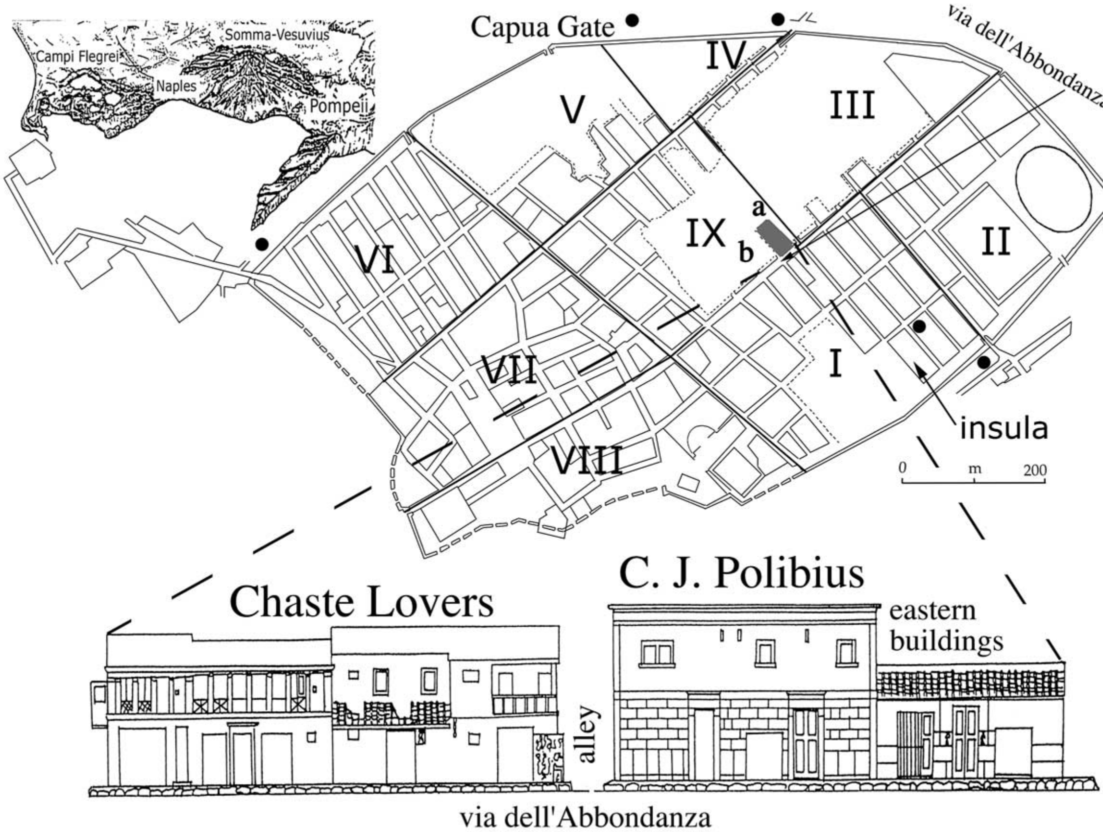

Fig. 1. Plan view of Pompeii showing the location of the Polibius' house (grey rectangle), the house of the Chaste Lovers and their relative outcrops, (a) and (b). Dots represent locations of the other outcrops studied. Roman numbers indicate locations of 'regiones'. Lower part: facades of the two buildings. Inset: sketch map showing the relative position of Pompeii and Mount Vesuvius.

3. General stratigraphy of the AD 79 deposit at Pompeii

This stratigraphy is based on seven sections located close to the city walls and inside the city (Fig. 1). A composite section of the deposit of the AD 79 eruption cropping out at Pompeii with a lithological and lithofacies description is illustrated in Fig. 2. We prefer to use a new descriptive nomenclature rather than the previously adopted (model-driven) genetic terminology (e.g. fall, flow and surge layers by Sigurdsson et al., 1985 and eruptive units by Cioni et al., 1996). A correlation between the previous stratigraphic nomenclature of the AD 79 deposit at Pompeii and that used in this study is also illustrated in Fig. 2. The AD 79 deposit consists of a lower white to grey pumice fall bed (units A and B), 2.8 m thick, overlain by stratified ash and pumice PDC layers variable in thickness from a few decimetres to 3 m (units C–L). This upper sequence is interstratified with minor, thin and lithic-rich fall layers (units D, G and I). The main fall bed (unit A) is grain-supported and is composed mainly of angular pumice lapilli clasts with minor wall rock lithic clasts of volcanic (lavas) and sedimentary (limestone) origin. Coarse ballistic blocks, both of pumice and wall rock nature, are scattered through the bed with a maximum concentration in the upper grey horizon (unit B). The base of the PDCs succession is made up of three very thin layers (unit C): a couple of massive ash layers with rare, rounded, fine pumice lapilli interlayered with a very thin sandy layer made up by small, rounded pumice clasts. This unit is capped by a massive, 4.5-cm-thick, well sorted fall layer rich in lithic clasts (unit D). The deposit that overlies this fall layer is a matrix-supported, stratified bed rich in rounded pumice lapilli in the basal part with numerous sedimentary structures (e.g. dunes and cross stratification) towards the top (unit E). The uppermost part of the sequence comprises a succession of plane parallel ash layers with abundant accretionary lapilli (units F, H and L) alternating with three, very thin, lithic-rich fall layers (units G and I). The increase of fine ash together with the presence of accretionary lapilli suggest a change from magmatic to phreatomagmatic style of the eruption in correspondence of unit F. Rare impact sags are present at the base of unit G; the lower fine grained ash layer (F) is deformed by lithic fragments up to 9 cm in diameter.

The main structural features of the recognised units are exemplified at the Nola Gate section, where the AD 79 pyroclastic sequence thickens in correspondence of a Roman road enclosed between an embankment that rests on the city walls and an enclosure wall (Fig. 3). Both the thick coarse pumice fall layers (units A and B) and the thin lithic-rich fall layers (units D, G and I) maintain a uniform thickness on the steep slope (25°) of the Roman embankment. The lower PDC unit (C) shows a relatively uniform thickness on the slopes (4–8 cm) and thickens in the depression (25 cm). The main PDC unit (E) is topographically controlled, filling the depression. Its lower layers are completely confined within the depression (E1), while its upper layers drape the topography thinning toward both the sides (E2).

4. Stratigraphy inside Pompeii

The most complete stratigraphic sections of the AD 79 deposit inside the city are located a few metres from the eastern wall of the Polibius' house, in the garden and immediately west of the house of the Chaste Lovers, which is, in turn, located a few metres west of the Polibius' house, i.e. locations (a) and (b) in Fig. 1. The detailed stratigraphic reconstruction of these two sections is of absolute importance, even beyond the objective of the present study, since they represent extremely rare examples of deposits of the AD 79 eruption still preserved in the city of Pompeii. Most of the previously studied stratigraphic sequences were, indeed, located either outside the city walls (Sigurdsson et al., 1985; Santacroce, 1987; Lirer et al., 1993) or in their vicinity (Rittmann, 1950; Di Girolamo, 1964; Cioni et al., 1996; Yokoyama and Marturano, 1997).

4.1. The house of the Chaste Lovers

This outcrop is located in a narrow alley (a few metres wide) between two vertical walls on the

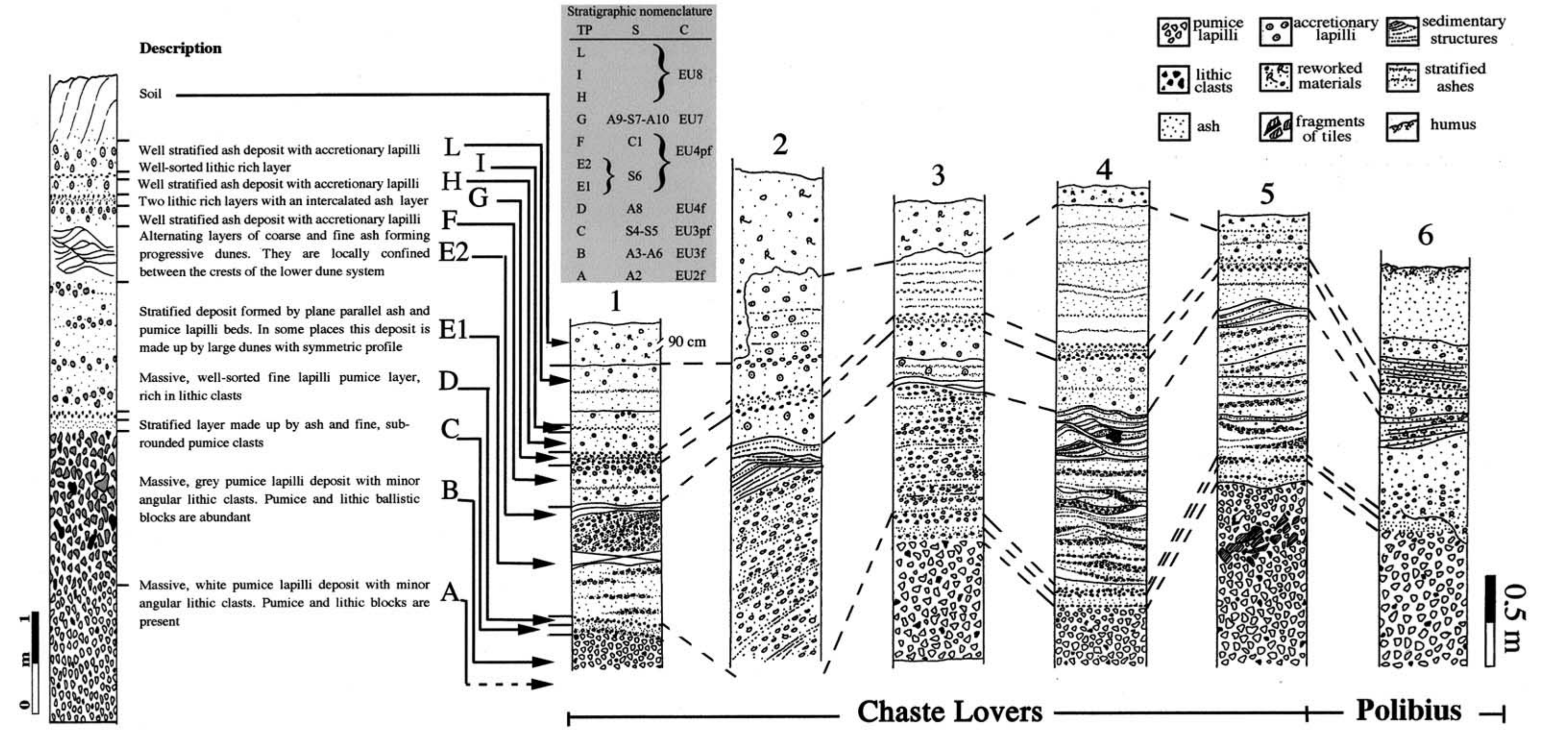

Fig. 2. Left: composite stratigraphic section showing the maximum thickness of the units of the AD 79 deposit at Pompeii. A lithofacies description is also illustrated. Right: detailed stratigraphic columns along the western side of the house of the Chaste Lovers and in a hole dug a few metres from the eastern perimeter wall of the Polibius' house. For location of the sections, see Figs. 1 and 4. Inset: relationship between the stratigraphy presented in this paper (TP) and those published by Sigurdsson et al., 1985 (S) and Cioni et al., 1996 (C).

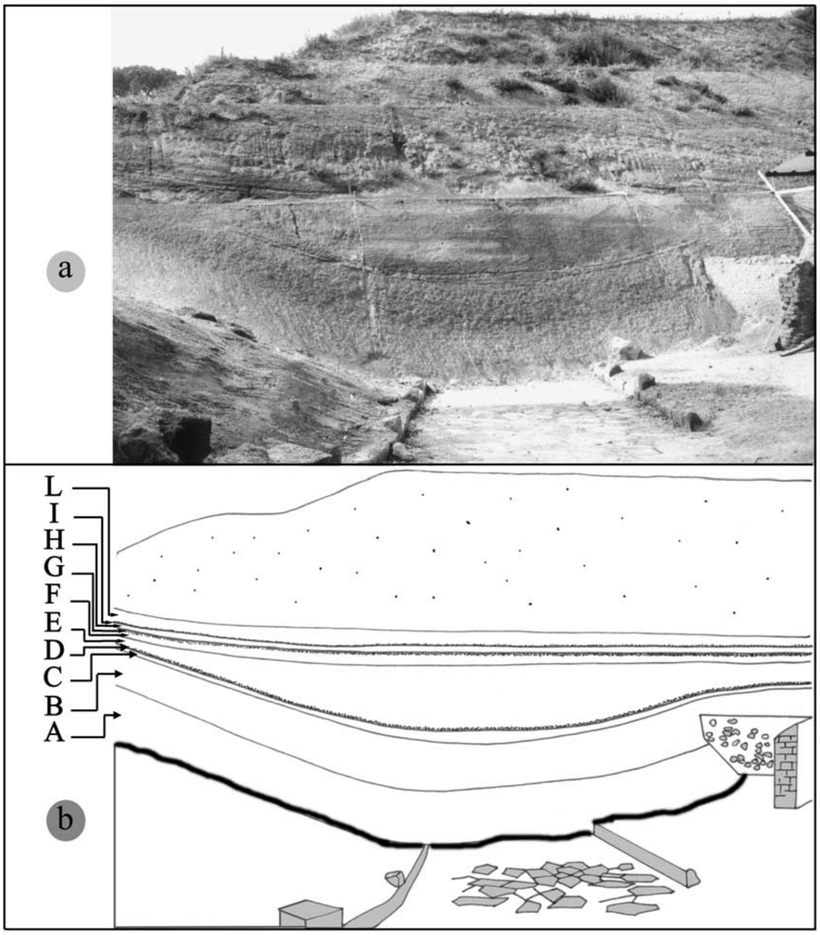

Fig. 3. (a) The complete sequence of the AD 79 pyroclastic deposit at Nola Gate (for location, see Fig. 1). The pyroclastic deposit thickens in correspondence of a Roman road enclosed between an embankment that rests on the city walls and an enclosure wall. (b) Sketch of the geometry of the different units distinguished throughout the AD 79 deposit. Note the mantling nature of the fall units (A, B, D, G, and I) while the PDC units show different geometric relationships with respect to the palaeo-topography. Unit C mantles the topography and thickens in the depression; unit E is valley-ponding, filling the topographic depression. The upper part of the sequence (dotted layer) is made of reworked material accumulated during past excavations (actually this material has been removed).

western side of the house of the Chaste Lovers (Reg. IX, 12, 5–7). The outcrop is 28 m long and averages 2.5 m in height. The cut strikes N150° and is radially oriented with respect to the vent. The succession is made up of a PDCs deposit of stratified ash and pumice lapilli overlying the thick pumice lapilli fall (Fig. 4); the base of the deposit (white pumice lapilli, unit A) is not outcropping. Fig. 2 shows five stratigraphic sections that have been measured in detail from the outcrop and lateral facies variations. The fall deposit (unit B) is not continuously outcropping and its thickness ranges from 0 to 1.2 m. It is massive, composed of grey pumice lapilli and minor lithic clasts (both lavas and limestone) showing a maximum diameter of 7.5 cm. An easily recognisable erosional surface separates it from a 8-cm-thick unit made up of fine, sub-rounded pumice clasts with increasing fine ash toward the top (unit C). It is overlain by a massive, well sorted, 6-cm-thick unit formed of angular lithics and minor pumice clasts (unit D). This whole sequence is covered by

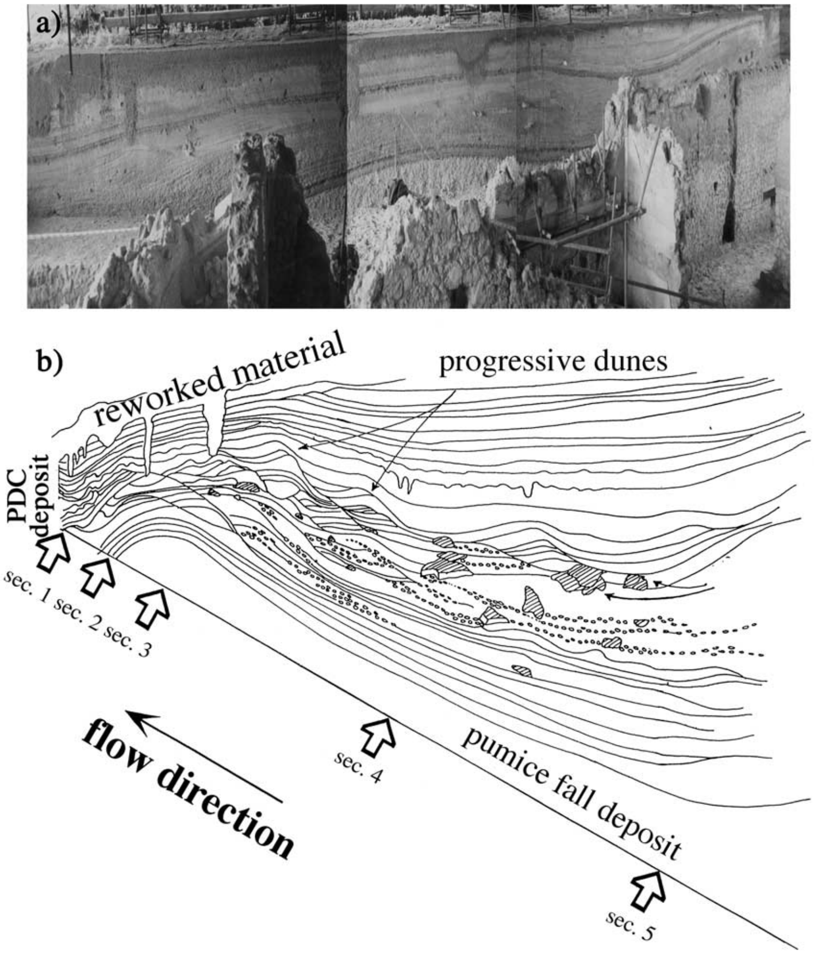

Fig. 4. Sedimentary structures in the AD 79 deposits close to the house of the Chaste Lovers. (a) Truncated walls of the house of the Chaste Lovers (foreground); the AD 79 pyroclastic succession (background). (b) Sketch of the stratigraphic succession showing the main sedimentary structures of the deposits. The wave-shaped boundary line between the basal fall pumice and the overlying PDCs deposit is worth noting. The progressive crests of the dunes are well evident in the middle part of the sequence. The arrows show the exact location of the detailed stratigraphic sections reported in Fig. 2. The scale changes in this perspective.

a 69–115-cm-thick bed showing dunes the average wavelength and amplitude of which are 15 and 0.7 m, respectively (unit E1); they are formed of alternating layers of fine ash and coarse pumice lapilli becoming thicker and coarser in down-current direction. The dune profile is symmetric, both the flanks of the crest dipping around 15°. If compared to subaqueous analogues, these dunes can be classified as 'medium dunes' (Ramsay et al., 1996). Another, smaller kind of dune that is finer grained, is present in between the crests of the previous dune system. Their wavelength/amplitude ratio is lower (6 vs. 20) and their maximum thickness reaches 35 cm (unit E2; Fig. 5). They are comprised of alternating layers of fine and coarse ash; their crests are cuspate and asymmetrical, the up-current and the down-current flanks dipping 15° and 13°, respectively. The lee slope is also concave upward. These dunes are progressive since their crests tend to migrate down-current towards the southeast. Massive and accretionary lapilli-rich ash layers, 16–45 cm thick, overlie the

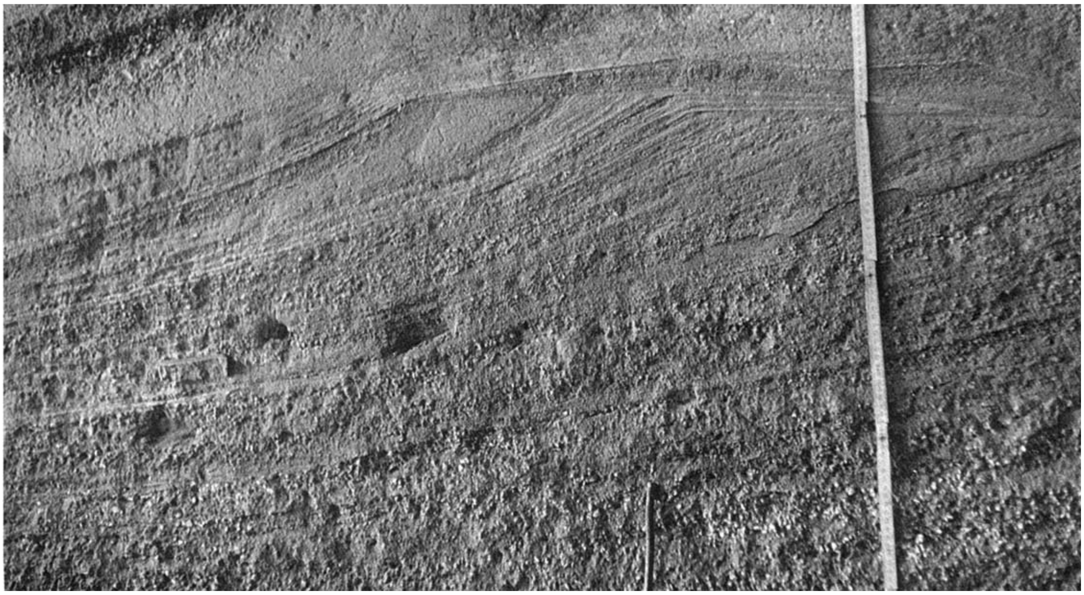

Fig. 5. Unit E2 forming progressive dunes in the central part of the pyroclastic current deposits at the house of the Chaste Lovers. Flow direction is from right to left. Scale is in 20-cm intervals

dune beds (unit F). Each bed shows an upward increase of the abundance of accretionary lapilli. Above them, two lithic-rich fall levels form a characteristic couple separated by a 2-cm-thick ash layer (unit G). The lithic-rich levels are massive, well sorted and made up by angular clasts; their respective thicknesses are 4 and 3.5 cm. At the top of this unit another ash deposit with accretionary lapilli, 12–15 cm thick, is present (unit H). Overlying this unit there is one more thin (1.5 cm), lithic-rich fall level (unit I). Finally, a stratified ash deposit, 20–62 cm thick, caps the sequence (unit L): individual beds are massive and contain sparse accretionary lapilli. The whole succession is locally eroded and channels are filled with reworked pyroclastic material, 10–90 cm thick (unit M).

4.2. Near the Polibius' house

This outcrop is located on the eastern side of the room [DD] in Polibius' house; some further excavation was required to obtain better exposure. The section is almost 2 m high, but the base of the deposit cannot be observed. The pumice lapilli layer (unit B), 83 cm thick, is overlain by a 4-cm-thick ash horizon that includes a thin (1 cm) coarse ash unit (unit C). A massive, well sorted, 5-cm-thick fall bed, mainly formed of lithics and minor pumice clasts (unit D), follows. This part of the sequence ends up with a lens of reworked material cut into the underlying units up to the top of layer B. Above it, the deposit is strongly layered and mainly made up of PDCs products. The first horizon is made up by well rounded pumiceous lapilli and subordinate ash (unit E1); the lapilli are mainly concentrated in the lower part (thickness ranges from 19 to 38 cm). Next, a conformable layered ash horizon, 9–16 cm in thickness, is present (unit E2). This level is, in turn, overlain by another ash level, 11 cm thick, massive and very rich in accretionary lapilli (unit F). Two thin lithic-rich and well sorted airfall layers, respectively 3 and 1.5 cm, overlie unit F. They enclose a 1.5-cm-thin ash horizon (unit G). The final deposit is a layered ash horizon, 56 cm thick (unit H and L), with a thin lithic-rich level (unit I) located a few centimetres from the base. The sequence is covered by the modern soil.

5. Investigation in the C.J. Polibius' house

5.1. Location and description of C.J. Polibius' house

C.J. Polibius' house is located in Via dell'Abbondanza (Reg. IX, 13, 1–3), one of the main roads in the centre of Pompeii (Fig. 1), at a height of 32 m above sea level; the ground on which it is located slopes towards the road. The shape of the building is nearly rectangular, 48 by 18 m, with the larger side perpendicular to the main road; its area is 850 m^2 (Fig. 6). The building is bounded by roads on the southern and western sides and by other buildings to the north and east. Two floors are present: 37 rooms are located on the ground floor and 19 on the upper floor, the former being identified by means of one or two capital letter(s) in Fig. 6.

For the sake of simplicity, the house can be subdivided into three zones: front, middle and rear. In the front part two floors are present:

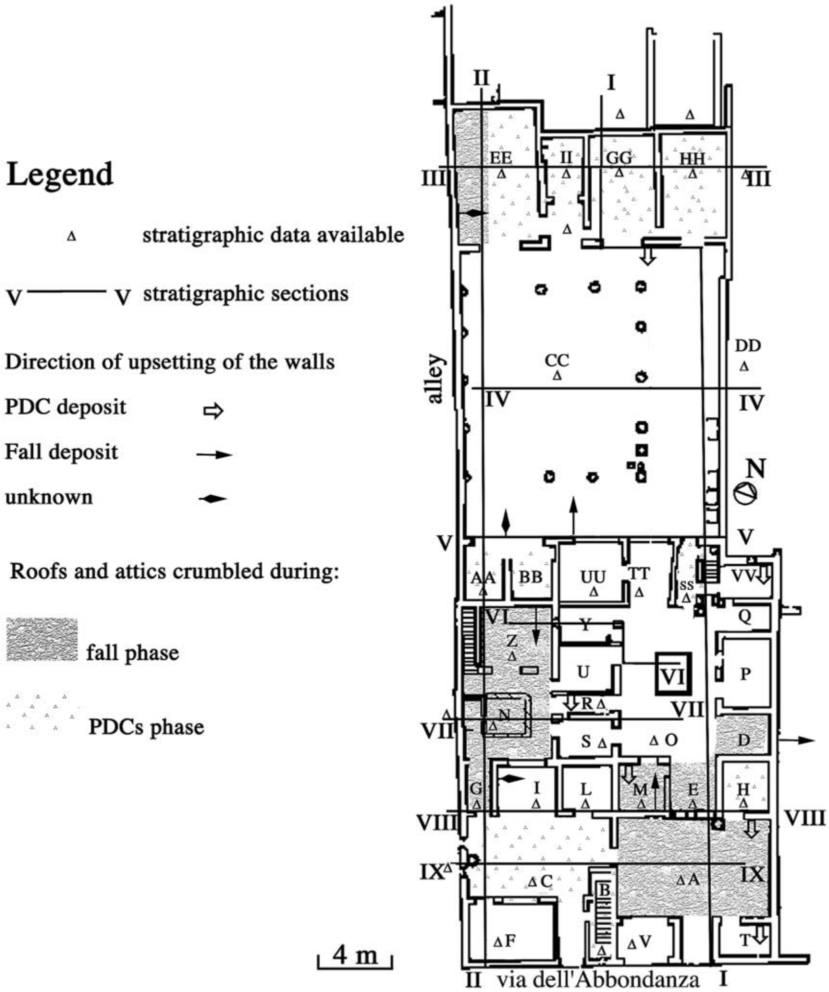

Fig. 6. Ground floor plan view of Polibius' house. Rooms indicated by capital letters. Rooms of which roofs and walls collapsed during the first fall phase are distinguished from those of which the building structures collapsed during the emplacement of PDCs. Note the directions of upsetting of the walls during the two main eruptive phases: random directions in the fall deposit and exclusively towards south in the PDCs deposit. The locations of the stratigraphic sections illustrated in Figs. 7 and 11 are also shown.

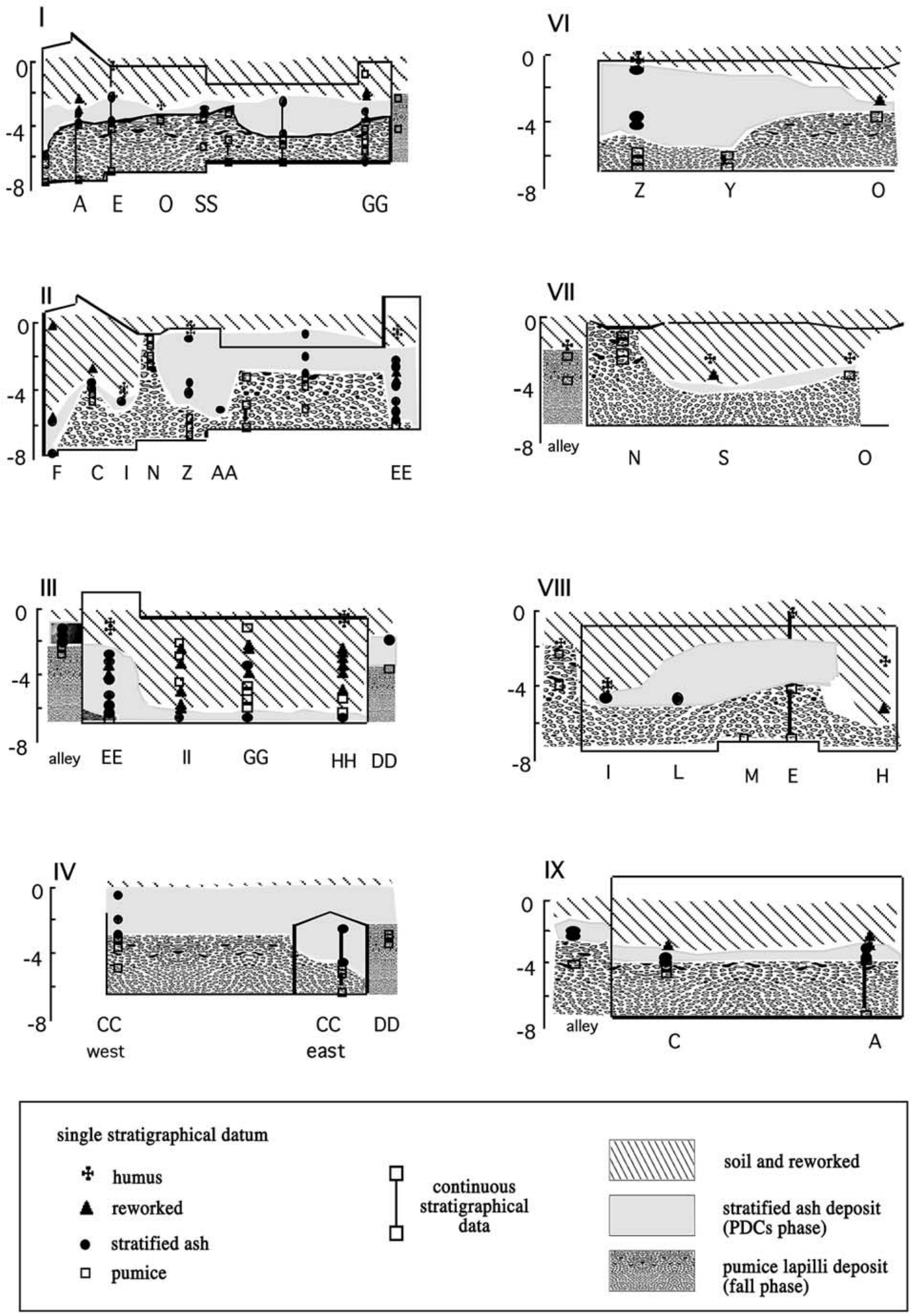

Fig. 7. Stratigraphic sections inside the Polibius' house showing the pyroclastic succession defined with lithostratigraphic data from the excavation reports. The thickness of the distinguished deposits (fall lapilli pumice deposit, stratified ash and pumice PDCs deposit, reworked pumices and soil) change remarkably in the different rooms. The external profile of the reconstructed building is also reported. Zero height corresponds to the ground level at the time of the excavation; horizontal distance is not to scale. Section traces are reported in Fig. 6.

the maximum height is about 9 m along Via dell'Abbondanza and 6.5 m towards the interior. Two impluvia are present in this area, a main one [O] and a secondary one [N]. The middle zone of the building is a square-shaped garden 100 m^2 wide; this is surrounded by a portico on three sides (north, east and south) and bounded by the 5.4-m-tall perimeter wall of the building on the fourth side. In the rear zone the upper floor is absent and the maximum height reached is 6.2 m. The roofs are very articulated; according to the current reconstruction of the house, none of them were flat. In the front zone of the house, they were re-built in order to almost completely drain rain water towards the impluvia [O] and [N]. The roofings on the northern, eastern and southern porticos dip towards the garden; the one on the western side bears a cuspate roofing dipping towards both the garden and the outer road. Because of the sloping ground towards Via dell'Abbondanza, the position of the floor rises toward the rear part of the building. As a general rule, the rooms in the front are either at the same level of [A] or 70 cm higher; in the garden and the rear zone the floor elevation is 1.2 m.

5.2. Stratigraphy of the AD 79 deposits inside the Polibius' house

Based on the large number of observations reported in the excavation logs, a reliable stratigraphic reconstruction could be made in the majority of the Polibius' house rooms. The stratigraphic sequence in 29 of the 37 rooms on the ground floor was reconstructed. Fig. 6 illustrates the rooms for which at least one datum is available. In order to synthetically show the stratigraphic sequence, eight sections were reported (Fig. 7) showing: (1) the floor profile; (2) the roof profile and the location of the outer perimeter walls of the house according to the way they were rebuilt; (3) the lithotypes observed at the different stratigraphic heights; (4) the position of the boundary between the white–grey lapilli fall deposit and the upper stratified ash and pumice PDCs deposit; and (5) the upper limit of the stratified ash and pumice PDCs deposit.

With respect to its main features, this sequence looks very similar to those previously described in Sections 4.1 and 4.2: a thick basal pumice deposit is overlain by a PDCs succession locally covered with reworked material or humus. Nevertheless, the thickness variations observed in the pumice deposit (1–5 m) are very significant: the greatest thicknesses are observed in the two impluvia [N] and [O], in the peristyle and the alleys and gardens located immediately outside the house (sections 2, 3 and 5; Fig. 7). The overlying PDCs succession also shows thickness variations (from few tens of cm to 4 m). In this case the deposit is thicker where the pumice lapilli fall is thinner and vice versa; an approximately uniform total thickness is thus maintained. The reworked material, the thickness of which is also variable, is sometimes reported as being incorporated into the primary deposit. This is a case of the reworking taking place during the breaching of walls when the first exploratory wormholes were dug. In other cases, i.e. [II] and [HH], the primary deposit was almost totally lacking and only reworked material was found. The whole sequence is capped by a soil whose thickness ranges from a few tens of centimetres to 2 m. The presence of a peculiar stratigraphic sequence (section 3 and Fig. 7) in [II], [GG] and [HH] is extremely interesting. Here, an ash layer of a few centimetres to 40–50 cm thick is directly laid on the floor. Above it, a thick pumiceous deposit probably of reworked material is present. Along the western wall (still intact) of the peristyle, dune-shaped bedforms related to the second phase of the eruption are easily recognised (Fig. 8): their wavelength is around 8 m and their amplitude ranges from 30 cm for the lowermost to 45 cm for the uppermost one. Their crests do not show any clear up- or down-current migration, thus implying a stationary wave. The height of the base of the lowermost dune marks exactly corresponds to the boundary between pumice fall and PDCs deposit as described in the excavation books.

5.3. State of the objects found

A remarkable number of objects were found during the excavations in the building. A thor-

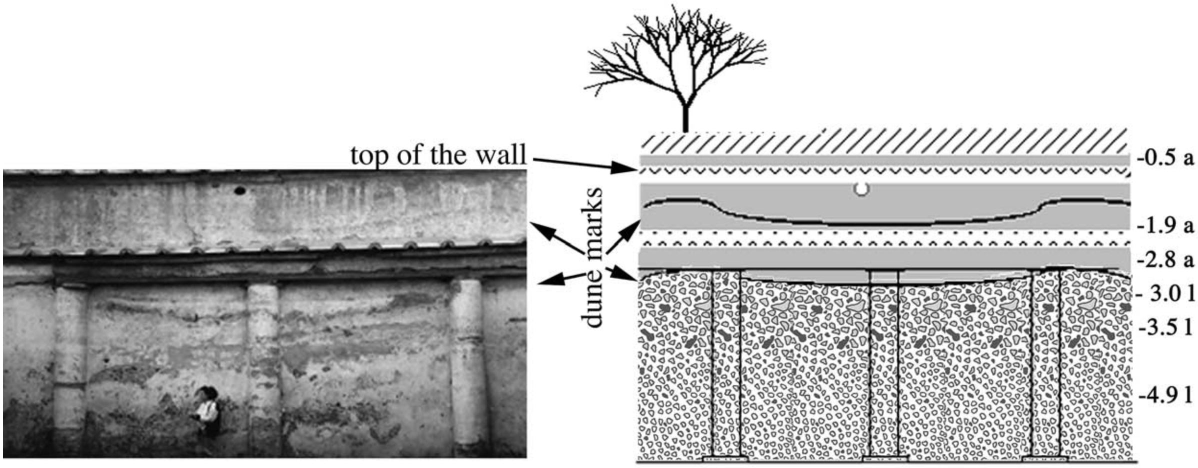

Fig. 8. Left: picture of the western wall of the peristyle. The marks of two wavy surfaces can be observed above and below the roofing testifying to the presence of dunes from a typical pyroclastic current deposit. Right: reconstruction of the boundary between the fall pumice and the stratified PDCs deposit. The marks left by the pyroclastic currents deposit in the western wall of the peristyle are reported: it can be observed that the basal mark corresponds to the boundary between the two deposits.

ough analysis of all of them would be far beyond the aim of the present research. Rather, it was decided to focus our attention on those fragile objects such as glasses and earthenware, the condition of which was a good indicator of the thermal and mechanical stresses during the different eruptive phases and the burial of the house. Several amphorae crushed by a big fallen roof were found on the floor of [A], amphorae and other earthenware were found intact on the floors of [TT], [C], [UU] and [BB]: all of them were enclosed in a thick layer of pumice lapilli. Many other objects, intact or broken, were found in the pumice lapilli deposit 1–3 m above the respective floors in rooms [D], [N], [G], [A], [R], and [BB]. Earthenware, mainly in fragments, were also found in the PDCs succession. The objects contained in 5 closets located under the roof along the eastern wall of the peristyle formed an extremely interesting discovery. The lower part of the closets was buried under the pumice lapilli and the upper part under the ash and pumice PDCs deposit. The wood slowly rotted out during the centuries leaving several astonishingly well preserved objects in the hardened ash and pumices: bottles, jugs, dishes, jars, glasses and several earthenware pieces. Most of them were intact and perfectly preserved.

5.4. Carbonised wood and traces of fire

Remains of carbonised wood were found in the front part of the house. They mainly consisted of roofbeams supporting the ceiling of the ground floor and, to a minor extent, tables or doorposts, still in place or collapsed to the ground. All of these remains were found preferentially within the fall pumice and only rarely within the PDCs deposit. The condition of the plasters and frescoes on the walls of the ground floor ruled out the possibility that great fires took place during or immediately after the eruption. Only the walls of room [Z] were entirely covered in soot, probably as a result of local combustion. In addition, some studies carried out on the glasses found in the building revealed that only in one case (bottleneck from closet IV in the peristyle; Verità et al., 2001) the temperature reached a value sufficiently high (620°C) to completely deform the object.

5.5. Skeletons

All of the recovered skeletons were found in rooms [GG] and [HH] in the rear of the building, the only exception being two human skulls coming from the upper part of the pumice lapilli deposit (probably locally reworked) in the peristyle.

Fig. 9. Some of the skeletons in room [GG]. Skeletons (III) and (IV) are above an ash layer, 20–40 cm thick, lying directly on the floor. The skull of skeleton (I) is close to the feet of skeleton (IV).

All of the four skeletons from [GG] (Fig. 9) were lying on an ash layer variable in thickness. The head of the first (I) skeleton was 30 cm above the floor in the northeastern corner; the remaining part of the body was found in the northwestern corner, partly directly on the floor and partly 30 cm above it. The second (II) and third (III) skeletons were lying on the floor, respectively along the western wall and in the middle of the room. The fourth (IV) skeleton was found along the eastern wall; the legs and the rest of the body were respectively 20 and 40 cm above the floor.

Seven skeletons were recovered in [HH]. The first (I) skeleton, located along the northern wall, was lying above some tiles and other ceiling debris; it was buried into a mixed deposit of ash, pumices and stucco fragments from the ceiling. The second (II) and third (III) skeletons were on the floor in the northwestern corner; they were covered with pumice lapilli and ceiling stucco. The fourth (IV) skeleton was found along the western wall, 40 cm above the floor. The fifth (V) and sixth (VI) skeletons were in the middle of the room, lying on a thin ash layer and under stucco fragments from the ceiling. The seventh (VII) skeleton consists of the small bones of a foetus found in the abdominal region of the mother's skeleton (II). Some casts were found within the ash deposit. They are related to some tables, probably beds, located along the northern and western wall in [HH]. Skeletons (I) and (IV) may originally have been lying upon them.

5.6. Collapses

A great amount of debris from walls and roofs was found. According to the excavation reports, collapses during the eruption lowered the average height of the walls 3–4 m.

5.6.1. Attics and roofings

At the moment of excavation, no roofs or attics were found to be in situ; debris from them was found both in the basal pumice fall and the overlying stratified ash and pumice PDCs deposit (Fig. 6). Parts of the roof of [A], [M], [E], and [D], the attic of [Z], and the roofings of [N] and [G], all of them recovered from the pumice lapilli, were lying on the respective ground floors; the attics of the upper floors and the roofs of [C], [B], [H], [SS], [AA], [GG], [II], [HH], and [BB] were found in the PDCs deposit. In particular, the ceiling of [SS] was found to be only 20 cm lower than its original level. On the contrary, the western, eastern and northern roofings of the peristyle, buried by the stratified ash and pumice deposit, were found still above the perimeter wall. The roofing on the northern side was partially destroyed, but the others suffered very little damage. Only few roofing-tiles and bent-tiles were missing from the western roofing, whereas the eastern one was practically still intact. It is important to mention that the original level of these roofings was 2 m lower than the level of those in the front and rear zones of the house. The stratigraphic height of the tiles within the volcanic products in [EE] establishes the timing of collapses of the ceiling in the building. In the western part of the room the ceiling was smashed to the ground under the load of the pumice lapilli fall deposit, whereas in the eastern part the cast of a bed headboard bent by the falling ceiling was observed within the PDCs deposit. In addition to the roofings and attics described above, several tiles, either intact or in fragments, were recovered at various stratigraphic heights in all the rooms of the building. For instance, fragments of tiles were recovered from throughout the whole thickness of the deposit in room [EE].

5.6.2. Walls

Nearly all of the walls were found to be partly or entirely demolished. In particular, only the western corner of the facade and the lower part of some inner walls were still in place on the upper floor. According to the excavation reports, the walls buried in the PDCs deposit had mainly collapsed southwards, whereas those in the fall lapilli did not show any predominant direction of collapse (Fig. 6). It is also worth mentioning that, as a general rule, the north–south trending walls were less damaged than those trending east–west. Fig. 10 shows the average heights of the transversal walls of the house. Even removing the topographic effects (sloping ground), the amount of demolition was higher moving from the main facade towards the peristyle and then decreases again in the rear of the building. Fig. 11 shows five transversal cross-sections along walls located at increasing distance from the facade of the building. In all of them, a channel-shaped profile of the demolished walls can be observed. These profiles have different depths and their bases have been measured at different heights from the ground floor. The northernmost profile is reported in the excavation reports at the top of room [EE] (Fig. 11), with its depth less then 1 m and its base at the top of the ground floor (about 6 m height). The middle profile is more then 6 m deep and its base is a few tens of centimetres above the ground floor. The southernmost one is about 4 m deep and its base is nearly on the upper floor. These profiles largely correspond to the boundary between the basal fall and the overlying PDCs deposit. Within the house

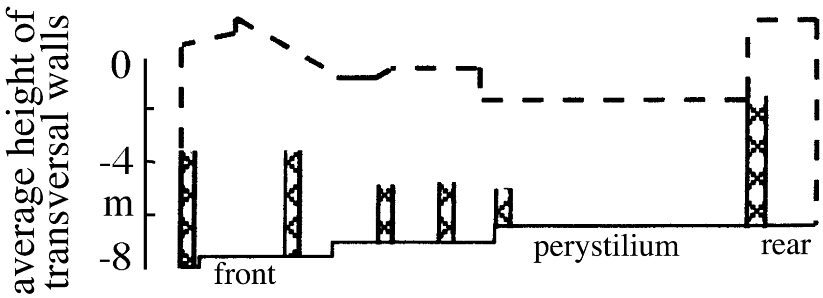

Fig. 10. Variations in the average height of the east–west trending (transversal) walls in the Polibius' house; the variations of the ground level are taken into account.

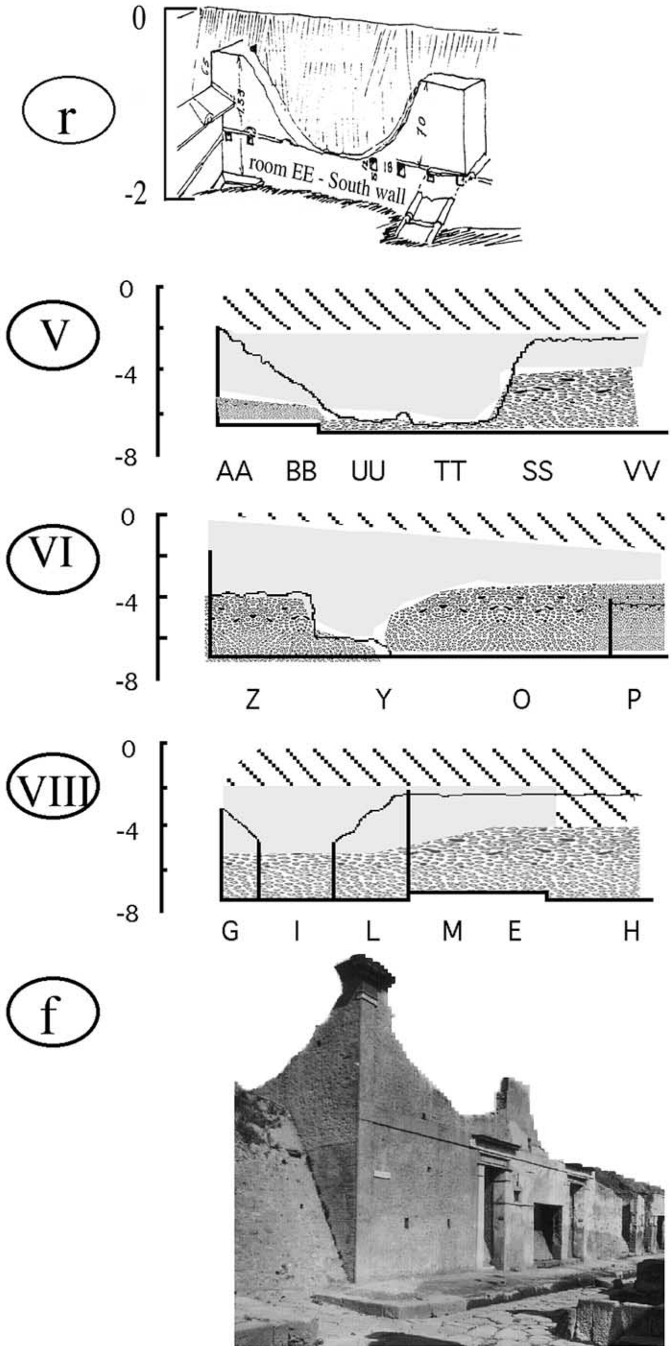

Fig. 11. Sections along some of the transversal walls of the house showing the concave upper profile of the walls. (r) Top of room [EE] redrawn from excavation journals. (V), (VI) and (VIII) sections reconstructed during this study. (f) Picture of the facade as found during the excavations. Boundaries between the different lithotypes are shown for sections (V), (VI) and (VIII). The correspondence between the wall heights and the contact between the fall and the PDCs deposit is worth noting. The locations of the sections are reported in Fig. 6. Legend as in Fig. 7.

it is important to point out two other intriguing observations: (1) the transverse walls in the rear of the house were still intact at the time of excavation; and (2) the metal hinges of the doors of the rear rooms lay on the floor under the PDCs deposit.

5.7. *Extent to which the roofs and walls affected the distribution of the pyroclastic fall deposit*

The stratigraphy of the products of the AD 79 eruption inside the Polibius' house is anomalous with respect to the surrounding areas (Fig. 7), the main difference consisting in thickness changes of the fall deposit. Remarkable variations were indeed observed in the peristyle [CC], in the alleys around the building, and, as already reported in Section 5.2, in rooms [N] and [O]. Also, the fall pumice deposit in the garden of the peristyle thins towards the sheltered corridor of the eastern portico (section 4; Fig. 7), probably as a result of pumices rolling down from the thickening heap in the centre of the garden.

The present restoration of the building, with all of the roofs dipping at 15° towards both the surrounding alleys and rooms [CC], [N] and [O], would explain the additional amount of fallout deposit as being due to the rolling down of the falling pumices from the adjacent roofs.

Evaluating the exact timing of the roof collapses is not straightforward. If an accumulation rate of 15 cm/h (Sigurdsson et al., 1985) and an average density of 650 kg/m^3 are assumed for the falling pumice, an incremental load of 100 kg/m^2 per hour is realised. Unfortunately, since no data on the yield strength of the Pompeii roofs are available in the literature, the critical thickness causing the collapse cannot be determined. On the other hand, studies carried out on several recent eruptive events (Blong, 1984) report roof collapses to occur with thicknesses ranging 0.1–1 m, a value well matched by the 40 cm calculated by Sigurdsson et al. (1985). As a consequence, roof collapses in Polibius' house might have taken place 1–6 h after the beginning of the eruption. On the other hand, the PDCs deposit belonging to the second eruptive phase, lying directly on the floor in many rooms of the rear part of the house, suggests some of the roofs be still in place after the end of the initial pumice fall phase. All of the above data clearly show that a different response of the roofs of the building took place during the first phase of the eruption. Those in the front part of the house collapsed, whereas those in the central and rear zones did not. Since the possibility of different pumice amounts falling on the different parts of the building can be ruled out completely, it is proposed that the roofs in the front zone were much flatter than those in the current restoration of the building and allowed an unusual accumulation of the falling pumices, eventually collapsing under the pumice load. The steeper roofs in the rear part of the house and the peristyle allowed the falling pumices to roll and slide down and accumulate in the adjacent impluvia and the garden, respectively.

6. State of the buildings in the whole city of Pompeii

To investigate the damage suffered by the whole city of Pompeii we evaluated the state of the buildings all over the city (Fig. 12a). A limit to this investigation is the partial reconstruction (restoration) of many buildings and the lack of good reports from ancient excavations (most of the city has been excavated in the past centuries). Our survey shows that the type of destruction suffered by the city can be described in the following observations:

(1) The ground floor is partly intact in most of the buildings, whereas the upper floor is almost completely demolished.

(2) Most of the destruction is stratigraphically related to unit E. In fact, as exemplified by the recently excavated House of Chaste Lovers, material from demolished walls lay inside this unit (Fig. 12b,c) as well as some of the victims of the PDCs phase of the eruption (Luongo et al., 2003).

(3) The east–west oriented walls are by far more damaged than those striking north–south.

(4) It is still possible to observe a channel-shaped profile in many of these demolished walls.

(5) In many cases, the northern, vent-facing

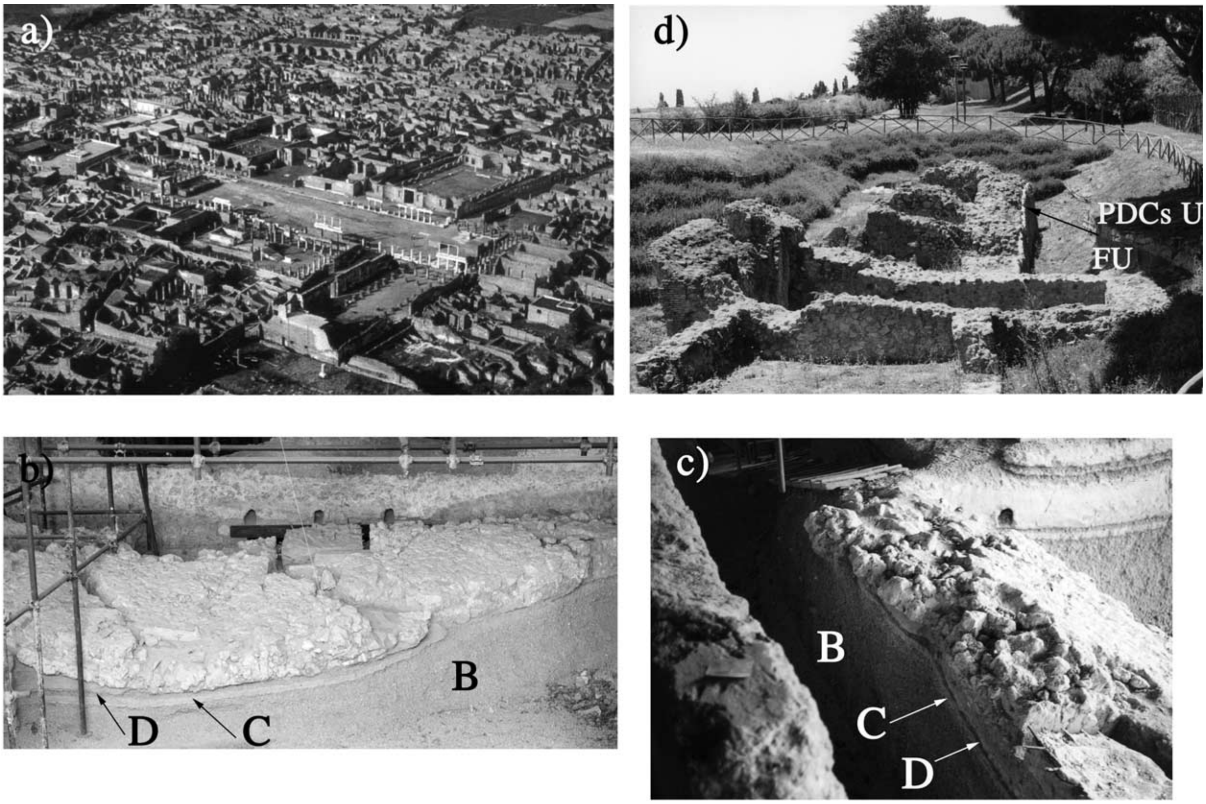

Fig. 12. State of the buildings at Pompeii. (a) Aerial view of the city. Note that the upper floors of most buildings are missing. (b) Front view of a wall pulled down in the house of the Chaste Lovers. The wall, transversal to the flow direction, lays in the E1 unit. Note the darker, lithic-rich unit D below the wall. (c) Rear view of the same toppled wall. On the left, the still standing wall found in the fallout deposit; on the right, the upper part of the wall laying above unit D. (d) Section of the city walls close to Capua Gate showing a high amount of destruction in the northern, volcanic vent-facing side. Flow direction from right to left. Key: FU, fall units; PDCs U, pyroclastic density current units. The arrow links the base of the PDCs deposit with the profile of the destroyed wall.

part of the buildings was more damaged than the southern one (Fig. 12d).

(6) The northern (relatively proximal) and southern (relatively distal) sectors in the city were affected in the same way.

7. Analysis of the behaviour of the pyroclastic currents

A major contribution to understanding the PDCs transport and emplacement mechanisms was provided by comparing large-scale (i.e. whole city) and small-scale (i.e. building by building) distribution of damages. The distribution and type of the damages noticed throughout the city is inhomogeneous although the east–west oriented walls are more completely destroyed. Locally, a more regular destruction pattern is recognisable; the height of demolished walls decreases toward south.

Recent studies (Valentine, 1987; Fisher, 1990; Druitt, 1992, 1998; Freundt and Bursik, 1998; Freundt et al., 2000) and direct observations of PDCs (e.g. Mount St. Helens and Pinatubo eruptions) showed that these currents are clouds of gas and volcanic ash tens to hundreds of metres thick thee particle concentration of which increases towards the base. In these flows particles are mainly transported in suspension by turbulence (transport system) and settling progressively from a basal depositional system. During the transport a vertical flux of grains (suspended-load fallout) is supplied from the transport system to the underlying depositional system. Deposition is controlled by particle concentration, suspended-load fallout rate, the grain-size distribution and the flow power (Lowe, 1982, 1988; Druitt, 1991). The presence of diffuse sedimentary structures within the PDCs AD 79 deposit at Pompeii suggests the dilute and expanded nature of these pyroclastic currents. As a consequence, only the lowermost part of such currents has interacted with the buildings at Pompeii.

To explain type and distribution of the damage mentioned above, the following model of the emplacement of the AD 79 PDCs at Pompeii is proposed. The finding of toppled walls (and victims) in unit E indicates a cause–effect relationship between the emplacement of the parental PDC and the destruction of the buildings. This means that the thin ash layer C was emplaced without any significant amount of destruction. Probably, it was deposited by the distal and dilute part of a PDC. In fact, a decrease in concentration away from the vent has been inferred from field features of several PDCs deposits (e.g. the 18 May 1980 Mount St. Helens blast, Druitt, 1992; the Suwolbong tuff ring in Korea, Sohn and Chough, 1989). The large-scale inhomogeneous distribution of damage suggests a non-uniform behaviour of the pyroclastic currents. As in the 1902 St. Pierre eruption surges (Fisher and Heiken, 1982), the AD 79 pyroclastic currents demolished mostly the walls that happened to be perpendicular to their flow direction. The finding of well preserved

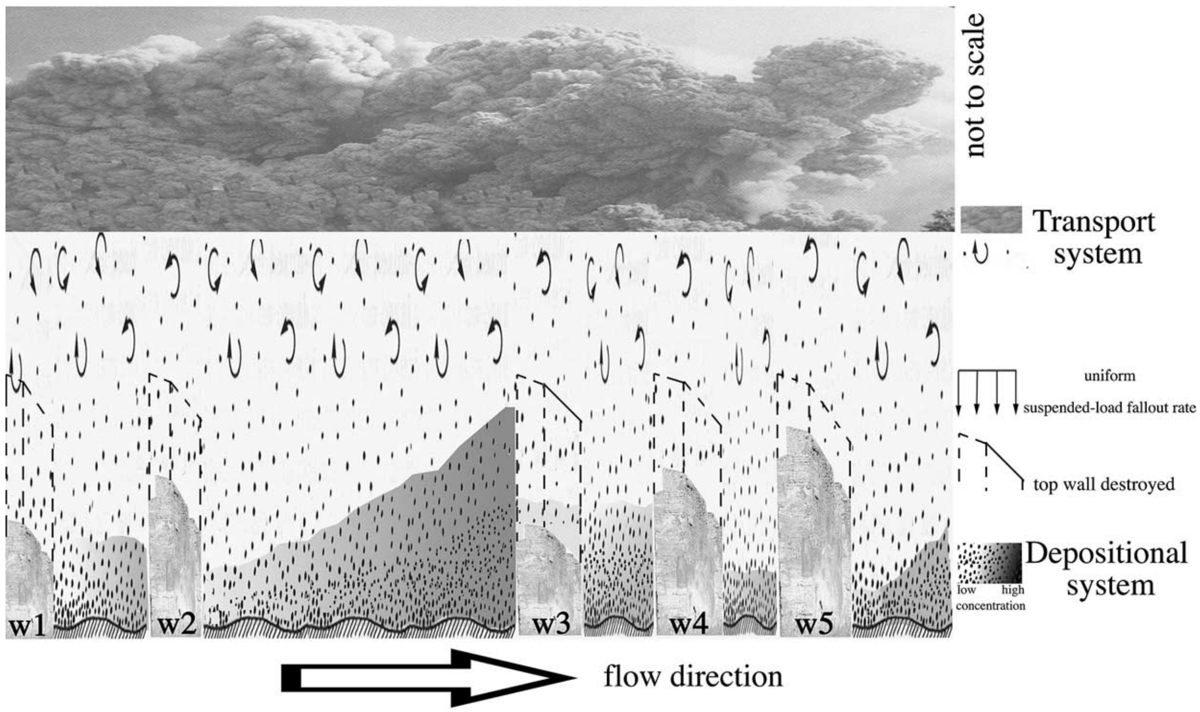

Fig. 13. Sketch of a PDC flowing on the Pompeii urban structures. It is possible to distinguish an upper transport system that supplies, with an uniform rate, particles to a basal depositional system, variable in thickness. Two series of walls, transversal to the flow direction, are widely spaced. Near the first two obstacles (walls on the left), the depositional system is thin with a relatively low concentration of pyroclasts. From the first to the second series of obstacles, there is enough space to restore a thick basal layer with relatively high concentration. This basal part has sufficient energy to deeply topple the transversal walls. The presence of the following closely spaced obstacles slow down the depositional system that losses part of its load; as a consequence, the thickness and concentration of the depositional system decreases progressively in correspondence of each wall.

brittle objects in closets located laterally to the channel-shaped profile of the demolished walls, inside the Polibius' house, testifies that the destructive impact of the PDCs is restricted along well defined paths. Indeed, the areas outside the channels represent places where PDCs show essentially depositional behaviour. The channelling of the basal part of the currents along the central axis of the buildings is probably an effect of the bounding of the longitudinal walls. Furthermore, as in the case of the Polibius' house, the walls were progressively less damaged down-current for each single building; however, where an open space (10–20 m) occurs between two closely spaced (2–3 m) series of walls, the amount of demolition became high again (Fig. 13). It is suggested that this trend could reflect a temporary reduction of kinetic energy within the depositional system due to local loss of mass (sedimentation) and velocity after a series of repeated impacts against the buildings. The loss of kinetic energy reduces the capacity of the PDCs to destroy the walls and erode the underlying pumice fall deposit. The basal depositional system could restore its physical characteristics once every series of obstacles was overridden thanks to the continuous supply of particles from the upper high-energy transport system that did not suffer any breaking action by these urban obstacles. A new decrease of kinetic energy occurs wherever a new series of closely spaced obstacles occurs transversal to the flow direction. The depositional system is non-uniform in terms of concentration and occurs as a series of longitudinal rarefactions and condensations in response to the distance between successive obstacles (assuming a constant supply of particles from the upper transport system). Consequently, we suggest that local and temporary fluctuations of kinetic energy within the depositional system can be induced by the interaction between the urban structures and the base of the PDCs.

Recently, Valentine (1998) estimated the dynamic overpressure necessary to completely destroy the buildings of the nearby city of Herculaneum by the PDCs of the AD 79 eruption at 35–70 kPa. The extensive damage suffered by the Pompeii buildings is possibly related to an analogous PDC overpressure.

There is peculiar damage in the Polibius' house that allows us to refine the proposed flow model. We know both from the volcanic vent location and the sedimentary structures – namely dunes and cross-stratification – that the pyroclastic currents flowed southwards. The location of the hinges inside the rear rooms of the Polibius' house demonstrates the knocking down of the doors towards the north (contrary to the previously documented north–south PDCs flow direction). Laboratory experiments about the effects of topography on propagation and sedimentation of density currents confirm that the presence of an obstacle of sufficient amplitude and transversal to the flow direction will lead to a partial blocking of the current and the production of a wave which propagates upstream (Bursik and Woods, 2000). We suggest that the present evidence is consistent with the production of a reflected flow against the southern transversal walls of the peristyle. This reflected flow moved across the peristyle towards the rear of the house that was sheltered by the direct impact of the PDCs by the adjacent buildings located to the north of the Polibius' house. It struck the wall and knocked down the doors towards the interior.

8. Emplacement temperature of the pyroclastic products

Several lines of evidence rule out the possibility of a high emplacement temperature for all of the volcanic products covering Pompeii. In the first place, the typical textural features of high-temperature deposits (Branney and Kokelaar, 1992; Freundt and Schmincke, 1995) are totally absent from the observed stratigraphic sections of the AD 79 eruption. Moreover, a large amount of accretionary lapilli are present in the upper part of the stratigraphic sequence (units F, H and L), testifying to a depositional temperature not in excess of 100°C (Schumacher and Schmincke, 1991). Other strong evidence is provided by the large number of fugitive bodies buried in the middle of unit E (Luongo et al., 2003): the temperature of the previously accumulated products (of both fall and PDC origin) would not have been so high as to prevent the Pompeii inhabitants from attempting to escape the disaster. Further evidence comes from studies carried out on the previously mentioned (Section 5.4) deformed glass fragment, the present tensional state of which results from rapid cooling (Verità et al., 2001), thus ruling out the presence of a very hot and slowly cooling enveloping pyroclastic deposit. Initially, the glass probably softened because of a local combustion in the cupboard. In the same way, the large amount of carbonised wooden relics recovered from the pumice lapilli are to be attributed to mineralisation rather than to combustion phenomena.

9. Chronology of the events: the effects of the AD 79 eruption on Pompeii

A reconstruction of the timing of the destructive events in the city has been attempted. In the early afternoon of August 24, a pumice fall started burying the city of Pompeii. During this first phase of the eruption several roof collapses occurred, evident by abundant debris and tiles found in the lapilli fall deposit. A significant number of victims has also been found in this deposit (38% of the total of Pompeii victims; Luongo et al., 2003). They probably died as a consequence of the building's collapse. The accumulation rate of the deposit in the outdoor areas of the city is estimated at 15 cm/h. In the zones of the buildings where material sloughed from roofs, the accumulation rate reached values as high as 25–30 cm/h. Within 6 h the roofs and part of the walls of the buildings had collapsed under the pumice load.

On the morning of August 25, many buildings had been destroyed almost completely and only some edifices were still standing. A remarkable thickness of pumice lapilli, 1–5 m, had filled the impluvia and the rooms the roofs of which had collapsed. Also, the peristyles and the alleys had been filled to these depths. The lapilli pumice fall deposit, generally 3 m thick, totally buried the lower part of the buildings, partly protecting them from the impact of the later pyroclastic currents. The first PDC flowed through the city depositing the basal ash layer C and causing irrelevant damage. A discrete explosion produced a fall that formed the lithic-rich layer D. A local episode of reworking suggests a brief pause before the emplacement of the next PDC. It showed a greater destructive force, flattened most of the (especially transversal) walls in its north–south path. This PDC buried the ruins under a few metres of coarse ash and pumice deposit (unit E). A final phreatomagmatic phase, punctuated by three lithic fall episodes, emplaced the upper part of the succession (F–L units).

A more detailed scenario has been reconstructed for the Polibius' house. During the first phase of the eruption a great quantity of pumice lapilli fell on the building (Fig. 14a), producing the collapse of the front part of the house (Fig. 14b) in a few hours. Probably as a consequence of these events, the inhabitants of the Polibius' house decided to hide in the rear rooms [GG] and [HH], the roofs of which, probably steeper than those in the front of the house, had not been damaged by the falling material. The pyroclastic currents arrived from the north, travelling parallel to the long sides of the building: the northernmost wall, east–west oriented, was little, if at all, damaged by these currents because of the protection by the adjacent buildings. The pyroclastic currents overtopped the rear part of the house. They moved into the garden and advanced towards the front of the house. We suggest that the PDC that emplaced unit E eroded the underlying pumice fall deposit and totally destroyed the upper floor and the ground floor walls perpendicular to the flow direction (Fig. 14c). This current was channeled between the longitudinal walls focusing its destructive power along the axis of the channel. Outside of the erosional channel, walls and objects were better preserved. In the rear of the building only the room [EE], the western roof of which had already collapsed under the pumice lapilli (see Section 5.6.1), was invaded from above by the pyroclastic currents. The remaining rooms, the roofs of which had remained in place and the floor of which had not been covered with the fall pumice, were invaded through the peristyle (Fig. 14c). No escape was possible for the people who had taken shelter there. The ash, mixed with pieces from the roofs, reached every corner of

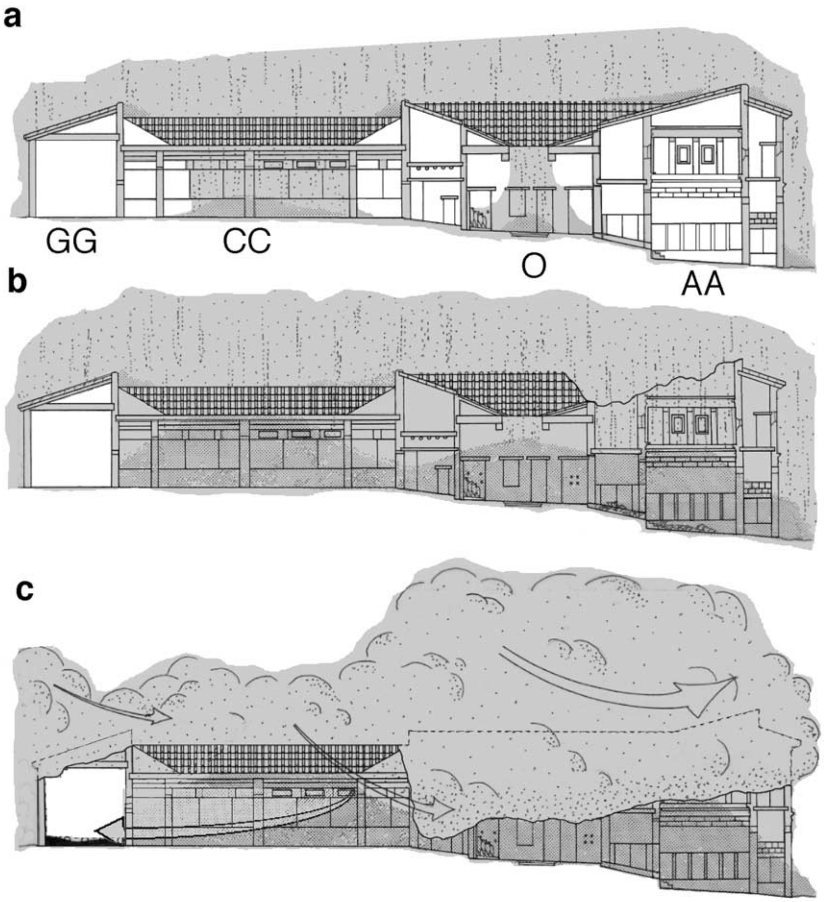

Fig. 14. The destructive effects of the different eruptive phases on the Polibius' house. The section is drawn according to trace I in Fig. 6; Mount Vesuvius is to the left of the building. (a) Fall products accumulate in the alleys, on the roofs, in the peristyle and the rooms with impluvium during the early hours of the eruption. (b) Roofs and attics of some front rooms collapse under the pumice lapilli load. (c) Pyroclastic currents by-pass the rear rooms and destroy the east–west trending walls in the front part of the house; a reflected flow invades the rooms where the inhabitants had taken shelter.

the rooms. A very hard and compact layer formed under the beds: the skeletons were found lying on it. In the end, the roofs of the rear rooms also collapsed, covering the PDCs deposit with a reworked ash and pumice deposit

10. Risk

The present research allows us to draw some conclusions concerning the impact of explosive volcanic eruptions onto urban environments. First, it is possible to state that, as far pumice fall is concerned, risk is strongly dependent on the slope of the roofs. Flat and low-angle roofs are prone to collapse under the pumice load, whereas steeper roofs tend to drain laterally the falling material, causing the local accumulation of thicker deposits (up to 5 m in the case of the AD 79 eruption at Pompeii). The potential danger of these deposits should be taken into account well in advance, especially in the case of long lasting eruptions and/or high accumulation rates. Buildings should be planned so that neither obstruction of the ways out nor overload of nearby structures can occur. It is very important to point out that the roof and wall collapses at Pompeii during the pumice fall phase of the eruption caused 38% loss of lives. From a broader point of view this means that, if roofs are not properly constructed, a relatively high level of damage can be associated with these kinds of eruptive events. In particular, as the roofs of the buildings are flat and horizontal in the modern urban areas around Mount Vesuvius, they too will be easily overloaded and collapse. A second consideration applies to the pyroclastic currents. They had a destructive impact on the structures that happened to strike perpendicular to their flow direction, whereas they little, if at all, affected those that happened to be parallel. A clear example of this phenomenon in the Polibius' house was provided by the surprisingly intact objects found in the closets located along the eastern wall of the peristyle (see Section 5.3)

Acknowledgements

We are grateful to Professor Guzzo, superintendent at Pompeii for inviting the authors to participate in the investigation at the Polibius' house. We also thank Dr. A. Ciarallo and her collaborators for their logistic help and their interest in our research. We are deeply grateful to Livio Ruvo for critically reviewing a previous version of this paper. The editorial expertise of B. Marsh and the helpful comments of two anonymous referees also helped to improve the manuscript. We extend our thanks to Dave Lentz for his final revision of the manuscript.

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