J-READING
JOURNAL OF RESEARCH AND DIDACTICS IN GEOGRAPHY
2, 8, December, 2019, pp. 5-30 DOI: 10.4458/2801-01

Death, Survival and Damage during the 79 AD Eruption of Vesuvius which destroyed Pompeii and Herculaneum

Roberto Scandone[a], Lisetta Giacomelli[b], Mauro Rosi[c]
[a] INGV – Osservatorio Vesuviano, Naples, Italy and Dipartimento di Matematica e Fisica, University of Roma Tre, Rome, Italy
[b] Italian Association of Volcanology, Italy
[c] Dipartimento di Scienze della Terra, University of Pisa, Pisa, Italy
Email: robertoscandone@gmail.com

Received: November 2019 – Accepted: December 2019

Abstract

The eruption of Vesuvius of 79 AD is the first large explosive eruption described in detail by Pliny the Younger. The eruption began with a high eruptive column depositing a thick airfall pumice deposit to the South East of the volcano, and it was followed by the emplacement of destructive glowing avalanches which destroyed the cities of Pompeii, Herculaneum and Stabiae.
In this paper we re-evaluate the succession of the events based on the letters of Pliny, the volcanic deposit and the extensive damages caused also by the earthquakes occurring during the eruption. We estimate the impact of the synchronous seismic activity by evaluating its intensity and effects on the wider Campanian plain and drawing novel isoseismal maps. We suggest that the strong intra-eruption seismicity conditioned the behavior of the inhabitants of Pompeii during the eruption, compelling many of those, that were still in the houses to flee from the collapsing buildings. We suggest also a different timing of the travel of Pliny the Elder from that proposed by earlier authors We infer an earlier destruction of Herculaneum during the first day of the eruption, as witnessed by the Elder during his travel from Misenum to the vesuvian region, which compelled him to deviate to Stabiae where he died, the following day, a few minutes after the inhabitants of Pompeii.

Keywords: Vesuvius, Eruption of 79 AD, Pompeii, Herculaneum, Pumice Fall, Pyroclastic Density Currents, Earthquakes

1. Introduction

The eruption of Vesuvius of 79 AD is the first large explosive eruption described in detail by contemporary witnesses. Pliny the Younger made an accurate narrative of the main features of the eruption and nowadays, volcanologists term Plinian the eruptions with the same characteristics.

The eruption began with a high eruptive column depositing a thick airfall pumice deposit to the South East of the volcano, and it was followed by the emplacement of destructive glowing avalanches, formerly called pyroclastic flows and surges which are now defined Pyroclastic Density Currents, (PDC), which spread almost radially from the volcano with a major

runout to the West, South and South East. Druitt (1998), employs the term Pyroclastic Density Currents to identify the flows of pyroclastic material that range from expanded turbulent suspensions to highly concentrated granular flow.

The eruption destroyed two major cities of the Roman Empire, Pompeii and Herculaneum, as well as country villas, suburbs, and dwellings over a radius of more than 10-18 km from the volcano. The former city was initially covered by the airfall deposit 2.5-3.5 m thick, and later by the emplacement of PDCs; Herculaneum was mostly destroyed by PDCs.

Most of the vesuvian territory was buried under a thick pyroclastic deposit and the memory of the lost cities vanished until 1738, when the first excavations revealed the extent of the eruptive destruction first at Herculaneum, and later (1748) at Pompeii and surrounding areas.

Extensive damages on a wider area were also likely caused by the seismic activity accompanying the eruption.

The eruption is important not only from a volcanological point of view, but also because it froze the buried cities like a time capsule. The houses, the artefacts of two entire cities along with their inhabitants were preserved untouched for centuries representing a formidable snapshot of the daily life of a Roman city. The discovery prompted the birth of archaeology with the continual improvement of the methods of excavation and preservation of the uncovered artefacts through trial and errors. Such process is still continuing nowadays with difficulties and uncertainties.

Several authors have made the reconstruction of the eruptive sequence based on the stratigraphy of the products and the contemporary chronicles (Lirer et al., 1973; Sheridan et al., 1981; Sigurdsson et al., 1982, 1985; Carey and Sigurdsson, 1987; Cioni et al., 1992, 1999; Gurioli et al., 1999, 2002, 2005, 2007).

De Carolis et al., 2002, Luongo et al., 2003, Giacomelli et al., 2003, De Carolis and Patricelli, 2013 made a detailed survey of the victims of Pompeii, Herculaneum and suburbs trying, whenever possible, to make a distinction between those found within the airfall deposits and the many more found on top of it, within the PDC sequence.

The scope of this paper is to assemble a novel analysis of available information for a better understanding of the timing of eruption phenomena, of the loss of life and to better understand the possible causes to the different behaviour of the inhabitants in the different places and better ascertain the extent of damages caused by the eruption by revising the existing bibliography. We in particular try to estimate the impact of the synchronous seismic activity by evaluating its intensity and effects on the wider Campanian plain and make inferences on the role of intra-eruption seismicity in conditioning the behaviour of the inhabitants of Pompeii during the eruption.

2. The description of the eruption by contemporaries

Pliny the Younger wrote two letters to the historian Tacitus describing the events that led to the death of his uncle, Pliny the Elder, because of the eruption of Vesuvius. Recent critics (see for example Guadagno, 1993; Eco, 1994) have cast serious doubt on the reliance of most of Pliny the Younger narrative, written mainly to exalt the heroic role of the Elder as driven not only by scientific curiosity but also by the attempt to rescue the inhabitants living at the foot of the exploding volcano. In the second letter the role of the Younger is that of a true Roman citizen observing the catastrophe with calm indifference in contrast with that of his mother and neighbors. However, there are too many descriptions that are too precise and fitting the dynamics of the eruption, that we believe they truly reflect the remembrance of a catastrophe that must have remained carved in the memory of a young, seventeen boy even 25 years after the event.

Recently it has been raised again the longstanding discussion of the date of the eruption. A dispute, dating back several centuries, proposes different dates ranging between the 24th August to the 1st November. The former date is taken by the most ancient codex of the letter, Laurentianus Mediceus 47.36 (sec. IX) which reports “Non. Kal. Sept(ember)” or the 24th of August; another codex reports “Nov.(ember) Kal.” or the 1st November (Stefani, 2006; Ricciardi, 2009). Recent archeological discoveries: the findings of fruits (nuts,

hazelnuts, pomegranates) (Figure 1) typical of the Autumn, and the uncovering in the Casa del Bracciale d'Oro of a coin of Emperor Titus with a title (IMP XV) obtained only after September of 79 AD, give credit to the later date (Stefani, 2006; Stefani and Borgoncino, 2007).

Figure 1. Archeological findings at Villa Regina (Boscoreale) that suggest an Autumn date for the eruption. a) Sealed jars containing grape must, b) pomegranate, c) hazelnut, d) figs. Photo: Giacomelli and Scandone.

However, from a pure volcanological point of view, the question is irrelevant, but for the duration of certain volcanic phenomena observed by Pliny, as, in the Roman calendar, the duration of the diurnal hour changed with the season, being longer during the summer and shorter during the autumn and winter. In any case the difference between the sunrise for the different dates is in the order of 1 hour.

In the following, we will make use of the translation of J.B. Firth (1910) reporting only the passages of volcanological relevance. In the Appendix we report a more extended version.

> *My uncle was stationed at Misenum,* [Figure 2] *where he was in active command of the fleet, with full powers. On the 24th of August, about the seventh hour, my mother drew his attention to the fact that a cloud of unusual size and shape had made its appearance. He had been out in the sun, followed by a cold bath, and after a light meal he was lying down and reading. Yet he called for his sandals and climbed up to a spot from which he could command a good view of the curious phenomenon.*

Figure 2. The Port of Misenum and, in the background, the internal lagoon, base of the fleet (Classis Praetoria Misenensis Pia Vindex,) commanded by Pliny the Elder. Photo: Giacomelli and Scandone.

> *Those who were looking at the cloud from some distance could not make out from which mountain it was rising – it was afterwards discovered to have been Mount Vesuvius – but in likeness and form it more closely resembled a pine-tree than anything else, for what corresponded to the trunk was of great length and height, and then spread out into a number of branches, the reason being, I imagine, that while the vapour was fresh, the cloud was borne upwards, but when the vapour became wasted, it lost its motion, or even became dissipated by its own weight, and spread out laterally. At times it looked white, and at other times dirty and spotted, according to the quantity of earth and cinders that were shot up […]. He ordered a Liburnian galley to be got ready […].*
>
> *Already ashes were beginning to fall upon the ships, hotter and in thicker showers as they approached more nearly, with pumice-stones and black flints, charred and cracked by the heat of the flames, while their way was barred by the sudden shoaling of the sea bottom and the litter of the mountain on the shore. He hesitated for a moment whether to turn back, and then, when the helmsman warned him to do so, he exclaimed, "Fortune favours the bold; try to reach Pomponianus". The latter was at Stabiae, separated by the whole width of the bay, for*

the sea there pours in upon a gently rounded and curving shore. . […]., and was waiting for the wind which was blowing on shore to fall. [Figure 3]

In the meantime, broad sheets of flame, which rose high in the air, were breaking out in a number of places on Mount Vesuvius and lighting up the sky, and the glare and brightness seemed all the more striking owing to the darkness of the night. […].

But by this time the courtyard leading to the room he occupied was so full of ashes and pumice-stones mingled together, and covered to such a depth, that if he had delayed any longer in the bedchamber there would have been no means of escape. So, my uncle was aroused, and came out and joined Pomponianus and the rest who had been keeping watch. They held a consultation whether they should remain indoors or wander forth in the open; for the buildings were beginning to shake with the repeated and intensely severe shocks of earthquake and seemed to be rocking to and from as though they had been torn from their foundations. Outside again there was danger to be apprehended from the pumice-stones, though these were light and nearly burnt through, and thus, after weighing the two perils, the latter course was determined upon. […]

They placed pillows on their heads and secured them with cloths, as a precauion against the falling bodies. […] Then the flames, and the smell of sulphur which gave warning of them, scattered the others in flight and roused him. Leaning on two slaves, he rose to his feet and immediately fell down again, owing, as I think, to his breathing being obstructed by the thickness of the fumes and congestion of the stomach, that organ being naturally weak and narrow, and subject to inflammation. When daylight returned – two days after the last day he had seen – his body was found untouched, uninjured, and covered, dressed just as he had been in life. The corpse suggested a person asleep rather than a dead man.

We must recall that a different version of the death of Pliny the Elder is given in the story of his life by Suetonius in the De Viris Illustribus:

He lost his life in the disaster in Campania. He was commanding the fleet at Misenum, and, setting out in a Liburnian galley during the eruption of Vesuvius to investigate the causes of the phenomenon from nearer at hand, he was unable to return because of head winds. He was suffocated by the shower of dust and ashes, although some think he was killed by a slave, whom he begged to hasten his end when he was overcome by the intense heat

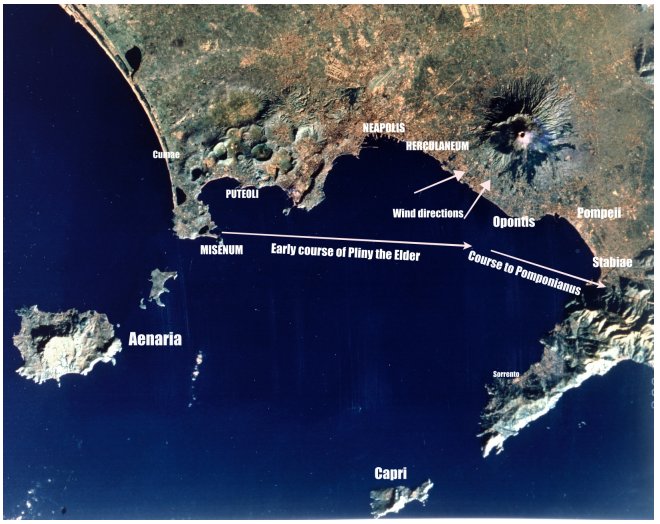

Figure 3. Course followed by Pliny the Elder after leaving Misenum; firstly, toward Herculaneum or Oplontis, and then after the early destruction of Herculaneum toward Stabiae. Arrows show the direction of wind in the proximity of Vesuvius during the Plinian phase (redrawn after image Nasa).

Was this the reason for the letters of Pliny the Younger rehabilitating the figure of the uncle?

The second letter was written to report the behavior of Pliny the Younger at Misenum.

But on that night the shocks were so intense that everything, round us, seemed not only to be disturbed, but to be tottering to its fall

[…]. It was now the first hour of the day, but the light was still faint and weak. The buildings all round us were beginning to totter, and, though we were in the open, the courtyard was so narrow that we were greatly afraid, and indeed sure of being overwhelmed by their fall.

[…]. We came to a halt when we had passed beyond the buildings and underwent there many wonderful experiences and terrors. For although the ground was perfectly level, the vehicles which we had ordered to be brought with us began to sway to and from, and though they were wedged with stones, we could not keep

them still in their places. Moreover, we saw the sea drawn back upon itself, and, as it were, repelled by the quaking of the earth. The shore certainly was greatly widened, and many marine creatures were stranded on the dry sands. On the other side, the black, fearsome cloud of fiery vapour burst into long, twisting, zigzag flames and gaped asunder, the flames resembling lightning flashes, only they were of greater size. […].

Soon afterwards the cloud descended upon the earth and covered the whole bay; it encircled Capri and hid it from sight, and we could no longer see the promontory of Misenum. […]. Then the ashes began to fall, but not thickly: I looked back, and a dense blackness was rolling up behind us, which spread itself over the ground and followed like a torrent. [, when the blackness of night overtook us, not that of a moonless or cloudy night, but the blackness of pent-up places which never see the light. […].

[…]. but the darkness came on again, and the ashes once more fell thickly and heavily.

As said earlier we believe that the passages that we reported are too close to actual volcanic phenomena and confirmed by the stratigraphy of deposits, to be only an invention. We will make use of them and other facts to draw some inferences on the eruption.

3. The reconstruction of the eruption based on the stratigraphy of products

The uncontrolled urbanization of the vesuvian area has destroyed many volcanic outcrops that were still visible no more than forty years ago. At the same time, the archeological digging of the roman cities and the restoration of the collapsed edifices has cancelled the deposits and their impact on the urban network of the roman towns, as well as the possibility to perform new analysis of the effect of each single volcanic episode.

So, we must rely on the past detailed study that were made on the eruption products (Lirer et al., 1973; Sigurdsson et al., 1985; Cioni et al., 1992, 1999; Gurioli et al., 1999, 2002, 2005, 2007).

We mainly use those of Cioni et al. (1992, 1999) complemented by the detailed correlation of the impacts on Herculaneum and Pompei made by Gurioli et al. (1999, 2002, 2005, 2007).

Following Cioni et al., 1992, we use the term Eruption Unit for a deposit that can comprise one or more beds, emplaced by a single pulse or phase characterized by a well-defined eruptive mechanism (Gurioli et al., 2002).

The generalized eruption stratigraphy of Cioni et al., 1992,1999, is shown in Figure 4.

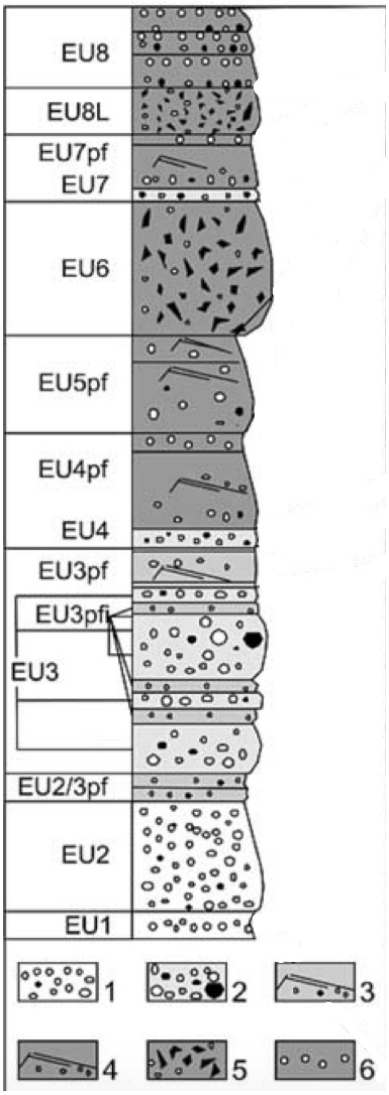

Figure 4. Stratigraphy of the products of the eruption by Cioni et al., 1992.

The eruption began with a series of weak explosions (phreatomagmatic explosions) which deposited a thin ash layer (EU1) mostly East of the volcano with a maximum thickness of 5 cm. The ash bed contains accretionary lapilli and was likely produced by low level, vapor-rich explosions bended towards the east by low level

tropospheric wind (Sigurdsson et al., 1985) (Figure 5).

Shortly after this event, but we cannot be sure of the timing, there was the onset of the fully convective, sustained eruption column growing in height from 14 to 27 km (Carey and Sigurdsson, 1985) which lasted for several hours (7h according to Sigurdsson et al., 1985, 9h according to Macedonio et al., 1988).

The column was dispersed to the South East by the dominant jet stream and deposited a thick layer of white pumices (EU2) with a thickness of approximately 1 m near the volcano and at Pompeii. At Herculaneum there is no trace of this deposits because was upwind.

After the end of this phase, when the deposition of the gray pumice was already initiated, occurred the first dramatic episode of the eruption with the emplacement of a hot PDC (EU2/3pf). The first PDC, due to a partial collapse of the eruptive column, engulfed the city of Herculaneum depositing a layer up to 1.5 m thick, with building remains (roof tiles, columns, and woods from the edifices; Figure 6). It likely killed the inhabitants that were grouped on the seashore (Sigurdsson et al., 1985; Gurioli et al., 2002). The temperature of the flow was in the order of 380 °C (Cioni et al. 2004) to 500 °C (Mastrolorenzo et al. 2001) at Herculaneum. This same PDC hit the villae in the Terzigno area but did not reach Pompeii.

The emplacement of the first PDC was more or less coincident with a change in composition of the erupted magma (EU2/3pf). From that moment onwards the reestablished sustained eruption column, up to 32 km high, caused the deposition of the grey pumice fallout bed. During this phase there were at least 4 partial collapse of the column generating PDCs (EU3pf).

The pumice was deposited to the South-East, (Figures 7 and 8) and the PDC spread mostly to the West, South and South East. These PDCs hit also Oplonti and the country villas (Villae Rusticae) at the foot of the volcano like the one in the proximity of Boscoreale called Villa Regina.

Figure 5. Eruption deposits at Pompeii outside Porta Nolana, resting directly on the Roman road. Photo: Giacomelli and Scandone.

Figure 6. Deposits of the early pyroclastic density currents at Herculaneum in the tunnel in the wall facing the excavations. They were responsible for the deaths inside the arcades. Photo Giacomelli and Scandone.

The first PDC (EU3pf1) left a deposit 1 m tick in Herculaneum, the following (EUpf2) is up to 7 m thick in Herculaneum. The first 3 PDC reached only the North Western periphery of Pompeii leaving a thin ash deposit 2- to 7 cm thick (Gurioli et al., 2007). The last one EU3pf, generated by the final collapse of the eruption column, left a deposit 4 to 30 cm thick at Pompeii.

The rapid withdrawal of magma from the shallow reservoir, as often occurs during large explosive eruption, caused a drop of pressure within the magmatic system and the failure of the rocks overlaying the magma chamber, as signaled by the seismic activity reported by

Pliny the Younger, in the night between 24 and 25, i.e. during the entire EU3 phase, and increasing at the end of this phase.

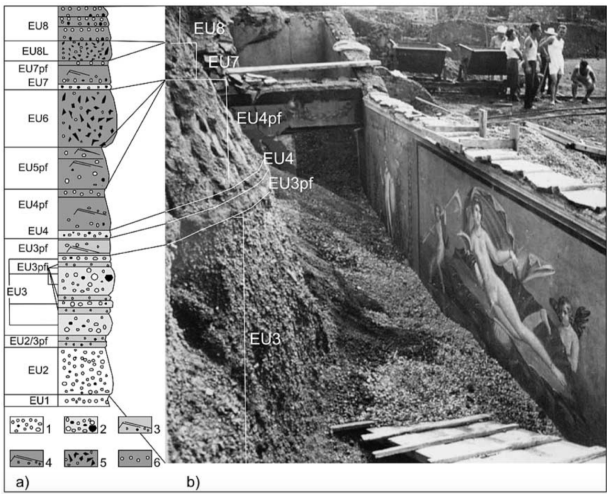

Figure 7. The correlation of the Eruption Units with the sequence of the pyroclastic deposits in the archaeological excavations at Casa della Venere (regio II, insula II), Pompeii. Source: modified after Gurioli et al., 2007.

The failure of the rocks surrounding the magma chamber, along with the surrounding hydrothermal system, possibly caused some early explosive interaction of magma and water characterizing the following eruptive phases. It is not clear if these early collapses and interaction were also responsible of the column collapses.

After a brief restoration of an eruption column (EU4f), the climactic phase of the eruption occurred. The eruptive phase was heralded by the occurrence of the most energetic, probably lasting several minutes, seismic events reported by Pliny the Younger early in the morning of 25. The highly energetic seismic events were accompanied by the withdrawal of the sea that also lasted minutes followed by a Tsunami. Soon after, the most powerful PDC (EU4pf) was reported to engulf all the surroundings of the volcano finally sealing the fate of Herculaneum and Pompeii where it overpassed the city walls and destroyed all the buildings laying above the layers of pumices (Sigurdsson et al., 1982; Cioni et al., 2002; Gurioli et al., 2007) and extended till Stabiae (where it left a more than 50 cm thick deposit) and the Surrentine peninsula (Figure 9).

Two other PDC (EU5 and EU6) are mostly found in the areas more proximal to the volcano. The second one has abundant lithics of carbonate rocks and rocks forming the upper part of the volcano (Cioni et al., 1992; the debris flow deposit of Sigurdsson et al., 1985).

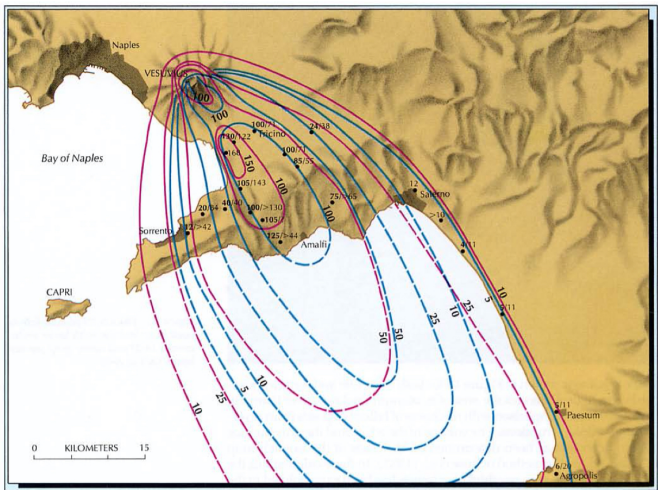

Figure 8. Distribution of the isopachs (lines of equal thickness) of the deposits of the pumice air fall (in cm). *Blu for white pumices; Red for grey pumices.* Source: modified after Sigurdsson et al., 1985.

Finally, there was the emplacement of 2 other PDC (EU7 and Eu8) which left an ash deposit in Pompeii. The last one is rich in accretionary lapilli (pisolites) indicating abundant presence of steam vapor in the eruptive cloud (phreatomagmatic explosions). Overall the two phases EU2 and EU3 left a deposit of pumice 2.5 to 5 m thick in Pompeii (Figure 8).

According to Macedonio et al., 1988, the two phases of pumice fall lasted for 19 hours basing on the estimate on the cumulative erupted mass divided by of the mass eruption rate estimated by the height of the eruption column (Carey and Sigurdsson, 1985). However, the phases of column collapse and emplacement of intra-plinian PDCs are not considered in this estimate of duration. There is no possibility of estimating the duration of the PDC phases basing on the thickness of their deposits (Figure 9). According to Sigurdsson et al., 1985, 19 hours was the total duration of the eruption.

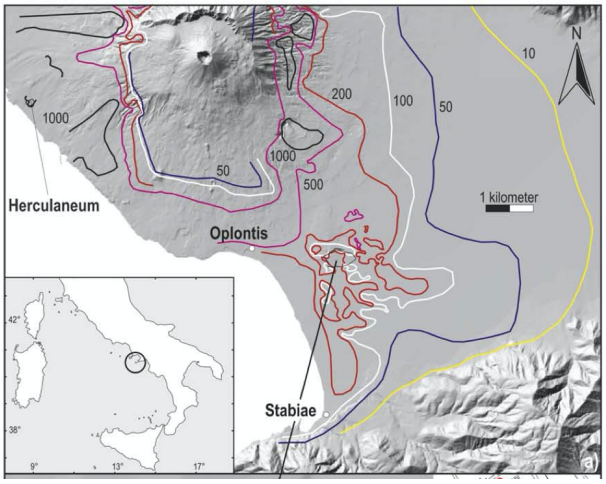

Figure 9. Isopachs of the cumulative thickness of the pyroclastic density currents (in cm). *Yellow maximum extent of the deposits*. Source: modified after Gurioli et al., 2007.

4. The seismic activity before and during the eruption of 79AD

On 5 February of 62 AD a devasting earthquake struck Pompeii and Herculaneum causing widespread destruction. There is a longtime discussion on the date of this event due to the different dating provided by Seneca and Tacitus.

(63 AD) Seneca Naturales Questiones 6, 1, *An earthquake occurred on 5 February under the consulship of Regulus and Verginius, which caused widespread destruction and fear in Campania, never safe from this occurrence*,

(62 AD) Tacitus. Annals. 15, 22, *Under the same consuls the Gymnasium* (of Naples*) was struck by a lightning and was burned, and the same image of Nero melted. The famous city of Campania, Pompeii was in large part destroyed by an earthquake.*

The majority of authors seems to prefer the date of 62 AD.

Whichever was the date, the damages were widespread at Pompeii and Herculaneum and minor at Nuceria and Naples. The extensive reparations were still underway before the 79 AD at Pompeii and Herculaneum. An inscription for the restoration of a temple of Magna Mater at Herculaneum is referred to Vespasianus in 76 AD.

Other testimonies are found in Pompeii like an epigraph attesting the restoration of the temple of Isis, or bas-relief showing the effects of the event (Figure 10).

Figure 10. Evidences of the 62 AD earthquake. (top) Epigraph of Vespasianus (76 AD) for the restoration of the temple of Magna Mater at Herculaneum (Napoli Museo Archeologico Nazionale); (Middle) Bas-relief in the house of Cecilio Giocondo in Pompeii with the effects of the earthquake (Exhibition in Rome, Scuderie del Quirinale, 2019); (bottom) Epigraph for the restoration of the Temple of Isis at Pompeii in the name of the private citizen Popidius Celsinus (Napoli Museo Archeologico Nazionale). Photos: Giacomelli and Scandone.

The earthquake of 62 AD attracted most of the interest of the researchers in the attempt to understand the occurrence of precursors and their effect on the cities of Pompeii and Herculaneum (Boschi et al., 1995; Cubellis and Marturano, 2002, 2006, 2013; Ruggeri et al., 2018). One more earthquake probably struck the area in 64 AD causing damages at Naples as reported by Tacitus.

Lesser attention has been devoted to the seismicity occurring during the eruption (Boschi et al., 1995; Cubellis and Marturano, 2006).

Pliny the Younger reports in his first letter that for several days before (the eruption) the earth had been shaken, but this fact did not cause fear because this was a feature commonly observed in Campania" (*praecesserat per multos dies tremor terrae, minus formidolosus quia Campaniae solitus*). It is difficult in the excavations of Pompeii to understand if the repair works, still underway, were in relation with the earthquake of 62 or the damages caused by a precursory earthquake swarm. Some rush interventions seem to precede the eruption by a little, like a pole sustaining a jamb at Villa Regina, ex-

tensive repair works visible in many houses of Pompeii, as to its water distribution network (Figure 11).

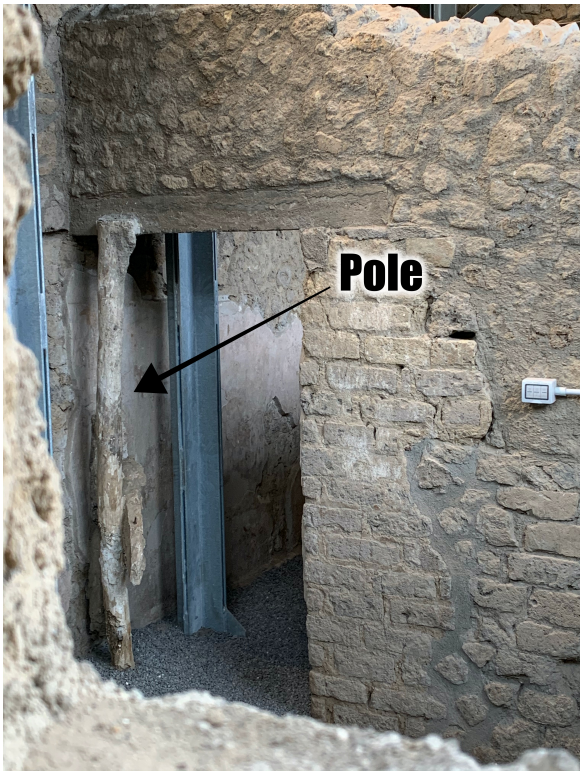

Figure 11. A pole that supports a jamb at Villa Regina. Photo: Giacomelli and Scandone.

As reported in the second letter of Pliny, during the night of the first day of the eruption, the houses of Misenum where shaken by earthquakes that caused much panic. Pliny the Younger and his mother escaped in the open heading northwards from the town of Misenum and as soon as they had passed beyond the buildings, the most important and long-lasting earthquake crisis occurred shortly after day-break. The seismic intensity they felt at Misenum was such that wheeled charts on flat land were shaken back and forth even if chocks were placed against the wheels. Sigurdsson et al. (1985) underscore that in this same moment "Pliny the Younger gives a vivid description of the prelude to a tsunami… accompanying the earthquakes, where the sea surges back upon itself "as though forced back by the tremors of the earth" leaving marine animals stranded".

At the same time in his first letter, referring to his uncle in Stabiae, *by this time the courtyard leading to the room he occupied was so full of ashes and pumice-stones mingled together, and covered to such a depth, that if he had delayed any longer in the bedchamber there would have been no means of escape. So, my uncle was aroused, and came out and joined Pomponianus […] for the buildings were beginning to shake with the repeated and intensely severe shocks of earthquake and seemed to be rocking to and fro as though they had been torn from their foundations.*

The cause of this earthquake swarm has been understood only recently in the course of another eruption occurred at Mt St Helens in 1980 (Scandone and Malone, 1985; Scandone and Giacomelli, 2001). Often, during explosive eruptions there is an increase with time of magma discharge rate (Figure 12).

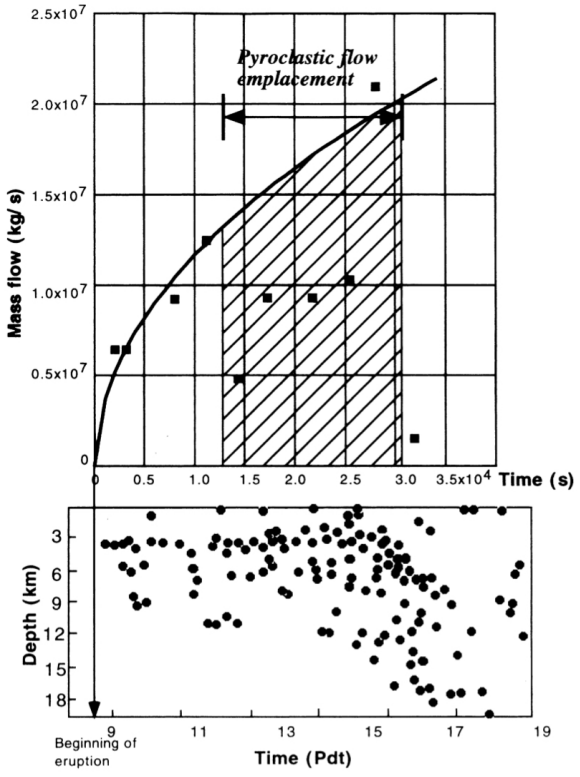

Figure 12. Evolution with time of eruptive parameters during the eruption of St. Helens in 1980. (top) Increase of the eruption rate; the closed squares indicate the eruption rate estimated by the height of the eruptive column. (Bottom) Time-depth distribution of earthquakes hypocenters during the eruption; note the downward migration with time. Source: Scandone and Giacomelli, 2001.

The discharge may be so high that the eruptive column may not remain sustained and collapse to the ground forming pyroclastic density currents. At the same time the rapid discharge of magma causes a sudden decompression in the magma chamber with the failure of the rocks surrounding it (Figure 13). The earthquakes resulting from this syn-eruptive process are so much stronger as the higher the eruption rate and the size of the chamber (higher decompression rate and larger rock mass involved in rock faulting).

High magnitude, shallow earthquakes have been observed during several explosive eruptions in the last 100 years. Three main categories of eruption-related earthquakes can be classified as: i) induced by explosive plinian to sub-plinian events, unrelated to caldera collapse; ii) incremental calderas collapses related to mafic volcanic systems in which magma is laterally drained from a shallow reservoirs; iii) Catastrophic caldera collapses induced by large volume explosive eruptions.

Examples of the category (I) are the 1914 Sakurajima eruption, Japan where an earthquake M=7.1 occurred right after the main explosive phase (Abe, 1992), the Nabro 2011 eruption (Eritrea) where earthquake up to M=5.8 to 5.8 occurred during and immediately after the event (Goitom et al., 2014). Example of category (ii) are represented by the caldera formation of Fernandina caldera (Galapagos - Ecuador) in 1968 where 8 earthquakes with M>5 occurred (Filson et al., 1973) and very recently at Bardarbunga 2014-15 eruption (Iceland) where 18 earthquakes with magnitude comprised between M_w=5.5 and M_w=5.8 occurred (Gudmundsson et al., 2016). Examples of category (iii) are the caldera collapse related Novarupta/Katmai eruption, Alaska, 1912, where the main collapse of Mount Katmai (5.5 km^3 caldera volume) was marked by the occurrence of a seismic crisis which included a formidable sequence of M= 6.3, 7.0, 6.8 and 6.6 events (Abe, 1992). Syn-eruptive seismicity is thus always present during and immediately after explosive, plinian-type events, but it is significantly augmented if a caldera formation is involved and if the caldera collapse occurs in a catastrophic manner rather than in an incremental manner.

The eruption of Pinatubo is another well documented example of a large-scale explosive event. The eruption began with a series of Plinian events at 13.09 of June 14th 1991, and culminated with a climactic phase at 13.42 of June 15th, terminating at 22.30 of the 15th (Wolfe and Hoblitt, 1996). The erupted volume was in the order of 5 km^3 similar to that of Vesuvius 79 AD. The earthquakes started to be felt after 15.39 of June 15th. The national Earthquake Information Center (NEIC) reported 29 events with a body wave $m_b \geq 4.5$ and 6 with a body wave magnitude $m_b \geq 5$; the largest magnitude was of 5.7. The earthquakes were felt at a rate of 1 per minute at a distance of 35 km from the volcano. On 16, the rate of occurrence was of 150 earthquakes per hour, with magnitudes ≥2.0 and rapidly decayed on the following week (Mori et al., 1996).

The event produced also a small caldera, but the volume of the structure is largely accounted by lithic material which was erupted in large volume during the last lithic-rich PDC.

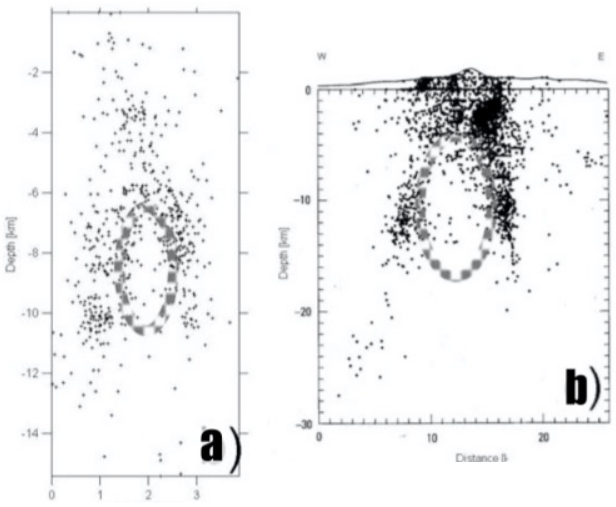

Figure 13. Distribution of earthquakes occurred during and after the eruptions of a) St Helens (USA) in 1980; b) Pinatubo Philippine , 1991. The dotted lines indicate the location of the magma chamber. Source: modified after Scandone and Acocella, 2007.

We can try to estimate the magnitude of the earthquakes occurring during the eruption of 79 AD basing on the Intensity at different localities. There are five epigraphs documenting the reparation works made after the eruption of 79 AD (Boschi et al., 1995) (Figure 14). Four are dedicated to Emperor Titus between 80 and 81 AD, and one to Emperor Domitianus. The first refers

to the restoration of edifices in Naples because of earthquakes. It is an inscription in black stone presently at the National Archeological Museum of Naples (Renna, 1992).

The second one refers the reparation of a clock in Sorrentum, destroyed by earthquakes, currently at the Museum Correale of Sorrento. The third one reports the restoration of a temple in the proximity of Nola (Sampaolo, 1986). This same author reports also another epigraph, from Nola, now lost (CIL X, 1264), relative to the restoration of the collapsed Theater. The fourth, dubious one, refers of generic damages at Salerno (Paci, 1991) The fifth inscription reported by Johannowsky (1986) was found at Nocera (the roman Nuceria Alfaterna) and is attributed to Domitianus in the year 82 AD, even if his name was cancelled for the Damnatio memoriae. It pertains to the restoration of the Theater, collapsed for the earthquakes.

It is interesting to note that, at difference from those referring to the earthquake (terremotu) of 62 AD, all these inscriptions make reference to earthquakes (terremotibus) possibly indicating the many ones occurring, not only before but also during the eruption and not, as previously thought, also to the earthquake of 62.

We may estimate a Macroseseismic Magnitude from the Intensity, by applying the Bakun and Wentworth's (1997) relation for Ii (Intensity) and Ri (distance from the source) hypothesizing the epicenter below the Vesuvius

$$M = (I_i + 1.72 + 0.0212\ R_i)/1.4$$

Where I_i is the Intensity at place i and R_i is the distance from the epicenter. However, for shallow earthquakes, the values so estimated may provide value in excess of 1 degree (Cubellis and Marturano, 2002).

In Table 1 we report all the localities where it is possible to make an estimate of the Intensity, their distance from Vesuvius and the Macroseismic Magnitude corrected for the effect of shallow depth.

There is a substantial convergence toward corrected values between 5.3 and 6.28 with a mean of 5.89 remarkably similar to the maximum magnitude of the earthquakes occurred at Pinatubo. It must also be stressed that the result so obtained is due to the cumulative effects of all the seismic swarm occurred during the eruption.

Figure 14. Epigraphs pertaining to the earthquakes of 79 AD. A) Titus, restoration of a clock in Sorrento (Museo Correale, Sorrento) (photo by Giacomelli and Scandone), b) Titus restoration of edifices in Naples (Museo Archeologico Nazionale, Napoli), (Photo by Sergio Izzo) c) Fragments of an epigraph attributed to Titus in Salerno, (modified after Paci, 1991). d) Reproduction of the epigraph of Domitianus for the restoration of the Theater of Nuceria Alfaterna (after Joannowski, 1986).

We can draw the isoseismal map obtained by the macroseismic observations (Figure 15) and compare them with the isoseismal map made by Cubellis and Marturano (2002) for a 3.7-4.1 magnitude earthquakes occurred at Vesuvius in 1999. Although it is not entirely correct, a rough estimate is obtained by increasing their isoseismal lines of 4-5 degrees to fit the observed intensities at the mentioned places.

We can observe that Pompeii and Herculaneum are well within the Intensity IX-X isoseism and must have suffered extensive damages not only for the effects of the eruption, but also for the earthquakes that, at Pompeii, resulted more damaging because of the load of the pumices on the roofs. We also stress that the earthquakes, occurred during the eruption of 79 AD, are by far larger than that occurred in 62 AD, with effects observed at a larger distance.

Place	Distance from Vesuvius (km)	Intensity	Macroseismic Magnitude Corrected (uncorrected)	Source
Naples	13.9	VIII	6.15 (7.15)	CIL, 1883
Nola	14.2	VIII	6.16 (7.16)	Joannhowski, 1986
Nocera	14.2	VIII	6.16 (7.16)	Boschi et al.,1995
Sorrento	22.5	VIII	6.28 (7.28)	Boschi et al.,1995
Salerno	34.8	VII	5.4 (6.4)	Paci, 1991
Misenum	29.27	VII	5.3 (6.3)	Pliny the Younger
Stabiae	15.92	VII-VIII	5.8 (6.8)	Pliny the Younger

Table 1. Localities where it is possible to make an estimate of the Intensity and Macroseismic Magnitude corrected for the effect of shallow depth.

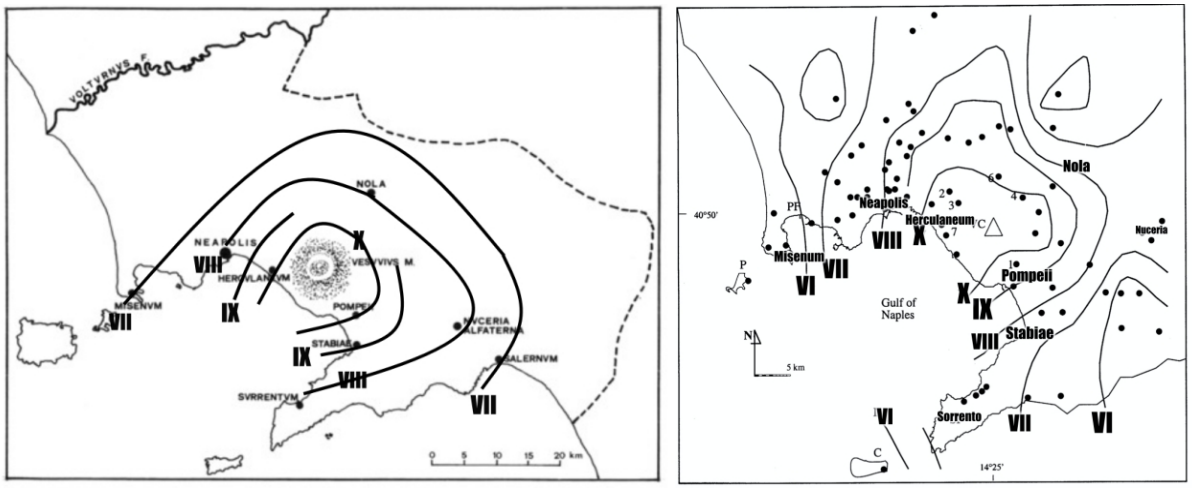

Figure 15. Isoseismal map for the earthquakes of 79 AD estimated by the actual intensities (left); drawn according to the damages observed, modifying the isoseismal map of Cubellis and Marturano, 2002 (right).

5. The Victims of the Eruption

De Carolis et al., 1996 made a detailed inventory of the victims found within the city of Pompei basing on the excavation reports made since 1748. This study was used by Luongo et al., 2003, and Giacomelli et al., 2003, to infer the possible causes of death during the eruption. De Carolis and Patricelli, 2013, have extended the inventory to the places outside Pompeii comprising Herculaneum, Oplontis, the port area of Pompeii and Stabiae.

Although it is not possible a detailed positioning of the human remains within the volcanic deposit, it is possible to make a rough distinction between the bodies found within the pumice deposits and those found embedded in the ash of the PDCs. In Pompeii, and in the immediate surrounding areas, there is evidence that a substantial number of people were found above the pumice layer and within the ash of the PDCs.

In 1863, the archeologist Giuseppe Fiorelli devised a method to obtain the cast of the victims found in the ashes above the pumices, where the percolation of human tissues with time left a void in the ash that preserved the form of the body. By injecting liquid gypsum into the void, it was possible to obtain the image of the dead (Figure 16).

The cast of the body of the victims permitted to crystallize the last moments of life of the fugitives of Pompeii. This procedure was not possible for the dead in the pumice or wherever the lack of pumices below the bodies, did not allow the slow percolation of human tissues and the preservation of the form of the body in the ash.

Figure 16. One of the first cast made by Fiorelli at Pompeii, in 1863 in the vicolo degli Scheletri, now in the house of Sirico. Photo: Giacomelli and Scandone.

A detailed study of the findings was made for a few outcrops, including those called Casa dello Stabiano in Pompeii where the casts of the victim are found above the pumice layer and the PDC unit EU3pf and possibly buried within EU4Pf (Luongo et al., 2003; Santacroce, 2018) (Figure 17)

Photographs from the time of the excavation in the 1960s, in the nearby outcrop called Orto dei Fuggiaschi (Figure 18), suggest that the casts of the victims, before being removed from their original position, were at the same stratigraphic level as many other found in the ashes above the pumices, like the bodies in the courtyard of the Casa del Criptoportico.

Figure 17. The casts of victims in Casa dello Stabiano at Pompei from above and the side; they rest directly over the first PDC reaching Pompeii above the pumice fall deposit. Note also the change of color of pumice from white to grey. Photo: Giacomelli and Scandone.

In the past, there was no such attention to a stratigraphic excavation that could position the victims at a particular stratigraphic level, and after the casts were made, they were always removed from their original position.

Unfortunately, such practice is still in use nowadays, even if attempt to define the stratigraphic position is performed when volcanologists are present at the excavations.

The number of victims remains uncertain even for the use, until the middle of 1800 of throwing the bones with the excavated material.

The majority of the victims found in the pumices are within houses, often men with children and women, some pregnant, and only a few are found outside suggesting that they were compelled to remain indoor. Many of the bodies have broken bones suggesting collapse of the houses. Victims found in the ash have often the so-called boxer posture common for the victims in hot pyroclastic flows because caused by the muscle contraction for heat (Figure 19). The total number of victims is 1800.

Figure 18. The digging of the cast at the so-called Orto dei Fuggiaschi at Pompeii in 1961 from a RAI movie of the time. The casts are at the same stratigraphic level of those of Casa dello Stabiano. Source: RAI.

Figure 19. Comparison of victims found in pyroclastic flows. (Up) casts of victims of Pompeii. (photo by Giacomelli and Scandone), (Bottom) Victims in the eruption of Merapi Volcano in Indonesia (after Schiffman, 2011), and at Mt Lamington in Papua New Guinea (after Taylor, 1958). All have the typical posture of the boxer due to the contraction of muscle for the heat.

To these, it must be added an unspecified number of human remains of the order 100, not directly described in excavation reports but simply indicated as findings of human bones, so that the total number of found victims ascend to 1900.

In Table 2, we provide a resume of the detailed tables of De Carolis et al., 1998, and De Carolis and Patricelli, 2013, summarizing the findings at Pompeii and outside.

Locality	Bodies within the Pumice inside houses	Bodies within the Pumice outside houses	Bodies within the ashes inside houses	Bodies within the ashes outside houses	Totals
Pompeii	345	49	334	316	1044
Pompei suburbs	36	1	62	71	170
Boscoreale	45		10		55
Scafati			5		5
Terzigno			12		12
Torre Annunziata			54		54
Herculaneum			38	311	349
Stabia			101		101
Castellammare			1		1
Gragnano			7		7
S. Antonio Abate			2		2
Totals					1800

Table 2. The findings at Pompeii and outside regarding bodies within the Pumice inside houses, bodies within the Pumice outside houses, Bodies within the ashes inside houses, Bodies within the ashes outside houses

6. The damages and the survivors

The eruption and the associated earthquakes caused widespread destruction at Pompeii, Herculaneum, Oplontis, Stabiae and in all the vesuvian territory. Extensive damages were produced, after the eruption, by numerous mudflows caused by the mobilization of loose ashes by rainstorms (Lirer et al., 2001). Some of them are still visible in Torre Annunziata (Figure 20). Besides the effects of the PDC, all the area to the South east of the volcano was covered by a loose sheet, up to 3 m thick, of pumices extending well into the steep slopes of the Sorrentine peninsula. Rapid erosional processes driven by steep slopes subsequently reworked the soft and loose pyroclastic material leading to tens of metres of valley filling, alluvial fan growth, and fan delta formation (Cinque and Robustelli, 2009). Some of these events, occurred immediately after the eruption, eventually buried Roman villas in S. Antonio Abate and Positano and lasted up to 120 years after the eruption (Cinque and Robustelli, 2009).

The earthquakes hit areas which had not been affected seriously by the PDC like Naples, Nola and Nuceria causing extensive damages that were repaired in the following years as attested by the numerous epigraphs. As at Pompeii, at Stabiae, Sorrento and Salernum, the earthquakes effect was aggravated by the blanket of pyroclastic deposit that had accumulated on the roofs of the edifices. Still years later, during Adrian empire, the reopening of the road between Nuceria and the restored Stabia, was possible only by building walls that prevented the sliding of pumices (Renna, 1992).

Figure 20. Deposits of lahar (mudflows) topping the grey pumice and a roman wall. Photo: Giacomelli and Scandone.

Immediately after the eruption, the emperor Titus, as attested by Suetonius, nominated two ex-consuls (Curatores restituendae Campaniae) to superintend the repairs works and the legal question arising for the deaths of so many citizens.

The disaster left a great impression on the contemporaries which transpire in the works of poets and in the mention of historians.

We recall the poet Martial which first mentions the cities of Pompei and Herculaneum

> *Here is the Vesuvius, once green with shady vineyards, here a precious grape was overflowing the tubs; Bacchus loved these leaps more than the hills of Nisa, on this mountain the Satyrs in the past dissolved their dances; this, of Sparta more pleasing, was the seat of Venus* (Pompeii)*, this was the place renowned for the name of Hercules* (Herculaneum)*. Now everything lies submerged in flames and in sad lapillus: now they would not want the gods that they had been allowed to exercise so much power here.*

The restoring of Naples and surrounding places is recalled in the work Silvae by the Neapolitan poet Statius (probably composed between 89 and 96 AD). In Silvae III, 5, addressing to his wife Claudia:

> *The Vesuvian peak, the tempest of fire from that ominous height, have not so utterly cowed and drained our cities of men. They still stand strong in their sons. Westward the halls of Dicarcheus (*Pozzuoli*) that arose at Phoebus' ordinance, the haven and the shore that welcomes all the world northward the towers that rival the expanse of imperial Rome, the towers that Capys filled with his Teucrian pilgrims. And there too is* our own *Parthenope (*Naples*), that can scarce shelter her own people, and has scant room for settlers. […] it be your pleasure to repair to steaming Baiae's alluring beach, or to the haunted shrine of the inspired Sibyl. The cape that bears upon it for monument the Trojan's oar or the flowing vineyards of Bacchus-haunted Gaurus and the homes of the Teleboae, where the Pharus, to guide anxious mariners, uplifts a beacon bright as the nomad Queen of night; or to those Surrentine ridges, dear to sturdy Lyaeus, that Pollius, my friend, honours above all with his dwelling place; to the healing waters of Inarime (*Ischia*) or to Stabiae reborn* (Translated by Slater, 1908).

How many were the survivors of the eruption that may have left Pompeii and Herculaneum before or even during the eruptions? The answer is not simple because we do not know the exact number of inhabitants before the eruption to compare with that of the deaths. What should be taken in mind is that these cities had suffered from the effects of the earthquakes of 62 and 64 and possibly several other before the eruption. The city of Pompeii was the site of repairing works and many of the houses were not inhabited and many temples were still to be repaired, and the same water distribution system was not working (Dickman, 2005).

Probably the estimate of 15000-20000 people (the capacity of the amphitheater) living only in Pompeii is an overestimate. We believe that, at most, such estimate of 15000-20000, should be addressed to the all population living in the Vesuvian suburbs, which compares, for example, with a population of 40000 living in the same area in 1631. As often has been the case during volcanic eruptions, the precursory seismicity is so relevant that even people not knowing anything of volcanoes flee the site at the first signs of unrest, as was the case during the Vesuvius eruption of 1631 (Braccini, 1632). The victims are those too scared to take any decision or prevented by minors or disabled relatives. We believe that the approximately 1900 bodies found, and perhaps as many as another 1000 in the unearthed territory, may represent the maximum number of people that died during the eruption (4000 during the 1631) which ascend to a percentage ranging between 15 and 19% of the total population which compare with the 10% loss during the 1631 eruption.

As for the refuges, an important clue where they escaped, has been recently provided by the fundamental work of Steve L. Tuck (2019). He examined the known names of the inhabitants of Pompei and Herculaneum and accurately compared with those of the surrounding cities where those names were not present before the 79 AD. The not surprising result is that the inhabitants of Herculaneum and Pompeii found refuge mostly at Puteoli, Neapolis, Cumae, and Ostia,

all to the north of the destroyed towns. A predominance of names coming from Pompeii was found at Cumae and Puteoli, whereas in Neapolis there was evidence of families from both cities. It should be recalled that in Neapolis there was an area called Regio Herculanensis. Supporting evidence for a sudden increase of the population at Neapolis, Puteoli and Cuma is also the building of new infrastructures and temples in the period after the eruption, in many cases with the imperial support (Tuck, 2019).

We suggest that the flight to the cities to the north of the volcano was driven by the extensive damages made by the airfall deposit to the South-East, which required a longer recovering time because of the loss of arable land, and the frequent landslides and mud flow affecting the entire Sorrento and Salerno area.

They went to the North also because it was the path, they followed the most before the eruption, and in any case the one that most rapidly led away from Vesuvius. To the east, towards the Apennines, they were at that time places of difficult access.

7. Discussion and Conclusions

In order to assess the timing of the destruction of the vesuvian suburbs it is necessary to correlate the deposition of the eruption products with the known time of the travel of Pliny the Elder and the occurrences observed by Pliny the Younger at Misenum. Such timing has been proposed by Sheridan et al., 1981, Sigurdsson et al., 1982, Macedonio et al., 1988, Scandone and Giacomelli, 2000, Giacomelli and Scandone, 2002, among the others. Here we draw a different scenario based on the Letters of Pliny, the succession of events proposed by Cioni et al., 2002, Gurioli et al., 2002, 2005, 2007, the succession of earthquakes felt at Misenum and Stabiae, the distribution of victims in all the vesuvian district.

An important point, not previously fully underlined, is the early destruction of Herculaneum by the arrival of EU2/3pf at the end of the phase of white pumice fall deposition. We believe that this dramatic event was witnessed by Pliny the Elder during his travel to the devasted region (Figure 21).

> *Already ashes were beginning to fall upon the ships, hotter and in thicker showers as they approached more nearly […] while their way was barred by the sudden shoaling of the sea bottom and the litter of the mountain on the shore (iam vadum subitum, ruinaque montis litora obstantia).*

As it has already been pointed out by Ricciardi (2009), the term *ruina montis* was used by the Romans to indicate the quarrying operation when landslides were caused by the disruption of galleries. We believe that the shoaling and the litter of the mountain are the evidence of the first PDC engulfing all the southern side of the volcano, where possibly was also located Rectina Villa, and that the Elder may have observed such occurrence and the consequent death of all the inhabitants living at Herculaneum.

Other have suggested that the shoal may have been caused by the pumice on the sea, but they must have been even more abundant toward Stabiae where they were blown by the stratospheric winds.

Figure 21. Dead found in the arcades of the beach of Herculaneum and the boat turned over on the beach of Herculaneum. Photo: Giacomelli and Scandone.

With the favor of the wind, Pliny the Elder may have reached Stabiae in a short while. Actually, we believe that he was compelled to land in Stabiae because of the wind. Many authors suppose that the distribution of the air fall deposit suggests a North-Western wind blowing also at sea level. We recall that the direction of air-fall deposits is governed by the Jet Stream at the tropopause (about 10 km asl); this does not imply the same wind at sea level. A somehow more significant information about the wind di-

rection in the lower part of the troposphere is offered by the dispersal direction of the basal ash fall deposit. The ash is clearly dispersed eastward indicating that in the early morning of 24, the wind in the first 5 km was blowing from west to east. If the same wind direction was present at sea level it would have further facilitated the travel of Pliny the Elder from Misenum towards the Rectina's villa and later on would have made almost impossible for the Stabians to flee via sea. However, during large explosive eruption with a sustained eruption column, a strong air influx, necessary to maintain the buoyancy of the column, occurs at the base of the volcano. The Plinian eruption is likely to have caused strong hurricane winds toward the volcano and the ships travelling toward Pompei may have been engulfed in this storm.

This scenario is confirmed by the variation of the thickness of the air-fall pumice (Sigurdsson et al., 1985) (Figure 22, bottom) which shows a relative thinning toward the volcano with respect to Pompeii, justified by the blowing of strong winds toward the volcano up to a distance of at least 10-12 km Thus the pumices were partly recycled with the eruption column and their deposition was hindered.

A possible occasional pause, at the moment of the first eruption collapse, may have permitted to Pliny the Elder to seek refuge in the nearest safe anchorage of Stabiae, in a moment when it was possible to see also the place in the pause of the pumice fall. This has occurred approximately 7-9 hours after the beginning of the eruption. We are compelled to suggest that the beginning of the eruption has not occurred at 1 pm as observed by the Pliny at Misenum, but some hours before as already suggested by Sigurdsson et al., 1982, 1985.

The timing of the travel is strongly constrained by the time necessary to Pliny the Elder to reach a high place where observe the eruption at Misenum, to go back to the naval base, order the preparation of the quadriremes and the time necessary to reach Stabiae. This last part could have lasted more than 7.3 and 5.5 hours at an average speed of 3-4 knots. So, a conservative estimate of the time needed to arrive to Stabiae is between 11-9 hours.

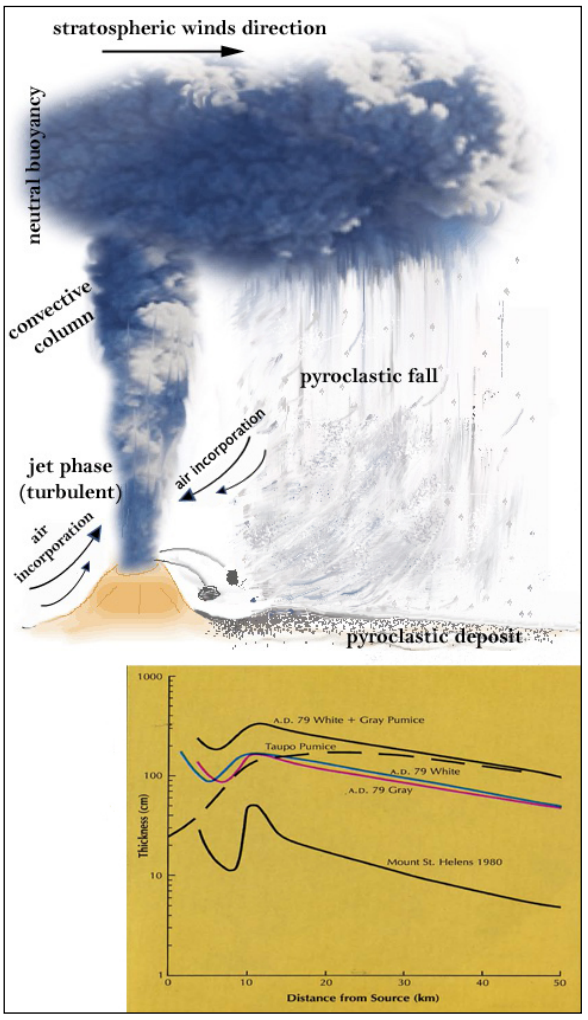

Figure 22. Mechanism of deposition from a Plinian eruption column. The deposits are dispersed by the jet stream, but the deposition in the proximal areas is governed by the low-level winds rushing toward the volcano with a relative thinning of the deposit (drawn by the authors). In the lower part is shown the thickness of the deposit of the Plinian fall of the 79 AD eruption. Source: Sigurdsson et al., 1985.

The beginning hour depends on the exact date of the eruption, if in Summer or Autumn, because we infer that the arrival at Stabiae occurs shortly before sunset. On 24 October, at this latitude the sunset occurs at 6:17 pm and dawn is at 7:31 am. On 24 August, the sunset occurs at 7.50 pm and dawn is at 6:20 am. The start of the eruption is possibly between 9 and 10 in the morning.

The night was troubled by earthquake shock of increasing violence that occurred mostly during the eruption of the grey pumice and the em-

placement of the four EU3pf. By this time all the inhabitants living to the west of Pompei may have already died as a consequence of the earlier PDCs.

Only those inside the houses at Pompei and its suburbs, and Stabiae were still living, protected by the distance from the volcano, the wall of the city, and the shelter, barricaded inside the houses (Figure 23).

However, the increasing collapses of the roofs loaded by pumice and the terrifying increasing earthquakes compelled these inhabitants, that had otherwise survived the first phase of the eruption, to attempt fleeing from the safe refuge of the houses.

This scenario is also suggested by the behavior of Pliny the Elder at a greater distance from the volcano:

> *But by this time the courtyard leading to the room he occupied was so full of ashes and pumice-stones mingled together, and covered to such a depth, that if he had delayed any longer in the bedchamber there would have been no means of escape. […]. They held a consultation whether they should remain indoors or wander forth in the open; for the buildings were beginning to shake with the repeated and intensely severe shocks of earthquake and seemed to be rocking to and fro as though they had been torn from their foundations. Outside again there was danger to be apprehended from the pumice-stones, though these were light and nearly burnt through, and thus, after weighing the two perils, the latter course was determined upon. […]. They placed pillows on their heads and secured them with cloths, as a precaution against the falling bodies. Elsewhere the day had dawned by this time, but there it was still night, and the darkness was blacker and thicker than any ordinary night.*

So, they left the houses because of earthquakes during the fall of the pumice. If the duration of the grey pumice fall, lasted 10 hours (Macedonio et al., 1988), the end of the EU3 phase would occur at 6 am (if a summer date is considered) or 1 hour and half earlier if the Autumn date is considered. In both cases, to fit Pliny the Younger timing (one hour after sunrise), we must hypothesize a longer duration for the EU3 phase, justified by the duration of the EU3pf events.

Figure 23. The entrance to the Efebo House was blocked by a pole that prevented the pumice from breaking through the door. Photo: Giacomelli and Scandone.

At Misenum, shortly one hour after the dawn, Pliny the Younger reports the occurrence of the strongest and long-lasting seismic events along with the occurrence of a Tsunami.

> *We saw the sea drawn back upon itself, and, as it were, repelled by the quaking of the earth* […] *the black, fearsome cloud of fiery vapour burst into long, twisting, zigzag flames and gaped asunder, the flames resembling lightning flashes, only they were of greater size.* […].
>
> *Soon afterwards the cloud descended upon the earth and covered the whole bay; it encircled Capri and hid it from sight, and we could no longer see the promontory of Misenum.*

At this same moment, Pliny the Elder was engulfed by the hot avalanche reaching Stabiae and the western Sorrentine peninsula.

At Pompeii, people made the same choice, at the same moment as Pliny the Elder. We speculate that, the temporary decline of eruptive activity (cessation of the pumice fallout) combined with the occurrence of the strongest, caldera-forming, seismic events (M=5.8-6.2), likely caused the simultaneous and widespread collapse of edifices. It was this sudden and frightening event which eventually induced the survivals to flee their shelters seeking safety outside. They had however to make the travel above the deposit of EU3pfi and EU3pf, that offered a difficult path to the presumed safety despite the still hot deposit above meters of non-consolidated pumices. Unfortunately, at that point, they were swept away by the arrival of the EU4pf which occurred after a brief pumice fall of grey pumice and when the caldera collapse reached the surface activating a massive release of pyroclastic material from multiple vents.

We summarize the sequence of events in Figure 24.

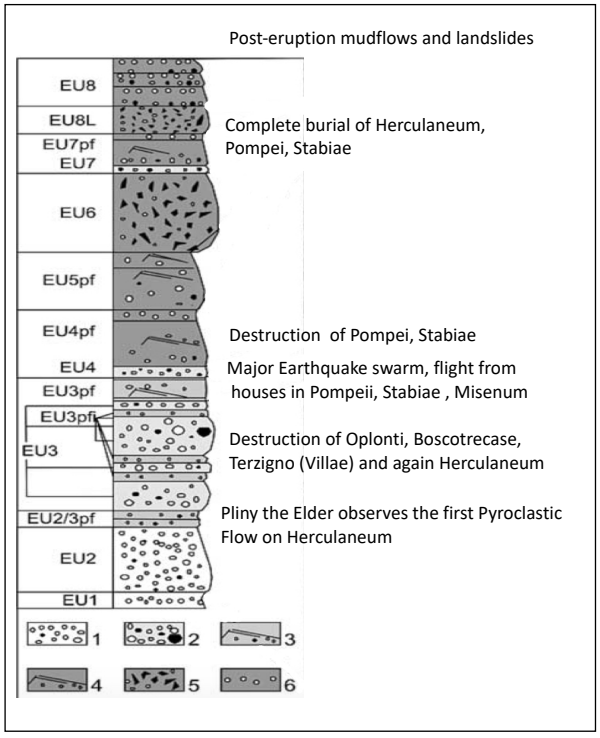

Figure 24. The sequence of events in relation with the stratigraphy of products.

Our reconstruction finds a striking similarity with what happened during the only plinian-type eruption of Vesuvius for which we have a detailed historical account: the 1631 eruption.

The reconstruction of the eruption made using deposit stratigraphy and the historical chronicles enabled Rosi et al. (1993) to highlight the occurrence of two main climactic eruptive phases: the plinian phase initiated in the morning of 16 December associated to the emplacement of a pumice fallout and the pyroclastic flow phase which occurred in the morning of 17 December. The two eruption phases were separated by hours of less energetic explosive activity and the occurrence of short-lived earthquakes. The second climactic phase was shortly preceded by the occurrence of a 5'-long, highly energetic earthquake along with a widespread withdrawal of sea in the gulf of Napoli (tsunami). The earthquake culminated with the sinking of the cone which was witnessed by people in Napoli (Braccini, 1632), the formation of a 1200m diameter caldera and the emission of PDCs (Carafa, 1632). Both the 79 and the 1631 eruptions produced a climax of the hazard and the largest number of victims as a result of earthquakes and PDC's produced in connection with the caldera collapse (Orlandi, 1632).

The occurrence of the most energetic seismic crisis in coincidence with caldera collapse induced by plinian eruption is in turn in excellent agreement with what have been observed in similar events around the World in the past 100yrs. As it regards the tsunami origin of both 79 and 1631, they share the same characteristics and appear to be generated from slumping of seafloor sediments in the gulf of Napoli mobilized by the same caldera-forming earthquake as also suggested by Sigurdsson et al. (1985).

It is certainly surprising that more than 1000 peoples had survived for so long within the houses of the city of Pompeii in a truly dramatic atmosphere, during the night, under the shower of pumice lapilli with lightnings and earthquakes rocking the edifices. Only the increasing violence of the earthquakes drove part of them outside the houses in search of a difficult safety.

The progressive increase of the violence had been signaled by the increasing size of the pumice and lithics falling on the city, but this knowledge was only recognized 2000 years later.

We can end this note by citing the words of Braccini (1632) during the eruption of 1631 *Perituri non recipunt consilia* (Those that are to die do not accept advise); we hope that these events may serve as a warning for the future.

Acknowledgements

We acknowledge the thoughtful reviews by anonymous reviewers. We thank Carlo Doglioni for pointing out the problem of cooperation between volcanologists and archaeologists from which originated the present work.

References

1. Abe K., "Seismicity of the caldera making eruption of Mount Katmai, Alaska in 1912", *Seismological Society of American Bulletin*, 82, 1992, pp. 175-191.
2. Bakun W.H. and Wentworth C.M., "Estimating earthquake location and magnitude from seismic intensity data", *Bulletin seismological Society of America*, 87, 1997, pp. 1502-1521.
3. Boschi E., Ferrari G., Gasperini P., Guidoboni E., Smriglio G. and Valensise G., *Catalogo dei Forti Terremoti in Italia dal 461 a.C. al 1980*, Bologna, Istituto Nazionale di Geofisica, 1995.
4. Braccini G.C., *Dell'Incendio fattosi al Vesuvio a' XVI Dicembre 1631, e delle sue cause ed effetti*, Naples, Roncaglioli, 1632.
5. Carafa G., *In Opusculum de novissima Vesuvj conflagratione. Epistola Isagogica* (II ed.), Naples, Egidio Longo, 1632.
6. Carey S. and Sigurdsson H., "Temporal variations in column height and magma discharge rate during the 79 A.D. eruption of Vesuvius", *Geological Society America Bulletin*, 99, 1987, pp. 303-314.
7. Cinque A. and Robustelli G., "Effetti catastrofici distali della eruzione del Vesuvio nel 79 d.C.: evidenze sedimentarie e geoarcheologiche in Penisola Sorrentina", *Méditerranée*, 112, 2009, pp. 95-100.
8. Cioni R., Gurioli L., Lanza R. and Zanella E., "Temperatures of the A. D. 79 pyroclastic density current deposits (Vesuvius, Italy)", *Journal of Geophysical Research*, 109, 2004.
9. Cioni R., Gurioli L., Sbrana A. and Vougioukalakis G., "Precursory phenomena and destructive events related to the Late Bronze Age Minoan (Thera, Greece) and AD 79 (Vesuvius, Italy) Plinian eruptions: Inferences from the stratigraphy in the archaeological areas", in McGuire W.G. et al., *The Archaeology of Geological Catastrophes*, *Geological Society London Special Publications*, 171, 2000, pp. 123-141.
10. Cioni R., Marianelli P. and Sbrana A., "Dynamics of the AD 79 eruption: Stratigraphic, sedimentological and geochemical data on the successions of the Somma-Vesuvius southern and eastern sectors", *Acta Vulcanologica*, 2, 1992, pp. 109-123.
11. Cubellis E. and Marturano A., "Mt. Vesuvius: a macroseismic study of the earthquake of 9 October 1999", *Journal of Volcanology and Geothermal Research*, 118, 2002, pp. 339-351.
12. Cubellis E. and Marturano A., "Analysis of historical and present earthquakes at Vesuvius for seismic hazard evaluation, XY0701 EGU *Session NH5.03: Volcanic Hazards and Risks* (Vienna, 2-7 April 2006), Poster, 2006.
13. Cubellis E. and Marturano A., "Felt index, source parameters and ground motion evaluation for earthquakes at Mt. Vesuvius", *Annals of Geophysics*, 56, 4, 2013.
14. De Carolis E. and Patricelli G., "Rinvenimenti di corpi umani nel suburbio pompeiano e nei siti di Ercolano e Stabia", *Rivista di Studi Pompeian*, XXIV, 2013, pp. 11-32.
15. De Carolis E., Patricelli G. and Ciarallo A., "Rinvenimenti di corpi umani nell'area urbana di Pompei", *Rivista di Studi Pompeiani*, IX, 1998, pp. 75-123.
16. Dickman J.A., *Pompeji, Archeologie und Gesschicte, Munchen*, Verlag Bech, 2005.

17. Eco U., *Sugli specchi e altri saggi*, La nave di Teseo, 1994.
18. Filson J., Simkin T. and Leu L., "Seismicity of a caldera collaps: Galapagos Islands 1968", *Journal Geophysical Research*, 78, 1973, pp. 8591-8622.
19. Firth J.B, *The letters of the Younger Pliny*, New York, Walter Scott, 1910.
20. Giacomelli L., Perrotta A., Scandone R. and Scarpati C., "The eruption of Vesuvius of 79 AD and its impact on human environment in Pompei", *Episodes*, 26, 3, 2003, pp. 234-237.
21. Giacomelli L. and Scandone R., *Vesuvio, Pompei, Ercolano: eruzioni e escursioni*, Milan, BE-MA, 2001.
22. Goitom B. et al., "Pre-, Syn- and Post Eruptive Seismicity of the 2011 Eruption of Nabro Volcano, Eritrea", *Geophysical Research Abstracts*, 2014.
23. Guadagno G., "Il viaggio di Plinio il Vecchio verso la morte" (Plin Ep. VI 16), *Rivista di Studi Pompeiani*, 6, 1993, pp. 63-76.
24. Gudmundsson M. et al., "Gradual caldera collapse at Bàrdarbunga volcano, Iceland, regulated by lateral magma outflow", *Science*, 353, 2016.
25. Gurioli L., Cioni R. and Bertagna C., "I depositi di flusso piroclastico dell'eruzione del 79 d.C.: Caratterizzazione stratigrafica, sedimentologica e modelli di trasporto e deposizione", *Proceedings Società Toscana Scienze Naturali, Memorie*, Ser. A, 106, 1999, pp. 61-72.
26. Gurioli L., Cioni R., Sbrana A. and Zanella E., "Transport and deposition of pyroclastic density currents over an inhabited area: The deposits of the AD 79 eruption of Vesuvius at Herculaneum, Italy", *Sedimentology*, 49, 2002, pp. 929-953.
27. Gurioli L., Pareschi M.T., Zanella E., Lanza R., Deluca E. and Bisson M., "Interaction of pyroclastic currents with human settlements: Evidences from ancient Pompeii", *Geology*, 33, 2005, pp. 441-444.
28. Gurioli L., Zanella E., Pareschi M.T. and Lanza R., "Influences of urban fabric on pyroclastic density currents at Pompeii: 1 Flow direction and deposition", *Journal Geophysical Research*, 11, 2007.
29. Johannosky W., "Terrae Motus: un'iscrizione nucerina relativa al restauro del Teatro", in Livadiè C. (Ed.), *Tremblements de Terre eruptions volcanique et vie des hommes dans la Campanie antique*, Naples, Centre Jean Berard, 1986, pp. 91-93.
30. Lirer L., Pescatore T., Booth B. and Walker G.P.L., "Two plinian pumice-fall deposits from Somma-Vesuvius, Italy", *Geological Society American Bulletin*, 84, 1973, pp. 759-772.
31. Lirer L., Vinci A., Alberico I., Gifuni T., Bellucci F., Petrosino P. and Tinteri R., "Occurrence of intereruption hyperconcentrated flood flow deposits on Vesuvio", *Sedimentary Geology*, 139, 2, 2001, pp. 151-167.
32. Luongo G., Perrotta A., Scarpati C., De Carolis E., Patricelli G. and Ciarallo A., "Impact of 79 AD explosive eruption on Pompeii II: causes of death of the inhabitants inferred by stratigraphical and areal distribution of the human corpses", *Journal of Volcanology and Geothermal Research*, 126, 2003, pp. 169-200.
33. Macedonio G., Pareschi M.T. and Santacroce R., "A numerical simulation of the Plinian fall phase of 79 A.D. eruption of Vesuvius", *Journal of Geophysical Research*, 93, 14, 1988, pp. 14817-14827.
34. Mastrolorenzo G., Petrone P.P., Pagano M., Incoronato A., Baxter P.J., Canzanella A. and Fattore L., "Herculaneum victims of Vesuvius in AD 79", *Nature*, 410, 2001, p. 769.
35. Mori J., White R., Harlow D., Okubo P., Power J., Hoblitt R., Laguerta E., Lanuza L. and Bautista B., "Volcanic earthquakes following the 1991 climactic eruption of Mount Pinatubo, Philippines: Strong seismicity during a waning eruption", Newhall C. and Punongbayan R. (Eds.), *Fire and Mud:*

Eruptions and Lahars of Mount Pinatubo, Philippines, Seattle, University of Washington Press, 1996, pp. 339-350.

36. Orlandi G., La cinquantesima bellissima relazione e di quanto è succeduto insino ad oggi, Naples, *Scoriggio Lazzaro*, 1632.
37. Paci G., "Tito a Salerno, Epigrafia", *Actes du colloque international d'épigraphie latine en mémoire de Attilio Degrassi pour le centenaire de sa naissance. Actes de colloque de Rome*, École Française de Rome, 1991, pp. 691-704.
38. Renna E., *Vesuvius Mons*, Naples, Procaccini, 1992.
39. Ricciardi P., *Diario del Monte Vesuvio*, Edizioni Scientifiche Artistiche, 2009.
40. Rosi M., Principe C. and Vecci R., "The 1631 Vesuvius eruption. A reconstruction based on historical and stratigraphical data", *Journal of Volcanology and Geothermal Research*, 58, 1993, pp. 151-182.
41. Sanpaolo V., "Dati Archeologici e fenomeni vulcanici nell'area nolana. Nota preliminare", in Livadiè C. (Ed.), *Tremblements de Terre eruptions volcanique et vie des hommes dans la Campanie antique*, Naples, Centre Jean Berard, 1986, pp. 113-119.
42. Santacroce R., "L'eruzione del Vesuvio del 79 d.C. e la distruzione di Ercolano e Pompei", 2018, www.vesuvioweb.com.
43. Scandone R. and Acocella V., "Control of the aspect ratio of the chamber roof on caldera formation during silicic eruptions", *Geophysical Research Letters*, 34, 2007.
44. Scandone R. and Giacomelli L., "Il Risveglio dei Vulcani Esplosivi", *Le Scienze*, 386, 2000, pp. 90-96.
45. Scandone R. and Giacomelli L., "The Slow boiling of magma chambers and the dynamics of explosive eruptions", *Journal of Volcanology Geothermal Research*, 110, 2001, pp. 121-136.
46. Scandone R. and Malone S.D., "Magma supply, magma discharge and readjustment of the feeding system of Mount St. Helens during 1980", *Journal of Volcanology Geothermal Research*, 23, 1985, pp. 239-252.
47. Schiffman L., Volcanic Fury Overwhelms Indonesia, 2011, https://www.popsci.com/science/.
48. Sheridan M.F., Barberi F., Rosi M. and Santacroce R., "A Model of plinian eruptions of Vesuvius", *Nature*, 289, 1981, pp 282-285.
49. Sigurdsson H., Carey S., Cornell W. and Pescatore T., "The eruption of Vesuvius in A.D. 79", *National Geographic Research*, 1, 1985, pp. 332-387.
50. Sigurdsson H., Cashdollar S. and Sparks R.S.J., "The eruption of Vesuvius in AD 79: Reconstruction from historical and volcanological evidence", *American Journal of Archaeology*, 86, 1982, pp. 39-51.
51. Slater D.A., *The Silvae of Statius*, Oxford, Clarendon Press, 1908.
52. Stefani G., "La vera data dell'eruzione", *Archeo*, 10, 260, 2006, pp. 10-13.
53. Stefani G. and Borgongino M., "Ancora sulla Data dell'eruzione", *Rivista di Studi Pompeiani*, 18, 2007, pp. 204-206.
54. Taylor G.A.M., "The 1951 eruption of Mt Lamington", *Bureau of Mineral Resources, Geology & Geophysics, Bulletin*, 38, 1958.
55. Tuck S.L. "Harbors of Refuge: Post-Vesuvian Population Shifts in Italian Harbor Communities", in Petersen J.H. and Bargfeldt N. (Eds.), *Reflections. Harbour City Deathscapes in Roman Italy and Beyond*, Analecta Romana Instituti Danici, 2019.
56. Wolfe E.W. and Hoblitt R.P., "Overview of the Eruptions", in Newhall C.G. and Punongbayan R.S. (Eds.), *Fire and Mud*, Seattle, University of Washington Press, 1996, pp. 3-20.

Appendix

Letters of Pliny the Younger (Epistulae VI, 16, 20)

The first letter and the Fate of Pliny the Elder

My uncle was stationed at Misenum, where he was in active command of the fleet, with full powers. On the 24th of August, about the seventh hour, my mother drew his attention to the fact that a cloud of unusual size and shape had made its appearance. He had been out in the sun, followed by a cold bath, and after a light meal he was lying down and reading. Yet he called for his sandals and climbed up to a spot from which he could command a good view of the curious phenomenon. Those who were looking at the cloud from some distance could not make out from which mountain it was rising – it was afterwards discovered to have been Mount Vesuvius – but in likeness and form it more closely resembled a pine-tree than anything else, for what corresponded to the trunk was of great length and height, and then spread out into a number of branches, the reason being, I imagine, that while the vapour was fresh, the cloud was borne upwards, but when the vapour became wasted, it lost its motion, or even became dissipated by its own weight, and spread out laterally. At times it looked white, and at other times dirty and spotted, according to the quantity of earth and cinders that were shot up […]. He ordered a Liburnian galley to be got ready […]. He was just leaving the house when he received a written message from Rectina, the wife of Tascus, who was terrified at the peril threatening her - for her villa lay just beneath the mountain, and there were no means of escape save by shipboard – begging him to save her from her perilous position. So, he changed his plans, and carried out with the greatest fortitude the task, which he had started as a scholarly inquiry.

He had the galleys launched and went on board himself, in the hope of succouring, not only Rectina, but many others, for there were a number of people living along the shore owing to its delightful situation. He hastened, therefore, towards the place whence others were fleeing, and steering a direct course, kept the helm straight for the point of danger, so utterly devoid of fear that every movement of the looming portent and every change in its appearance he described and had noted down by his secretary, as soon as his eyes detected it. Already ashes were beginning to fall upon the ships, hotter and in thicker showers as they approached more nearly, with pumice-stones and black flints, charred and cracked by the heat of the flames, while their way was barred by the sudden shoaling of the sea bottom and the litter of the mountain on the shore. He hesitated for a moment whether to turn back, and then, when the helmsman warned him to do so, he exclaimed, "Fortune favours the bold; try to reach Pomponianus". The latter was at Stabiae, separated by the whole width of the bay, for the sea there pours in upon a gently rounded and curving shore. Although the danger was not yet close upon him, it was none the less clearly seen, and it travelled quickly as it came nearer, so Pomponianus had got his baggage together on shipboard, and had determined upon flight, and was waiting for the wind which was blowing on shore to fall. My uncle sailed in with the wind fair behind him, and embraced Pomponianus, who was in a state of fright, comforting and cheering him at the same time. […]. [Figure 3].

In the meantime, broad sheets of flame, which rose high in the air, were breaking out in a number of places on Mount Vesuvius and lighting up the sky, and the glare and brightness seemed all the more striking owing to the darkness of the night. My uncle, in order to allay the fear of his companions, kept declaring that the country people in their terror had left their fires burning, and that the conflagration they saw arose from the blazing and empty villas. Then he betook himself to rest and enjoyed a very deep sleep […]. But by this time the courtyard leading to the room he occupied was so full of ashes and pumice-stones mingled together, and covered to such a depth, that if he had delayed any longer in the bedchamber there would have been no means of escape. So, my uncle was aroused, and came out and joined Pomponianus and the rest who had been keeping watch. They held a consultation whether they should remain indoors or wander forth in the open; for the buildings were beginning to shake with the repeated and intensely severe shocks of earthquake and seemed to be rocking to and from as though they had been torn from their foundations. Outside again there was danger to be apprehended from the pumice-stones, though these were light and nearly burnt through, and thus, after weighing the two perils, the latter course was determined upon. With my uncle it

was a choice of reasons which prevailed, with the rest a choice of fears.

They placed pillows on their heads and secured them with cloths, as a precaution against the falling bodies. Elsewhere the day had dawned by this time, but there it was still night, and the darkness was blacker and thicker than any ordinary night. This, however, they relieved as best they could by a number of torches and other kinds of lights. They decided to make their way to the shore, and to see from the nearest point whether the sea would enable them to put out, but it was still running high and contrary. A sheet was spread on the ground, and on this my uncle lay, and twice he called for a draught of cold water, which he drank. Then the flames, and the smell of sulphur which gave warning of them, scattered the others in flight and roused him. Leaning on two slaves, he rose to his feet and immediately fell down again, owing, as I think, to his breathing being obstructed by the thickness of the fumes and congestion of the stomach, that organ being naturally weak and narrow, and subject to inflammation. When daylight returned – two days after the last day he had seen – his body was found untouched, uninjured, and covered, dressed just as he had been in life. The corpse suggested a person asleep rather than a dead man.

The second letter and the behavior of Pliny the Younger at Misenum.

After my uncle had set out, I employed the remainder of the time with my studies, for I had stayed behind for that very purpose. Afterwards I had a bath, dined, and then took a brief and restless sleep. For many days previous there had been slight shocks of earthquake, which were not particularly alarming, because they are common enough in Campania. But on that night the shocks were so intense that everything, round us, seemed not only to be disturbed, but to be tottering to its fall. My mother rushed into my bedchamber, just as I myself was getting up in order to arouse her if she was still sleeping. We sat down in the courtyard of the house, which was of smallish size and lay between the sea and the buildings […]. It was now the first hour of the day, but the light was still faint and weak. The buildings all round us were beginning to totter, and, though we were in the open, the courtyard was so narrow that we were greatly afraid, and indeed sure of being overwhelmed by their fall. So that decided us to leave the town. We were followed by a distracted crowd, which, when in a panic, always prefers someone else's judgment to its own as the most prudent course to adopt, and when we set out these people came crowding in masses upon us, and pressed, and urged us forward. We came to a halt when we had passed beyond the buildings and underwent there many wonderful experiences and terrors. For although the ground was perfectly level, the vehicles which we had ordered to be brought with us began to sway to and from, and though they were wedged with stones, we could not keep them still in their places. Moreover, we saw the sea drawn back upon itself, and, as it were, repelled by the quaking of the earth. The shore certainly was greatly widened, and many marine creatures were stranded on the dry sands. On the other side, the black, fearsome cloud of fiery vapour burst into long, twisting, zigzag flames and gaped asunder, the flames resembling lightning flashes, only they were of greater size. […].

Soon afterwards the cloud descended upon the earth and covered the whole bay; it encircled Capri and hid it from sight, and we could no longer see the promontory of Misenum. […]. Then the ashes began to fall, but not thickly: I looked back, and a dense blackness was rolling up behind us, which spread itself over the ground and followed like a torrent. "Let us turn aside," I said, "while we can still see, lest we be thrown down in the road and trampled on in the darkness by the thronging crowd." We were considering what to do, when the blackness of night overtook us, not that of a moonless or cloudy night, but the blackness of pent-up places which never see the light. […].

A gleam of light now appeared, which seemed to us not so much daylight as a token of the approaching fire. The latter remained at a distance, but the darkness came on again, and the ashes once more fell thickly and heavily. We had to keep rising and shaking the latter off us, or we should have been buried by them and crushed by their weight. […]. At length the blackness became less dense and dissipated as it were into smoke and cloud; then came the real light of day, and the sun shone out, but as blood red as it appears at its setting. Our still trembling eyes saw that everything had been transformed, and covered with a deep layer of ashes, like snow. Making our way back to Misenum, we refreshed our bodies as best we could, and passed an anxious, troubled night, hovering between hope and fear. But our fears

were uppermost, for the shocks of earthquake still continued, and several persons, driven frantic by dreadful prophecies, made sport of their own calamities and those of others. For our own part, though we had already passed through perils, and expected still more to come, we had no idea even then of leaving the town until we got news of my uncle.

