The Herculaneum victims of the 79 AD Vesuvius eruption: a review

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Summary - *The scientific study of the victims of the 79 AD Vesuvius eruption began with the first discovery in the 1980s of hundreds of skeletons of people who had taken refuge in the suburban area of Herculaneum. Hundreds of human victims were found crowding the beach and a series of waterfront chambers, fixated into a final posture by the first of the deadly incoming pyroclastic currents. The towns of Herculaneum, Pompeii and other Roman settlements up to 20 kilometers away were suddenly hit and overwhelmed by successive ash-avalanches, fast moving clouds of hot volcanic ash and gases known as pyroclastic surges, capable of killing all residents who were not yet evacuated. Given the impossibility of access to the skeletal remains of the Pompeiians locked within the plaster casts and the sparse occasional finds of victims elsewhere, most of the anthropological studies focused on the victims discovered in Herculaneum. The first investigations were carried out to detect the biological and pathological features of these people. More recent multidisciplinary studies on the victims' skeletons and their volcanological context shed light on the dynamic impacts of the 79 AD Plinian eruption on the area around the volcano and on its inhabitants. The effects of the high temperatures of the surges as suffered by the remaining resident population were revealed, with crucial implications for the present-day risk of a similar outcome to around three million people living close to the volcano, including metropolitan Naples.*

Keywords - *79 AD Vesuvius eruption, Herculaneum victims, Pompeii plaster casts, Bioanthropology, Taphonomy.*

Introduction

The Roman towns and their inhabitants buried by the 79 AD eruption of Vesuvius represent an anthropological, archaeological and historical heritage that is unmatched in the world. The first of the buildings to be uncovered in the excavations was the theatre in Herculaneum in 1710. A whole urban settlement, including its remaining doomed inhabitants, was gradually revealed as to how it was buried, at the time of the catastrophe and then preserved for almost two millennia under volcanic deposits (Gore & Mazzatenta, 1984; Pappalardo, 1990; Budetta, 1993, 1996; Pagano, 2000; Pirozzi, 2000; Guzzo & Guidobaldi, 2005).

The remarkable state of preservation was achieved through rapid burial by volcanic deposits tens of meters thick. Buildings are often preserved up to the second floor, as well as wooden furniture, frescoes, mosaics, statues, pitchers and other bronze objects. Even organic matter is preserved better than almost anywhere else in the ancient world: bread, olives, fish remains, grains, as well as fresh and dried fruit such as figs, dates, pomegranates, walnuts, almonds. But - above all - the most exceptional discovery of the last few decades has been the victims' bodies, found in great number in the suburban area (Fig. 1).

In the mid-1800s, the making of the first casts by filling the cavities identified in the ash deposit in Pompeii with liquid plaster of Paris (Stefani, 2010), a method already tested on the remains of furniture (Garcia, 2006), was to be only the beginning of a series of discoveries of human victims which would resonate both in Italy and later worldwide (Osanna, 2016).

The discovery of more or less well-preserved archaeological structures of Roman age has never been a novelty in Italy, but the integral preservation of an entire town, including aspects of daily life, private houses and public buildings, and

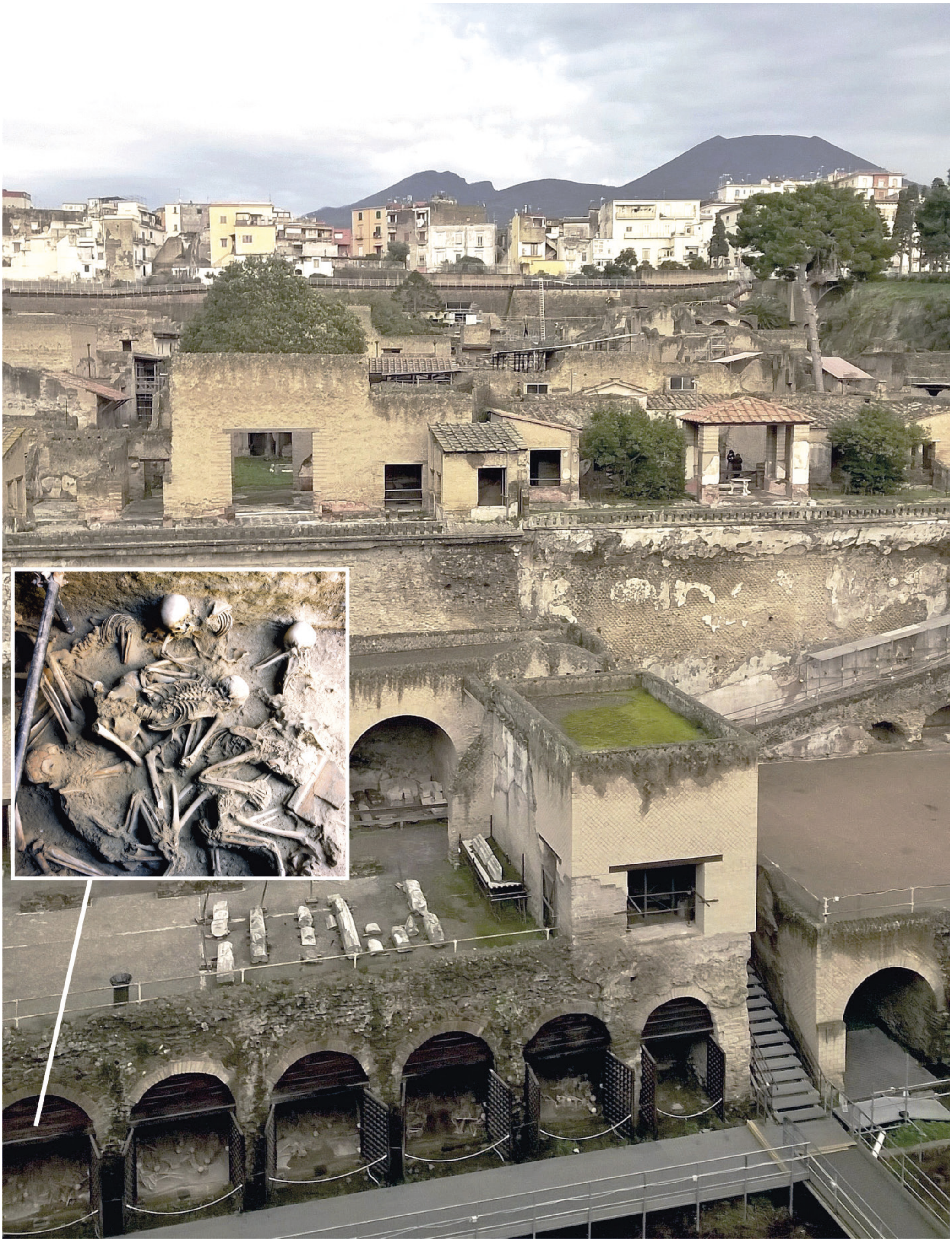

Fig. 1 - Present-day view of the Herculaneum archaeological site. The waterfront chambers, filled with fiberglass casts of the victims discovered in the 1980s and 1990s. In the box, the original skeletons in situ, before the excavation started. The colour version of this figure is available at the JASs website.

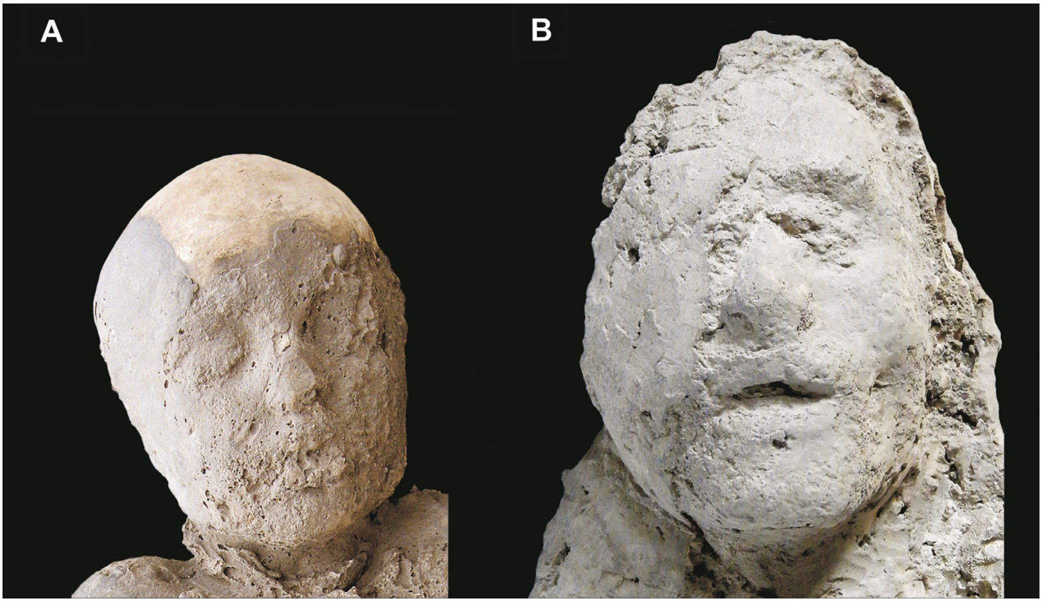

Fig. 2 - Victims found in the "Garden of fugitives" in Pompeii. A. The face of a child (cast no. 23, male); B. The incomplete physiognomy shown by this plaster cast is the result of partial immersion of the victim in the pumice deposit underneath the layer of volcanic ash covering the victim's corpse. Only the part of the body placed in the ash deposit allows the formation of a hollow cavity after the slowly decay of soft tissues: therefore, the cast was obtained by filling the empty space with plaster (cast no. 67, male, adult). The colour version of this figure is available at the JASs website.

even the finding of its dead bodies is an absolute *unicum*. The first discovery in the 1980s and, later, in the 1990s of hundreds of victims inside a number of chambers on what used to be the ancient seafront of Herculaneum (Pagano, 2003a) proved to be of extraordinary value not only for historical and archaeological reconstructions, but also for the scientific studies that have arisen on the devastating consequences for a whole population struck by a sudden natural catastrophe (Sigurdsson *et al.*, 1982, 1985; Capasso, 2000a; Mastrolorenzo *et al.*, 2001a; Giacomelli *et al.*, 2003; Luongo *et al.*, 2003a,b; Mastrolorenzo *et al.*, 2004).

As a result of a particular dynamic of the eruption that caused different effects depending on the distance from the volcano, the victims found in the deposits of ash which accumulated during the devastating secondary phase (surge and flow pyroclastic currents) have additional uniqueness. This is represented by the opportunity to permanently fix individual features by filling with plaster the body imprints impressed in the volcanic ash deposit which had cooled and hardened around the victims' corpses (Stefani, 2010). Thanks to these exceptional discoveries the bodies of men, women and children have been preserved in their physical integrity and physiognomy, including the folds of the clothing they wore, or their personal belongings. Yet, above all, we can appreciate their faces bearing the expression of the last instant before death (Fig. 2), which we know today to have been instantaneous (Mastrolorenzo *et al.*, 2010; Petrone *et al.*, 2018).

Background

The study of the victims of past natural disasters is able to influence the perspectives of anthropological studies and analysis (Petrone, 2011a, 2019). The human remains found in the Roman towns buried in AD 79 by the Plinian eruption of the Somma-Vesuvius complex are clear evidence of this. Field investigations and studies in situ and in the laboratory of what we can call "living fossils" for some years have allowed scholars to acquire information of absolute novelty and value both from a historical and scientific standpoint, depending on the type of approach and method of study adopted. This "field laboratory" has developed into a paleo-forensic and bio-archaeological investigation of a mass volcanic catastrophe (Petrone & Fedele, 2002; Petrone, 2011b; Petrone *et al.*, 2014). Field and laboratory research carried out initially on the victims of Herculaneum (Mastrolorenzo *et al.*, 2001a) was later extended to the victims found in the surge deposits in Pompeii (plaster casts), and those discovered in the Villa B of Oplontis (Mastrolorenzo *et al.*, 2010). More recent research finally revealed in detail the heat effects suffered by the victims and the cause of death in Herculaneum (Petrone *et al.*, 2018).

The multidisciplinary analysis based on the taphonomic and bio-anthropological study of skeletal remains in their original context, alongside the archaeological and geological investigations concerning the relationships between human remains, personal objects and volcanic ash deposits, proved to be fundamental for a new interpretation of events that occurred in each eruptive phase at gradually increasing distances from the volcano. This approach provided alternative new hypotheses on the effects of the eruption on people and structures, and, ultimately, the causes of death of the resident population in the towns of Herculaneum and Pompeii, as well as in several villas and suburban settlements up to a distance of 20 kilometers away from the volcano (Petrone *et al.*, 1999; Mastrolorenzo & Petrone, 2000; Mastrolorenzo *et al.*, 2001a,b,c; Petrone, 2002; Mastrolorenzo *et al.*, 2002; Giacomelli *et al.*, 2003; Luongo *et al.*, 2003b; De Natale *et al.*, 2004; Petrone, 2005; Petrone & Pagano, 2005; Petrone, 2007; Lazer, 2008; Petrone *et al.*, 2018).

Volcanological context

Somma-Vesuvius is an active volcano, one of the most dangerous on Earth. Almost three million people live nearby in metropolitan Naples and surroundings, in the area immediately threatened by possible future eruptions (Mastrolorenzo *et al.*, 2006; Barberi *et al.*, 2007; Baxter *et al.*, 2008; Neri *et al.*, 2008; Marzocchi Woo, 2009; Linde *et al.*, 2017). The eruptive history of Vesuvius based on stratigraphic evidence shows that the volcano tends to have on average a great eruption approximately every 2,000 years (Sheridan *et al.*, 1981; EOS NASA, 2006; Lockwood & Hazlett, 2010).

In AD 79 a sudden Plinian event with volcanic pumice fallout and subsequent ash-avalanches caused total devastation and thousands of victims over an extensive area (Sigurdsson *et al.*, 1985; Mastrolorenzo *et al.*, 2004). The initial fallout phase was dispersed south and south east of Vesuvius up to a distance of tens of kilometers (Barberi *et al.*, 1990). The later pyroclastic surges and flows (rapid gravity-driven currents of volcanic ash and hot gases generated by the collapse of the Plinian eruptive column) reached up to 30 kilometers west, southwest and south from the vent (Sigurdsson *et al.*, 1982, 1985; Mastrolorenzo *et al.*, 2006).

In the early eruptive phase the first fatalities occurred in Pompeii as a result of roofs and floors collapsing due to pumice accumulation (Giacomelli *et al.*, 2003; Luongo *et al.*, 2003a). In the next hours, the inhabitants of Herculaneum (Maiuri, 1958a, 1977) and Pompeii (Maiuri, 1958b; Luongo *et al.*, 2003b), as well as those from nearby settlements and villas (e.g. Villa B at Oplontis) (Fergola, 2003; Nunziante *et al.*, 2003; Thomas, 2015), who did not escape in time, were overwhelmed by a series of hot surge clouds (Dobran *et al.*, 1994; De Carolis & Patricelli, 2013).

At Herculaneum, about 350 people who had taken refuge in 12 waterfront chambers (Fig. 3) were suddenly engulfed by the abrupt collapse of the rapidly advancing first pyroclastic surge (Sigurdsson *et al.*, 1982). In just a few hours the towns of Herculaneum, Pompeii and Stabiae, situated respectively about 6, 10 and 16 kilometers

Fig. 3 - The seafront area of Herculaneum. Representation of the human victims discovered on the beach and inside the waterfront chambers (1990s excavations).

from the volcano, were completely buried by subsequent pyroclastic currents (Sigurdsson *et al.*, 1985), whose eruptive deposits reached a maximum thickness of 20 meters in Herculaneum (Sigurdsson *et al.*, 1982; Mastrolorenzo *et al.*, 2004). The archaeological investigations of the last three centuries has brought to light several Roman settlements and hundreds of human victims, even at a distance of 20 kilometers as far as Stabiae and suburban villas in Gragnano nearby (Ruggiero, 1881; De Carolis *et al.*, 2003; De Carolis & Patricelli, 2013).

Recent global eruptions show that pyroclastic density currents are the dominant hazard in densely populated areas (Baxter, 1990; Druitt, 1998; Hansell *et al.*, 2006; Baxter *et al.*, 2005, 2008; Auker *et al.*, 2013). Dilute pyroclastic density currents (PDCs) or surges are typically intensely hot (200-500 °C) fast-moving clouds (100 to 300 km/hr) of fine ash, in an environment low in free oxygen content and rich in superheated steam and other volcanic gases (Sigurdsson *et al.*, 1985; Baxter, 1990). In such conditions survival is likely to be impossible, particularly in areas closer to the vent (Baxter *et al.*, 2017). In PDCs, thermal injury may be at least as important as asphyxia in causing immediate death (Baxter, 1990).

In the main proximal body of a surge the temperature may be as high as 400-500°C, but with temperatures of 200-300°C being more common in distal regions (Baxter, 1990; Baxter *et al.*, 2017). These temperatures are analogous to those of the 79 AD pyroclastic surges that hit first Herculaneum, at the foot of the volcano, and later Pompeii, as determined with various methods, including thermoremanent magnetization (TRM) on lithic clasts (Kent *et al.*, 1981; Incoronato *et al.*, 1997; Cioni *et al.*, 2004; Giordano *et al.*, 2018), bone analysis vs heating experiments (Mastrolorenzo *et al.*, 2010), and charcoal reflectance (Caricchi *et al.*, 2014).

Pyroclastic surges are responsible for emplacement of the largest widespread ash deposit in the suburban area of Herculaneum (Sigurdsson *et al.*,1982, 1985). Rapid deposition of extremely fine-grained ash into thermally stratified volcanic deposit (Sparks *et al.*, 1976) on the beach and within the waterfront chambers, and abrupt entrapment and burial of the victims' corpses by the hot ash surge (Sigurdsson *et al.*,1982, 1985) could have protected them from being altered by diagenetic processes (Allison *et al.*, 1991), thus resulting in the exceptional preservation of fully articulated skeletons (Baxter, 1990; Petrone, 2011a; Petrone *et al.*, 2018).

The date of the eruption

The date of the Plinian event of 79 AD has long been debated. The controversy was recently reawakened following the discovery of a charcoal writing on the wall of a room of the "House with

Garden" in Pompeii, which refers to the date of October 17 (sixteen days before the Calends of November), but without any specific indication of the year (ANSA.it, 2018).

There are several interpretations of literary sources. The date of August 24th - which has always been the most accredited - refers to that indicated in the letter of Pliny the Younger (nephew of Pliny the Elder, admiral of the Roman fleet based in Misenum) to Tacitus. However, medieval transcripts of Pliny's letter report several different dates, such as 1st and 23rd November, and also October 30th and 24th (Pappalardo, 2019). The latter came back particularly in vogue after the recent discovery of the wall inscription mentioned previously. The date of October 24th would seem plausible, also considering the interpretation of a coin found in the "House of the Golden Bracelet", and two epigraphic testimonies (Stefani, 2006; Rolandi *et al.*, 2007). The autumn date would also be confirmed by other archaeological finds, such as the discovery of wine amphorae presumably used for fermentation and fall-ripening fruits such as figs, pomegranates, dates, plums, chestnuts and grapes (Borgongino & Stefani, 2002; Pappalardo, 2019).

Interestingly, during a recent survey of the victims' skeletal remains from Herculaneum made by the author (P.P.), a fair number of charred remains of grape seeds and chewed grape berries were found. The presence of both grape seeds and berries may well be considered as the remains of a fleeting meal, even if in the absence of more detailed analyses it is not possible to exclude they were raisins.

Historical and archaeo-anthropological context

The first discovery of human victims of the eruption dates back to the early Bourbon excavations reported by the Spanish military engineer Alcubierre, just one year after the exploration of Herculaneum using tunnels, and is dated 18 November 1739 (Ruggiero, 1885). In 1831 the first victim was discovered in open-air excavations, in a room on the first floor of the House of the Skeleton (Ruggiero, 1885), followed in 1932 by six victims found in the *apodyterium* of the men's sector of the Central Baths (Pagano, 2003b). In all, in Herculaneum, the 18th century excavations of the tunnels have uncovered 12 victims, followed by seven other corpses in the open pit excavations during the following century, and 19 around the middle of the 20th century, the latter during investigations led by Amedeo Maiuri, erstwhile director of the archaeological site (De Carolis & Patricelli, 2013).

The first finding of victims in Pompeii dates back to 1766, whose discovery aroused considerable sensation, and was followed by the 34 bodies brought to light two years later, the largest group of victims hitherto discovered (De Carolis *et al.*, 1998). But only in 1863 were the features of a human body first set in a plaster cast, a new technique adopted in Pompeii by Giuseppe Fiorelli, archaeologist and director of the excavations (Stefani, 2010). Since then, at least 1,300 bodies of victims have been found in the town (De Carolis *et al.*, 1998). For at least two centuries the history of the last minutes of life and the death of the inhabitants of the cities and the villas located at the foot of Vesuvius was based on the assumption that all the residents at the time of the eruption had died of slow asphyxiation due to the inhalation of lethal gases. The evidence for such a mode of dying lay in the protective attitude of the victims, as the postures of many casts seemed to testify (Maiuri, 1961; Baxter, 1990).

In Herculaneum, a new campaign of excavations started at the beginning of the 1980s (Pagano, 2003a; Guidobaldi, 2007). After removing huge amounts of tuff deposits, the seafront area of the town was reached, leading to the exceptional discovery of a number of human skeletons. On the beach and in five of the 12 waterfront chambers some 150 victims of the eruption were uncovered, buried by volcanic debris (Gore & Mazzatenta, 1984; Bisel, 1987). These skeletons, initially removed from the ash deposit and studied by Sara Bisel (Bisel,

Fig. 4 - Fiberglass cast of victims. A group of victims found during archaeological investigations in the 1990s. At the bottom left, a young pregnant woman leaning back against the tuff wall, with an adult male and three children next to her (Herculaneum, chamber no. 11). The colour version of this figure is available at the JASs website.

1986, 1987, 1988, 1991), were the subject of several bioanthropological studies (Torino *et al.*, 1995; Capasso & Di Domenicantonio 1998; Capasso L. & Di Tota, 1998; Capasso, 1999; Capasso & Capasso, 1999; Capasso, 2000a,b; Capasso *et al.*, 2000; Torino & Fornaciari, 2000; Capasso, 2001, 2002; Chiummo, 2002; Geraci *et al.*, 2002; Guarino, 2002; Ottini *et al.*, 2002; Petrone *et al.*, 2002a, b; Capasso, 2007; Schmidt *et al.*, 2015). Further archaeological investigations conducted in the early 1990s in the other chambers brought to light an additional large group of human victims, left untouched within the ash surge deposit (Budetta, 1993). These human remains were the subject of an enhancement project based on a new approach (Petrone, 2011a, 2019), aimed at enhancing this exceptional archaeological and anthropological context through the making of casts from glass fibre (Pagano, 1999; Arzarello *et al.*, 2000; Petrone, 2002; Pagano, 2003a; Petrone, 2005; Guidobaldi, 2007). After archaeological investigation and final recovery of these victims' skeletons by the author (P.P.) from 1997 to 1999 (Petrone & Fedele, 2002; Pagano, 2003a; Petrone, 2019), casts of victims were finally placed in the original context of discovery as they appear today at the site (www.madeinpompei.it, 2018) (Fig. 4).

In approximately two decades some 350 human skeletons, those of two horses and a dog, alongside a boat and dozens of coins and gold, silver, bronze and glass personal objects have been brought to light (Franchi Dell'Orto, 1993; Pagano, 2000; D'Ambrosio *et al.*, 2003). After the discovery of this thriving Roman port city, with its ruined houses almost entirely preserved from the rapid burial by eruptive products, and of some victims found scattered inside buildings, the scenario of the disaster was finally complete. In a few hours the catastrophic volcanic event had completely buried the towns of Herculaneum and Pompeii, and most of the settlements and villas in nearby Vesuvius (Sigurdsson *et al.*, 1985), causing thousands of casualties (Mastrolorenzo *et al.*, 2010; Petrone *et al.*, 2018).

The joint bioarchaeological and taphonomic study of the skeletons prior to their removal allowed the investigators to verify the interactions between victims' bodies and the volcanic ash deposit (Mastrolorenzo *et al.*, 2001a, 2010; Petrone, 2011; Petrone *et al.*, 2014). The resulting site evidence combined with new data from most recent laboratory bones analysis provided key information on the heat-induced effects on people (Petrone *et al.*, 2018). Bioanthropological and paleopathological studies were also carried out on the same skeletal sample (Petrone *et al.*, 2011, 2013; Guarino *et al.*, 2017; Martyn *et al.*, 2018; Petrone *et al.*, 2019).

Bioarchaeological and taphonomic study

Because of their uniqueness, the human remains from Herculaneum, exceptionally preserved over time, have been considered "time capsules", capable of unveiling the details of an unexpected and sudden catastrophe (Petrone, 2011a, 2019). During a new campaign of excavation which started in June 1997 on behalf of the Superintendent of Pompeii, two years of site investigation identified key information on the direct and indirect effects caused by the surge on people, and the way they died. Particular attention was given to the relationship between archaeological stratigraphy, human remains and volcanic deposit, by means of a multidisciplinary survey (Mastrolorenzo *et al.*, 2001b, 2010; Petrone *et al.*, 2018).

Unlike previous investigators, the idea was to answer questions, such as: what made the integral preservation of victims' postures and skeletal joints possible? What mechanism could explain the floating of bodies within the ash bed deposit? Or why did so many skeletons show cracking of skulls and long bones, or contracted hands and feet? What were those reddish residues found on the bones and in the ash filling the skulls, or impregnating the ash deposit in which the bodies were buried? And finally, how could the vital attitude of the victims be explained? All of these questions were answered by site and laboratory investigation, as summarized below.

The posture of the victims, of particular importance for a reconstruction of the taphonomic processes related to the rapid deposition of the volcanic products, proved to be essential to assess the causes of death of people at Herculaneum by engulfment from hot pyroclastic flows. The overall evidence showed for the first surge an extremely high temperature, estimated to be at least 500 °C, hot enough to cause instant death of the inhabitants(Mastrolorenzo *et al.*, 2001a). We hypothesize that the exudation of boiling blood from the sagittal venous sinus, testified in some victims' skulls by evidence of heat hematoma, and the increase in pressure resulting from bleeding in the various compartments of the brain caused instantaneous death and the cessation of any vital activity before the victims had time to display a defensive reaction (Petrone *et al.*, 2018). Hands, feet and the whole body underwent an instantaneous thermal-induced muscular contraction, and the positions of their bodies were fixed by the sudden deflation of the ash bed occurring soon after its emplacement (Mastrolorenzo *et al.*, 2010). Their skulls exploded, their bones and teeth broke, and the soft tissues vanished, causing body tissues to be rapidly replaced by the ash (Petrone *et al.*, 2018). The temperature decrease caused the ash bed to cool and harden (Mastrolorenzo *et al.*, 2001a), thus preserving the skeletons in the postures in which they died by the impact with the scorching ash cloud (Mastrolorenzo *et al.*, 2001b; Petrone *et al.*, 2018). The cooling of the ash deposit at Herculaneum does not appear to have lasted long, as reported by Giordano and colleagues (2018), and as has also been recently noted through reflectance of charcoal, which showed a maximum temperature of about 500 °C (Petrone *et al.*, 2019, in press).

With regard to the passage of pyroclastic flows, in Herculaneum, both in the city and in the suburban area, no appreciable evidence of substantial mechanical effects on the victims was detectable. In Pompeii, during the initial phase of pumice fallout, most of those who had sheltered inside the buildings died due to the roofs and floors collapsing (Giacomelli *et al.*, 2003; Luongo *et al.*, 2003a). People outside, mostly walking on the layers of pumice, were instantly killed by the subsequent third and fourth pyroclastic surges, and rapidly covered by volcanic debris - just as had happened a few hours before to the inhabitants of Herculaneum who took refuge within buildings, on the beach and inside the seafront chambers. The evidence shows that all people, once the town was hit by the first scorching ash cloud of the lethal surge, would have died in a fraction of a second, as testified by the corpses' stance as if suspended in the last instant of life (Petrone *et al.*, 2018).

Our study of the heat effects on corpses was later extended to the victims found in the surge deposits in Pompeii and Oplontis. The victims' bodies mostly showed postures preserved in "suspended" actions, most likely indicative of sudden death (Mastrolorenzo *et al.*, 2010). The apparent defensive position seen in the Pompeii victims, repeatedly cited by various scholars in support of a slow death and terrible suffering, was actually due to the fixed flexion of extremities and limbs induced by heat due to protein coagulation and shortening of the muscles around the time of death, a posture known as "pugilistic attitude" (Baxter, 1990) (Fig. 5).

The analysis of the human bodies found in Pompeii revealed further useful information for a better understanding of the effects of the eruption. The faces of the victims are particularly significant, especially in those cases in which the physiognomic features are very well preserved. A radiographic examination carried out by computerized axial tomography (CAT) on a skull belonging to an adult male shows swollen lips (edema) protruding, which reflect the high temperature swelling inside the mouth (Fig. 6). Comparison of the face of another Pompeii victim with that of a young soldier who died in the explosion of a tank in Iraq shows as well common heat-induced features (Fig. 7). Another interesting feature is represented by those individuals covering their mouths with cloths in their last attempt to breathe (Fig. 8). In cases of death by uncomplicated suffocation, the victim is typically found in a relaxed position (Baxter, 1990).

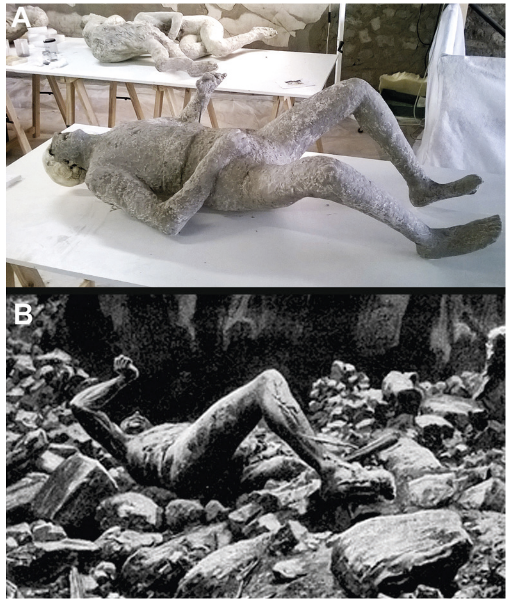

Fig. 5 - "Pugilistic attitude" of victims from historical eruptions. A. Pompeii, 79 AD (Macellum, cast no. 31, male, adult); B. Monte Pelée, 1902 (male, adult). The colour version of this figure is available at the JASs website.

In order to estimate the temperature reached by the lethal pyroclastic surge, we performed macroscopic analyses, optical microscopy, histochemistry and electron microscopy (SEM) of bone samples from the Vesuvian sites. We then compared the data with those from several modern bone samples (human hand phalanx) heated to temperatures from 100° C to 800° C (Mastrolorenzo *et al.*, 2010). The comparison between structural changes detected in the victims' bone and recent bones treated in the laboratory suggested that people were exposed to temperatures of about 500° C in Herculaneum, 600° C in Oplontis and 250°C - 300° C in Pompeii, at 6, 7 and 10 kilometers' distance from the volcano, respectively.

The appearance of vital postures in most of the 79 AD victims suggests that all residents within 10 to 20 kilometers from the volcano

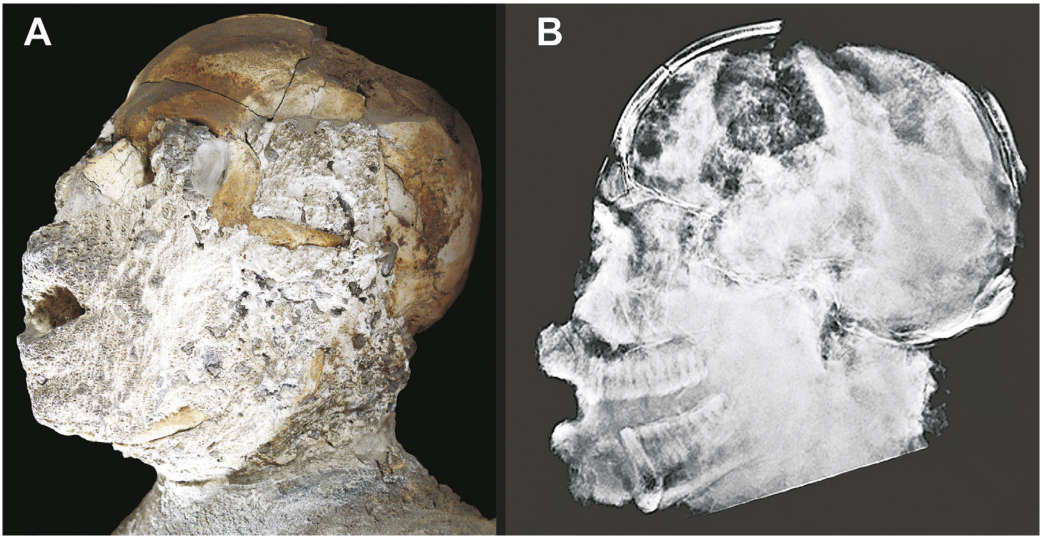

Fig. 6 - Head and skull CT of a victim. A. Face bearing the typical signs of exposure to intense heat; B. Computed Tomography (CT) scan showing strong swelling of the lips and increase in thickness of the soft facial tissues (Pompeii, House of the golden bracelet, plaster cast no. 20, male, adult). The colour version of this figure is available at the JASs website.

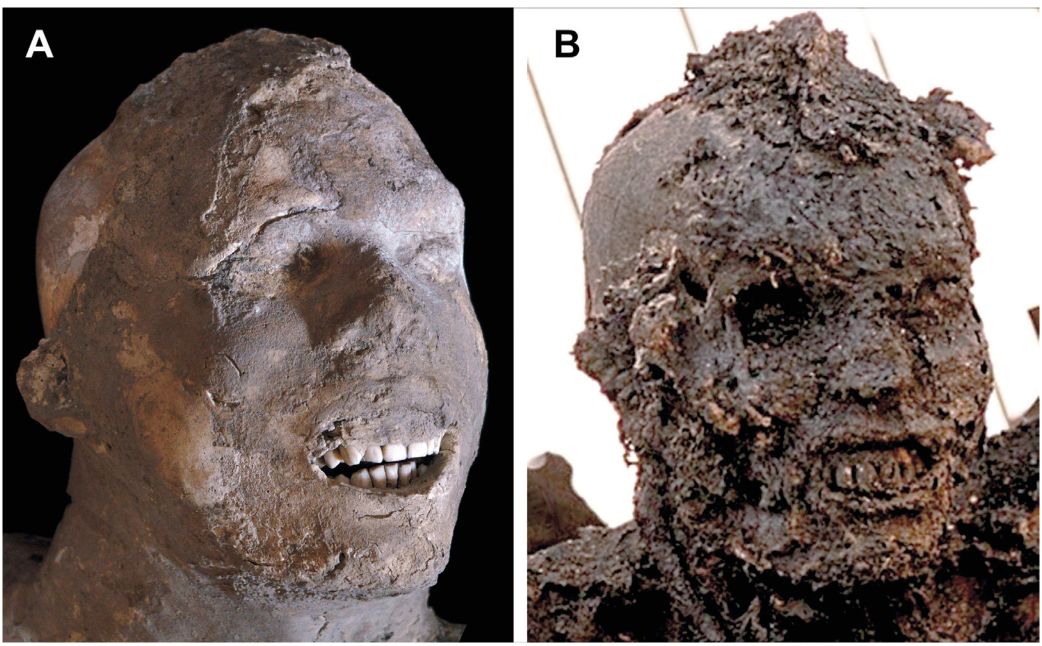

Fig. 7 - Victims exposed to intense heat. A. Face of a 79 AD victim (Pompeii, House of the golden bracelet, plaster cast no. 8, young adult, male); B. Face of a soldier who died in the explosion of a tank in Iraq (young adult, male). The colour version of this figure is available at the JASs website.

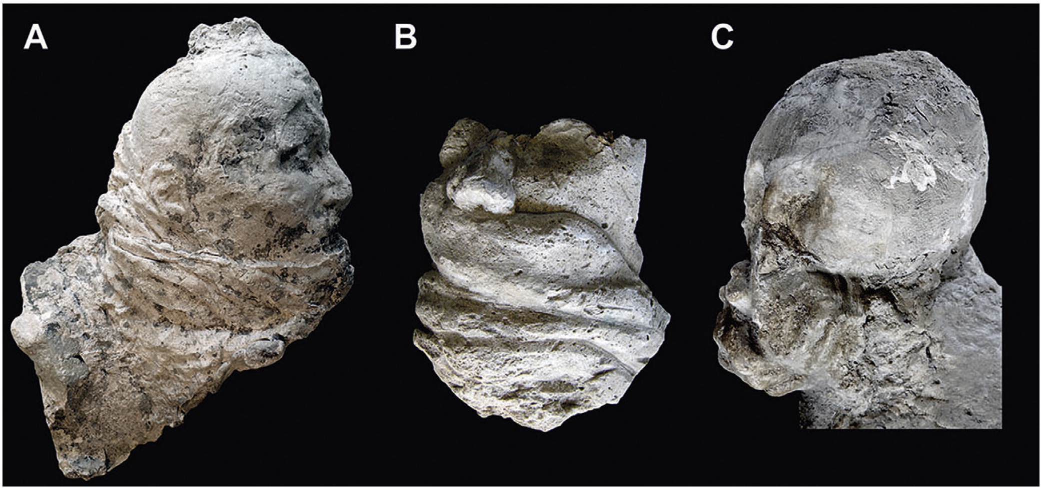

Fig. 8 - Victim postures in the extreme attempt to breathe. A. Villa Regina, Boscoreale, plaster cast no. 80 (woman, adult); B. Thermal baths of Sarno, Pompeii, plaster cast no. 87 (male?, adult); C. House of Marcus Fabius Rufus, Pompeii, plaster cast n. 3 (male, adult). The colour version of this figure is available at the JASs website.

were killed instantly by the pyroclastic currents, including those who had survived the initial fall-out phase of the eruption while sheltering inside buildings, both in Herculaneum and in Pompeii. These results are supported by the study of a previous Plinian eruption that overwhelmed the Campanian plain in the Early Bronze Age (3945 ±10 cal BP, San Paolo Belsito, Naples, South Italy) (Fedele & Petrone, 1999; Sevink *et al.*, 2011). The Avellino pumice event is manifested by exceptional discoveries such as fully preserved villages, with abandoned huts, objects, animals and, above all, human casualties (Fig. 9). Evidence of survival at about 15 kilometers from the volcano is documented by the footprints of thousands of people fleeing in a north-westerly direction during the eruption (Petrone & Fedele, 1996; Mastrolorenzo *et al.*, 2006). The most recent field and laboratory research conducted on the sites buried by the Vesuvius eruptions shows the hazard facing the three million residents in metropolitan Naples and surroundings in the event of a future Plinian eruption (Mastrolorenzo *et al.*, 2006; Hall, 2007; EOS NASA, 2006).

Heat effects and causes of death

The effects of the eruption on the inhabitants of Herculaneum and the other urban settlements close to the volcano have been the subject of several studies (Baxter, 1990; Capasso, 2000a; Mastrolorenzo *et al.*, 2001a,b; Capasso, 2001; Petrone, 2002; De Carolis & Patricelli 2003; Giacomelli *et al.*, 2003; Luongo *et al.*, 2003b; Mastrolorenzo *et al.*, 2004, 2010; Petrone, 2011a; De Carolis & Patricelli, 2013; Petrone *et al.*, 2018). Apart from the casualties of the initial pumice fallout phase by building collapse in Pompeii (De Carolis & Patricelli 2003; Luongo *et al.*, 2003a; De Carolis & Patricelli, 2013), studies on the causes of death mostly refer to the effects of heat associated with the emplacement of pyroclastic surge clouds in both Herculaneum (Capasso, 2000a; Mastrolorenzo *et al.*, 2001b; Hansell *et al.*, 2006; Mastrolorenzo *et al.*, 2010; Petrone *et al.*, 2014, 2018) and Pompeii (Baxter, 1990; Luongo *et al.*, 2003b).

Although hot surges have been mostly accepted as a major cause of mortality in the 79 AD eruption, there are some differences in interpretation

Fig. 9 - Human victim of a protohistoric eruption of Vesuvius. Adult female found in the pumice bed deposit of the Avellino event (3945 ±10 cal BP, Old Bronze Age, San Paolo Belsito, Naples, South Italy). The colour version of this figure is available at the JASs website.

Fig. 10 - Human victims discovered in the seafront area of Herculaneum. Skeletons showing a "life-like" stance: a child (A) (Ind. 41) and young adult male (B) (Ind. 22) unearthed from the ash surge deposit (chamber 10). The child's corpse displays flexure only of the upper limbs, indicative of an incipient "pugilistic attitude". Unlike Pompeii, full exhibit of this heat-induced stance is never found in the victims' corpses at Herculaneum. The colour version of this figure is available at the JASs website.

depending on the distance from the volcano and, within the same site, on the place where victims were found. As regards Herculaneum, more recent studies agree on the instant death of people discovered in the sea shore area (Petrone, 2011a; Schmidt *et al.*, 2015; Petrone *et al.*, 2018), although some authors hypothesized a gradient of heat-induced effects. Thus, even if nearly every skeleton had some evidence of bone thermal exposure (changes in color, charring, fracturing) (Capasso, 2001; Mastrolorenzo *et al.*, 2001a; Shmidt *et al.*, 2015; Petrone *et al.*, 2018), the few victims found on the beach were assumed to show greater thermal effects compared to those sheltering inside the chambers (Capasso, 2000a; Shmidt *et al.*, 2015). Based on the previous assumption, it was also hypothesized that death was instantaneous only for people found on the beach, while those taking refuge in the chambers would have died of asphyxiation (Capasso, 2000a, 2001). However, a comparative analysis of the full skeletal sample has not yet been performed, the victims' samples coming from different excavation surveys (Bisel, 1987, 1991; Petrone, 2002; Petrone *et al.*, 2018) studied and stored separately. With regard to previous interpretations on the causes of death, particularly at a greater distance than in Pompeii, death by asphyxiation in both pumice fallout and pyroclastic surge phases has long remained the most accredited hypothesis (Maiuri, 1961; Giacomelli *et al.*, 2003; Luongo *et al.*, 2003b; De Carolis & Patricelli, 2003).

The latter accounts are at variance with the search for volcanological evidence of PDCs (Sigurdsson *et al.*, 1982, 1985) and a first forensic interpretation concerning the victims found in the surge deposit (Baxter, 1990), as well as with more recent multidisciplinary studies. Taphonomic, bio-anthropological and volcanological site investigations and laboratory evidence (Mastrolorenzo *et al.*, 2001a; Petrone *et al.*, 2018), coupled with results from heating experiments on recent human bone samples (Mastrolorenzo *et al.*, 2010), have shown that Herculaneum's residents were instantly killed by the extremely high temperature of the emplacing first pyroclastic surge, although it had been previously believed that death had occurred by slow suffocation from ash inhalation. Skull and bone charring and cracking, as well as instant hand and foot contraction (flexor reflex by the nociceptive C fibers) (LaMotte & Campbell, 1978) and spine hyperextension, have been described as thermally induced major effects on the victims' skeletons unearthed from both the beach and the sea-front chambers (Capasso, 2000a, 2001; Mastrolorenzo *et al.*, 2001a; Petrone *et al.*, 2014; Shmidt *et al.*, 2015; Petrone *et al.*, 2018). Histological and ultra-structural investigation has revealed linear and polygonal cracking of the intra- and inter-osteonic structure associated with incipient recrystallization (Mastrolorenzo *et al.*, 2010), bone changes typically induced by heat (Shipman *et al.*, 1984; Fernández Castillo *et al.*, 2013). Evidence of sudden death is provided by the victims' corpses, appearing to be suspended in their last vital action (Fig. 10). The lack of a voluntary self-protective reaction or agony probably suggests that any vital activity had to stop within a time shorter than the conscious reaction time (Brinkmann *et al.*, 1979). The vital aspect shown by the victims in Herculaneum, Pompeii and the other Vesuvian sites shows that people were alive at the time of the postural stiffening, and its widespread presence indicates that the entire resident population was exposed to the same lethal conditions. As also observed in the other sites buried by the 79 AD eruption, the overall evidence suggests the occurrence of thermally-induced instant death of the inhabitants in the Vesuvius area up to at least 20 kilometers from the vent (Baxter, 1990; Mastrolorenzo *et al.*, 2001a; Petrone & Fedele, 2002; Mastrolorenzo *et al.*, 2010; Petrone *et al.*, 2014, 2018).

Recent studies

Very recent taphonomic and laboratory investigation has lent new insights into the effects related to the sudden impact of the pyroclastic ash surge on the resident population and the cause of death at Herculaneum (Petrone *et al.*, 2018). Key features of body exposure to intense heat have been ascertained, like skull cracking (Fig. 11), as detected by recurrent clear-cut fractures, with

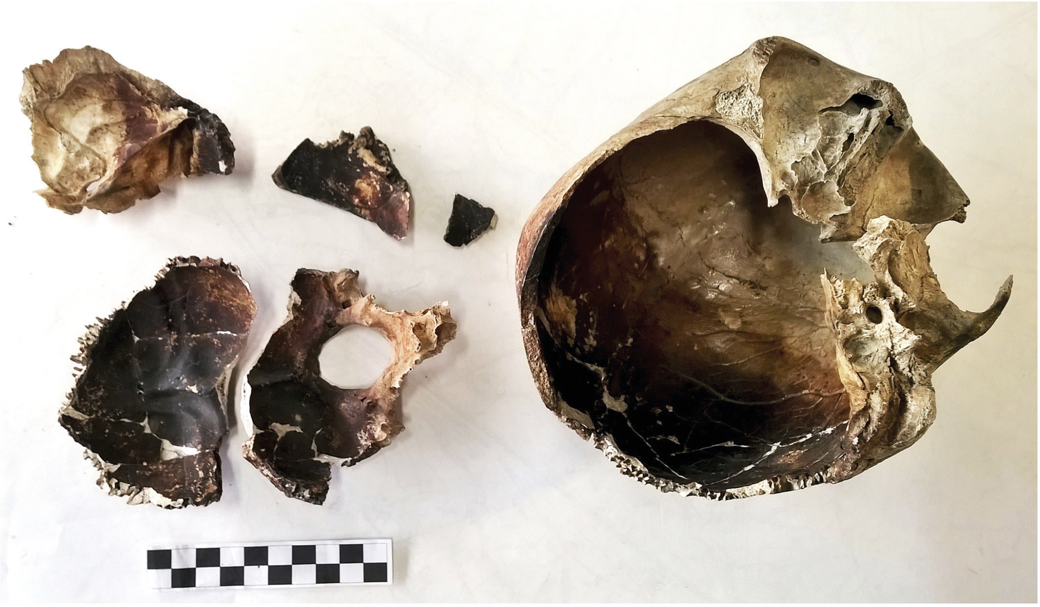

Fig. 11 - The effects of heat on the victims' skull. Skull exploded and charred (Herculaneum, chamber 12, ind. 3, male). The colour version of this figure is available at the JASs website.

sharp margins like those seen in cremated bones. Dark staining is typically associated with these cracked areas, whose exposed surface is charred as well. Interestingly, fractures are always limited to the charred bone areas. A recurrent feature is the dark staining of the inner table beside a zone of unchanged color, with a distinct blackened/non-blackened pattern. This evidence is concomitant with the pattern of bone cracking, since dark stained areas often exhibit fissure fractures, or may even be exploded, while those of unchanged color are never affected by such major heat effects.

A significant feature of the inner cranial table is the brown staining of the vascular grooves (*sulci arteriosi* and *sulci venarum*). In some cases dark staining of the intracranial cavity appears to be gradual, the bone progressively appearing natural/pale yellow, bright brown, dark brown and black (Munsell, 1954). Pale yellow is indicative of minor thermal exposure (≤ 200 °C), whereas darker bone coloration matches with higher temperatures (300 to 400-500°C) (Shipman *et al.*, 1984; Nicholson, 1993; Walker *et al.*, 2008; Mastrolorenzo *et al.*, 2010; Ellingham *et al.*, 2015).

An extraordinary find concerns skulls filled with ash, which indicates that after vanishing the brain was replaced by ash (Fig. 12). The presence of such an ash cast in all victims, even those showing minor heat effects, provides evidence that the pyroclastic surge was sufficiently hot and fluid to penetrate the intracranial cavity soon after soft tissues and organic fluids vanished, as supported by the intracranial micro stratigraphy showing lamination by successive apposition of thin ash layers.

New examination of the victims' skeletons and the taphonomic context has revealed the preservation of atypical red mineral residues encrusting the bones, which also impregnate the volcanic ash filling the skulls and the ash-bed deposit (Petrone *et al.*, 2018) (Fig. 13). Analysis by inductively coupled plasma mass spectrometry (ICP-MS) (EPA, 2014) reveals an extremely high amount of iron in the class of red incrustations detected from the cranial and postcranial bones, the ash filling the intracranial cavity, and the ash-bed. In contrast, samples of ash (surge deposit) and sand (chamber bottom) not impregnated by red residues showed an almost negligible amount of iron. These findings indicate that the extremely high content of iron could not be ascribed to volcanic ash or other volcanic products, suggesting that it might have originated from the victims' body fluids.

This matter was further addressed by Raman spectroscopy on selected and representative samples in order to identify or exclude various iron-containing compounds. Special attention was paid to detect and discriminate the possible preservation heme or heme-degradation products within the red mineral residues (Neugebauer *et al.*, 2012). For this purpose, a number of samples were selected on the basis of iron content data provided by ICP-MS and analyzed using a Raman micro-spectroscopy with 514 and 647 nm excitation. Microscopically heterogeneous residues showing spots of different colors were sampled several times in different areas. Twelve samples did not provide any Raman band, while eleven samples showed Raman features. Among the latter, some of them taken from red encrusted material showed iron-related bands, consistently with ICP-MS analysis.

On the basis of these results, the amounts of iron and iron oxides have been associated to the final products of heme iron upon thermal decomposition. The significant putative evidence of hemoprotein thermal degradation and additional evidence of heat-induced effects on the bones suggest the rapid vaporization of body fluids and soft tissues of victims resulting from exposure to the intense heat of the ash-avalanches.

Fig. 12 - Brain ash casts from a victim's skull. Brain-like ash cast (lateral view) from an adult male (Herculaneum, chamber 12, ind. 4, male). The colour version of this figure is available at the JASs website.

Fig. 13 - Evidence of red mineral residues from Herculaneum. A thick red layer impregnates the ash deposit under the skeleton. The colour version of this figure is available at the JASs website.

Conclusions

The multidisciplinary site investigations and the lines of research carried out on the victims of the 79 AD eruption proved to be of fundamental significance for the biological, historical and archaeological reconstruction of the population living at the foothills of Mt. Vesuvius. Scientific studies continue unabatedly, and new ongoing research promises to reveal key information of absolute novelty regarding the biological kinship and the social mobility of Herculaneum's inhabitants, within the economic and social relationships of this rich Roman town with other countries in the Mediterranean basin. As an integral part of the most recent major archaeological discoveries, the 79 AD victims can be considered as "time capsules", being an entire cross-section of a living Roman society, suspended in time and place as a result of a huge, unexpected natural catastrophe, which incredibly preserved intact entire urban settlements, including aspects of daily life. The skeletal population of Herculaneum and its archaeological context represent a unique testimony among the known archaeological sites for its exceptional finds so far, and those awaiting discovery in the near future.

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