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# Thermal interactions of the AD79 Vesuvius pyroclastic density currents and their deposits at Villa dei Papiri (Herculaneum archaeological site, Italy)

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A B S T R A C T

Pyroclastic density currents (PDCs) can have devastating impacts on urban settlements, due to their dynamic pressure and high temperatures. Our degree of understanding of the interplay between these hot currents and the affected infrastructures is thus fundamental not only to implement our strategies for risk reduction, but also to better understand PDC dynamics. We studied the temperature of emplacement of PDC deposits that destroyed and buried the Villa dei Papiri, an aristocratic Roman edifice located just outside the Herculaneum city, during the AD79 plinian eruption of Mt Vesuvius (Italy) by using the thermal remanent magnetization of embedded lithic clasts. The PDC deposits around and inside the Villa show substantial internal thermal disequilibrium. In areas affected by convective mixing with surface water or with collapsed walls, temperatures average at around 270 °C (min 190 °C, max 300 °C). Where the deposits show no evidence of mixing with external material, the temperature is much higher, averaging at 350 °C (min 300 °C; max 440 °C). Numerical simulations and comparison with temperatures retrieved at the very same sites from the reflectance of charcoal fragments indicate that such thermal disequilibrium can be maintained inside the PDC deposit for time-scales well over 24 hours, i.e. the acquisition time of deposit temperatures for common proxies. We reconstructed in detail the history of the progressive destruction and burial of Villa dei Papiri and infer that the rather homogeneous highest deposit temperatures (average 350 °C) were carried by the ash-sized fraction in thermal equilibrium with the fluid phase of the incoming PDCs. These temperatures can be lowered on short time- (less than hours) and length-scales (meters to tens of meters) only where convective mixing with external materials or fluids occurs. By contrast, where the Villa walls remained standing the thermal exchange was only conductive and very slow, i.e. negligible at 50 cm distance from contact after 24 hours. We then argue that the state of conservation of materials buried by PDC deposits largely depends on the style of the thermal interactions. Here we also suggest that PDC deposit temperatures are excellent proxies for the temperatures of basal parts of PDCs close to their depositional boundary layer. This general conclusion stresses the importance of mapping of deposit temperatures for the understanding of thermal processes associated with PDC flow dynamics and during their interaction with the affected environment.



## 1. Introduction

The main impact factors of pyroclastic density currents (PDCs) within their inundation areas are their temperature and dynamic pressure. While dynamic pressure is quantitatively related to the local momentum of the current (i.e. the instantaneous mass discharge over a certain area, e.g. a building; Dioguardi and Dellino, 2014), factors affecting the local temperature are much less understood. The general understanding is that, given an initial temperature of the pyroclastic mixture at vent (which largely depends on magma composition, possible interaction with ground- or surface-water, and amount of cold lithics excavated), the mass flux fundamentally controls the thermal energy dissipation within PDCs (Doronzo et al., 2016; Giordano and Doronzo, 2017; Trolese

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et al., 2017), along with the entrainment of cold materials such as accidental lithics, vegetation, surface water and snow (e.g. Paterson et al., 2010). The available datasets for temperature of pyroclastic flow deposits either directly measured or retrieved from various methods (Table S1 in Appendix 1 in Supplementary material) indicate that temperatures may vary substantially and almost irrespectively of the PDC size, chemistry, lithic content, and lithofacies (e.g. Cioni et al., 2004; Zanella et al., 2015; Pensa et al., 2015a; Trolese et al., 2017). For example, ash clouds associated with confined PDCs have been observed to leave behind thin and cold veneer deposits at Tungurahua volcano in 2006 (Eychenne et al., 2012) while similar occurrences were able to burn houses at Montserrat in 1997 and Merapi in 2010 (e.g. Jenkins et al., 2013). Similarly, thick valley pond ignimbrite deposits are known to vary from completely and laterally extensively welded (e.g. Willcock et al., 2013; Lavallée et al., 2015) to unwelded, with $T$ ranging from $>600\,^\circ$C (e.g. Lesti et al., 2011; Trolese et al., 2017) to low temperatures close to detection limits of common methods (e.g. McClelland et al., 2004). Given these uncertainties, much debate has fueled the literature on defining the actual significance of temperature proxies measured in the PDC deposits (e.g. McClelland and Druitt, 1989; Cioni et al., 2004; Paterson et al., 2010; Sulpizio et al., 2008, 2015; Zanella et al., 2015; Pensa et al., 2015a, 2015b). The most used proxy is the thermal remanent magnetization (TRM) of lithic clasts, and for example McClelland and Druitt (1989), Bardot (2000), Cioni et al. (2004) and Zanella et al. (2007) made a distinction between the temperature of pyroclastic flows and that of their deposits. Based on the longer time required for thermal equilibration of lithics respect to their residence in the flow, TRM-derived $T$ are commonly interpreted as reflecting the deposit temperature rather than that of the parent flow.

Even longer is the equilibration time for charcoalification of wood (Scott and Glasspool, 2005; Caricchi et al., 2014). Furthermore, by comparing the TRM on lithics and the degree of charcoalification of wood, Pensa et al. (2015a, 2015b) warned us about the complicated history of pre-heating of lithic clast which may be extracted anywhere from deep in the conduit, from the vent, or picked up along flow, all potentially carrying very different temperatures at their final landing.

Other important though rather poorly explored topics are: i) what is the relative contribution to the final temperature at deposition of the polycomponent and polydispersed pyroclastic debris, and ii) how long it takes for the deposit to significantly depart from the temperature of the parent pyroclastic flow when compared with the characteristic time of thermal equilibration for the different proxies.

In this paper, we analyze in detail the temperature of the pyroclastic flow deposits of the AD79 eruption at Vesuvius. Unlike other previous work that approached the problem at the volcano scale (e.g., Cioni et al., 2004; Zanella et al., 2007, 2015), we work here to define the thermal interactions over time of one building progressively buried by hot PDC deposits. We use TRM analysis of lava lithic clasts sampled across stratigraphy and different lithofacies of the PDC deposits in and around the Roman Villa dei Papiri at Herculaneum, famous for the unique preservation of rare and delicate papyri documents (Guidobaldi et al., 2009; Mocella et al., 2015). The innovative contribution of our site-specific approach is to clarify the importance of fine-scale interactions of PDC deposits with the urban fabric, which determine significant local variations in temperature and cooling rates. Such variations may explain the variable thermal impact observed on infrastructures and other archaeological remains in the Villa dei Papiri, as well as in the nearby city of Herculaneum and in other main cities affected by the AD79 eruption, e.g. Pompeii and Oplontis. Our field dataset and thermal numerical modeling indicate that the morphological configuration of the contact between the hot PDC deposits and the cold edifice determines the time scale of the thermal exchange, promoting much faster cooling where debris derived from the partial collapse of the edifice mixed with the pumice and ash PDC deposits. Furthermore, we interpret the temperature of the PDC deposit derived from TRM as largely recording a disequilibrium temperature dominated by the ash fraction, which cannot be substantially different from that of the parent flow. Hence, with the exception of local effects associated with physical mixing with water or sediment or other external cold materials, such as collapsed wall debris, the deposit temperature closely reflects the flow dynamic processes that determine the extent of heat loss of the ash fraction prior to deposition.

## 2. Summary of the AD79 eruption and the deposits of Herculaneum excavations

The chronology of the AD79 eruption is based on the accounts of Pliny the Younger and translated to processes and timing by Sigurdsson et al. (1982, 1985). The stratigraphy has been divided into 8 Eruption Units by Cioni et al. (1992, 2004). The stratigraphy in Herculaneum is described in Gurioli et al. (2002).

The eruption started on August 24 at around noon with a not better specified phreatomagmatic event (EU1: phreatomagmatic ash). At around 1PM a buoyant column rose up to 30–33 km high (Carey and Sigurdsson, 1987) producing stratified SE-ward-dispersed fall deposits. The first pulse lasted till around 8PM (EU2f phonolitic white pumice lapilli) and the second across the night (EU3f phonotephritic gray pumice lapilli). During this early phase, partial collapses produced the pyroclastic flows (EU2/3pf and EU3pf) that reached Herculaneum (Barberi et al., 1989).

During the following day, on August 25, the onset of the caldera collapse eventually led to the generation of radially spreading pyroclastic flows (EU4-5-6-7; Cioni et al., 2004; Gurioli et al., 2007), with lithic rich breccias (EU6) and evidence for magma–water interaction (Barberi et al., 1989; Cioni et al., 1992). The eruption ended with the deposition of a thick, phreatomagmatic, accretionary lapilli-bearing ash (EU8).

According to the stratigraphy in Gurioli et al. (2002) and Caricchi et al. (2014), Herculaneum did not receive the deposition of the initial pumice fallout, being cross-wind respect to dispersal axis. The stratigraphic succession records the PDC deposits (E2/3pf; EU3pf) associated with the partial collapses of the column during the transition between phonolitic EU2 and phonotephritic EU3 phases, and later PDC deposits of the caldera forming phase (EU4 to EU8).

## 3. Previous work, materials and methods

The stratigraphy and sedimentology of the AD79 Vesuvius eruption deposits have been studied in detail in several works (e.g. Lirer et al., 1973; Sigurdsson et al., 1982, 1985; Carey and Sigurdsson, 1987; Cioni et al., 1992; Yokoyama and Marturano, 1997; Gurioli et al., 2002, 2005). The temperature of emplacement of the PDC deposits has been investigated with various methods, including TRM on lithic clasts (Kent et al., 1981; Cioni et al., 2004; Gurioli et al., 2005; Zanella et al., 2007, 2015), bone fragment analysis (Mastrolorenzo et al., 2001), and charcoal reflectance (Caricchi et al., 2014). The inferred deposit temperatures retrieved from the various proxies range from $100\,^\circ$C to $500\,^\circ$C, with most common values around 250–370 °C (see Appendix 1). These data represent an excellent benchmark to our study, as they provide the overall thermal framework for the AD79 PDC deposits, which allows us to go into the detail of the PDC thermal impact at the individual building scale, something that has never been previously attempted. We selected as case study the aristocratic Roman Villa