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Thermal interactions of the AD 79 Vesuvius pyroclastic density currents and their deposits at Villa dei Papiri (Herculaneum archaeological site, Italy)

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(Article begins on next page)

1	Thermal interactions of the 79AD Vesuvius pyroclastic density currents and their
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16	Abstract. We studied the temperature of emplacement of pyroclastic density currents
17	deposits that destroyed and buried the Villa dei Papiri, an aristocratic Roman edifice
18	located just outside the Herculaneum city, during the 79AD plinian eruption of Mt Vesuvius
19	(Italy). We used the Thermal Remanent Magnetization of lithic clasts embedded in the
20	PDC deposits to retrieve accurate measures of the deposit temperature. The deposit
21	shows substantial internal thermal disequilibrium. In areas affected by convective mixing
22	with surface water or with collapsed walls, temperatures average at around 265°C (min
23	190°C, max 300°C). Where the deposits show no evidence of mixing with external
24	material, the temperature is much higher, averaging at 350°C (min 300°C; max 440°C).
25	Numerical simulations and comparison with temperatures retrieved at the very same sites
26	from the reflectance of charcoal fragments indicate that such thermal disequilibrium can be
27	maintained for time-scales well over 24-48 hours, i.e. the acquisition time for common

28 proxies of emplacement temperatures. We therefore reconstructed in detail the history of 29 the progressive destruction and burial of Villa dei Papiri and infer that the deposit 30 temperature is virtually the same as that of the incoming PDCs. This conclusion is very 31 important as it solves a long standing debate on the actual relationships between the PDC 32 deposit temperatures and those of the parent flows. Here we suggest that PDC deposit 33 temperatures are excellent proxies for the temperatures of basal parts of PDCs close to 34 their depositional boundary layer and therefore that mapping of deposit temperatures gives 35 essential insights for thermal processes within PDCs and during their interaction with the 36 affected environment.

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- 38

39 **1. Introduction**

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41 The main impact factors of pyroclastic density currents (PDCs) within their inundation 42 areas are their temperature and dynamic pressure. While dynamic pressure is 43 guantitatively related to the local momentum of the current (i.e. the instantaneous mass 44 discharge over a certain area, e.g. a building; Dioguardi & Dellino, 2014), factors affecting 45 the local temperature are much less understood. The general understanding is that, given 46 an initial temperature of the pyroclastic mixture at vent (which largely depends on magma 47 composition, possible interaction with ground- or crater lake-water, and amount of cold 48 lithics excavated), the extent and efficiency of air ingestion during the collapse and ground 49 hugging flow phases are the most effective ways for a pyroclastic density current to loose 50 temperature, along with the entrainment of cold materials such as accidental lithics, 51 vegetation, surface water and snow (see Paterson et al., 2010). However, the available 52 dataset for temperature of pyroclastic flow deposits either directly measured or retrieved 53 from various methods (Table S1 in Appendix 1) indicates that temperatures may vary

54 substantially and almost irrespectively of the PDC size, chemistry, lithic content, lithofacies 55 (e.g. Cioni et al., 2004; Zanella et al., 2014; Pensa et al., 2015a). For example, ash clouds associated with confined pyroclastic density currents have been observed to leave behind 56 57 thin and cold veneer deposits at Tungurahua 2006 (Eychenne et al., 2012) while similar 58 occurrences were able to burn houses at Montserrat 1997 and Merapi 2010 (e.g. Jenkins 59 et al., 2013). Similarly, thick valley pond ignimbrite deposits are known to vary from 60 completely and laterally extensively welded (e.g. Willcock and Cas, 2014; Lavallée et al., 61 2015) to unwelded with T ranging from T > 600°C (e.g. Lesti et al., 2011) to low 62 temperatures close to detection limits of common methods. 63 Given these uncertainties, much debate has fuelled the literature on defining the actual significance of temperature proxies measured in the deposits (e.g. McClelland and Druitt. 64 65 1989; Cioni et al., 2004; Paterson et al., 2010; Sulpizio et al., 2015; Zanella et al., 2014; Pensa et al., 2015a). The most used proxy is the Thermal Remanent Magnetization (TRM) 66

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.

72 Even longer is the equilibration time for charcolification of wood (Scott and Glasspool,

⁷³ 2005; Caricchi et al., 2014). Furthermore, by comparing the TRM on lithics and the degree

of charcoalification of wood, Pensa et al (2015a,b) 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

77 temperatures at their final landing.

Other important though rather poorly explored topic 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.

83 In this paper we analyse in detail the temperature of the pyroclastic flow deposits of the 79 84 AD eruption at Vesuvius which destroyed the city of Herculaneum during the evening-night 85 between August 24 and 25. Unlike other previous works that approached the problem at a 86 large scale (e.g., Zanella et al., 2014), we work to define the interaction over time of 87 incoming PDCs with one building. We extend the dataset presented in Caricchi et al. 88 (2014) which was only based on charcoal fragments and integrate with TRM analysis of 89 lithics from many sites in and around the Roman Villa dei Papiri, across stratigraphy and 90 different lithofacies. The presented dataset and a numerical modeling of the thermal 91 behaviour of the deposit suggest that proxies for PDC deposit temperature largely record a 92 disequilibrium temperature dominated by the ash fraction and that this temperature cannot 93 be substantially different from that of the parent flow. Hence, with the exception of local 94 effects associated with physical mixing with water or sediment or other external cold 95 materials, the deposit temperature closely reflects the flow dynamic processes that 96 determine the extent of heat loss of the ash fraction prior to deposition.

97

98 2. Summary of the 79 AD eruption and the deposits of Herculaneum excavations
 99

The chronology of the 79 AD 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, 1996, 2004). The stratigraphy in
Herculeneum is described in Gurioli et al. (2002).

104 The eruption started on August 24 at around noon with a not better specified

105 phreatomagmatic event (EU1: phreatomagmatic ash). At around 1PM a buoyant column

106 rose up to 30-33 km high (Carey and Sigurdsson, 1987) producing stratified SE-ward-

107 dispersed fall deposits. The first pulse lasted till around 8PM (EU2f phonolitic white pumice

108 lapilli) and the second across the night (EU3f phonotephritic grey pumice lapilli). During

109 this early phase, partial collapses produced the pyroclastic flows (EU2/3pf and EU3pf) that

110 reached Herculaneum (Barberi et al., 1989; Cioni et al., 2000a,b).

111 During the following day, on August 25th, 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,

115 phreatomagmatic, accretionary lapilli-bearing ash (EU8).

According to the stratigraphy in Gurioli et al. (2002) and Caricchi et al. (2014),

117 Herculaneum did not receive the deposition of the initial pumice fallout, being cross-wind

118 respect to dispersal axis. The stratigraphic succession records the PDC deposits (E2/3pf;

119 EU3pf) associated with the partial collapses of the column during the transition between

120 phonolitic EU2 and phonotephritic EU3 phases, and later PDC deposits of the caldera

121 forming phase (EU4 to EU8).

122

123

124 **3. Previous works, materials and methods**

125

126 The stratigraphy and sedimentology of the 79 AD Vesuvius eruption deposits have been

127 studied in detail in several works including their temperature with various methods (e.g.

Lirer et al., 1973; Kent et al., 1981; Sigurdsson et al., 1982, 1985; Carey and Sigurdsson,

129 1987; Cioni et al., 1990, 1992, 1996, 2000a, 2000b; Yokoyama and Marturano, 1997;

130 Mastrolorenzo et al., 2001; Gurioli et al., 2002, 2005; Caricchi et al., 2014).

131 Villa dei Papiri was an aristocratic Roman villa located just outside the main

132 Herculaneum city (Fig. 1a,b), along the 79 AD Roman coastline (Guidobaldi et al.,

2009) The Villa was reached by the early intra-plinian PDC and progressively buried and
 partially destroyed by the following PDCs which deposited more than 30 m of dominantly
 massive and chaotic lapilli tuff (Fig. 1c,d).

136 The temperature of the deposit that buried and destroyed the Villa dei Papiri is herein 137 retrieved from the determination of the Thermal Remanent Magnetization (TRM) of the 138 lithic clasts embedded in the lapilli tuff of units EU2/3pf, EU3pf, EU4 (Fig. 1c,d). Details on 139 the method are given in Appendix 1. We sampled lithics in the size range of 1-3 cm ca 140 taken from massive and chaotic facies (Appendix 2). Eight sites (VP1, VP2, VP5.1-3-5-7-141 10, VP9) were sampled where the ash matrix < 1mm represents > 75% of the deposit 142 (Gurioli et al., 2002). Additional four sites were sampled were the deposit is fines-depleted 143 within a large gas-pipe (VP8) within a strongly zeolitised facies (VP6), and where it is 144 mixed with coarse debris from the collapse of the Villa (VP3, VP4). Four out of our twelve 145 sampling sites (i.e. VP1, VP2, VP3, VP4) also correspond to the very same sites where emplacement temperatures had been previously interpreted from charcoal fragments in 146 Caricchi et al. (2014). We devised this sampling strategy because charcoal equilibrates 147 with the embedding deposits in timescales of 10¹ hours, usually 24 hours or more (Scott 148 and Glasspool, 2005; Caricchi et al., 2014), while cm-sized lithics do so within much 149 shorter timescales, usually $< 10^{\circ}$ hours (Bardot and McClelland, 2000; Cioni et al., 2004). 150 By comparing TRM data and published charcoal data from the very same sites we aim 151 therefore at appreciating the influence of thermal disequilibrium processes, such as those 152 153 associated with the cooling of the deposit which may produce a significant departure of the recorded temperatures and those of the first arrival, as well as processes associated with 154 155 the internal re-equilibration of temperatures carried by the poly-component and polydispersed pyroclastic material in its interaction with topography and infrastructures. 156

157

158 **INSERT FIG. 1 HERE**

159

160 **4. Results**

161

162 4.1 Thermal Remanent Magnetization of lithic clasts

163

The magnetization components of a lava fragment embedded in a PDC deposit reveal its thermal history. In a simplified model, if the lava fragment is re-heated after its formation, it shows two magnetization components: i) a high-T component, representing what remains of the TRM, originally acquired by the ferromagnetic grains in the lava throughout their blocking temperature (T_b) spectrum, and ii) a low-T component, result of the PDC reheating process.

The analysis of the Zijderveld diagrams (Fig. 2) provides the magnetization components 170 171 and the re-heating temperature (T_r) interval. For each of the 190 measured specimens we 172 determined a T_r interval and classified the behavior during the demagnetization process 173 into four different types (labeled A to D), as proposed by Cioni et al. (2004), on the base of the relation between specimen T_b spectrum and re-heating temperature (T_r). Details are 174 given in Appendix 1. Here we just recall that, depending on the assemblage of magnetic 175 176 grains within a clast, for two types (i.e. C and D) a heating interval is obtained. Instead, types A and B are characterized by one magnetization component, the primary high-T and 177 178 the secondary low-T component, respectively. In both these cases it is not possible to get 179 any information on the T_r.

The Zijderveld diagrams analysis provided successful results, i.e. a heating interval, in 72% of the total (Fig. 2). For type C, the T_r intervals were determined in a range of 40 °C (Fig. 2a, b); for type D, during demagnetization a clear curvilinear trend is displayed, as highlighted in Fig. 2c, and the T_r interval is wider, normally more than 80 °C. For the remaining, the 9% is represented by A (Fig. 2d) + B types, the 19% by unresolvable cases, where the angle between the two magnetization components was <15° (Porreca, 2004). During thermal demagnetization, specimens mostly proved to have a high magnetic stability and no alteration, as evidenced by magnetic susceptibility variations, were detected.

All the lithics of site VP8 show three magnetization components, whose layout highlights two T_r intervals: one in the range 280-320 °C, the other in the range 160-200 °C. The former is fully consistent with the T_r intervals determined in all the other sampling sites; the latter represents the lowest T_r intervals within *Villa dei Papiri*.

193

194 INSERT FIG 2 HERE

195

196 Having determined all the T_r intervals, for each sampling site we prepared an overlapping 197 diagram (Fig. 3): the temperature of the deposit T_{dep} is in the range where the greatest 198 number of T_r intervals falls. This method has its main limit in the qualitative approach. 199 Nevertheless, the fact that both the studied deposits and the lithic fragments are 200 heterogeneous (no information is at priori available on the thermal history of the lava clasts 201 and on their magnetic properties) reinforces the reliability of the results (Zanella et al., 202 2014). Besides, a statistical approach for T_{dep} estimation based on the Gaussian method 203 has been recently applied to the Minoan eruptive deposits of Santorini (Tema et al., 2015). 204 Results obtained from the mathematical method were fully consistent with those from the 205 overlapping method. T_{dep} intervals are listed in Table 1. The T_{dep} varies from 180 to 440 °C with mean value ranging from 280-340 °C (Table 1). This range is fully consistent with the 206 207 T_{dep} values already reported for the 79 AD deposits around Vesuvius (Cioni et al., 2004). 208 The lowest interval is displayed in VP8, whose lithic clasts have been sampled in a gas-209 pipe.

210

211 INSERT FIG. 3 AND TABLE 1 HERE

213 4.2 Interpretation of TRM data

215	TRM data at Villa dei Papiri show quite a large variability ranging from 180°C to 440°C.
216	These data are consistent with previously published data on deposit temperature obtained
217	from charcoal fragments at the very same localities (Fig. 1; Table 1; cf. Caricchi et al.,
218	2014). We therefore trust the values obtained (cf. Pensa et al., 2015b) that need, though,
219	to be addressed for their variations in such a very limited area. These variations partly
220	reflect the stratigraphy, where the three sites sampled in lower unit EU2/3pf, VP4, VP6 and
221	VP8, show the lowest T_{dep} values (Fig. 1 and Table 1). In particular site VP8, with a T_{dep} of
222	180-200°C, was sampled within a large gas pipe generated by the interaction of the
223	incoming PDC with the sea shoreline (Fig. 4b and Appendix 2), while site VP6, with a T_{dep}
224	of 280-320°C, within the zeolitised halo around the pipe (Fig. 1d and Appendix 2), likely
225	generated by the upward percolation of vapourised seawater. Site VP4, with a T_{dep} of 260-
226	300°C, is instead sampled in a breccia facies made of mixed pyroclastic material and
227	debris from collapsed wall of the Villa (Fig. 4c and Appendix 2). At this site VP4 the
228	temperature from TRM of lithics is in perfect agreement with that retrieved by Caricchi et
229	al. (2014) from reflectance analysis of chacoal fragments embedded in the very same site
230	(Table 1). We interpret therefore the low values associated with EU2/3pf with a significant
231	interaction of the incoming PDCs with the environment, either seawater or the partially
232	destroyed Villa. Data from the upper units EU3pf and EU4 (VP1, VP2, VP5.1-3-7-10) are
233	on average much higher (Table 1) and indicate temperatures that are consistent with
234	maximum values reported in literature as characteristic of the 79 AD deposits outside
235	towns (Cioni et al., 2004; Zanella et al., 2007; 2014). Noticeable exceptions are sites VP3
236	and VP5.5. Site VP3 is located inside the building where the EU4 deposit is admixed with
237	collapsed walls (Fig. 4d and Appendix 2). Also for this site data from reflectance analysis of

238 chacoal fragments embedded in the very same site are available (Caricchi et al., 2014; Table 1) and match perfectly with our TRM data, so like for VP4 we interpret the lower 239 temperatures in terms of cooling effect of the edifice debris. Site VP5.5 is instead 240 241 somewhat problematic as it is far from the edifice and closely surrounded by sites 242 characterised by much higher temperatures, so this may either be an outlier or a site 243 affected by some cooling agent difficult to identify (e.g. a close gas pipe present in the third 244 dimension but invisible along the exposed face where lithics had been sampled; Fig. 1c). 245 In summary the average of the mean values obtained for each of the sites affected by 246 evident cooling agents (VP4, VP6, VP8, VP3) gives a value of 265°C (Fig. 5). This 247 temperature contrasts with a similar average for sites unaffected by evident cooling agents (VP1, VP2, VP5.1-3-5-7-10, VP9) where the value is 348°C (Fig. 5). It must be noticed that 248 sites VP1, VP2 and VP5.1 are located at distances of less than 1 m from the intact Villa 249 walls (Fig. 1c) and bear no edifice debris inside. This indicates that the presence of the 250 Villa edifice was "felt" by the deposit in terms of heat transfer generating thermal 251 252 disequilibrium at short time and length scales only where the collapsed walls physically 253 mixed with the pyroclastic material, whereas in absence of physical mixing with cold 254 debris, the pyroclastic deposit is very poorly affected by the temperature of the substrate. 255 Similarly, the convective mixing with seawater is an efficient cooling agent for the PDC 256 deposit.

257

258 INSERT FIG. 4 AND FIG. 5 HERE

259

260 **5. Numerical Modeling**

261

In order to better understand the time and length scales of the thermal interaction between
 PDC deposits and the Villa dei Papiri edifice we performed numerical simulations of the

burial of the Villa with the Heat3D software (Wohletz, 2008). We define a 3 m x 3 m 264 computational domain with a 5 cm cell-grid. We computed the conductive heat transfer 265 between the hot PDC deposits and the wall of the Villa at ambient temperature, as 266 267 convection in the deposit can be disregarded. We defined two configurations (Fig. 6a,b): 268 configuration A is aimed at simulating the contact between the vertical wall of the Villa and 269 the PDC deposit within a distance of 2 m from the wall (e.g. VP1, VP2, VP5-1); 270 configuration B is aimed at simulating the collapse of the wall and the mixing with the PDC 271 deposit (e.g. VP3 and VP4). Table 2 shows the parameters used to characterise the 272 building and the deposit physical properties.

273

274 INSERT TABLE 2 HERE

275

We simulate the PDC deposit as a continuum at the scale of simulation with a density of 276 1200 kg m⁻³ and thermal conductivity of 0.7 W m⁻¹ K⁻¹, specific heat 1200 J kg⁻¹ K⁻¹ and 277 initial T of 350°C, taken as the average of our data away from the building (from transect 278 VP5) and in agreement with previous estimations. Time steps of the numerical solutions 279 are determined by the dimension of the cells so that the minimum simulated is 15 minutes, 280 281 lower than the time of acquisition of the TRM signal by the analysed lithics. Runs simulated 48 hours of thermal exchange between the ignimbrite and the Villa, that is 282 longer than the time of acquisition for charcoal. We therefore are able to analyze the 283 284 temperature variations in the deposit in a time-frame that encompasses the time-scales of acquisition for both proxies. 285

Results indicate that configuration A promotes very little heat transfer during the first 48
hrs, with a T drop of less than 50°C in the deposit at 50 cm distance from the contact with
the wall and almost no variations at 1 m distance (Fig. 6c). This explains why the
temperatures acquired by both the lithic and the charcoal proxies at sites even close to the

Villa (e.g. VP2) but where the structure did not collapse do record accurately the

291 emplacement temperatures with very small departures from the initial values.

By contrast, results from configuration B (Fig. 6d) indicate that the mixing between a

collapsed wall and the PDC deposit promotes a very fast and efficient heat transfer due tothe enhanced contact surface available.

295

296 INSERT FIG. 6 HERE

297

298 Fig. 6d shows that the initial thermal disequilibrium, though highly simplified geometrically, 299 rapidly smooths with a T drop of more than 100°C inside the PDC deposit domains in the first 3 hours of simulation and smooths to an average value of less than 200°C, that is 300 301 more than 150°C less than initial, after 6 hours. At the same time, once re-equilibrated, the 302 temperatures in the collapsed domain remain almost constant to the end of the simulation 303 after 48 hours. Runs performed for configuration B with a finer cell-grid of 0.5 cm in a 30 cm x 30 cm domain (Appendix 3) indicate that the thermal equilibration occur within the 304 first 15 minutes. These results explain the relatively similar and low T recorded by both 305 306 lithic and charcoal at sites VP3 and VP4, i.e. where the PDC deposits are fully mixed with 307 portion of collapsed walls of the Villa.

308

309 **6. Discussion**

310

What we know about thermal processes within pyroclastic density currents and their deposits is still rather vague. Current knowledge relies on a very limited number of direct measurements of deposit temperatures taken with thermocouples from the shallowest part of deposits when and where approachable, and a number of studies of the TRM of embedded lithic clasts and reflectance of charcoal (Table S1, in Appendix 1). Some of the main still open questions are: i) what is the actual relationship between the temperature of 317 the deposit and the temperature of the parent current; ii) what temperature is actually recorded by commonly used deposit proxies, considering (a) the inherent thermal 318 319 disequilibrium of the poly-dispersed and poly-component pyroclastic material (b) the local 320 interaction with the environment and (c) the density and thermal stratification within PDCs. 321 Data from the Villa dei Papiri show that temperatures retrieved from TRM of lithic clasts 322 are in excellent agreement with temperatures derived from the reflectance of charcoal 323 fragments taken at the very same sites by Caricchi et al. (2014) (Table 1, Fig. 5). This 324 agreement indicates that temperatures in the deposit at each site remained stable for timescales comparable with the acquisition times for both proxies, i.e. for at least 24-48 hours. 325 326 These results are also in good agreement with numerical simulations, which show, within 48 hours, a substantial stability of the temperature close to initial values even very close to 327 a cold substrate, which in our case is the wall of the Villa (Fig. 6b). This is due to the low 328 thermal conductivity of glass shards and crystals that form the ash matrix, so that, in 329 absence of convective effects promoted for example by water vapourization or other kinds 330 331 of physical mixing with cold materials (e.g. collapsed intrastructures), the timescale of deposit cooling is much longer than that required for equilibration of lithics and charcoal 332 333 fragments: this suggests that the values retrieved from our proxies record the deposit 334 temperature very close to that of emplacement. Our data therefore indicate that, in the case of Villa dei Papiri, the highest measured temperatures away from areas of obvious 335 336 mixing of the deposit with either water (e.g. VP8) or collapsed walls (e.g. VP3, VP4) represent not only the deposit temperatures but are very close to the emplacement 337 temperatures. We also notice that lithics sampled for our TRM analyses have been taken 338 339 from massive and chaotic lapilli tuff facies, where the ash fraction, both coarse and fine, represents between 50 and 90%wt, with most common values >75%wt of the deposit 340 (Gurioli et al., 2002; Appendix 2). Available literature indicates that particles in the ash 341 342 fraction equilibrate almost instantaneously with the ambient (e.g. Wilson et al., 1978;

343 Thomas and Sparks, 1992). The ash fraction can therefore be assumed as continuously thermally equilibrated within flow and at deposition. Possible sources of thermal 344 inhomogeneity (both as heat sources or heat sinks) in the deposit could therefore be 345 346 related to the presence of large lapilli or bomb sized clasts. Bomb sized clasts in the primary 79 AD deposits at Villa dei Papiri are very rare and lapilli represent usually less 347 348 than 10-15% wt of the deposit. These proportions already suggest that the largest 349 contribution to the deposit temperature is provided by the ash fraction inside which the 350 lithics (and the charcoal measured in Caricchi et al., 2014) have been sampled. The 351 deposit temperatures retrieved from sites with no visible convective interaction with either 352 water or collapsed walls, though variable, all sit at the high-end of the thermal spectrum of the deposits (> 300 °C) and strongly suggest a common origin, which we interpret as 353 354 provided by the ash matrix. If that is true, as we believe our data clearly indicate, than the measured deposit temperature not only is very close to the emplacement temperature, but 355 also to the temperature of the basal and more concentrated part of the flow close to the 356 357 depositional boundary layer (sensu Branney and Kokelaar, 2002)(Fig. 7). We therefore conclude that, close to their flow boundary layer, incoming PDCs at Herculaneum had a 358 359 bulk temperature > 300 °C and based on the most frequent values retrieved most likely 360 around 350 °C (Fig. 5), carried essentially by the most abundant ash fraction. This conclusion is very important as it answers a long-standing debate on the actual 361 362 significance of the deposit temperature in respect to the parent flow. We suggest here that the emplacement temperature of ash-matrix supported PDC deposits essentially reflects 363 364 that of the parent flow even very close to substrate (Fig. 7), as conductive cooling of the 365 deposit is much slower than the acquisition time for commonly used proxies, namely lithic clasts and charcoal. 366

Based on the above considerations we propose a detailed reconstruction of the
 destruction and burial of the Villa dei Papiri from the PDCs that stroke Herculaneum during

the evening and night between the 24 and the 25 of August 79AD (Fig. 8).

The first PDC that reached the Villa was EU2/3pf, i.e. the PDC that formed at the transition 370 371 between the two main sustained plinian phases EU2 and EU3 both SE-ward directed and 372 therefore not recorded at Herculaneum (Fig. 8a,c; Gurioli et al., 2002). The PDC was able to unroof the Villa and partially destroy sections of it, but most of the main structure 373 374 remained in place. Debris mixed within EU2/3pf deposits at site VP4 relate to such event 375 (Fig. 8b). At the same time the PDC crossed the coastline just in front of the Villa, entered 376 the sea depositing and pushing forward the sea-shore (Fig. 8b). Deposit temperatures are highly dishomogeneous (Table 1), with the lowest measured in this study (180-200°C) and 377 378 reflect rapid post-emplacement heat transfer processes of mixing with sea-water/vapour and debris. Timescales of such processes are < 1 hour, i.e. the time-scale needed for 1-3 379 380 cm sized lithics to equilibrate with the embedding deposits (Cioni et al., 2004). After a pause associated with the restoration of the EU3 buoyant plume which kept depositing 381 pumice fallout to the SE of the volcano (Fig. 8c), a second major PDC reached the Villa dei 382 383 Papiri site, EU3pf, which partly buried the still standing main edifice and invading most of its interior (Fig. 8d). EU3pf however did not cause major collapses to the structure, nor it 384 385 interacted with the sea-water, previously buried by the EU2/3pf deposits. Deposit 386 temperatures in EU3pf average at around 350°C (Table 1 and Fig. 5) even within or very close to the Villa (VP1, VP2), both from TRM data presented herein and from charcoal 387 data presented by Caricchi et al. (2014), and reflect the average temperature of the parent 388 PDC close to its depositional boundary layer (Fig. 7). The following PDC, EU4pf, reached 389 the Villa after the transition from the buoyant EU3 phase and the beginning of the caldera 390 391 collapse phase which was thereon dominated by PDCs (Fig. 8e,f). With the arrival of the EU4 PDC the Villa was completely buried and the deposits are locally mixed with debris 392 from the collapsed walls of the summit floor that is totally unroofed (Fig. 8g). Based on the 393 394 highest temperatures retrieved in EU4 we interpret the parent PDC to have arrived in town

with a temperature just above 350°C close to its depositional boundary layer, that is similar
to that of the previous EU3pf.

397

398 INSERT FIG. 7 AND FIG. 8 HERE

The main conclusions are:

399

410

400 **7. Conclusions**

We have presented a detailed study of the temperature of the 79 AD PDC deposits that 401 402 progressively destroyed and buried a large ancient Roman edifice, the Villa dei Papiri, at 403 Herculeneum. We measured the TRM of lithic clasts embedded in the ash matrix of 404 massive and chaotic facies and compared the results with temperatures retrieved from the reflectance of charcoal fragments collected at the very same sites by Caricchi et al. (2014). 405 406 The excellent overlap between the two datasets allows to draw several important 407 conclusions very relevant for our conceptual and physical understanding of pyroclastic 408 density currents, as well as to reconstruct in detail the history of the thermal interaction 409 between the incoming PDCs and the Villa dei Papriri edifice and its environment.

411 1) The temperature of the ash-matrix supported, massive and chaotic PDC deposits 412 remains stable over time-scales of 24-48 hours that encompass the different acquisition times for both TRM and charcoal proxies; this temperature stability suggests that the 413 emplacement temperature of the ash-matrix, where unaffected by external factors (see 414 415 point 2 below), cannot be substantially different from that of the deposit at the time of 416 acquisition; in turn the temperature of the basal part of the current, close to its depositional boundary layer prior to deposition cannot be substantially different and we conclude that 417 418 the deposit temperature is an excellent proxy for the temperature of the base of PDCs. 2) The temperature of PDC deposits is significantly and quickly affected by external factors 419 across the acquisition times of TRM and charcoal proxies only where convective mixing 420 421 occurs, either with external water, rock debris or else; such occurrences define local

422 thermal domains within the PDC deposits and their thermal disequilibrium with the surroundings can be maintained for time-scales much longer than 24-48 hours. 423 424 3) The reconstruction of the thermal interactions at Villa dei Papiri shows that the first 425 incoming PDC had the largest degree of mixing with both debris from the unroofing of the 426 edifice and partial collapses, along with the interaction with the sea facing the Villa; the 427 following PDCs were thermally affected by the Villa only where collapsed occurred, 428 otherwise the purely condictive thermal equilbration along standing walls takes much 429 longer than 24-48 hours even at <50 cm from contact between PDC deposit and wall. 4) The average PDC deposit temperature at Villa dei Papiri is around 350°C, which we 430 431 indicate as that of the parent PDCs. The significant drop from magmatic temperature 432 (around 850 °C for fragmenting trachy-phonolitic magma; Cioni et al., 1995) could be due 433 to a combination of eruptive (e.g. magma water interaction and/or air entrainment in the column during collapse) and flow processes (e.g. air/water/vegetation ingestion along 434 flow). The substantial homogeneity of the temperatures obtained spatially for the 79 AD 435 436 PDC deposits (Cioni et al., 2004), very similar to all other PDC deposits along the history of 437 Vesuvius (Zanella et al., 2014) suggest some common process that needs further 438 investigations.

439

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- 441 This work was funded by the DPC grant
- 442

443

444 **Figure captions**

445

Figure 1: a) location of Villa dei Papiri and Herculaneum respect to Vesuvius; b) detailed
map of the Villa dei Papiri excavations and location of sampling sites; c,d) volcano-ward

and sea-ward views of the Villa dei Papiri archeological excavation and location of
sampling sites (VP) in relation with the stratigraphy of the 79 AD eruption. Temperature
ranges in blue indicate results from TRM of lithic clasts obtained in this study, compared
with values obtained from charcoal by Caricchi et al. (2014) indicated in red. White
numbers indicate elevations in m a.s.l. (photo and elevation survey courtesy of
Superintendence for Archaeology of Herculaneum).

454

Figure 2: Examples of the demagnetization results: Columns (left to right): (1) Normalized

456 intensity (J/J0) decay curve. The grey bar shows the re-heating range; (2) Zijderveld

457 (1967) diagram: solid/open dots represent declination/apparent inclination; figures

458 represent T values (°C). Red/blue line are the interpolated high-T and low-T magnetization

459 components, respectively; (3) Equal-area projection: solid/open dots represent lower/upper

460 hemisphere. Examples refer to type C (a) and (b), D (c) and A (d).

461

Figure 3: Deposition temperature at site VP6. The site Tdep is estimated from theoverlapping Tr ranges for

464 all lithic clasts sampled at this site. On the left, twin-specimens are limited by a square.

465 Frequency-histogram

466

Table 1: Site deposition temperature, Tdep (°C). Legend: n/N number of Tr interval in the overlapping range out of number of measured lithic clasts; type A, B, C, D as in Cioni et al. (2004). The question mark indicates the unresolvable Zjiderveld diagrams. Tchar indicates temperatures retrieved by Caricchi et al. (2014) from the analysis of the reflectance of charcoal fragmants sampled at the very same sites.

472

473 Figure 4: a) plan view of sampling sites (see also Fig. 1); b) detail of the large gas pipe

474 affecting EU2/3 ; c) basement floor of the Villa where the EU2/3 ignimbrite is both mixed
475 with collapsed debris and affected by sea-water mixing; d) third floor of the Villa where the
476 EU4 ignimbrite is partly mixed with collapsed debris; data in red (and in (c)) are from
477 Caricchi et al. (2014).

478

Figure 5: Deposit temperature at each measured site (see Fig. 1 for location). Open circle
indicate the mean values for TRM samples and bars the related T interval; Red bars
indicate temperatures retrieved from charcoal reflectance from Caricchi et al (2014). The
average of undisturbed and mixed facies are given by dashed lines.

483

Table 2: Physical properties of rocks used for the simulation in Heat3D (from Turcotte and
Schubert, 2014; Eppelbaum et al., 2014).

486

Figure 6: Main results of the Heat3D numerical modeling of heat transfer between the ignimbrite (red domain) and the wall (blue domain) for the two chosen configurations at t=0: A is the intact wall; B is the collapsed wall mixed with the ignimbrite; the cell-grid is 5 cm. Diagrams below each initial configuration show the temperature evolution over 24 hours taken along the green line.

492

Figure 7: Cartoon illustrating the different thermal interactions of the incoming PDC with the environment, which promote rapid changes of temperature of the deposit in different though very close settings. Note that T°C at the base of the incoming PDC is everywhere ~350°C, similar to that of the deposit unless mixing with either debris or water occurs during emplacement.

498

499 Figure 8: Reconstruction of the progressive destruction and burial of the Villa dei Papiri;

stratigraphic units according to Gurioli et al. (2002); chronology according to Sigurdsson et
al (1982). See text for explanation.

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- 503
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Eruption Site Unit ^a		6dV	EU4pf VP3		VP5-10	VP5-7	VP5-5	EU3pf VP5-3	VP5-1	VP2	VP1	VP6	EU2/3pf VP8	VP4	^a According to Cioni

Table Click here to download Table: Table 2 physical properties.pdf

	initial T (°C)	density (kg/m3)	thermal conductivity (W/m-K)	Specific Heat (J/kg K)
ignimbrite	350	1200	0,7	1200
wall	20	2000	1	980

Foglio1

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