Influence of town on PDC temperature

Influences of urban fabric on pyroclastic density currents at Pompeii (Italy), part II: temperature of the deposits and hazard implications

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During the AD 79 eruption of Vesuvius, Italy, the Roman town of Pompeii, was covered by 2.5 m fallout pumice and then partially destroyed by pyroclastic density currents (PDCs). Thermal remanent magnetization (TRM) measurements performed on the lithic and roof tile fragments embedded in the PDC deposits allow us to quantify the variations in the temperature ($T_{dep}$) of the deposits within and around Pompeii. These results reveal that the presence of buildings strongly influenced the deposition temperature of the erupted products. The first two currents which entered Pompeii at a temperature around 300-360 °C, show drastic decreases in the $T_{dep}$, with minima of 100-140 °C found in the deposits within the town. We interpret these decreases in temperature as being the result of localized interactions between the PDCs and the city structures, which were only able to affect the lower part of the currents. Down flow of Pompeii, the lowermost portion of the PDCs regained its original physical characteristics, emplacing hot deposits once more. The final, dilute PDCs entered a town that was already partially destroyed by the previous currents. These PDCs left thin ash deposits which mantled the previous ones. The lack of interaction with the urban
fabric is indicated by their uniform temperature everywhere. However, the relatively high
temperature of the deposits, between 140 and 300 °C, indicates that even these distal, thin ash
layers, capped by their accretionary lapilli bed, were associated with PDCs that were still hot
enough to cause problems for unsheltered people.

KEYWORDS: Pompeii, temperature, magnetic fabric, pyroclastic density currents.

1. Introduction

Pyroclastic density currents (PDCs) are the primary cause of death during explosive eruptions
[Tanguy et al., 1998]. These currents are hot mixtures of gas, pumice and lithic fragments, ranging
in size from fine ash up to metric blocks and bombs [e.g. Freundt and Bursik, 1998; Druitt, 1998].
In the proximal locations their destructive effect is mainly due to their high momentum and
temperature [e.g. Baxter et al., 2005]. In distal locations, where the currents have already lost a
large portion of their solid load, their hazard is associated with their high concentration in fine ash
[e.g. Horwell and Baxter, 2006], coupled with their high velocity and temperature [e.g. Todesco et
al., 2002]. Thus, in order to assess the hazard posed by PDCs to human populations, it is extremely
important to understand PDC dynamics and their physical characteristics. In addition, educational
efforts, based on scientific analyses of PDC emplacement and their effects, will likely improve the
chances of survival of, or correct response to, future eruptions.

Observations made in villages and areas devastated by PDCs report evidence of sudden death
and survival among groups of people sheltering in the same house and even in the same room, as
during the eruption of Mt. Pelée, Martinique, in 1902 [Anderson and Flett, 1903,]. There is also
evidence for survival of certain individuals, when the majority of people in area impacted by PDC
were killed, as for example during the 1980 eruption of Mt St Helens (USA) [Bernstein et al., 1986]
or during the dome-collapse-fed pyroclastic flows of 1991 at Mount Unzen [Baxter et al., 1998]. In
addition, during the 1902 eruption of Mt. Pelée un-burnt material was found in close proximity to
incinerated objects [Lacroix, 1904]. The variable impact PDCs on human populations has been
explained at Montserrat in terms of survivors being located in areas marginal to the PDCs [Baxter et al., 2005]. However, this explanation cannot be applied for unconfined, diluted PDCs, as shown by Gurioli et al. [2005]. Further investigations are thus required if we are to understand these local variations in PDC dynamics, and how a PDC interacts with a town and its human population.

We attempt to resolve this issue through analysis of the PDC deposits of the AD 79 eruption of Vesuvius (Italy) which crop out within and around the Roman town of Pompeii. All PDCs that entered the town, even the most dilute ones, were density stratified currents whose lower part interacted with the urban fabric [Gurioli et al., submitted]. We use a combination of thermal remanent magnetization (TRM) and anisotropy of the magnetic susceptibility (AMS) analyses to obtain information regarding flow direction of these parent currents and deposit temperatures. These data, when integrated with volcanological field investigations, reveal that the presence of buildings strongly affected the distribution and accumulation of the erupted products; where the results of our analyses from the single, most destructive unit in the sequence have been presented in Gurioli et al. [2005]. Here, we build on these previous findings by now considered the TRM results from the entire eruptive sequence cropping out within and around Pompeii to infer the temperature of all of the deposits. This allows us to assess the cooling effect of the urban fabric on these currents and the effect of these currents on the inhabitants.

2. Volcanological setting and sampling

Pompeii is located 9 km southeast of Vesuvius (Figure 1) and the following reconstruction of events during the AD 79 eruption at that location is based on the analysis of Sigurdsson et al. [1985], Carey and Sigurdsson, [1997] and Cioni et al. [2000]. The town first experienced 7 hours of air fall comprising white pumice, lapilli and bombs (up to 3 cm in diameter), with scarce lithic blocks of up to 3 cm in diameter. This emplaced unit EU2 (Figure 2). The town then underwent 18 hours of grey pumice, lapilli and bombs (up to 10 cm in diameter) fallout to emplace EU3 (Figure 2); a deposit that is rich in lithic blocks of up to 7 cm
in diameter. During this Plinian phase, some PDCs were generated by the discontinuous collapse of marginal portions of the convective column. Only the last of these events (EU3pf1, Figure 2) was able to reach the north-western edge of Pompeii, but did not enter the town itself. This PDC left only a 2-3 cm thick ash layer interbedded with the fallout deposit. The town was then completely covered by a 5-30 cm thick ash layer (EU3pf, Figure 2) emplaced by very dilute PDCs, derived from the total collapse of the Plinian column. Locally EU3pf was able to interact with obstacles of a few decimetres in height, suggesting that its denser, thin lower part was capable of only filling minor negative depressions [Gurioli et al., submitted].

EU3pf was next mantled by a 3-6 cm thick, lithic rich (blocks up to 3 cm in diameter), grey pumice, lapilli and bomb (up to 3 cm in diameter) fall deposit (EU4, Figure 2), emplaced from a second, short-lived, lithic-rich column. The collapse of this second column generated the most powerful, turbulent, PDC of the eruption. This was able to partially destroy the town and left relatively coarse-grained, cross stratified, meter-thick deposits (EU4pf, Figure 2). EU4pf was able to interact with obstacles of a few meters in height, showing significant interaction with the town [Gurioli et al., 2005].

Finally, the settlement was buried by a 1 m thickness of very dilute PDC and air-fall deposits (EU7 and EU8, Figure 2) consisting of ash and accretionary lapilli emplaced during the last, phreatomagmatic phase of the eruption. The EU7 sequence (Figure 2) comprises two centimetre-thick grain supported, lithic-rich lapilli beds, separated by a 1-to-3-cm thick cohesive ash layer, and capped by a coarse ash layer, which is in turn covered by a massive pisolite bearing fine ash bed. EU8 then comprises an alternation of normally graded, ashy bedsets, each up to 10 cm thick (Figure 2). Each bedset is characterised at its base by a massive-to-crudely stratified facies followed by accretionary lapilli facies. In general, the EU7 and EU8 deposits mantled a town that had already been severely damaged by the preceding currents (mainly EU4pf) [Gurioli et al., submitted].
Within this sequence we sampled undisturbed sites in open country around the city, as well as sites along the city walls and within the town, both along the roads and inside the rooms (Figure 1). As described in *Gurioli et al.* [2005] we collected lithics and stripped roof tiles on which we could perform TRM analyses. At least 5 lithic or tile fragments were collected from each unit at each site giving a total of more than 200 samples. The tile fragments and the larger lithic clasts (Figure 3) were first oriented using clinometer, magnetic compass and, whenever possible, sun compass, before being removed from the outcrop. Usually two specimens were cut from individual fragments to improve accuracy in the estimate of the deposition temperature interval. The great majority of lithic clasts in the AD 79 deposits, and thus around 70% of our samples, are fragments of a few mm in dimension (Figure 3). They were considered as un-oriented samples, because their small size prevents accurate orientation. The presence of fragments of plaster and roof tiles picked up and heated by the PDCs makes the Pompeii deposits particularly suitable for such a study. As already discussed in *Evans and Mareschal* [1986], *Marton et al.* [1993], *Zanella et al.* [2000] and *Cioni et al.* [2004], building fragments within the deposits are reliable magnetic thermometers, because they were cold when they were picked up by the PDC.

3. Measurement of deposition temperature using TRM

The thermal remanent magnetization (TRM) acquired during the cooling of a magmatic rock records the polarity, direction and intensity of the Earth’s magnetic field at the time of cooling. Such paleomagnetic information is widely used in geodynamics and stratigraphy. However, thorough investigation of the TRM features may yield information on the physical processes which led the remanence acquisition and help in understanding the emplacement mechanisms of magmatic rocks. This applies to pyroclastic deposits, whose formation results from combination of thermal and sedimentological processes. Paleotemperature investigation of pyroclastic rocks, emplaced by PDCs, was pioneered by *Aramaki and Akimoto* [1957] and *Chadwick* [1971]. Their
assumption was straightforward. If a deposit was emplaced hot (where hot means at higher temperature than the Curie point of magnetite), then the primary remanence of the embedded lithic fragments would have been erased. A secondary remanence was then re-acquired during the subsequent cooling. All fragments were magnetized at the same time and their TRM directions are therefore well clustered. In contrast, if the emplacement temperature was cold each fragment would have retained its own primary TRM acquired when the parent rocks formed. In this case, the TRM directions are randomly distributed because of the chaotic movements during emplacement.

Following Chadwick [1971], Hoblitt and Kellog [1979] applied a more quantitative procedure, based on thermal demagnetization of the fragments. This technique allows derivation of the TRM blocking temperature ($T_b$) spectrum and thus identification of the distinct TRM components acquired in different temperature ranges, usually referred to as high-$T_b$ and low-$T_b$ components. Such an analysis yields an estimate of the actual temperature reached by the fragment upon re-heating within the pyroclastic material, this being the maximum unblocking temperature ($T_{b_{max}}$) of the low-$T_b$ component.

Further work has improved this methodology [e.g. McClelland and Druitt, 1989; Bardot, 2000] and have revealed some complications to the initial assumptions. According to the simplest model, paleomagnetic estimates of the deposition temperature relies on two basic assumptions:

1) During PDC transport and deposition heat is transferred from the hot gas and fine-grained material to the cold clasts. For clasts larger than 2-5 cm, thermal equilibrium is mainly reached during residence in the deposit rather than the emplacing current. In fact, the time required to reach thermal equilibrium within the current is longer than the time of residence in the flow [Cioni et al., 2004]. For this reason, rock magnetic investigations give an estimate of the deposit temperature ($T_{dep}$) rather than the emplacement ($T_{emp}$) temperature.

2) The clasts’ remanence is a pure thermal remanent magnetization (TRM).
In cases where these assumptions are fulfilled, the natural remanent magnetization (NRM) of a clast consists of two TRM components characterized by different blocking temperatures ($T_b$). The high-$T_b$ component pre-dates the PDC emplacement. This was acquired when the lithic clast was originally formed. A part of this remanence is erased when the clast is re-heated within the PDC and then acquired as low-$T_b$ component when the PDC comes to rest and cools down. Considering the full $T_b$ spectrum of the clast, $T_{b\text{max}}$ is the temperature value which separates the two components. It can be identified by stepwise thermal demagnetization because the directions of the two components are different (Figure 4). The low-$T_b$ direction is close to that of the geomagnetic field at the time of the PDC emplacement, and it is the same in all clasts. The high-$T_b$ direction is fully random. According to the first assumption above, $T_{\text{dep}}$ may thus be derived from the mean $T_{b\text{max}}$ value derived from a number of clasts.

Estimation of $T_{\text{dep}}$, however, is not always as straightforward as in the above case [Grubensky et al., 1998]. The first problem is that we do not know the thermal history of the clast. It might have been either picked up cold along the slopes of the volcano, or ejected hot from the conduit, possibly being even hotter than the PDC within which it became entrained. In the second case, when the current stops the lithic fragment is still hotter than the surrounding fine-grained matrix and the $T_{b\text{max}}$ value found from rock-magnetism will be higher than $T_{\text{dep}}$.

The second problem concerns NRM which, in addition to the thermal (TRM) components, may also comprise chemical (CRM) and viscous (VRM) components. It has been shown by McClelland [1996] that a chemical remanence (CRM) may develop due to mineralogical changes during reheating. This will hinder the identification of the low-$T_b$ and high-$T_b$ components (Figure 4b). VRM is typical of ferromagnetic grains with low relaxation time, and thus low blocking temperature. According to theory [Pullaiah et al., 1975, Bardot and McClelland, 2000] a VRM component acquired at 20 °C in the course of the ~1930 years elapsed since the AD 79 eruption, is erased by heating at 125 °C in a time of 25 to 30 minutes, typical of a thermal demagnetization step in the laboratory. It may thus be indistinguishable from
very low $T_b$ secondary components. Moreover, a small VRM overprint often occurs in most rocks. The presence of a VRM overprint could partially affect identification of the true, low-$T_b$ TRM component and hamper the determination of its direction by principal component analysis \cite{Kirschvink1980}.

The problems outlined above do not always occur and when they do they can often be overcome. In the case of the Vesuvius AD 79 eruption, archaeological remains are of great help. Bricks and tiles, which have their own TRM typical of baked-clay artefacts, were picked up by PDCs at the ambient temperature and could not be heated at values higher than $T_{dep}$. The problems with CRM are also reduced sampling clasts of as different lithologies as possible, because different lithology means different magnetic properties.

In conclusion, the various clasts collected at an individual site may have had different thermal histories and have recorded more or less faithfully the $T_{dep}$. Following the approach of Cioni et al. \cite{2004}, the thermal overprint of a group of clasts by a PDC is better represented by what they have in common. The $T_{bmax}$ values derived from each individual clast may differ from each other because of the reasons summarized above, whereas the re-heating was a single event. The traces it left, $T_{dep}$, must be consistent at the site scale.

4. Standard measurements and peculiar cases

A total of 379 specimens were measured at the ALP laboratory (Peveragno, Italy) using a JR-5 spinner magnetometer, and Schonstedt and ASC TD-48 thermal demagnetizers. Small bits were measured using the plastic box + Plasticine technique of Cioni et al. \cite{2004}. Thermal demagnetization was carried out in steps of 40 °C between a starting temperature of 100 °C and a maximum of ~520 °C. Whenever sister specimens from individual clasts were available, a second demagnetization was carried out using the same 40 °C steps but starting at 80 °C. The data were then interpreted using the principal component analysis available as part of the Paleomac program \cite{Cogne2003}. 8
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On the basis of the demagnetization patterns, Cioni et al. [2004] distinguished four kinds of thermal behaviour in clasts embedded within the AD 79 PDC deposits. Type A is characterized by blocking temperatures higher than $T_{\text{dep}}$ and its primary TRM is therefore not affected by the re-heating. Type B has blocking temperatures lower than $T_{\text{dep}}$ and its primary TRM is completely erased during the re-heating. Type C is the archetype of lithic clasts with a TRM comprising two components with distinct $T_b$ spectra, which are well evident in the Zijderveld diagrams (Figure 4a). In Type D the two components are not very clear because the spectra more or less overlap, show a zigzag pattern, or have points that are too close to each other to be well distinguished (Figure 4b). Identification of $T_{\text{bmax}}$ is thus straightforward in Type C, more complicated in Type D. A similar classification was adopted by McClelland et al. [2004] whose Types 1a, 1b, 2 and 3 respectively correspond to the Types C, D, A, B types of Cioni et al. [2004]. In the present paper, we add Type E, which comprises a few tile fragments which show no evidence of re-heating. The normalized intensity decay curve (Figure 4c) shows that a fraction of their ferromagnetic grains have low blocking temperatures. The clasts NRM directions, however, do not change throughout demagnetization up to the highest values close to the Curie point and are different from that of the ambient field in AD 79. In the example, the direction of the characteristic remanent magnetization (ChRM), calculated using all steps and with maximum angular deviation MAD = 1° (Figure 4c), is $D = 356.5°$, $I = 2.3°$, where D is declination and I inclination. We have no explanation for the occurrence of these clasts and can only consider them as outliers, but which bear witness to the fact that the temperature distribution within thin pyroclastic deposits is far from uniform and can in fact be highly variable.

The pie diagram in Figure 5 summarizes the per cent occurrence of the five types in all clasts investigated in the present paper. Type C accounts for about 50 % of the clasts, Type D for about 45%, with the remainder are either being Type A or E. No Type B clasts were found in the present investigation.
An uncommon case is given by the plaster fragment sampled at site 18 (Figure 1). Hueda-
Tanabe et al. [2004] have shown that plaster may be used as archaeomagnetic material. Small
ferromagnetic grains are free to move when plaster is applied to a wall or floor, orienting their
magnetic moment parallel to the Earth’s magnetic field and then being blocked when the plaster
dries. The vector sum of the NRM of a plaster specimen is thus given by the NRM of its
individual grains. The process is similar to the orientation of the grains of ferromagnetic
pigments in red coloured murals, which also have been shown to record the ambient field
direction at the time of painting [Zanella et al., 2000]. The plaster sampled at Pompeii is a kind
of pozzolana, one of the most outstanding results of Roman civil engineering. It was made from
lime and grains of volcanic rocks from the sandy deposits of neighbouring rivers. A large
fraction of grains are 1-2 mm in size (Figure 6a), too large to be effectively oriented by the
Earth’s field. Thus, it can reasonably be assumed that the remanence direction varies from grain
to grain. At a first glance the thermal demagnetization diagram looks quite odd (Figure 6b).
Because each grain has its own $T_b$ spectrum, thermal demagnetization erases different fractions
of remanence in grains with different TRM directions, so that the direction of the resultant vector
varies randomly from one step to another, without any coherence. However, the low-temperature
demagnetization steps show a linear trend in the initial part of the Zijderveld diagrams (up to
180-200 °C in Figure 6b). This suggests that, in each individual grain, the fraction of remanence
with $T_b < T_{dep}$ was erased when the plaster was re-heated to the $T_{dep}$ of the pyroclastic material
filling the room and burying the walls. During cooling, all grains re-acquired a low-$T_b$
component showing the same direction, i.e. that of the Earth’s field, which is therefore coherent
throughout the specimen.

Another peculiar case is that of the lithics embedded in the fall deposits. The 16 lithics we
sampled were characterized by three TRM components: these being the expected high- and low-
$T_b$ components, as well as an intermediate-$T_b$ component with a distinct direction around
temperatures of 340 to 480 °C (Figure 7). No evidence for an intermediate-T_b component was found in the tile fragments embedded in these deposits.

As discussed in the previous section, most of our samples were fragments too small to be oriented in the outcrop. Out of a total of 379 specimens, 145 were oriented and 75 gave two clearly isolated components whose directions could be transformed to the geographical reference system. The directions of the high-T_b component were widely scattered, as expected (Figure 8); those of the low-T_b were more clustered. The site mean ChRM direction (D = 350.4°, I = 61.8°, Fisher’s semi-angle of confidence $\alpha_{95} = 7.4°$) is close to the AD 79 Earth’s magnetic field direction as given by archaeomagnetism [Tema et al., in press], even if its statistical definition is lower than usual in paleomagnetic investigations. This is often the case in paleotemperature investigations [McClelland et al., 2004; Tanaka et al., 2004]. In our case, this is mainly due to the fact that the analysis of the low-T_b component relies on few clustered points due to the low rate of decrease in the intensity of magnetization. Furthermore it may also be biased by a VRM. Even if the low-T_b directions of individual clasts show some dispersion, their overall mean (D = 352.0°, I = 53.7°, number of specimens N = 75, length of the resultant vector R = 69; $\alpha_{95} = 4.9°$) passes the Watson [1956] randomness test and is consistent with the archaeomagnetic direction (D = 354.3°; I = 58.0°; $\alpha_{95} = 1.7°$) derived from various materials studied at Pompeii (archaeological remains, fine-grained pyroclastics, lithic clasts) [Evans and Hoye, 2005; Tema et al., in press and references therein].

Final estimation of paleotemperature was completed following the technique of Cioni et al. [2004]. For each site and each eruptive unit, first the temperature interval which contains the maximum unblocking temperature ($T_{b_{\text{max}}}$) of the low-T_b component of each individual clast was derived from the demagnetization path. This was done by analysis of the normalized intensity decay curve, the Zijderveld diagrams and the equal-area plot of directions. As a conservative approach, directions separated by less than 15° were not considered as significantly different [Porreca, 2004], because a small angular deviation might be due to post-depositional settling of
the fragment within the still unconsolidated rock. $T_{dep}$ of each site and eruptive unit was then estimated from the overlap range of the temperature intervals of the individual fragments (Figures 9a, 9b, 9c1, 9c2, 9c3 and 9d).

5. The temperature of the AD 79 deposits around and within Pompeii

In the following discussion we present our data for the whole eruptive sequence present in Pompeii, unit by unit (Figures 9a, 9b, 9c1, 9c2, 9c3 and 9d). Where ever possible, we compare these results with the data obtained for the same units cropping out around Vesuvius by Cioni et al. [2004].

5.1 The fallout sequence (EU2-EU3 and EU4)

We collected just a few samples from the three main fallout deposits (EU2-EU3 and EU4), mostly to check whether they were emplaced hot and whether they were able to maintain a temperature high enough to heat artefacts. As already shown by several authors [e.g. Thomas and Sparks, 1992; Tait et al., 1998; Hort and Gardner, 2000] pumice clasts larger than 6 cm in diameter suffer little heat loss during their fall and can be emplaced at temperatures within 10-20% of their magmatic temperature [Thomas and Sparks, 1992]. Thus Plinian deposits, depending on their grain size, thickness and distance from the vent, can remain sufficiently hot to pose hazards to life and property [Thomas and Sparks, 1992]. For the fallout deposits in Pompeii, we found that the white fallout deposit had a temperature high enough to warm the tiles up to 120-140 °C (Figure 9a). Unfortunately, we could not collect any artefacts in the grey fallout, EU3, but we can assume that this deposit was even hotter than the white one, because of its coarser grained texture.

Within both the EU3 and EU4 fall deposits we also sampled lithic blocks. As previously discussed, all these lithics are characterized by three components (Figure 7). We assume that, while the high-$T_b$ component was acquired during clast formation, the low-$T_b$ component represents the temperature of the lithic at the point at which it fell to the ground. If this
hypothesis is correct the lithic fragments reached Pompeii at a minimum temperature of 180-220 °C during the EU3 fallout and 220-260 °C during the EU4 fallout (Figure 9a). We do not fully understand the meaning of the intermediate temperature component. It may represent heating during passage as part of the gas-thrust section of the plume and/or cooling experienced in the umbrella portion of the plume.

5.2 The first PDC entering Pompeii (EU3pf)

EU3pf deposits were sampled around and within Pompeii (Figure 10a). They show a large variation in their $T_{dep}$, ranging from 140 to 300 °C (Figures 9b and 10a). Nowhere else around Vesuvius do we find such high variability in EU3pf deposit temperatures [Cioni et al., 2004] (Figure 10b). Even the coldest outcrops located north of Vesuvius are relatively warm in comparison to those within Pompeii (Figure 10).

EU3pf in Pompeii shows the highest $T_{dep}$ (240-300 °C) in the northern sector (Figures 9b and 10a), outside the town. However, these values are lower than the 300 to 360 °C values obtained for the EU3pf deposits emplaced upstream of Pompeii, in the proximal sector (Figure 10b). We explain these results as the consequence of uniform cooling experienced by the current at this distance from the vent, due to the reduction of its total load which will decrease its thermal energy.

Lowest temperatures were recorded within the town and in the western sector, where $T_{dep}$ drops to 140-220 °C. Slightly higher values have been found in rural areas south of Pompeii, where the $T_{dep}$ is 220-260 °C [Cioni et al., 2004] (Figure 9b and 10a). These temperatures show that the EU3pf current, even if diluted and capable of only emplacing thin deposits, entered Pompeii with a minimum temperature of 260-300 °C. The decrease in temperature within Pompeii, indicates that the local interaction with the city structures had a cooling effect on the lower part of the current. South of Pompeii, the EU3pf current was unable to restore the same temperature it had before entering Pompeii, but it was still able to emplace hotter deposits than found within Pompeii with temperatures of up to 220-260 °C.
5.3 The most powerful PDC (EU4pf)

Temperature data obtained from the thick deposits of EU4pf display the largest variability in temperature at the scale of individual sampling sites, ranging from 100 to 320 °C (Figures 9c1, 9c2, 9c3 and 11a). These values differ from those obtained from the same deposits in non-urban areas around the volcano, (Figure 11b). In such non-urban locations, all sites yield temperatures of around 300°C (260-340 °C), irrespective of their distance from the vent [Cioni et al., 2004]. This relatively uniform temperature suggests a substantial homogeneity of the transport system of the EU4pf deposits in the Vesuvius area [Cioni et al., 2004].

In contrast, a large decrease in temperature occurs within Pompeii. In sites examined orientated along the axis of the flow direction (from the northwest edge of the city towards its southern edge), temperatures generally decline. As found for EU3pf, EU4pf also has highest T_{dep} values in the northern sector of Pompeii, where the T_{dep} range from 240 to 320 °C, with an average value of around 280 °C. A low value of 200-240 °C was found up flow the Villa dei Misteri, at site 2a (Figure 11a). We speculate that this anomalous value may be due to the presence of some structure up flow of this area, or some morphological high, not now visible because is covered by the deposits and the modern soil and vegetation.

Inside the town T_{dep} ranges from 100 to 220 °C, with an average value of 160 °C. Here the lowest values are found in three rooms with collapsed roofs, aligned parallel with the main flow direction. The lowest value that we found is located in the third of these three rooms, i.e. the furthest down flow [Gurioli et al., 2005]. These low values are consistent with cooling due to strong disturbances caused by the town and morphological features, such as the 3-meter-deep cavities presented by rooms with collapsed roofs (Figure 11a, sites 10, 12a and 12b), the 10-m-high cliff on the southern edge of the town (Figure 11a, sites 22c and 25), or collapsed walls (Figure 11a, sites 11 and 16). Down flow of the city walls, where there are no morphological or urban disturbances, the deposit temperatures are high once more (Figure 11a, sites 22a, 22b, 19a and 19b).
These results show that the presence of the settlement resulted in substantial cooling of the current over short distances. Roughness of the topographic/depositional surface increases the ability of the basal portion of the flow to decouple from the main flow and to form local vortexes, ingesting ambient air. Increases in turbulence, due to the surface irregularities caused by the presence of the town, are evident from upstream particle orientations which develop down-flow of obstacles or inside cavities [Gurioli et al., 2005] and from characteristic sedimentary structures such as fines-poor, undulatory, lenticular bedded facies on the lee side of the obstacles [Gurioli et al., submitted]. This would also cause air ingestion. Air ingestion into the lower system of the EU4pf current during passage over the urban canopy is the most reasonable cause of the observed strong temperature decreases. As shown in Cioni et al. [2004], the very high thermal diffusivity of air with respect to magma, and the intimate mixing between the air and gas-ash mixture, results in instantaneous thermal equilibrium during this process. Furthermore, the EU4pf current lasted for 8-10 minutes [Gurioli, 1999]; because we witness cooling this interval of time must be sufficient for the lower part of the current to entrain air and undergo cooling.

The amount of building material entrained by the current seems not to play an important role in cooling of the deposits, where we found no correlation between low temperatures and amount of building material. Furthermore, tile-fragment-rich zones within EU4pf deposits are present as small lenses (around 1-2 m long, 1 m high and less than 1 m wide) which probably did not have sufficient volume or extent to cool the deposits.

The roof tiles have very high thermal conductivity, as a result they will heat up very quickly. We estimate the characteristic time it takes to heat a cool object (roof tile) buried in a hot medium (the deposit) from \( \tau = D^2/\alpha \), in which \( D \) is the object dimension and \( \alpha \) is the thermal diffusivity of the object. Thermal diffusivity is calculated using the density and specific heat capacity for common brick [obtained from Holman, 1992], as well as the temperature dependent thermal conductivity which we calculate for clay following Vosteen and Schellschmidt [2003].
This gives $\tau$ of ~1 minute for our smallest (1 cm) objects, increasing to ~1.5 hours for our largest (10 cm) objects for heating from ambient to 200-400 °C. This means that all of our objects should have equilibrated with the temperature of the deposit within 1.5 hours, with the smallest objects reaching equilibrium in just a few minutes. Thus, although individual tile fragments entrained within the deposit were heated quickly, they robbed insufficient thermal energy from the surrounding hot body to cause significant cooling.

As shown in Gurioli et al [submitted], the urban canopy encouraged deposition and the upper portion of the current was not able to fully restore the sediment supply to the lower current. Our temperature results also show that the increase in surface roughness caused by the presence of the town caused strong variations in temperature. However, these variations were short-lived and confined to the lower part of the current. South and south east of Pompeii, at distances of up to 8 km from the town, EU4pf was able to emplace hot deposits once more [Cioni et al., 2004] (Figure 11b).

5.4 The final PDCs (EU7 and EU8)

Temperature data obtained from the thin deposits of EU7 and EU8 display the lowest variability in temperature at the scale of individual sampling sites. In EU7 we sampled the ash interlaid between the two lapilli beds (Figure 2d). This gives a temperature of between 210 and 260 °C, in agreement with the temperature range (180-240 °C) found by Cioni et al. [2004] between the vent area and Pompeii for this deposit. The second ash layer shows a highest temperature of 260-300 °C at Site 1 (Figure 12) but around and within Pompeii $T_{dep}$ ranges from 180-260 °C, without showing strong variations within the city. This behaviour agrees with a scenario within which there was interaction between this current and a town that was already partially covered by the previous deposits [Gurioli et al., submitted].

EU8 was sampled at just one site because we had difficulties in finding lithic fragments large enough to be suitable for measurement. It displays a $T_{dep}$ of 180-220 °C. A fragment of tile was also collected at site 16 (Figures 9d and 12) within the coarse grained ash layer of this
deposit. Even if the top of the deposit shows evidence of water condensation, the deposit at the base had a temperature able to heat the tile up to 130-180 °C.

6. Implications for volcanic hazard

In the early afternoon of August 24 AD 79 a pumice fall began which lasted until early in the morning of the following day. During this period Pompeii was covered by 3 meters of pumice. Within 6 hours the roofs and parts of the walls of the buildings had collapsed under the pumice load [Sigurdsson et al., 1985; Luongo et al., 2003a]. Luongo et al. [2003a, b] identify a significant number of victims within this deposit (38 % of the total number of victims, estimated to be about 1150). They probably died as a consequence of building collapse. Our new data reinforce this reconstruction, where we find that these deposits were emplaced with sufficient heat to be able to heat cold materials to 140 °C. We can therefore speculate that in some sites they could have been capable of causing damage by carbonisation of wood, such as roof beams, and skin burn upon direct contact. This hazard scenario was made even more dangerous by the scattered rain of large, very hot, lithic blocks.

In the early morning of August 25, the PDCs started to enter and devastate Pompeii [Cioni et al., 2000]. In Pompeii, features of both EU3pf and EU4pf show that the two currents were able to interact with the urban structures even in the first, very dilute case, suggesting that the currents were stratified, and capable of interacting with objects of the same height as the thickness of their depositional systems [Gurioli et al., submitted]. EU3pf interacted little with the fabric of the town, due to its very thin depositional system. However, its content of fine ash and relatively high temperatures would have made it hazardous to the human population, causing asphyxia and lung damage. Recent studies [Luongo et al., 2003a, b] suggest that the first diluted PDC (EU3pf) caused minimal damage in Pompeii. This is true for the building structures, but our evidence indicates that even this current was extremely dangerous for the inhabitants [Cioni et al., 2000]. Here we have been able to quantify this hazard, where the hazard results from the
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Temperature of this current and its composition of fine ash. Although the current left only a thin deposit, the current itself had a thickness of more than 10 m (the height of the ridge on which Pompeii was built). Furthermore, the current was hot, with a temperature of 140-300 °C. This temperature would have been very close to the average temperature within the current at Pompeii, an assumption made plausible by the abundance of fine-grained fragments that comprised the PDC at this distance from the vent [Cioni et al., 2004]. Finally, the grain-size of the EU3pf deposits indicates that 40-50 % of its mass was accounted for by particles of less than 0.1 mm in diameter [Gurioli et al., submitted]. Such a size represents dust that can be inhaled by humans. Assuming a minimum fractional particle volume concentration of about 1-5 x10^{-4} for this current and a minimum bulk density of 1000 kg/m^3 for the particles [Freundt and Bursik; 1998], the concentration of fine materials is between 0.03 and 0.15 kg/m^3. These values fall within the concentration range for inhalable dust capable of causing asphyxia [0.1 kg/m^3, Baxter et al., 1998] at ordinary temperatures. A temperature of 200 °C and ash concentration of 0.1 kg/m^3 are considered threshold values above which human survival is likely to be impossible [Baxter et al., 1998]. Furthermore this atmosphere would have persisted for several minutes, as suggested by the low terminal velocity of the fine particles and the aggradational model proposed for this current [Gurioli, 2000; Gurioli et al., submitted]. Thus, this PDC was extremely hazardous and, following Baxter et al. [1998], would have led to asphyxia and severe lung damage.

Invasion of Pompeii by EU4pf was almost instantaneous. If we assume flow velocities of 50-60 m/s [Esposti Ongaro et al., 2002], in agreement with the average mean grain size of the deposits [Gurioli et al., submitted], the EU4pf front took less than 10 s to cross the town. This second, more concentrated current had a more profound influence on the town. Its dense depositional system, coupled with its high velocity, was able to tear down some walls orientated at right angles to the main flow direction (i.e. east-west trending structures). This is in agreement with masonry vulnerability of the old Pompeii buildings that fall in the range of 1-5 kPa.
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[19] Nunziante et al., 2003] and simulated dynamic pressures of 1 kPa calculated for a PDC with a mass effusion rate of $5 \times 10^7$ kg/s and at a distance of 7.5 km from the vent [Esposti Ongaro et al., 2002]. The case of EU4pf is more clear-cut, in that it would have been completely lethal for any inhabitants surviving the previous PDC, a consequence of its high velocity, density, mass and temperature.

The final, dilute PDCs entered a town that was already partially destroyed by the previous currents. At this stage of the eruption, all the remaining population were dead [Sigurdsson et al., 1985; Cioni et al., 2000; Luongo et al., 2003a]. These currents just mantled the ruins left by EU4pf without inflicting further damage upon the buildings. However, even though these currents caused no further damage to Pompeii and its population, our data are significant in that they show that even distal, thin ash layers can be emplaced by currents that are still hot enough to cause problems for unsheltered people.

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Figure captions

Figure 1. Ancient Roman town of Pompeii. Dots = sites of studied sections; light areas = portions of ruins still buried by undisturbed AD 79 deposits. Inset upper right, shaded relief map of the of Vesuvius region.

Figure 2. AD 79 deposits at Pompeii. On the left, the schematic stratigraphy according to the nomenclature of Cioni et al. [1992, 2004]. The numbers in the brackets are the variation thickness of the studied deposits. From a) to d) particulars of the deposits within and around Pompeii (see figure 1 for site location). (1) White pumice lapilli and bombs. (2) Grey pumice lapilli and bombs. (3) Massive to stratified coarse-grained ash and grey pumice lapilli. (4) Accretionary lapilli in in coarse and fine ash matrix.
Figure 3. Hand sampling of lithic fragments and roman tiles from the PDC deposit matrix. The orientation of the main face of the tile is traced. Inset: standard paleomagnetic specimens and little bits embedded in the plasticine.

Figure 4. Stepwise thermal demagnetization of lithic clasts from the AD 79 deposits: a) type C clast; b) type D clast; c) type E clast (see text for further explanation).

Left: Zijderveld diagrams. Symbols: full dot = declination; open dot = apparent inclination.
Right: equal-area projections of the directions of magnetization. Symbols: full/open dot = positive/negative inclination. Directions in the Zijderveld diagrams are represented in the sample reference system; in the equi-areal projections the geographic reference system is used.

Figure 5. Pie diagram of the percentage occurrence of different types of fragments (see text for further explanation).

Figure 6. Stepwise thermal demagnetization of a plaster specimen from the AD 79 deposits.

a) plaster bit (front and transverse section).
b) normalised intensity decay curve and Zijderveld diagram of specimen T19a. Symbols as in Fig. 4.

Figure 7. Zijderveld diagrams of specimens of ballitic blocks from the fall-out deposit. For symbols see figure 4.

Figure 8. Equal-area projection of high-T_b (HT) and low-T_b (LT) component directions of the oriented specimens from EU4 pf at site 12a. Symbols: full/open dot = positive/negative inclination; star = site mean direction with α_95 confidence ellipse.
Figure 9. Evaluation of the AD 79 deposits temperature ($T_{\text{dep}}$), by overlap of individual fragments reheating temperature range (see text for further explanation). Types are shown left of the bar. Color: black = lithic fragment (mainly lavas); grey = tile; black dot = plaster.

a) EU2, EU3 and EU4 fall deposits.

b) EU3pf deposits

c) EU4pf deposits

d) EU7pf I ash, EU7pf II ash and EU8 deposits.

Figure 10. $T_{\text{dep}}$ variation of EU3pf:

a) within and around Pompeii.

b) around the Vesuvius area [modified from Cioni et al., 2004].

Figure 11. $T_{\text{dep}}$ variation of EU4pf:

a) within and around Pompeii.

b) around the Vesuvius area [modified from Cioni et al., 2004].

Figure 12. $T_{\text{dep}}$ variation of EU7pf I ash, EU7pf II ash and EU8, within and around Pompeii.

Figure 13. Destructive effects of the AD 79 deposits in Pompeii: a) collapsed roof tiles in the fall-out deposit (photo courtesy Soprintendenza di Pompeii); b) skeletons in the ash deposits inside a room (photo courtesy Soprintendenza di Pompeii); c) collapsed wall by EU4pf; d) bodies rolled in EU4pf deposits. In c) and d) the arrow indicates the main flow direction.
The AD 79 sequence in the Pompeii area (site 7)

EU2-EU3 (site 13)

EU3pf-EU4pf (site 12)

EU7-EU8 (site 8)
a) Specimen: L74a
EU4pf (Site 1)

b) Specimen: L73g1
EU3pf (Site 1)

c) Specimen: T48a
EU4pf (Site 10)