Geophysical Journal International

Geophys. J. Int. (2015) **203,** 33–47 doi: 10.1093/gji/ggv267

GJI Geomagnetism, rock magnetism and palaeomagnetism

Palaeomagnetic analysis on pottery as indicator of the pyroclastic flow deposits temperature: new data and statistical interpretation from the Minoan eruption of Santorini, Greece

E. Tema,[1,2] E. Zanella,[1,2] F.J. Pavón-Carrasco,[3] D. Kondopoulou[4] and S. Pavlides[5]

[1]*Dipartimento di Scienze della Terra, Università degli Studi di Torino, Italy. E-mail: evdokia.tema@unito.it*
[2]*ALP, Alpine Palaeomagnetic Laboratory, Peveragno, Italy*
[3]*Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy*
[4]*Department of Geophysics, School of Geology, Aristotle University of Thessaloniki, Greece*
[5]*Department of Geology, School of Geology, Aristotle University of Thessaloniki, Greece*

Accepted 2015 June 16. Received 2015 June 16; in original form 2014 December 5

SUMMARY

We present the results of palaeomagnetic analysis on Late Bronge Age pottery from Santorini carried out in order to estimate the thermal effect of the Minoan eruption on the pre-Minoan habitation level. A total of 170 specimens from 108 ceramic fragments have been studied. The ceramics were collected from the surface of the pre-Minoan palaeosol at six different sites, including also samples from the Akrotiri archaeological site. The deposition temperatures of the first pyroclastic products have been estimated by the maximum overlap of the re-heating temperature intervals given by the individual fragments at site level. A new statistical elaboration of the temperature data has also been proposed, calculating at 95 per cent of probability the re-heating temperatures at each site. The obtained results show that the precursor tephra layer and the first pumice fall of the eruption were hot enough to re-heat the underlying ceramics at temperatures 160–230 °C in the non-inhabited sites while the temperatures recorded inside the Akrotiri village are slightly lower, varying from 130 to 200 °C. The decrease of the temperatures registered in the human settlements suggests that there was some interaction between the buildings and the pumice fallout deposits while probably the buildings debris layer caused by the preceding and syn-eruption earthquakes has also contributed to the decrease of the recorded re-heating temperatures.

Key words: Archaeomagnetism; Rock and mineral magnetism; Volcaniclastic deposits.

1 INTRODUCTION

The Minoan eruption of Santorini that occurred during the Late Bronze Age (Betancourt 1987; Aitken *et al.* 1988; Hughes 1988; Manning 1988; Friedrich *et al.* 1990; Pyle 1990; Manning *et al.* 2006; Friedrich & Heinemeier 2009; Höflmayer 2012) is considered as one of the most catastrophic explosive events in the Mediterranean area. It produced a huge volume of volcanic products that covered the whole island and changed its morphology burying all human settlements under metres of pyroclastic deposits. Its impact on the society was very important and it is often related to the destruction of the Cycladic culture and Minoan civilization in southern Aegean (McCoy & Heiken 2000).

Archaeological and historical evidence available since the last century reveals that under meters of pyroclastic deposits, a Bronze Age civilization with advanced society organization life was in flourish. Systematic excavations carried out at the archaeological site of Akrotiri, at the southern part of Santorini, brought into light an important settlement, with advanced drainage system, sophisticated multiple floor buildings, beautiful wall-paintings and elaborated furniture and vessels that give proof of great development and prosperity. The excavations preserve the evidence of several earthquakes that occurred before and during the destructive volcanic event and show that the whole village was totally buried by the volcanic products of the eruption (Cioni *et al.* 2000).

In the present study, we use standard palaeomagnetic techniques in order to estimate the thermal effect of the Minoan volcanic products on the pre-Minoan habitation level. Pottery fragments collected from the surface of the pre-Minoan palaeosol at five sites as well as samples from the archaeological site of Akrotiri have been systematically studied (Fig. 1). The deposition temperatures of the first pyroclastic products have been estimated by the maximum overlap of the re-heating temperature intervals given by the individual fragments at each site (Cioni *et al.* 2004). A new statistical treatment, based on the Gaussian distribution of the temperature range given by each studied specimen, has also been applied for the first time here. The results of the two techniques have been compared and the deposition temperatures of the pyroclastic products at site level have

Figure 1. Map of Santorini with the location of the sampled sites. The star represents the presumed position of the inferred vent of the Minoan eruption.

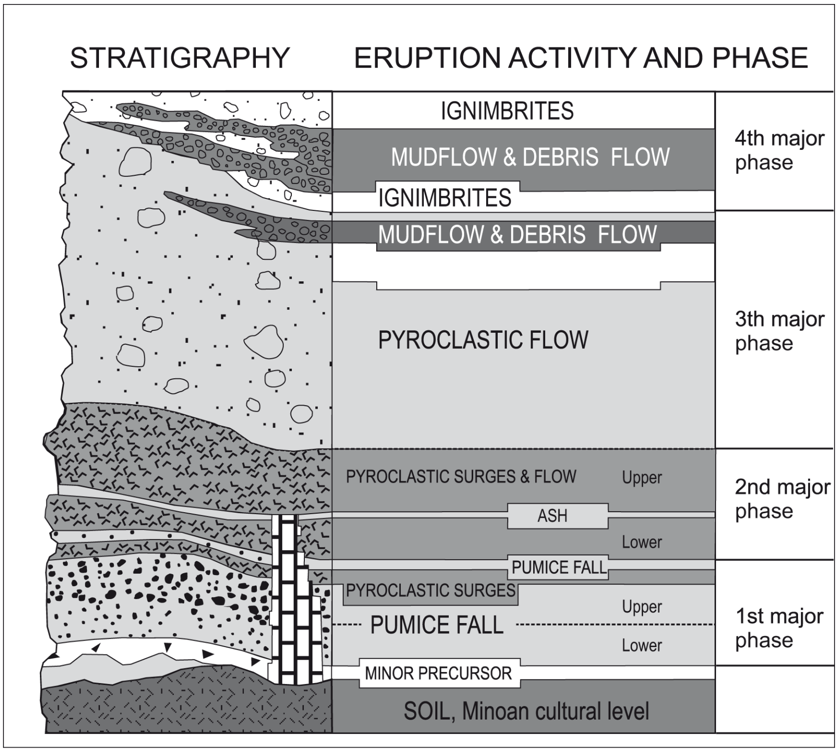
been estimated. The obtained results contribute to better understand the equilibrium temperature of the pyroclastic products that came in contact and covered the pre-Minoan soil while pottery collected inside the human settlement of Akrotiri has been used for the first time as a recorder of deposition palaeotemperatures in Santorini.

2 VOLCANOLOGICAL SETTING AND PREVIOUS STUDIES

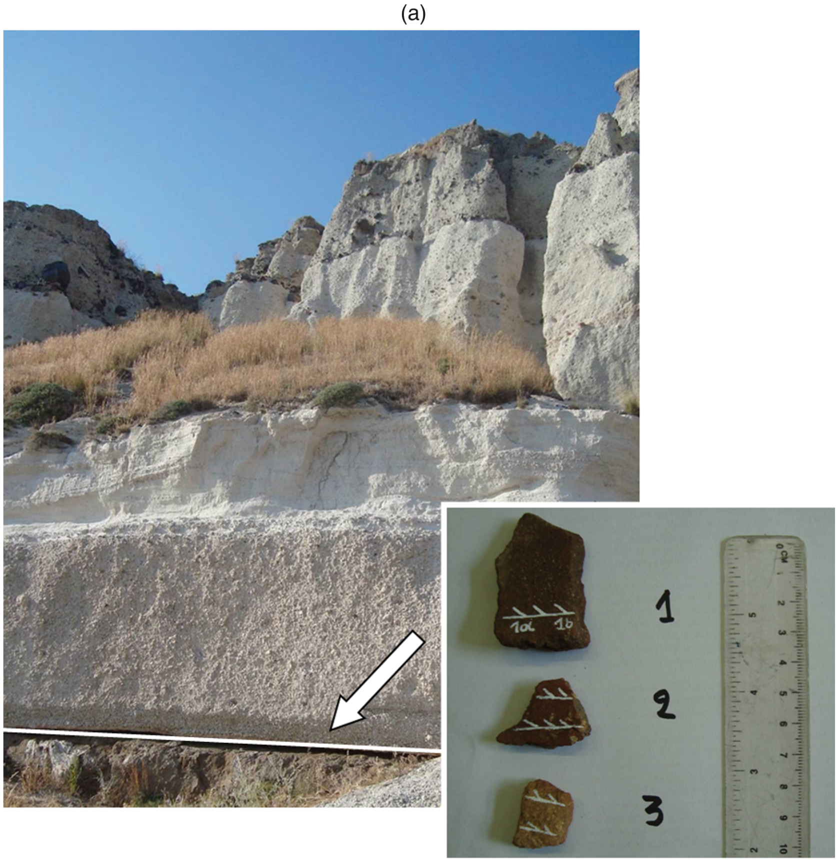
The volcanological characteristics of the Minoan eruption products have been extensively studied by several researchers (Bond & Sparks 1976; Heiken & McCoy 1984; Druitt *et al.* 1989; Heiken *et al.* 1990; Sparks & Wilson 1990; McCoy & Heiken 2000). According to these studies, the Minoan deposits are generally divided in four main phases reflecting changes on vent's geometry and eruption mechanisms (Fig. 2a). Before the beginning of the main Minoan eruption, a thin precursor tephra layer (around 4 cm) was first deposited. This layer has been interpreted as an initial phreatic eruption that together with earthquakes could have been responsible for evacuation of the island before the main eruption (Heiken & McCoy 1984).

The eruption began with the deposition of a typical Plinian pumice fall (Phase 1), the first volcanic product of the main eruption that came in contact with the pre-Minoan palaeosol, covering almost all the island with deposits locally up to 7 m high (McCoy & Heiken 2000). In this phase, a continuous discharge of magma in dry conditions was driven only by magmatic gas. The distribution of the fall deposits indicate the position of the inferred vent somewhere between the present-day Nea Kameni Island and the city of Fira (Bond & Sparks 1976; Sparks & Wilson 1990; McCoy & Heiken 2000; Fig. 1). After the Plinian air fall deposits, the intensity of the eruption increased. The deposition of surges and phreatomagmatic pyroclastic flows (Phase 2) is associated with clear phreatomagmatic explosive activity. These deposits consist of stratified and cross-bedded sequences that arrive up to 12 m, strongly controlled by the palaeotopography. During Phase 3, massive, poorly sorted mixtures of pumice and ash containing abundant lithic blocks with diameters up to 2 m were emplaced. The presence of such large lithic blocks with compositions similar to flows and hyaloclastites from the northern part of the island suggests that during this phase the caldera collapsed (Heiken & McCoy 1984). Finally, Phase 4 deposits, still under discussion, are probably a sequence of interbedded ignimbrites, lithic-rich base surge deposits, lithic-rich and debris flows (Bond & Sparks 1976; Heiken & McCoy 1984). They are mostly confined to coastal plains where they form sea cliffs of massive to stratified deposits that may reach a thickness of tens of meters.

Even though the volcanological characteristics of the deposits have been already thoroughly studied, till now only limited information about their deposition temperature and their effect in inhabited areas are available. Cioni *et al.* (2000) studied the impact of the eruptive products on the human settlement of Akrotiri. Their research showed that the Akrotiri settlement was badly damaged by earthquakes before the beginning of the eruption that created a building debris layer covering the Minoan soil. The fallout pumice bed (Phase 1), mantling the ruins, caused a partial destruction of the settlement while the deposition of the following pyroclastic flows (Phase 2) completed the entire coverage of the site.



(a)



(b)

Figure 2. (a) Stratigraphy of the Minoan eruption deposits. The wall shown in the lower part of the section represents the human settlements of Akrotiri archaeological site that interacted only with the first and second phases of the eruption (figure redrawn from McCoy & Heiken 2000). (b) General view of the volcanic deposits at the Megalochori quarry. The white line and arrow indicate the contact of the deposits with the palaeosol from which the studied samples have been collected. Inset: photo of the collected pottery fragments.

Table 1. Sampling sites and collected samples.

Sampling site	Geographic coordinates	Number of pottery fragments	Number of studied specimens
Megalochori quarry—SMC	36° 22′ 00″ N, 25° 25′ 12.0″ E	22	31
Apothikes (Remezzo)—PC1F	36° 21′ 36.6″ N, 25° 24′ 14.7″ E	25	46
Vlichada (Bar Theros)—BTC	36° 20′ 42.9″ N, 25° 25′ 30.0″ E	9	16
Agia Eirini (Tsikoura beach)—CAEIR	36° 23′ 35.8″ N, 25° 26′ 17.2″ E	11	16
West Almyra—WAC	36° 20′ 55″ N, 25° 25′ 9.1″ E	8	14
Akrotiri archaeological site—AKROTIRI	36° 21′ 05″ N, 25° 24′ 13″ E	33	47

The deposition temperature of these deposits was first investigated by Downey & Tarling (1984) and following by Tarling & Downey (1989) and Downey & Tarling (1991) who used palaeomagnetic measurements on Minoan tephra samples. Even though clear information about the type of samples studied and the exact sampling sites are not available in these publications, their results indicate emplacement temperatures that range from 250 to 400 °C for the Plinian airfall and 300–500 °C for the base surge deposits. McClelland & Thomas (1990) investigated the emplacement temperatures of the four phases of the Minoan eruption collecting pumice and lithic clasts from three sites and applying systematic thermal demagnetization procedures. Regarding Phase 1, they studied samples from two sites (Fira and Oia quarries, located in central and northern part of the island respectively, Fig. 1) and obtained a wide range of emplacement temperatures that vary from 150 °C to 350 °C, with the maximum distribution around 250–300 °C. McClelland *et al.* (1996) also studied the spatial distribution of emplacement temperatures of lithic clasts within Plinian tephra deposits of nine Santorini eruptions. In particular, for the Plinian airfall of the Minoan eruption, they studied five sites and estimated temperatures from 130 to 250 °C at site level. These results, coming from different authors, show an important distribution of temperatures while important within-site temperature variability is also observed.

More recently Tema *et al.* (2013a) studied both lithic clasts incorporated in the Plinian airfall of the Minoan eruption and ceramic fragments covered by the volcanic deposits, collected at Megalochori Quarry (Fig. 1). Systematic palaeomagnetic measurements revealed deposition temperatures ranging from 180–240 °C from lithic clasts and 140–180 °C from ceramic fragments. In their study they showed that the ceramic fragments covered and re-heated by the Minoan deposits can reliably represent the equilibrium temperature between the cold palaeosol and the overlying hotter pumice airfall. Compared to the lithic clasts, traditionally used up to now in most pyroclastic deposition temperature estimation studies (e.g. McClelland & Druitt 1989; Bardot & McClelland 2000; Zanella *et al.* 2008; Porreca *et al.* 2008; Paterson *et al.* 2010; Lesti *et al.* 2011), ceramic fragments present the advantage to be more thermally stable and to have a less complicated thermal history (they were cold when covered by or embedded in the volcanic deposits; see Zanella *et al.* 2007; Di Vito *et al.* 2009; Tema *et al.* 2013a,b). For this reason, in the present study we have focused our interest on deposition temperatures estimated through the study of pottery fragments coming from six different locations.

3 PALAEOMAGNETIC SAMPLING

Systematic sampling was carried out during three sampling campaigns that took place between 2011 and 2013. The studied ceramic fragments come from six localities: Megalochori Quarry, Apothikes (Remezzo), Vlichada, Agia Eirini, West Almyra and the archaeological site of Akrotiri (Table 1). All sites are situated at the southern part of Santorini island (Fig. 1), at distances that range from 5 to 9 km from the inferred vent of the Minoan eruption, probably located somewhere between the Nea Kameni Island and the present Fira town (Bond & Sparks 1976; Heiken & McCoy 1984; Sparks & Wilson 1990; McCoy 2009). At the northern part of the island, no pottery fragments were found at the contact between the palaeosol and the Minoan fallout.

All pottery fragments come from the contact between the pre-Minoan palaeosol and the first volcanic products of the Minoan eruption (Fig. 2b). They were spread on the palaeosol surface during the eruption and subsequently covered by the precursory volcanic activity ashes and/or incorporated at the first centimetres of the pumice fall. All collected fragments are small, generally varying from 1–4 cm, with only very few exceptions of bigger pieces up to 6 cm (Fig. 2b). Their small dimension makes it difficult to identify their exact provenance or use. However, most probably they were pieces of storage vessels used in the everyday life. The small dimensions, position and the very loose surrounding pumice matrix made impossible the *in situ* orientation of the collected pottery fragments; however a casual error was drawn for the laboratory measurements.

Sampling at the archaeological site of Akrotiri was realized in collaboration and under the guidance of the archaeologist Dr. Tania Devetzi. After several decades of systematic excavation, almost all the volcanic deposits that covered the excavated part of the Akrotiri archaeological site have been removed. Nowadays, remains of the pumice fall and pyroclastic surge deposits that had covered the ancient city can only be seen in few parts of the excavation, where they have been left as stratigraphic balk. Moreover, earthquakes that took place before and during the eruption importantly damaged the buildings, creating a debris destruction level that covered most of the structures (Cioni *et al.* 2000). These facts significantly limited our sampling, as most of the ceramics were already removed by the archaeologists or covered by the debris level and the places where they were still *in situ* and in direct contact with the volcanic deposits are very few. A total of 17 pottery fragments were collected from the open place of the 'Terrace of the Beds', south of the House of the Anchor, and from the open place north of the 'House of the Ladies', close to the roof's pillar. These were open places where a great number of domestic ceramic vases were accumulated, probably during an attempt of the habitants to restore their houses after some early precursor earthquakes. Archaeologists also provided us with two pottery collections of 16 pottery fragments found during the opening of the manholes 76 and 63Π. All studied ceramics were completely covered by Phase 1 Plinian fallout. Contrary to the case of Pompeii in Italy (Zanella *et al.* 2007), at the Akrotiri excavation no ceramic fragments or roof tiles were found embedded in the pyroclastic surge deposits of the second phase of the eruption. This is probably due to strong earthquakes that had already destroyed the roofs of the houses or/and the more violent pyroclastic surge flows draw everything away, most likely submerging them in the nearby sea coast.

A total of 108 pottery fragments were collected. Due to the small size of the samples, the preparation of standard cylindrical specimens (diameter 25.4 mm; height 22.5 mm) was not possible. To measure the small samples, plastic boxes and white plasticine were used, following the procedures described by Cioni *et al.* (2004). In the case of samples larger than 2 cm, two specimens were prepared from individual fragments in order to improve the accuracy in the estimation of the deposition temperature interval (Zanella *et al.* 2008). Following this procedure, 170 ceramic specimens were prepared and studied. Results from the Megalochori Quarry have been previously published by Tema *et al.* (2013a) and we have re-elaborated them here. Preliminary results from Apothikes and Vlichada can be found in Tema *et al.* (2013b); more results from these sites are presented here together with results of new sites and the archaeological site of Akrotiri.

4 METHODOLOGICAL RATIONALE AND MEASUREMENTS

The palaeomagnetic method used for the estimation of deposition temperature of volcanic rocks was first introduced by Aramaki & Akimoto (1957) and since then it was further developed and applied in several cases (e.g. Hoblitt & Kellogg 1979; Kent *et al.* 1981; Downey & Tarling 1984; McClelland & Druitt 1989; Bardot 2000; Cioni *et al.* 2004; Zanella *et al.* 2007; Sulpizio *et al.* 2008; Paterson *et al.* 2010). In most of these studies, standard thermal demagnetization procedures were applied on lithic clasts embedded in the deposits to estimate the deposition temperatures of pyroclastic density currents. Cioni *et al.* (2004) further developed such studies including also the analysis of the magnetization of roof tiles from Roman buildings at Pompeii and Herculaneum that were destroyed by the 79 AD eruption of Somma Vesuvius. More recently, Zanella *et al.* (2007) and Di Vito *et al.* (2009) also used baked clay human artefacts such as bricks, tiles and pottery embedded in volcanic deposits in order to estimate the deposition temperatures and to better understand the interaction between volcanic deposits and human settlements.

The methodological approach applied here is based on the main principles of palaeo- and archaeomagnetism. Baked clay artefacts contain magnetic particles that, when heated at high temperatures and cooled in the presence of the Earth's magnetic field, may acquire a thermal remanent magnetization (TRM) with direction parallel to the direction of the local field. Following this procedure, tiles, bricks and pottery have a primary magnetization acquired at the time of their initial heating during their production. If they are subsequently partly re-heated at temperatures lower than the Curie temperature of the included magnetic minerals, then a part of their initial magnetization with unblocking temperatures less than or equal to the maximum re-heating temperature will be lost and a new partial thermoremanent magnetization (pTRM) will be acquired. Such pTRM can be often acquired by ceramics found in contact with or incorporated into pyroclastic deposits; if the volcanic products were warm when deposited over the ceramic fragments, then once the thermal equilibrium between the hot pyroclastics and the cold ceramics is reached, the ceramics will be partially remagnetized, acquiring a secondary low-temperature magnetic component. In the case of oriented *in situ* baked clay artefacts, the original high temperature magnetic component would be casually oriented while the secondary low-temperature component would be uniformly oriented with direction parallel to the Earth's magnetic field at the time of the eruption. In the case of non oriented samples, the two magnetic components can still be distinguished as they will normally have different directions between them.

In the case of pottery used for cooking in the antiquity (cooking ware), it is possible to have a magnetic component acquired during their anthropogenic heating for food preparation. In such cases, the magnetic component that corresponds to the re-heating due to the pyroclastic deposits would always be the last acquired magnetic component, since the coverage from the deposits was the last heating event experienced by the ceramics. As stated before, due to the small dimensions of our samples, it is not possible to identify their use and recognize if they have been used for cooking or not. Nevertheless, their previous use still does not influence our results. If the temperature at which the ceramics were heated during cooking was higher than the temperature of the pyroclastic deposits produced by the eruption, then three components of magnetization should be identified: a high temperature component acquired during the initial heating of the ceramics (during their production), a intermediate component acquired due to their partial re-heating during their use as cooking vessels and a low-temperature component acquired at last, after their coverage by the pyroclastic products. On the other hand, if the cooking temperature was lower or equal to the temperature of the volcanic deposits, then it will have been overwritten and only the last magnetic component acquired during the deposition of the pyroclastic products will be preserved. In any case, the pyroclastic overprint will always correspond to the last registered magnetic component.

In order to investigate and separate the magnetic components present in the pottery fragments, systematic stepwise thermal demagnetization was applied. In the present study, all the specimens were thermally demagnetized at the ALP Palaeomagnetic Laboratory (Peveragno, Italy) using a TSD-2 Schonstedt furnace for heating/cooling and JR5/JR6 spinner magnetometers for measuring the magnetic remanence. Thermal demagnetizations were carried out in steps of 40 °C between a starting temperature of 60 °C and a maximum temperature varying between 500 and 620 °C. When twin specimens from individual samples were available, a second demagnetization group was carried out following the same 40 °C step but starting from 80 °C. After each step, the bulk magnetic susceptibility of all specimens was measured with a KLY-3 Kappabridge in order to detect possible mineralogical changes due to heating. In the case of large ceramic pieces, the remaining material was used for magnetic mineralogy experiments. Isothermal remanent magnetization (IRM) curves were obtained using an ASC pulse magnetizer to stepwise impart magnetic fields up to 1 T. Thermal demagnetization experiments of the three IRM components (Lowrie 1990) induced along the three sample axes were also performed on representative samples. First the maximum field (1.2 T) was applied along the *Z*-axis, then the intermediate field (0.5 T) along the *Y*-axis and finally the minimum field (0.1 T) along the *X*-axis. The temperature dependence of low-field magnetic susceptibility from ambient temperature up to 600 °C was monitored at the Palaeomagnetic Laboratory of IPGP (Paris) with a CS3 Kappabridge.

5 RESULTS

5.1 Magnetic mineralogy

Rock magnetic experiments were carried out in order to investigate the magnetic mineralogy and the thermal stability of the studied material. Most experiments were performed on representative samples from the different sites; however the limited number of samples collected from the Akrotiri archaeological site and their very small dimensions prevented any mineralogy experiment for this site.

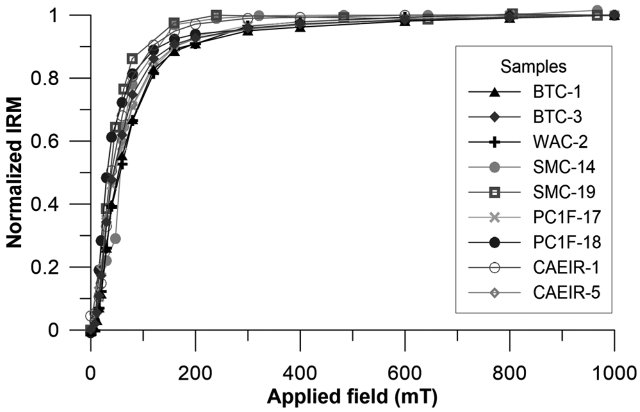


Figure 3. Isothermal remanent magnetization (IRM) acquisition curves for representative samples from the various studied sites.

IRM curves (Fig. 3) are very similar for all studied samples and indicate that the saturation of the magnetization is generally reached at fields varying from 0.2 to 0.4 T. No fraction remains unsaturated after the application of 1 T field, indicating the presence of a low-coercivity mineral such as magnetite. Thermal demagnetization of the three IRM components (Lowrie 1990) induced along the three sample axes also confirms the dominance of the magnetically soft fraction (<0.1 T). The medium component is generally weak and the hard component is almost negligible (Fig. 4). These results point to magnetite as the main magnetic carrier while minor quantities of hematite may be also present in some samples.

The thermal stability of all specimens was investigated by measuring the low-field bulk magnetic susceptibility at room temperature after each thermal demagnetization step. The studied samples show a general stable behaviour with only small magnetic susceptibility variations with increasing temperature (Fig. 5). These results are also confirmed by the continuous thermomagnetic curves obtained for representative samples (Fig. 6). The continuous heating and cooling curves are acceptably reversible. However, in some samples (e.g. samples SMC-1 and SMC-16 from Megalochori site), a low Curie phase with Curie temperature around 250–300 °C can be observed. Evidently, the thermomagnetic curves, performed only on representative samples, cannot guarantee the absence of magnetic changes for all the studied samples and some of them can still be affected by even more important mineralogical transformations. Nevertheless, pottery fragments that are normally heated at high temperatures during their production procedure are generally magnetically stable and they represent some of the most reliable recorders of the geomagnetic field. In any case, to guarantee that our results are not affected by possible secondary chemical overprint due to mineralogical transformations, we have addressed particular attention on the interpretation of the thermal demagnetization results. In the cases that some evidence of mineralogy changes was available, mainly perceived by overlapping blocking temperature spectra (McClelland *et al.* 2004), results were rejected or very cautiously treated (see the discussion in Section 5.2).

5.2 Principal component analysis

The results of the demagnetization analysis have been represented as intensity decay curves, Zjiderveld diagrams and equal area projections (Fig. 7). A re-heating (T_r) temperature interval was determined for each ceramic fragment analyzing the corresponding Zjiderveld diagrams. Most of the studied specimens show two TRM components, a low-temperature magnetization component, generally erased at 180–240 °C, and a high-temperature one, up to ∼580–620 °C. In 72 per cent of the cases, the magnetic behaviour during demagnetization corresponds to type C of Cioni *et al.* (2004), that is, two magnetization components with different direction and blocking temperature (T_b) spectra. This characteristic allows an estimation of the T_r in a range of 40 °C, which corresponds to the laboratory heating step. Examples of type C behaviour are shown in Figs 7(a) and (b), for specimens CAEIR6a from Agia Eirini and ACGU-3a from the House of Ladies at the Akrotiri archaeological site, respectively. In both cases the T_r interval was determined by the knee-path in the Zijderveld diagrams. Type C is the most favourable case of magnetization behaviour, as it provides well-defined temperature range clearly determined by the separation of the two TRM components. In the 12 per cent of the cases, type D behaviour (Cioni *et al.* 2004) is observed. In this type, two magnetization components are also present, but they are characterized by partially overlapping unblocking temperature spectra. This means that it is not possible to clearly separate the two components in a narrow temperature range, as in the case of type C behaviour, but the T_r interval may only be reliably defined within a more wide overlapping temperature interval (Zanella *et al.* 2015). Such behaviour may be caused by the presence of multidomain (MD) grains, which typically show low stability, while a secondary chemical remanent magnetization (CRM) may be also possible (McClelland *et al.* 1996; Bardot & McClelland 2000; Paterson *et al.* 2010), ascribed to the syn-eruptive oxidation of magnetite to maghemite. In the case of MD grains, the observed overlapping could be also related to the fact that in these cases blocking and unblocking temperature spectra are not equal. In the case of possible mineralogical transformations, the presence of a CRM can cause curvature to the vector plots and in these cases the re-heating temperatures may be over estimated (McClelland *et al.* 2004). For this reason, we have been particularly cautious in the interpretation of the re-heating temperatures from type D samples and we have considered a wide temperature interval, defined by the last point of the clearly low-temperature component and the first point of the clearly high temperature component. In this way, even if the temperature interval is wider than the one defined by type C samples, we are confident that the true re-heating temperature indicated by the secondary TRM (in type D, possibly overwritten by a partial CRM) is included in the wide re-heating interval considered. Examples of type D behaviour are given in Figs 7(c) and (d) for specimen BTC-8b, from Vlichada, and WAC-3a, from West Almyra, respectively. The T_r interval for type D is in the range of 120–180 °C, but the temperature interval can be wider with the increase of the overlapping spectra. None of the specimens falls in the A and B types of Cioni *et al.* (2004), which indicate the presence of a single TRM component, one with T_r lower than the minimum T_b and one with T_r higher than the maximum T_b, respectively (Zanella *et al.* 2015). In total, it was possible to determine a T_r interval, mostly of high quality, in the 84 per cent of the specimens.

In the remaining cases, we were not able to couple the specimens' demagnetization behaviour to any of the previously discussed types. In most of the remaining specimens, demagnetization data were tightly clustered (Fig. 7e), while in other cases, the two possible magnetization components differed in direction by small angles (<5°), so that the separation of the two components was not clear and their interpretation could have been arbitrary. In few specimens from the AC63P ceramic group collected at the archaeological site of Akrotiri, the demagnetization path was not towards the origin of the Zijderveld diagram. While the first two points evidence a limit in a clear interpretation of the Zijderveld diagrams, the third point

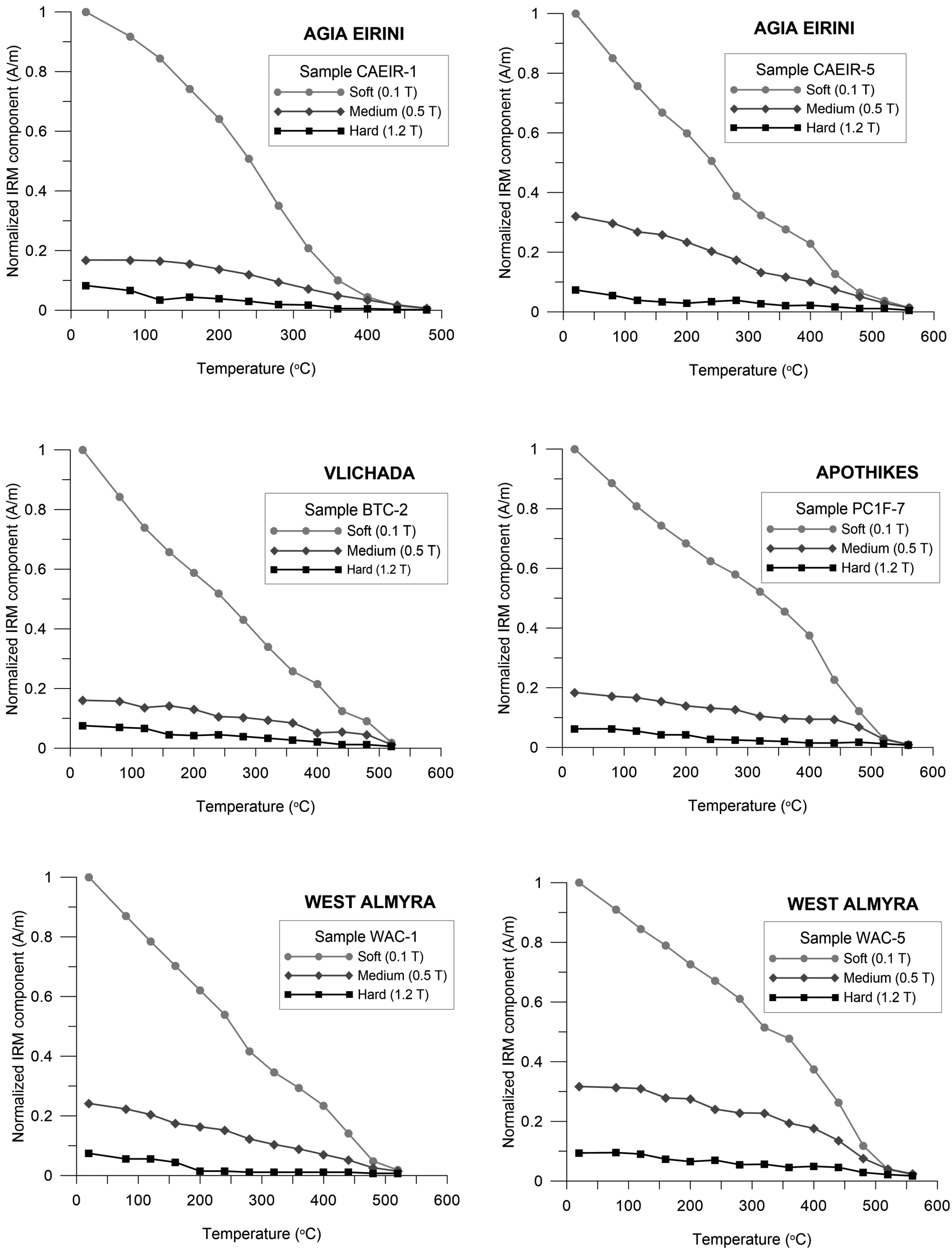


Figure 4. Stepwise thermal demagnetization of composite three axes IRM for representative samples. Symbols: dot, soft-coercivity component (0.1 T); diamond, medium-coercivity component (0.5 T); square, hard-coercivity component (1.2 T).

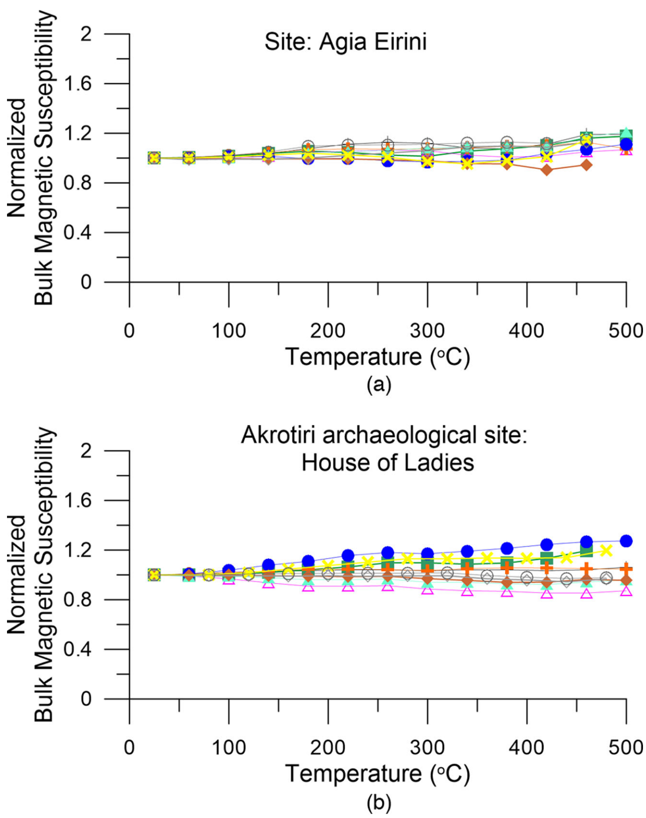


Figure 5. Normalized bulk magnetic susceptibility variations during the thermal demagnetization, measured after each heating–cooling circle.

is characteristic of a remagnetization process, occurred in the field or during the laboratory heating. To guarantee the quality of our results, all specimens with such demagnetization behaviour have been discarded.

5.3 Estimation of the deposition temperatures

The experimental T_r intervals calculated for each specimen from the interpretation of the Zijderveld diagrams have been used for the estimation of the deposition temperature (T_{dep}) at site level. To obtain the T_{dep}, two different approaches have been applied.

First, T_r temperatures at specimen level have been plotted and the T_{dep} for each site has been estimated by the maximum overlap of the specimens' T_r intervals, as described in Cioni *et al.* (2004, Fig. 8a). This approach is based on the fact that all ceramics coming from the same site should have experienced the same thermal effect caused by the overlapping warmer pyroclastic deposits. The capacity of each individual ceramic fragment to register this temperature varies according to the ceramic characteristics such as magnetic mineralogy, grain size and type. Nevertheless, the common temperature registered by the maximum number of specimens and given by the maximum overlap of the T_r intervals can be reliably considered as the most representative deposit temperature, after the thermal equilibrium between the cold ceramics and the warmer overlapping pyroclastic deposits was obtained. This approach for estimating the T_{dep} at site level is the one used up to now in similar studies (e.g. Cioni *et al.* 2004; Sulpizio *et al.* 2008; Zanella *et al.* 2008; Di Vito *et al.* 2009; Tema *et al.* 2013a) and even though it is often subjective, based only on the visual overlap of the T_r intervals, it can reliably give an estimation of the deposition temperatures of volcanic products.

Together with the 'traditional' overlapping method previously discussed, we have applied here for the first time a statistical approach for a more objective, mathematical calculation of the deposition temperatures at site level. According to this approach, the temperature range for each specimen has been translated to a Gaussian distribution considering the minimum (T_m) and maximum (T_M) temperature given by the interpretation of the Zijderveld diagrams. The difference between both values of temperatures provides the standard deviation of the Gaussian distribution ($\sigma = T_M/2 - T_m/2$) centred at the mean values of the temperatures ($\mu = T_M/2 + T_m/2$). After that, the probability density function (pdf) at site level is calculated as the normalized product (combination) of the different Gaussian distributions (Fig. 8b). The combined pdf estimates at any probability the range of temperature for the selected site. We have used here the 95 per cent of probability to define the temperature intervals given by the 95 per cent of the total area under the combined pdf. In Fig. 8(b), the different Gaussian distributions as well as the final combined pdfs are illustrated for representative sites, showing the re-heating temperature intervals calculated at 95 per cent of probability. The values of T_{dep} calculated using this mathematical method have been included in the Table 2 together with the values obtained by the 'overlapping method'. As expected, the results from the two techniques are in very good agreement, but the new statistical approach proposed here guarantees a more objective and mathematically based method for deposition temperature estimation at site level.

6 DISCUSSION

The Minoan eruption of Santorini is one of the most important and well studied catastrophic events in the Mediterranean area. Nevertheless, its thermal effects on the Pre-Minoan palaeosol and on the Late Bronze age settlements of the island are still poorly investigated. The results presented here aim to enrich our knowledge on the temperatures experienced by the habitation level when the equilibrium between the palaeosol and the pyroclastic deposits was obtained, offering for first time temperature data from the archaeological excavation of Akrotiri. Such data can be further used for volcanological and archaeological interpretations, as the temperature of the deposits is closely related to the destructive effects of the eruption and to volcanic hazard assessment.

Our study confirms that the use of palaeomagnetic methods can be a powerful tool for such investigations and the ceramics covered and/or embedded in the volcanic products can be excellent recorders of the equilibrium deposition temperatures. The T_r temperatures given by each ceramic fragment at site level are very consistent and even though in some cases temperature ranges of single specimens can be as large as 160 °C (e.g. Apothikes site: specimen PC1F-7a, Fig. 1 of supplementary material), the overlapping temperatures at site level are very well constrained by almost all studied samples, varying from 20 to maximum 40 °C (Fig. 8a). For example, for AC63P site, 7/7 T_r intervals fall in the range 140–180 °C; in Agia Eirini site, the deposition temperature is defined within a 20 °C range, from 180 to 200 °C, with only two outliers that do not fall in this range (Fig. 8a). The temperatures estimated for each site using the 'traditional' overlapping method are confirmed by the Gaussian statistical method proposed here, showing that they are well defined and independent of the elaboration technique used. The difference on the estimated temperatures from the two applied techniques are for all sites less than 30 °C, with the statistical approach giving slightly wider temperature ranges (Table 2 and Fig. 8).

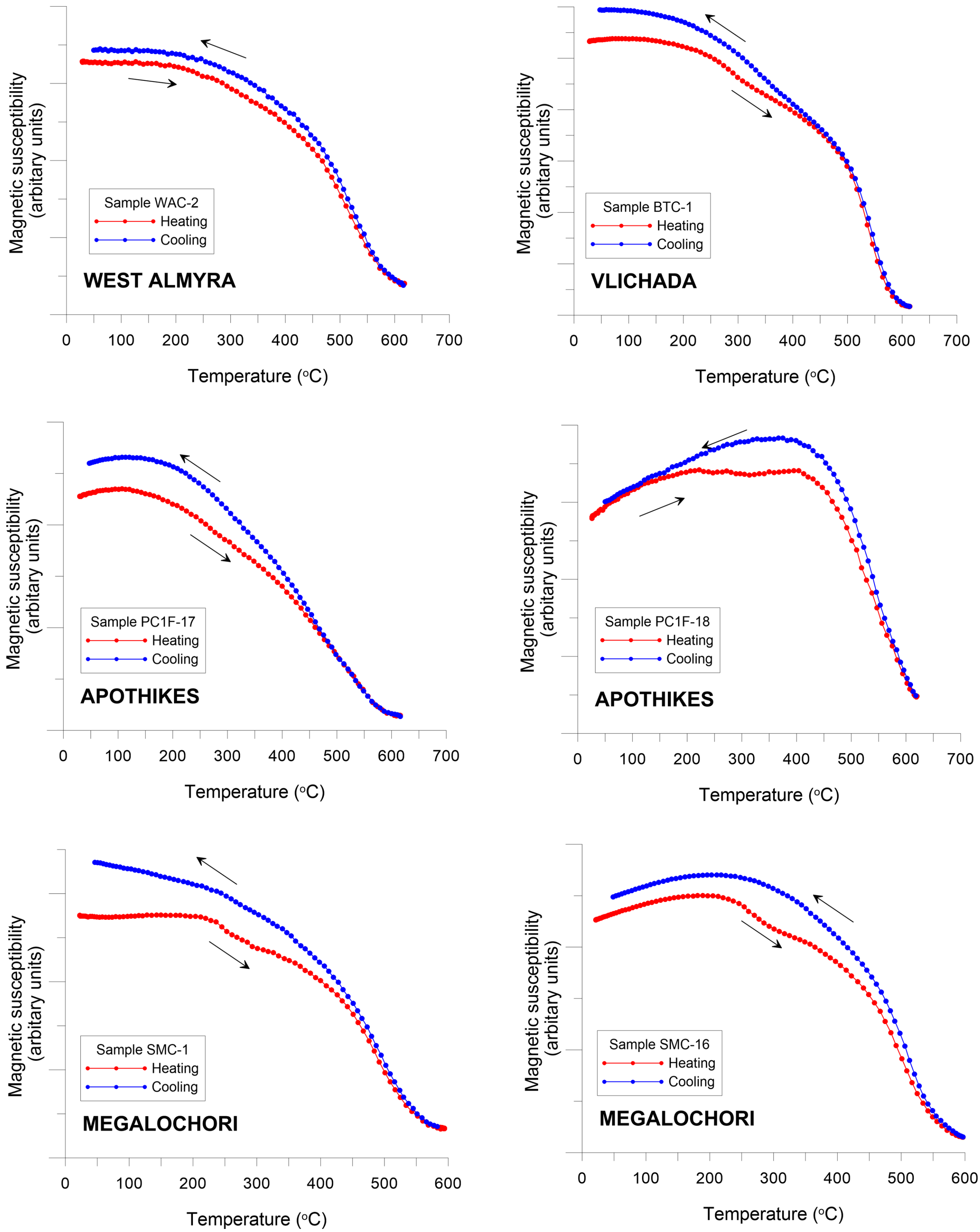


Figure 6. Continuous variation of the magnetic susceptibility with temperature for representative samples.

Nevertheless, the statistical approach guarantees a mathematical and objective treatment of the results, and calculates with 95 per cent of probability the deposition temperature of the volcanic deposits as experienced by the underlying ceramic fragments. For this reason, the statistically obtained temperatures at site level (rounding them to the nearest whole number) are here used for further considerations and this statistical approach is recommended for future studies.

The obtained results show that the precursor tephra layer and the first pumice fall of the eruption were hot enough to re-heat the underlying ceramics at temperatures of 160–230 °C (Fig. 9).

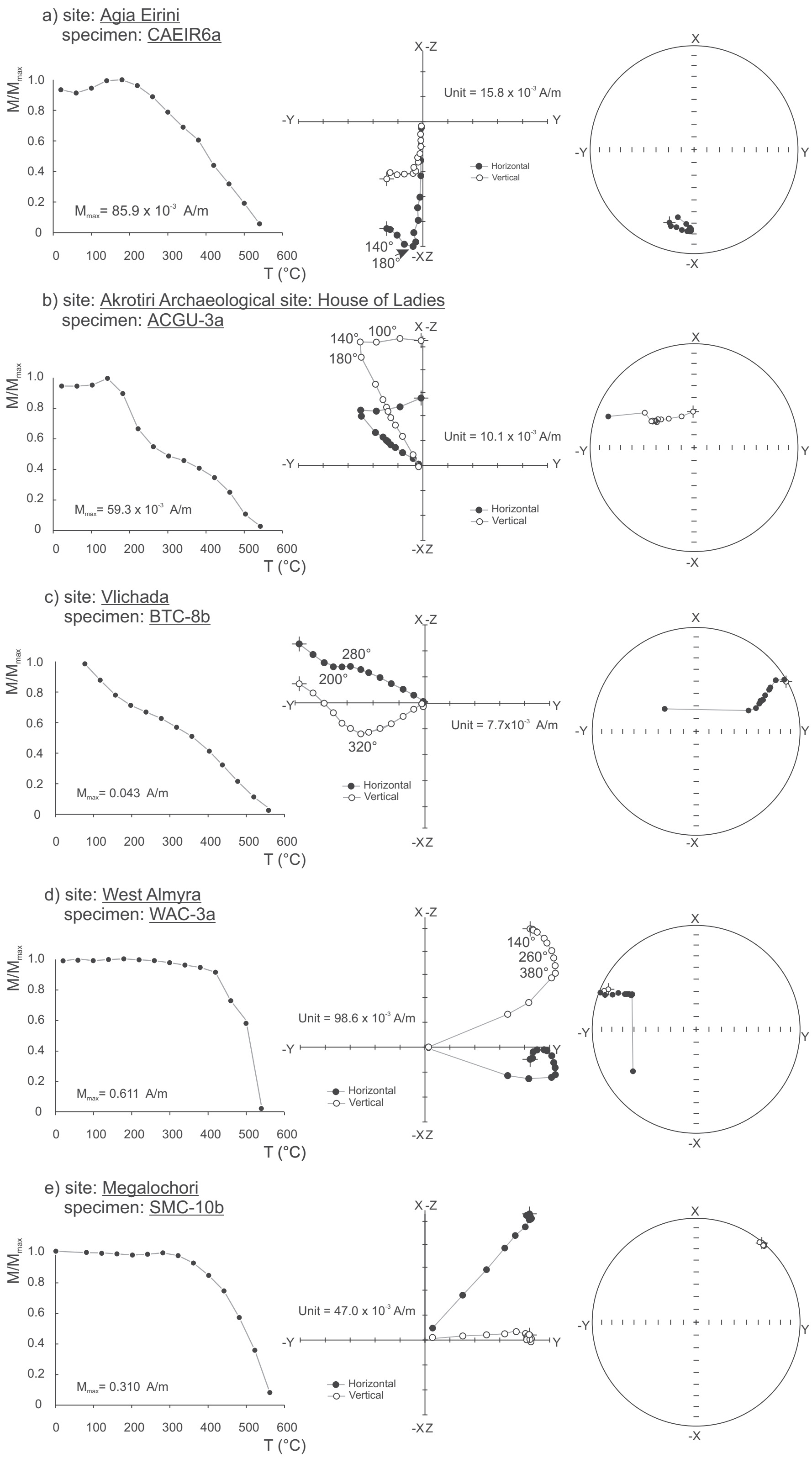


Figure 7. (a, b) Type C and (c, d) Type D stepwise thermal demagnetization results for representative samples. (e) Example of thermal demagnetization behaviour that due to the tightly clustered points has not been possible to interpret. Figure includes normalized intensity decay curves (left), Zijderveld diagrams (middle) and corresponding equal-area projections (right). Symbols: Zijderveld diagram: full/open dot, declination/apparent inclination; equal-area projection: full/open dot, positive/negative inclination.

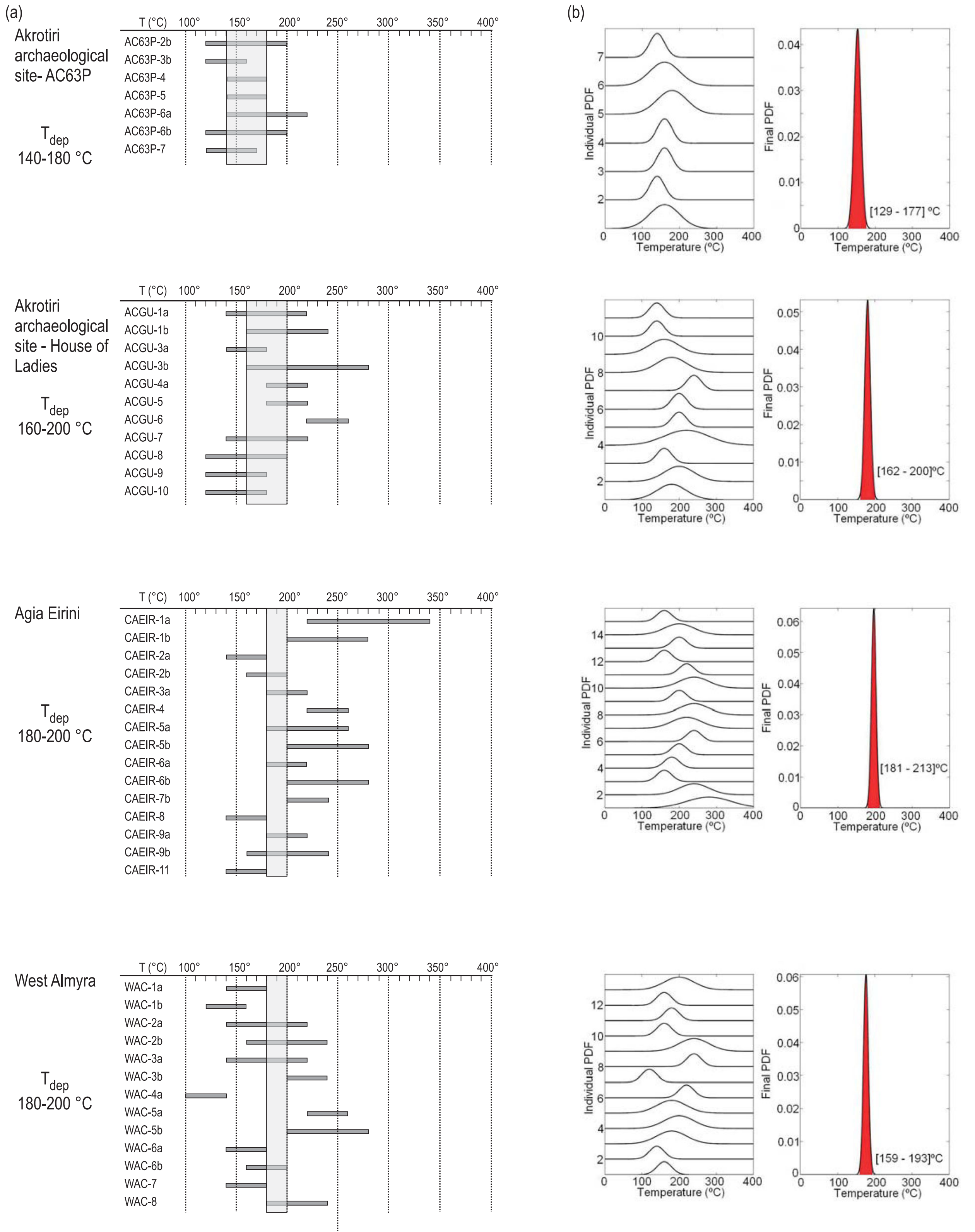


Figure 8. (a) Determination of the deposition temperature (T_{dep}) at site level for representative sites based on the maximum overlapping of the individual specimen re-heating temperature ranges. (b) Determination of the T_{dep} at site level based on the individual normalized Gaussian distributions for each specimen (left). The combined probability density function (pdf) for each site is calculated and the range of temperatures at 95 per cent of confidence is illustrated with red colour (right).

Table 2. Estimated re-heating temperatures at site level.

Site	Overlapping approach		Statistical approach
	n/N	$T_{\text{r-over}}$ (°C)	$T_{\text{r-stat}}$ (°C)
Megalochori quarry—SMC	21/24	160–180	164–186
Apothikes (Remezzo)—PC1F	32/36	180–200	177–196
Vlichada (Bar Theros)—BTC	11/14	220–240	195–229
Agia Eirini (Tsikoura beach)—CAEIR	13/15	180–200	181–213
West Almyra—WAC	10/13	180–200	159–193
Akrotiri archaeological site—Manhole AC63P	10/10	140–180	129–177
Akrotiri archaeological site—Manhole AC76	7/7	140–180	132–172
Akrotiri archaeological site—‘House of Ladies’	10/11	160–200	162–200
Akrotiri archaeological site—‘Terrace of Beds’	7/8	180–200	154–200

Site: re-heating temperature ranges estimated using the ‘overlapping approach’; n/N: number of specimens with re-heating temperatures included in the overlapping temperature range/number of specimens studied; $T_{\text{r-over}}$: temperature range in °C estimated with the ‘overlapping approach’; $T_{\text{r-stat}}$: temperature range in °C calculated from the ‘statistical approach’.

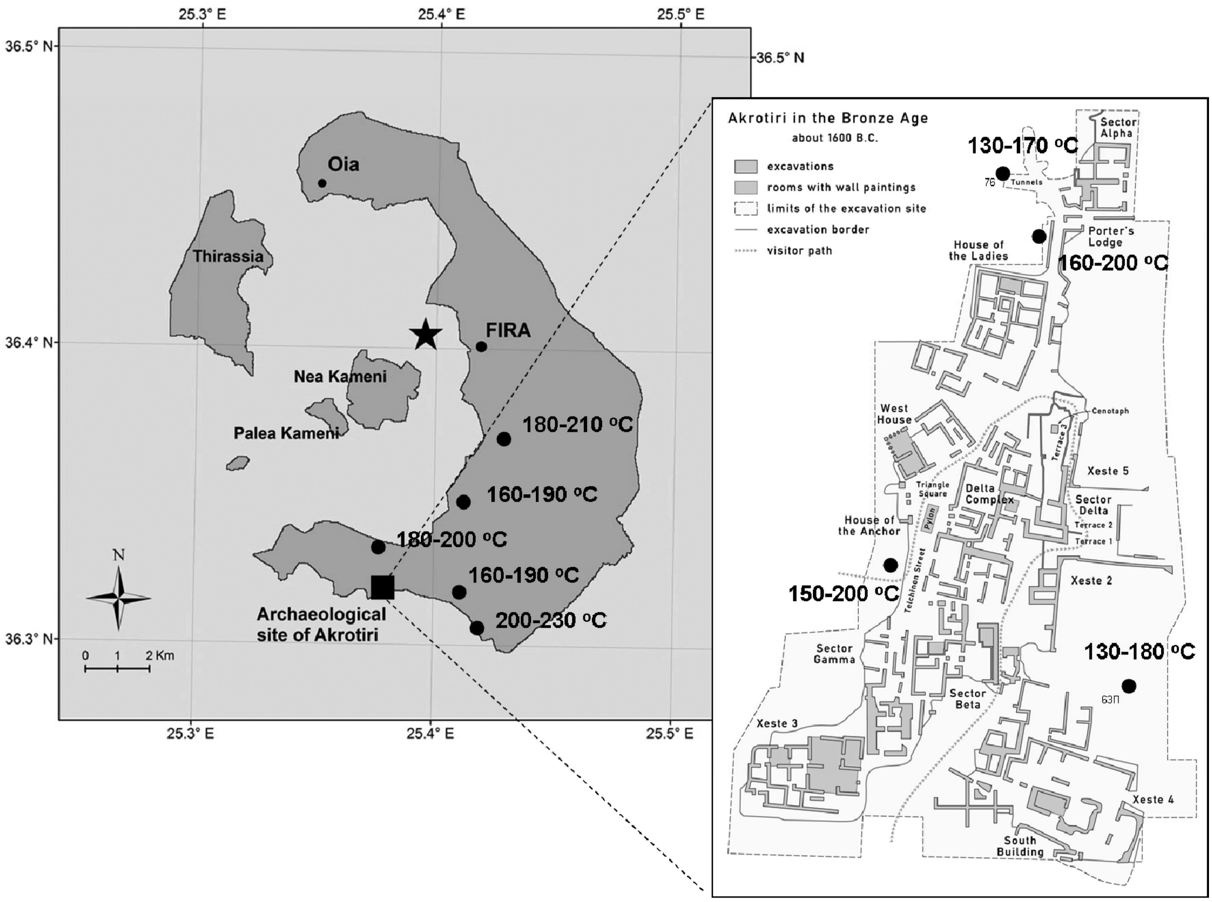


Figure 9. Geographical distribution of the estimated T_{dep} in the different sampling sites across Santorini island and inside the archaeological site of Akrotiri. (The Akrotiri excavation topographical map was downloaded from: *http://commons.wikimedia.org/ wiki/File:Map_Akrotiri_1600_BC-en.png*).

These temperatures are in good agreement with the temperatures estimated from lithic clasts from the pyroclastic pumice fall of the first eruption phase that indicate temperatures in the 180–240 °C range (Tema *et al.* 2013a). It is interesting to note that the obtained temperatures from all sites are very similar and no systematic variation with distance from the inferred vent of the eruption is observed. Agia Eirini site that is the closer one to the vent yields temperatures between 180–210 °C while Vlichada site that is the most distant one yields temperatures between 190–230 °C. It is difficult to say if the registered temperatures represent the temperature of the minor precursor tephra, the temperature of the pumice fall or the total thermal effect caused by the whole volcanic deposits volume, including also the probably much hotter pyroclastic surge deposits of the second and third eruption phases. Our results however, clearly show that the pre-Minoan habitation level experienced temperatures around 200 °C, and only small variations of few tens of degrees were registered between the different sites, probably depending on the local characteristics and topography.

Temperatures recorded by the ceramics collected from the archaeological site of Akrotiri are also well defined and vary from

130 to 200 °C (Fig. 9). All the studied ceramics indicate similar re-heating temperatures and differences in temperature across the village are rather small. The ceramic collection AC76 coming from the northern part of the excavation has registered the lower re-heating temperatures 130–170 °C while few meters in the south the ceramic collection coming from the open space close to the 'House of Ladies' records the higher temperatures 160–200 °C, that however differ only by 30 °C from those of AC76. Very similar temperatures are also recorded on the other ceramic collections, sampled from the southern part of the excavation (Fig. 9). These fairly uniform temperatures observed across the Akrotiri settlement suggest a relative homogeneity in the conditions during the thermal equilibrium of the ceramic fragments and the underlying volcanic deposits.

The temperatures registered inside the Akrotiri village are lower than those recorded in the other sampling sites that are not related to inhabited areas (Table 2 and Fig. 9). The record of lower temperatures in the Akrotiri habitation surface is probably due to the building debris layer that covered most of the streets and squares of the Akrotiri village, related to the partial destruction of the village from earthquakes that preceded the Minoan eruption (Doumas 1990; Cioni *et al.* 2000). Even though evidence for clearance and restoration works after the initial earthquakes and before the main eruption are given by the presence of piled boulders and large blocks at the sides of roads and buildings, still in several sites of the excavation, a layer of dust mixed with mortar, up to 10 cm thick, was interbedded between the building debris layer, the tephra of the eruption's opening phase and the Plinian fallout (Cioni *et al.* 2000). This layer could be related to the deposition and/or following reworking of the dusty material generated during the earthquake-induced collapse of the houses and can have caused the decrease of the temperatures recorded by the ceramics collected from different parts of the excavation.

The reduced temperatures registered inside the Akrotiri settlement, could be also caused by the interaction between the warm volcanic deposits with the cold human constructions. Similar lower deposition temperatures inside human settlements in respect to the undisturbed deposits have also been registered in other ancient villages destroyed by volcanic deposits such as Pompeii and Herculaneum (Cioni *et al.* 2004; Zanella *et al.* 2007). However, in the case of Pompeii, Zanella *et al.* (2007) have studied tiles and bricks embedded inside the pyroclastic density currents (PDCs) and the temperatures estimated correspond to the deposition temperatures of the PDCs and do not represent the re-heating temperatures at the habitation level. Nevertheless, their detailed study showed that the low temperature registered inside the archaeological site of Pompeii were caused by the interaction of the volcanic flows with the human settlements and the deposition of the PDCs was also importantly controlled by the topography of the village, with clear canalization of the flows in the roads and open spaces (Gurioli *et al.* 2005; Gurioli *et al.* 2007). In the case of Akrotiri village, no tiles, bricks or ceramics were found inside the pyroclastic flows of the second eruption phase; the human constructions were covered by the opening phase tephra and the Plinian fallout of the first main eruption phase while the pyroclastic surges deposited over the fallout probably were too violent, destroying and taking away the roofs and the upper parts of the houses. Even though the first fallout travelled through air and was deposited over the village, the lower temperatures inside the archaeological site presented here in respect to those in other non-inhabited sites indicate that there was still some interaction between the settlement and the fallout, resulting to its slightly cooling. The pumice fallout covered Akrotiri with a minimum thickness of 120 cm up to local thickness of around 170–200 cm, with preferential accumulation close to the buildings (Cioni *et al.* 2000), and filled also internal parts of the houses entering by the doors and windows. Building blocks were also found throughout the sequence of the pumice fallout, giving evidence of continuous, intense, syn-eruptive seismic activity and probably causing a drop of the temperatures experienced by the ceramics lying on the habitation surface.

Taking into consideration that Santorini is an active volcano, better understanding the characteristics of its past eruptive history is undoubtedly important for the assessment of future catastrophic events and volcanic hazard. The estimation of the deposit temperatures and their thermal effect on the habitation level provided in this study, incorporated with other volcanological and archaeological data, aims to contribute towards this direction. Certainly more data on the deposition temperatures of the different phases of the eruption would be still very important in order to reconstruct the thermal evolution of the eruption that completely destroyed but at the same time preserved for ever a part of the Aegean Late Bronze age civilization and culture.

ACKNOWLEDGEMENTS

This study would not have been realized without the precious collaboration of Prof Christos Doumas and Dr Tania Devetzi; they are both warmly acknowledged for the permission and help during sampling in the archaeological site of Akrotiri, the important information regarding the excavation and warm hospitality at the Akrotiri excavation guesthouse during the last sampling campaign. Maja Efstathiou is also warmly acknowledged for her collaboration and interest in our study. Dr Gerasimos Papadopoulos and A. Papadopoulos, G. Nikolaides and E. Mastoras are acknowledged for assistance during a preliminary sampling campaign. The archaeologist Dr Lefteris Zorzos is also acknowledged for the information provided and assistance in the field. Dr Giorgos Alexopoulos is thanked for interesting discussions during the Akrotiri sampling campaign and providing useful information about the excavation. Editors Andy Biggin and Manuel Calvo-Rathert and an anonymous reviewer are sincerely thanked for their useful comments on our manuscript.

REFERENCES

Aitken, M.J., Michael, H.N., Betancourt, P.P. & Warren, P.M., 1988. The Thera eruption: continuing discussion of the dating, *Archaeometry,* **30**(1), 165–181.

Aramaki, S. & Akimoto, S., 1957. Temperature estimation of pyroclastic deposits by natural remanent magnetism, *Am. J. Sci.,* **255,** 619–627.

Bardot, L., 2000. Emplacement temperature determinations of proximal pyroclastic deposits on Santorini, Greece, and their implications, *Bull. Volcanol.,* **61,** 450–467.

Bardot, L. & McClelland, E., 2000. The reliability of emplacement temperature Estimates using palaeomagnetic methods: a case study from Santorini, Greece, *Geophys. J. Int.,* **143,** 39–51.

Betancourt, P.P., 1987. Dating the Aegean Late Bronze age with radiocarbon, *Archaeometry,* **29,** 45–49.

Bond, A. & Sparks, R.S., 1976. The Minoan eruption of Santorini, Greece, *J. geol. Soc. Lond.,* **132,** 1–16.

Cioni, R., Gurioli, L., Lanza, R. & Zanella, E., 2004. Temperatures of A.D. 79 pyroclastic density currents deposits (Vesuvius, Italy), *J. geophys. Res.,* **109,** B02207, doi:10.1029/2002JB002251.

Cioni, R., Gurioli, L., Sbrana, A. & Vougioukalakis, G., 2000. Precursory phenomena and destructive events related to the Late Bronze Age

Minoan (Thera, Greece) and AD 79 (Vesuvius, Italy) Plinian eruptions; inferences from the stratigraphy in the archaeological areas, in *The Archaeology of Geological Catastrophes,* pp. 123–141, eds McGuire, W.G., Griffiths, D.R., Hancock, P.L. & Stewart, I.S., Geological Society Special Publication.

Di Vito, M. *et al.* 2009. The Afragola settlement near Vesuvius, Italy: the destruction and abandonment of a Bronze Age village revealed by archaeology, volcanology and rock-magnetism, *Earth planet. Sci. Lett.,* **277,** 408–421.

Doumas, C., 1990. Archaeological observations at Akrotiri relating to the volcanic destruction, in *Thera and the Aegean World, III,* Vol. 3, pp. 48–50, ed. Hardy, D. The Thera Foundation.

Downey, W.S. & Tarling, D.H., 1984. Archaeomagnetic dating of Santorini volcanic eruptions and fired destruction levels of Late Minoan Civilization, *Nature,* **309**(5968), 519–523.

Downey, W.S. & Tarling, D.H., 1991. Reworking characteristics of quaternary pyroclastics, Thera (Greece), determined using magnetic properties, *J. Volc. Geotherm. Res.,* **46,** 143–155.

Druitt, T.H., Mellors, R.A., Pyle, D.M. & Sparks, R.S.J., 1989. Explosive volcanism on Santorini, Greece, *Geol. Mag.,* **126,** 95–126.

Friedrich, L.W. & Heinemeier, J., 2009. The Minoan eruption of Santorini radiocarbon dated to 1613±13 BC: geological and stratigraphic considerations, in *Time's Up! Dating the Minoan Eruption of Santorini, Acts of the Minoan Eruption Chronology Workshop,* Vol. 10, pp. 57–63, ed. Warburton, D.A., Monographs of the Danish Institute at Athens.

Friedrich, W.L., Wagner, P. & Tauber, H., 1990. Radiocarbon dated plant remains from the Akrotiri excavation on Santorini, Greece, in *Thera and the Aegean World III,* Vol. 3, pp. 188–196, ed. Hardy, D.A., The Thera Foundation.

Gurioli, L., Pareschi, M.T., Zanella, E., Lanza, R., Deluca, E. & Bisson, M., 2005. Interaction of pyroclastic density currents with human settlements: evidence from ancient Pompeii, *Geology,* **336**(577), 441–444.

Gurioli, L., Zanella, E., Pareschi, M.T. & Lanza, R., 2007. Influences of urban fabric on pyroclastic density currents at Pompeii (Italy): 1. Flow direction and deposition, *J. geophys. Res.,* **112,** B05213, doi:10.1029/2006JB004444.

Heiken, G. & Mc Coy, F., 1984. Caldera development during the Minoan eruption, Thera, Cyclades, Greece, *J. geophys. Res.,* **89**(B10), 8441–8462.

Heiken, G. & McCoy, F., 1990. Precursory activity to the Minoan eruption, Thira, Greece, in *Thera and the Aegean World III,* Vol. 2, pp. 79–88, eds Hardy, D.A., Keller, J., Galanopoulos, V.P., Flemming, N.C. & Druitt, T.H., The Thera Foundation.

Hoblitt, R.P. & Kellogg, K.S., 1979. Emplacement temperatures of unsorted and unstratified deposits of volcanic rock debris as determined by paleomagnetic techniques, *Bull. geol. Soc. Am.,* **90,** 633–642.

Höflmayer, F., 2012. The date of the Minoan Santorini eruption: quantifying the 'Offset', *Radiocarbon,* **54**(3–4), 435–448.

Hughes, M.K., 1988. Ice layer dating of the eruption of Santorini, *Nature,* **335,** 211–212.

Kent, D.V., Ninkovitch, D., Pescatore, T. & Sparks, R.S.J., 1981. Palaeomagnetic determination of emplacement temperature of the Vesuvius AD 79 pyroclastic deposits, *Nature,* **290,** 393–396.

Lesti, C., Porreca, M., Giordano, G., Mattei, M., Cas, R.A.F., Wright, H.M.N., Folkes, C.B. & Viramonte, J., 2011. High-temperature emplacement of the Cerro Galán and Toconquis Group ignimbrites (Puna Plateau, NW Argentina) determined by TRM analyses, *Bull. Volcanol.,* **73,** 1535–1565.

Lowrie, W., 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties, *Geophys. Res. Lett.,* **17,** 159–162.

Manning, S.W., 1988. The Bronze Age eruption of Thera: absolute dating, Aegean chronology and Mediterranean cultural interrelations, *J. Med. Archaeol.,* **1,** 17–82.

Manning, S.W., Bronk Ramsey, C., Kutschera, W., Higham, T., Kromer, B., Steier, P. & Wild, E., 2006. Chronology for the Aegean Late Bronze Age, *Science,* **312,** 565–569.

McClelland, E. & Druitt, D.H., 1989. Palaeomagnetic estimates of emplacement temperatures of pyroclastic deposits on Santorini, Greece, *Bull. Volcanol.,* **51,** 16–27.

McClelland, E., Kondopoulou, D., Westphal, M. & Sophos, P.H., 1996. Palaeomagnetic estimation of emplacement temperatures of plinian airfalls on Santorini, Greece, in *The European Laboratory Volcanoes, Proceedings of the 2nd workshop,* eds Casale, R., Fytikas, M., Sigvaldasson, G. & Vougioukalakis, G., 2–4 May 1996, Santorini, Greece.

McClelland, E. & Thomas, R., 1990. A palaeomagnetic study of Minoan age tephra from Thera, in *Thera and the Aegean world III,* Vol. 2, pp. 129–138, ed. Hardy, D., Thera Foundation.

McClelland, E., Wilson, C. & Bardot, L., 2004. Palaeotemperature determinations for the 1.8-ka Taupo ignimbrite, New Zealand, and implications for the emplacement history of a high-velocity pyroclastic flow, *Bull. Volcanol.,* **66,** 492–513.

McCoy, W.F., 2009. The eruption within the debate about the date, in *Time's Up! Dating the Minoan Eruption of Santorini, Acts of the Minoan Eruption Chronology Workshop* Vol. 10, pp. 73–90, ed. Warburton, D.A, Monographs of the Danish Institute at Athens.

McCoy, F. & Heiken, G., 2000. The Late Bronze Age explosive eruption of Thera (Santorini), Greece: regional and local effect, *Geological Society of America,* Special paper, **345,** 43–70.

Paterson, G.A., Roberts, A.P., Mac Niocaill, C., Muxworthy, A.R., Gurioli, L., Viramonte, J.G. & Navarro, C., 2010. Paleomagnetic determination of emplacement temperatures of pyroclastic deposits: an underutilised tool, *Bull. Volcanol.,* **72,** 309–330.

Porreca, M., Mattei, M., Mac Niocaill, C., Giordano, G., McClelland, E. & Funiciello, R., 2008. Paleomagnetic evidence for low-temperature emplacement of the phreatomagmatic Peperino Albano ignimbrite (Colli Albani volcano, Central Italy), *Bull. Volcanol.,* **70,** 877–893.

Pyle, D.M., 1990. The application of tree-ring and ice-core studies to the dating of the Minoan eruption, in *Thera and the Aegean World III,* Vol. 3, pp. 167–173, ed. Hardy, D.A., The Thera Foundation.

Sparks, R.S.J. & Wilson, C.J.N., 1990. The Minoan deposits: a review of their characteristics and interpretation, in *Thera and theAegean World III* vol. 2, pp. 89–99. eds Hardy, D., Keller, J., Galanopoulos, V.P., Flemming, N.C. & Druitt, T.H., The Thera Foundation.

Sulpizio, R., Zanella, E. & Macías, J.L., 2008. Deposition temperature of some PDC deposits from the 1982 eruption of El Chichón volcano (Chiapas, Mexico) inferred from rock magnetic data, *J. Volc. Geotherm. Res.,* **175,** 494–500.

Tarling, D.H. & Downey, W.S., 1989. Archaeomagnetic results from Late Minoan Destruction Levels on Crete and the Minoan Tephra on Santorini, in *Thera and the Aegean World, III,* Vol. 49, pp. 149–159, ed. Hardy, D.A., The Thera Foundation.

Tema, E., Kondopoulou, D. & Pavlides, S., 2013a. Palaeotemperature estimation of the pyroclastic deposit covering the pre-Minoan palaeosol at Megalochori Quarry, Santorini (Greece): evidence from magnetic measurements, *Stud. Geophys. Geod.,* **57,** 627–646.

Tema, E., Pavlides, S. & Kondopoulou, D., 2013b. Late Bronze age pottery as indicator of the deposition temperatures of the Minoan pyroclastic products, Santorini, Greece, in *Bulletin of the Geological Society of Greece, vol. XLVII 2013, Proceedings of the 13th International Congress,* Chania, September 2013.

Zanella, E., Gurioli, L., Lanza, R., Suplizio, R. & Bontempi, E., 2008. Deposition temperature of the AD 472 Pollena pyroclastic density current deposits, Somma-Vesuvius, Italy, *Bull. Volcanol.,* **70**(10), 1237–1248.

Zanella, E., Gurioli, L., Pareschi, M.T. & Lanza, R., 2007. Influences of urban fabric on pyroclastic density currents at Pompeii (Italy): 2. Temperature of the deposits and hazard implications, *J. Geophys. Res.,* **112,** B05214, doi:10.1029/2006JB004775.

Zanella, E., Sulpizio, R., Gurioli, L. & Lanza, R., 2015. Temperatures of the pyroclastic density currents deposits emplaced in the last 22 kyr at Somma-Vesuvius (Italy), in *The Use of Palaeomagnetism and Rock Magnetism to Understand Volcanic Processes,* Vol. 396, Geological Society, doi:10.1144/SP396.5.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper:

Figure 1. (a) Determination of the deposition temperature (T_{dep}) at site level for the sites not included in Fig. 8 based on the maximum overlapping of the individual specimen re-heating temperature ranges; (b) Determination of the T_{dep} at site level based on the individual normalized Gaussian distributions for each specimen (left). The combined probability density function (pdf) for each site is calculated and the range of temperatures at 95 per cent of confidence are illustrated with red colour (right) (http://www.gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggv267/-/DC1).

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the paper.