

LATE BRONZE AGE POTTERY AS INDICATOR OF THE DEPOSITION TEMPERATURES OF THE MINOAN PYROCLASTIC PRODUCTS, SANTORINI, GREECE

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Abstract

The Minoan eruption of Santorini volcano (Greece) took place in the Late Bronze Age (17th century BC) and produced a great volume of volcanic products that covered the whole island and buried every human settlement under meters of pyroclastic deposits. In this study we used thermal analysis of the magnetic remanence carried by pottery fragments buried under the pyroclastic deposits in order to estimate the thermal effect of the Minoan volcanic products on the pre-eruption habitation level. A total of 70 samples, prepared from 45 independent pottery fragments, have been studied. Samples were collected from three different sites, situated at the southern part of the island. Stepwise thermal demagnetizations reveal that the pottery fragments generally carry a two-component remanent magnetization. Interpretation of the demagnetization results using the normalised intensity decay curves and the orthogonal projection diagrams indicates that most samples were re-heated at temperatures around 160-260 °C. The obtained results represent the equilibrium temperatures reached after the deposition of the pyroclastic fall and show that the pyroclastic fall deposits at distances around 6 to 9 km from the eruption vent were still hot enough to reheat the buried pottery at such temperatures.

Key words: Palaeomagnetism, Pyroclastic deposits, Deposition temperature, Pottery, Santorini.

Περίληψη

Η Μινωική έκρηξη του ηφαιστείου της Σαντορίνης που έλαβε χώρα κατά την Ύστερη Εποχή του Χαλκού (17^ο αιώνα π.Χ.) απέθεσε έναν τεράστιο όγκο ηφαιστειακών προϊόντων που κάλυψαν όλο το νησί και έθαψαν κάθε ανθρώπινο κτίσμα. Στην παρούσα μελέτη, παρουσιάζονται τα αποτελέσματα της θερμικής απομαγνήτισης κεραμικών θραυσμάτων που βρέθηκαν στην επαφή του προ-Μινωικού παλαιοεδάφους με τις πρώτες πυροκλαστικές αποθέσεις, με σκοπό την μελέτη της θερμικής επίδρασης των θερμών ηφαιστειακών υλικών στο παλαιοεδαφος όπου κατοικούσαν οι άνθρωποι πριν την έκρηξη. Συνολικά μελετήθηκαν 70 δείγματα που προέρχονται από 45 κεραμικά θραύσματα. Τα δείγματα συλλέχθηκαν από τρεις διαφορετικές τοποθεσίες στο νότιο μέρος του νησιού. Τα αποτελέσματα της σταδιακής θερμικής απομαγνήτισης των δειγμάτων δείχνουν ότι τα κεραμικά φέρουν δύο συνιστώσες μαγνήτισης που υποδεικνύουν ότι τα περισσότερα από αυτά αναθερμάνθηκαν σε θερμοκρασίες της

τάξεως 160-260 °C. Αυτές οι θερμοκρασίες αντιπροσωπεύουν τις θερμοκρασίες απόθεσης των πρώτων πυροκλαστικών προϊόντων που αποτέθηκαν πάνω στο Μινωικό έδαφος, μετά την αποκατάσταση της θερμικής ισορροπίας ανάμεσα στις θερμές αποθέσεις και το κρύο υπόβαθρο. Η μελέτη αυτή δείχνει ότι τα πρώτα πυροκλαστικά υλικά που αποτέθηκαν σε αποστάσεις 6 με 9 χιλιομέτρων από τον κρατήρα της Μινωικής έκρηξης, ήταν αρκετά ζεστά έτσι ώστε να προκαλέσουν αναθέρμανση των κεραμικών σε τέτοιες θερμοκρασίες.
Λέξεις κλειδιά: Παλαιομαγνητισμός, Πυροκλαστικές αποθέσεις, Θερμοκρασία απόθεσης, Κεραμικά, Σαντορίνη.

1. Introduction

Santorini has been, and still is, a unique natural laboratory where several disciplines found a prosperous ground for their development. A relatively less known one is the use of the magnetic properties of suitable materials (lithic clasts and/or archaeological artefacts) to estimate the deposition temperatures of the volcanic products produced by the various eruptions. This method has been already applied on lithic clasts from various series of the large explosive events which the island has experienced during the past 250000 years (McClelland & Druitt, 1989; Bardot & McClelland, 2000; Bardot, 2000). Several relevant studies have been also conducted in Italy, Mexico and Argentina (e.g. Cioni et al., 2004; Zanella et al., 2007; Sulpizio et al., 2008; Porreca et al., 2008; Di Vito et al., 2009; Lesti et al., 2011) and recently this technique was improved and extended involving also the study of human artefacts such as tiles and pottery.

The Minoan eruption (1613 $\pm$ 13 BC, Friedrich & Heinemeier, 2009) is the last large volcanic event which changed the morphology of the island to its actual aspect and is related to the destruction of the Cycladic culture and the Minoan civilization. Archaeological excavations, past and ongoing, put in light a rich evidence of human occupation which flourished during the Bronze age. The most prominent settlement, close to the modern village of Akrotiri, was totally buried by pumice and ash of the Minoan eruption which destroyed it, but at the same time also preserved it until its unearthing.

As a consequence of the island's "blanketing" by the Minoan eruption volcanic deposits, human artefacts among which pottery, were completely covered by the pyroclastic products and constitute today an additional source of information on the pyroclastic products deposition temperatures. It is well-known that baked clays contain various amounts of iron-oxides and can be magnetized during firing and subsequent cooling, under exactly the same physical principles which allow the magnetization of volcanics. Therefore, baked clays, abundant in archaeological sites, and in the present case lying under the Minoan eruptive products, can be used to reconstruct the deposition temperatures of the pyroclastic fall deposits within the sampling area.

In the present study we used carefully selected pottery fragments found on the surface of the pre-Minoan palaeosol and covered by the first eruption products. Standard palaeomagnetic techniques were used to estimate the prevailing temperatures reached after the deposition of the pyroclastic fall and the thermal equilibrium subsequently reached.

2. Materials and Methods

2.1. Palaeomagnetic Sampling

During two field campaigns carried out at 2011 and 2012, systematic sampling of ceramic fragments has been carried out at three locations: Megalochori Quarry (36° 22' 00" N, 25° 25' 12.0" E), Apothikes (Remezzo) (36° 21' 36.6" N, 25° 24' 14.7" E) and Vlichada (Bar Theros) (36° 20' 42.9" N, 25° 25' 30.0" E). Samples from Megalochori Quarry were first collected on May 2011 and the obtained results have been previously presented by Tema et al. (2013, *submitted*) while

samples from Apothikes and Vlichada were collected on August 2012 (Tema et al., 2013). All sampling sites are situated at the southern part of Santorini island (Figure 1), in distances that range from 6 to 9 km from the inferred vent of the Minoan eruption, probably located somewhere between the Nea Kameni Island and the present Fira town (Heiken & McCoy, 1984; McCoy, 2009). Identifying the sampling sites that could be appropriate for such study, was not an easy task: i) each studied site should offer a section of the Minoan eruption volcanic products. Moreover, the contact between the Minoan palaeosol and the first pyroclastic deposits should be clearly visible and approachable; ii) it should be an area occupied by human activity during the Minoan period in order to provide fragments from pottery and ceramic artefacts; iii) the collected ceramic fragments should be directly in contact and completely covered by the first pumice fall in order to be considered as reliable indicators of the re-heating temperature caused by the volcanic products. For this study, a total of 45 independent ceramic fragments have been collected; 22 from Megalochory Quarry, 16 from Apothikes and 7 from Vlichada (Bar Theros).



Figure 1 - Map of Santorini with the location of the studied sites.

All collected ceramics were completely covered by the precursory volcanic activity ashes and/or incorporated at the first three centimetres of the pumice fall. They are small fragments with dimensions varying from 1-4 cm (Figure 2) and probably belonged to some vases or plates for domestic use spread on the palaeosol surface during the eruption. Due to the small size of the collected ceramics the preparation of standard cylindrical specimens (diameter 25.4 mm; height 22.5 mm) was not possible. To measure such small pieces, 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 approach, from the 45 independent ceramic fragments, 70 specimens have been prepared and studied.

2.2. Contribution of Palaeomagnetic Methods to the Estimation of Deposition Temperatures

Palaeomagnetism has been widely applied in the last decades to tectonics, magnetostratigraphy, geomagnetic field modelling and to archaeology (archaeomagnetism). An additional and less known application consists to the estimation of pyroclastic deposits depositional temperature



Figure 2 - Photo of two ceramic fragments sampled at Vlichada.

through the determination of the partial thermal remanent magnetization (pTRM) of lithic clasts and/or ceramic fragments incorporated and/or covered by the volcanic deposits. This method has been thoroughly described by several authors (e.g. McClelland & Druitt, 1989; Zanella et al., 2007; Paterson et al. 2010) while others analysed potential factors affecting the reliability of the emplacement temperature estimates using palaeomagnetic methods (Bardot & McClelland, 2000; Porreca et al., 2008; Lesti et al., 2011).

The method is based on the following assumption: the lithic clasts found in the pyroclastic deposits and probably coming from cold lavas of previous eruptions contain magnetic minerals and carry a remanent magnetization acquired during their initial formation, oriented towards the Earth's magnetic field at the time of their cooling. These clasts are partially re-heated when incorporated in the hot mixture of ash and gases produced by a new volcanic eruption. A portion of their original magnetization is lost and they acquire a new partial thermoremanent magnetization, oriented along the Earth's magnetic field at the time of the emplacement. As a consequence, the natural remanent magnetization (NRM) of a lithic clast will consist of two TRM components of magnetization; an original, randomly oriented, high temperature component and a new, uniformly oriented, low temperature component.

Through an analogous procedure, ceramic fragments carry an initial magnetization acquired during heating at high temperatures and subsequent cooling at ambient temperature in a kiln during their production procedure. In the case of volcanic eruptions affecting inhabited areas, such ceramics are often found in contact with or incorporated into pyroclastic deposits that cover the human habitation surface (Di Vito et al., 2009). Since the volcanic products are usually hot 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 demagnetized and will acquire a secondary, low temperature, magnetic component.

In order to obtain reliable equilibrium deposition temperatures, the secondary magnetization component should be of thermal origin (thermal remanent magnetization, TRM) and not be altered by the effects of chemical overprinting (chemical remanent magnetization, CRM) due to field or laboratory alteration (McClelland & Druitt, 1989). For this reason, several tests are performed in order to assess the thermal origin of the secondary component. A serious advantage in using pottery fragments instead of lithic clasts for the estimation of emplacement temperatures lies in their origin. In fact, pottery resists better to chemical alteration than lithic clasts often fractured and trapping water and gases.

3. Measurements and Results

A total of 70 specimens from the three studied sites have been submitted to stepwise thermal demagnetization at the ALP Palaeomagnetic Laboratory (Peveragno, Italy). Thermal

demagnetization was performed with a TSD-2 Schonstedt furnace and the magnetic remanence of the samples was measured with a JR6 (AGICO) spinner magnetometer. Thermal demagnetization was carried out in steps of 40 °C between a starting temperature of 60 °C and a maximum of ~620 °C. Whenever sister specimens from individual ceramic fragments were available, a second demagnetization was carried out using the same 40 °C steps but starting from 80 °C. The results were then interpreted using the principal component analysis available as part of the Remasoft software (Chadima & Hrouda, 2006).

3.1. Thermal Stability of the Samples

In order to estimate the thermal stability of the samples, after each heating/cooling circle, the bulk magnetic susceptibility at room temperature was measured for all samples with a KLY-3 (AGICO) Kappabridge at the ALP Palaeomagnetic laboratory. Almost all pottery samples show a very stable behaviour and only negligible magnetic susceptibility variations with increasing temperature are observed (Figure 3). These results are also confirmed by the continuous thermomagnetic curves obtained for representative samples from Megalochori Quarry (e.g. sample MGC2- Figure 4). The continuous heating and cooling curves measured at IPGP (Paris) with a CS3 Kappabridge, show very good reversibility and suggest that the ceramics are thermally stable and there is no evidence for important magnetic mineralogy transformations during heating.

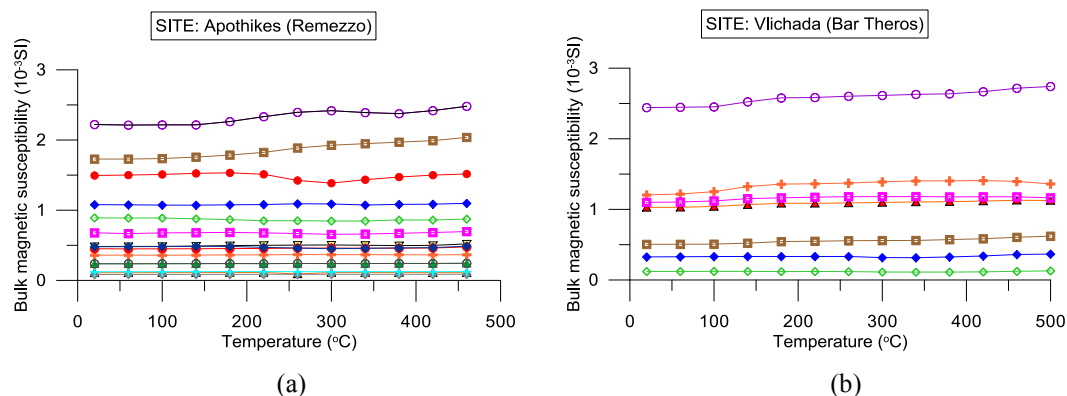


Figure 3 - Variations of the bulk magnetic susceptibility at room temperature after each heating-cooling circle during stepwise thermal demagnetization for ceramics from a) Apothikes and b) Vlichada.

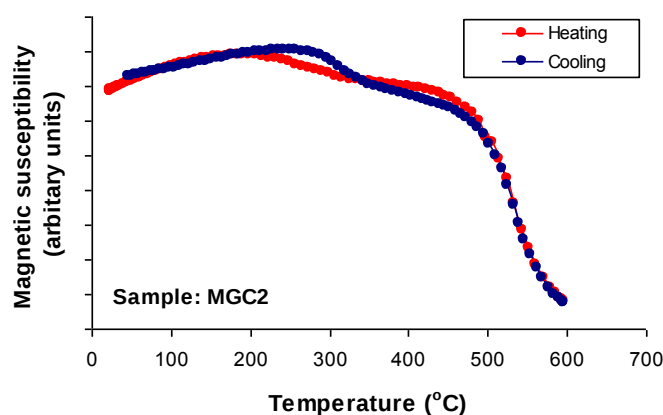


Figure 4 - Continuous variation of magnetic susceptibility with temperature (Sample MGC2, Megalochori Quarry).

3.2. Thermal Demagnetization Results

The thermal demagnetization results are interpreted using the normalised intensity decay curves and the orthogonal projection diagrams (Zijderveld, 1967). From the 70 demagnetized specimens, more than half of them (53 specimens) clearly show two components of magnetization: a high temperature component acquired during the initial heating of the ceramics (during their production involving heating in a kiln) and a low temperature component acquired during their partial re-heating caused by the overlapping hotter pyroclastic deposits. In most cases the two components are well defined and clearly distinguished from the Zijderveld diagrams, showing a sharp change in direction (Figure 5). In order to guarantee high quality of the obtained results, specimens

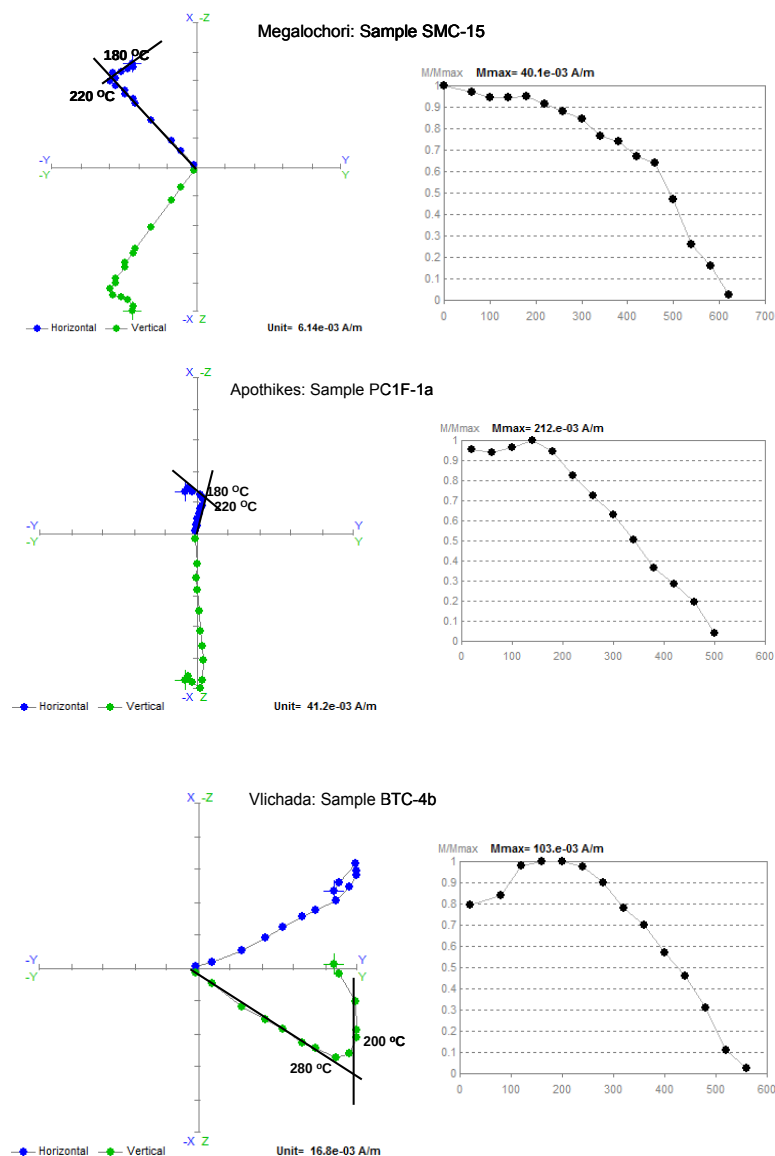


Figure 5 - Thermal demagnetization results illustrated as Zijderveld diagrams and NRM decay plots.

characterized by two magnetization components that however are not clearly separated, have been rejected. Few ceramic fragments show a three component magnetization; an initial characteristic magnetization component that is the one that passes through the origin of the axes in the Zijderveld diagrams and corresponds to the initial heating of the ceramics during their fabrication, a second high temperature component that indicates a partial re-heating at high temperatures around 420-460 °C, and a third low temperature component that indicates a final partial re-heating at lower temperatures around 180-220 °C. This intermediate temperature component, as already discussed by Tema et al. (2013, *submitted*) could be interpreted as a magnetization component acquired during the use of the ceramics that were often utilized to prepare and cook food and for this reason were in contact with fire or heated in domestic furnaces.

The ceramics re-heating temperatures have been estimated separately for each individual specimen from the intersection point of the low- and high- temperature magnetic component defined as the temperature interval between the highest temperature at which the low T_b component is present and the next temperature in the demagnetization sequence. Components with $T_b < 130$ °C have not been taken in consideration because they cannot be safely distinguished from a viscous magnetization overprint (Pullaiah et al., 1975; Bardot & McClelland, 2000). Estimated re-heating temperature intervals for each ceramic specimen based on the low-temperature magnetic component are illustrated in Figure 6 for each sampling site separately. The obtained results show that the estimated re-heating temperatures at specimen level vary from 120-240 °C at Megalochori, 120-300 °C at Apothikes and 140-280 °C at Vlichada. In all sites however, the maximum temperatures distribution is concentrated between 160 and 220 °C while 80% of the estimated temperatures from all sites are included in the 160-260 °C temperature range.

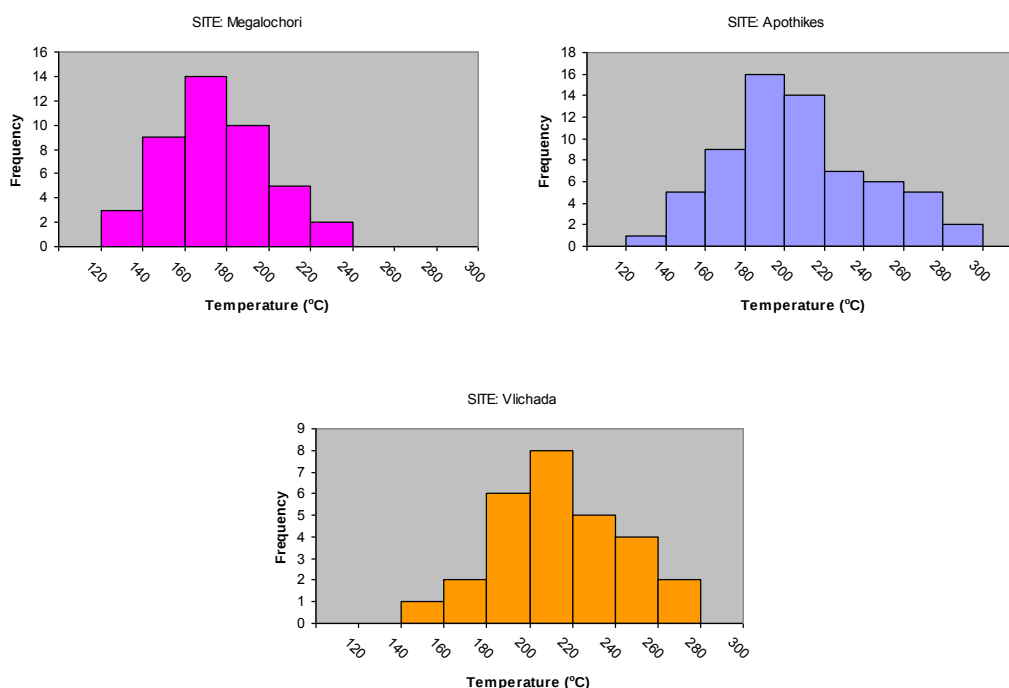


Figure 6 - Estimation of the re-heating temperatures of the studied ceramics from Megalochori, Apothikes and Vlichada sampling sites.

4. Conclusions

This study demonstrates that pottery fragments can be successfully used as indicators of the deposition temperatures of the overlapping pyroclastic deposits. Samples collected from three sites situated at the southern part of Santorini island revealed two well defined magnetic components and showed that most of the studied samples have been re-heated at temperatures ranging from 160 to 260 °C. The obtained results are in good agreement with the Minoan plinian airfall emplacement temperatures estimated by McClelland et al. (1996). These authors studied lithic clasts collected from the Minoan Plinian tephra deposits at five sites and they found temperatures ranging from 130 to 250 °C at site level. However, no literature data for deposition temperatures of the Minoan deposits based on ceramic fragments are available, and the new results presented here are the only ones available up to now.

The estimated temperatures represent the equilibrium temperatures reached after the deposition of the first pyroclastic products and show that the pyroclastic fall deposits at a distances as far as 9 km from the eruption vent were still hot enough to reheat the buried ceramics at such temperatures. A continuation of this study involving the investigation of re-heating temperatures from sites located also at the Northern part of the island would be of particular interest in order to obtain a spatial distribution of the thermal effects of the Minoan volcanic products on the pre-Minoan habitation level.

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