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ROCK MAGNETIC AND PALAEOMAGNETIC ANALYSES ON LITHIC FRAGMENTS FROM THE ARCHAEOLOGICAL SITE OF AKROTIRI, SANTORINI

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Abstract

Rock magnetic and palaeomagnetic analyses on lithic clasts collected from the pumice fall deposited inside the archaeological site of Akrotiri have been applied in order to estimate the deposition temperature of the first volcanic products of the Minoan eruption. A total of 50 lithic clasts have been collected from four different locations inside the excavation of Akrotiri. All samples have been stepwise thermally demagnetized and the obtained results have been interpreted through principal component analysis. The equilibrium temperature obtained after the deposition of the pumice fall varies from sample to sample but generally shows temperatures around 240-280°C. These temperatures are in good agreement with those estimated from lithic clasts from the Megalochori Quarry while they are higher compared with those from ceramic fragments from Akrotiri. The new temperature data presented here show that the pumice fall was still relatively hot when deposited inside the archaeological site and even if it interacted with the buildings, often causing the collapse of roofs, it still remained hot with mean temperature around 260°C.

Keywords: *Rock magnetism, Pumice fall, Lithic clast, Akrotiri archaeological site, Santorini.*

Περίληψη

Στην παρούσα εργασία μελετήθηκε η παραμένουσα μαγνήτιση θραυσμάτων λιθικών που βρέθηκαν μέσα στις αποθέσεις ελαφρόπετρας που κάλυψαν τον αρχαιολογικό χώρο του Ακρωτηρίου με σκοπό την εκτίμηση της θερμοκρασίας απόθεσης των πρώτων ηφαιστειακών υλικών που έφτασαν και αποτέθηκαν στον αρχαίο οικισμό. Συνολικά συλλέχτηκαν 50 λιθικά θραύσματα από τέσσερα διαφορετικά σημεία της ανασκαφής. Όλα τα δείγματα απομαγνητίστηκαν με σταδιακή θέρμανση και η ανάλυση των αποτελεσμάτων πραγματοποιήθηκε διαμέσου του διαχωρισμού των κυρίων συνιστωσών μαγνήτισης. Η θερμοκρασία απόθεσης που εκτιμήθηκε αντιπροσωπεύει την θερμοκρασία των λιθικών μετά την αποκατάσταση της θερμικής ισορροπίας μεταξύ αυτών και της θερμότερης ελαφρόπετρας και διαφέρει από λιθικό σε λιθικό. Παρ' όλα αυτά, στο μεγαλύτερο μέρος τους τα λιθικά δείχνουν ότι έχουν αναθερμανθεί σε θερμοκρασίες της τάξεως 240-280°C. Αυτές οι θερμοκρασίες είναι ανάλογες με τις θερμοκρασίες απόθεσης που εκτιμήθηκαν από την μελέτη λιθικών από το ορυχείο του Μεγαλοχωρίου ενώ είναι υψηλότερες από αυτές που εκτιμήθηκαν διαμέσου κεραμικών από την ανασκαφή του Ακρωτηρίου. Τα νέα αποτελέσματα θερμοκρασιών απόθεσης από λιθικά στο εσωτερικό του αρχαίου οικισμού δείχνουν ότι το στρώμα ελαφρόπετρας ήταν ακόμη ζεστό όταν αποτέθηκε μέσα στον αρχαιολογικό χώρο και παρότι ήρθε σε

επαφή με τα κτίρια προκαλώντας σε ορισμένες περιπτώσεις την πτώση των οροφών, παρ' όλα αυτά παρέμεινε θερμό με μέση θερμοκρασία περίπου 260 °C.

Λέξεις κλειδιά: *Μαγνήτιση πετρωμάτων, Ελαφρόπετρα, Λιθικά θραύσματα, Αρχαιολογικός χώρος Ακρωτηρίου, Σαντορίνη.*

1. Introduction

The Akrotiri archaeological site is located at the southern part of Santorini Island and is one of the most important Bronze Age human settlements in the Mediterranean area. The ancient city was destroyed and at the same time preserved under meters of pyroclastic deposits, produced by the violent Minoan eruption of Santorini volcano. Archaeological excavation brought into light a very advanced civilization and a well developed habitation settlement while at the same time gave evidence of important earthquake activity that took place before and during the destructive volcanic event (Doumas, 1974). The stratigraphy of the Minoan eruption inside the archaeological site of Akrotiri shows that most of the streets and squares were covered by a building debris layer produced by the partial destruction of the settlements due to the earthquakes preceding the Minoan eruption. This destruction layer was then covered by a thin layer of ash probably produced during the early opening phase of the eruption (Cioni *et al.*, 2000). The first product of the main eruption deposited at Akrotiri was a Plinian pumice fallout (Figure 1) with minimum thickness of 120 cm that locally arrive up to 170-200 cm, due to preferential accumulations close to the buildings (Cioni *et al.*, 2000). Over the pumice fall, pyroclastic surge deposits belonging to the second phase of the eruption were deposited in cross-stratified layers, completely burying the whole settlement. The massive, lithic-rich pyroclastic flow deposits of the successive phase of the eruption are missing from the Akrotiri archaeological site, probably deviated by, and/or channelled around the settlement into the topographic lows (Cioni *et al.*, 2000).

Figure 1 - View of the pumice fall deposited inside the archaeological site of Akrotiri.

Even though the stratigraphy of the Minoan eruption volcanic deposits has been thoroughly studied by several researchers (e.g. Bond and Sparks, 1976; Heiken and McCoy, 1984; Druitt *et al.*, 1989; Sparks and Wilson, 1990; McCoy and Heiken, 2000), available information regarding the temperatures of the pyroclastic products when deposited inside the archaeological site and their effect on the human settlements is still scarce.

Aramaki and Akimoto (1957) were the first to use rock magnetic and palaeomagnetic analysis to obtain information regarding the deposition temperature of pyroclastic rocks. Since then, several studies used lithic clasts embedded in volcanic deposits to better understand their characteristics and estimate their deposition temperature (e.g. Downey and Tarling, 1984; McClelland and Druitt, 1989; McClelland *et al.*, 1996; Bardot, 2000; Cioni *et al.*, 2004; Zanella *et al.*, 2007; Sulpizio *et al.*, 2008; Paterson *et al.*, 2010). In this study, standard palaeomagnetic techniques have been applied for first time on lithic clasts from the pumice fallout deposited inside the Akrotiri archaeological site in order to estimate the deposition temperature of the pyroclastic deposits and better understand their characteristics when interacting with human constructions.

2. Materials and Methods

2.1. Samples collection and preparation

Lithic clasts embedded into the first pumice fall layer were collected from four different locations inside the archaeological site of Akrotiri (Figure 2). During the last decades most of the volcanic deposits that covered the ancient city have been removed and therefore sampling was limited only at the parts of the settlement where the pumice fall and the overlaying pyroclastic surge deposits were preserved as stratigraphic testimonies. All samples collected have dimensions ranging from 1 cm to 3 cm.

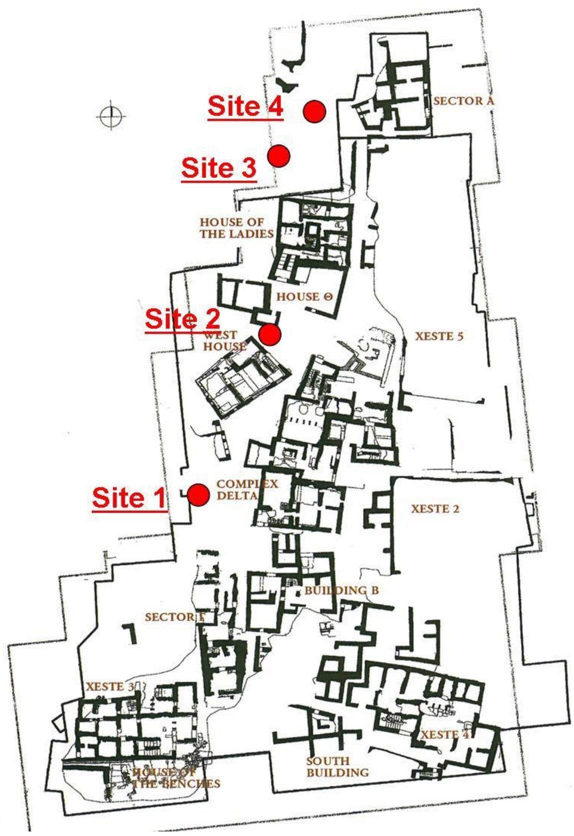

Figure 2 - Map of the Akrotiri excavation with the location of the sampling sites.

When possible, each lithic clast was divided at the laboratory in two small pieces and each of them was fixed into cubic palaeomagnetic boxes of standard dimensions (2x2x2 cm) using a smooth, white, non magnetic plasticine. This way, often two specimens from the same sample were prepared and studied. Even though samples were not oriented *in situ*, a white arrow was marked on their surface to facilitate the laboratory measurements. The samples were removed from the plastic boxes for the heating treatment while the use of the plasticine allowed their reposition at exactly the same position for the remanent magnetization measurement. A total of 74 specimens coming from 50 independent lithic clasts have been analysed; 20 from Site 1 (L1FKL), 19 from Site 2 (L1FOG), 12 from Site 3 (ATHL1) and 23 from Site 4 (AMTA).

2.2. Experimental procedure

The use of palaeomagnetic techniques to estimate the emplacement temperature of pyroclastic deposits is based on the assumption that during an explosive eruption, cold lithic clasts coming from the existing volcanic structure, are incorporated and heated into a hot mixture of ash and gases that is eventually deposited in certain distance from the eruption vent. The accidental lithic clasts will have a primary magnetization acquired prior to the eruption. If the pyroclastic deposits were emplaced above ambient temperature, the clasts will be then partially reheated during their incorporation into the deposit and a portion of their initial magnetization will be cancelled. A new secondary magnetization will thus be acquired during their cooling in the presence of the ambient Earth's magnetic field. This procedure produces two components of magnetization that can be isolated with progressive thermal demagnetization (Cioni *et al.*, 2004; Paterson *et al.*, 2010; Tema *et al.*, 2013a; Zanella *et al.*, 2015).

In this study, stepwise thermal demagnetization was carried out using a Schonstedt furnace for heating and cooling and JR5/JR6 spinner magnetometers for measuring the remanent magnetization. Thermal demagnetizations were carried out in steps of 40ºC between a starting temperature of 60ºC and a maximum temperature varying between 500ºC and 580ºC. When twin specimens from individual samples were available, a second demagnetization group was carried out following the same 40ºC step but starting from 80ºC. After each temperature step, the bulk magnetic susceptibility was measured with a KLY-3 Kappabridge (AGICO). All measurements were performed at the ALP palaeomagnetic laboratory (Peveragno, Italy).

3. Results

3.1. Magnetic susceptibility variation during heating

The bulk magnetic susceptibility of all specimens was measured at room temperature after each thermal demagnetization step in order to detect possible mineralogical changes during heating (Porreca *et al.*, 2007; Paterson *et al.*, 2010, Tema *et al.*, 2013a, 2015). The obtained values have been normalized to the initial susceptibility measured before any thermal treatment and plotted versus temperature (Figure 3). The results show that often important magnetic susceptibility changes occur during heating and in some cases susceptibility variation may arrive up to 50 % in respect to the initial value (Figure 3a). Such changes may reflect possible mineralogical transformations and the formation of a chemical remanent magnetization (CRM) that can affect the blocking temperature spectrum of a sample, obscuring the reliable isolation of the deposition temperature (McClelland and Druitt, 1989; Paterson *et al.*, 2010).

The obtained results confirm that lithic clasts are less thermally stable than the ceramic fragments embedded into pyroclastic deposits (Tema *et al.*, 2013a, b, 2015), probably because of their unknown and often complicated thermal history. Their interpretation and use for the determination of deposition temperatures could therefore be complicated and should be done with caution. In this study, to guarantee the reliability and the quality of the new results, lithic clasts that show important magnetic susceptibility changes have been rejected and the final results are based only on samples that show a stable thermal behavior up to 400ºC (Figure 3b) and/or are characterized by a clear interpretation of the secondary magnetic component.

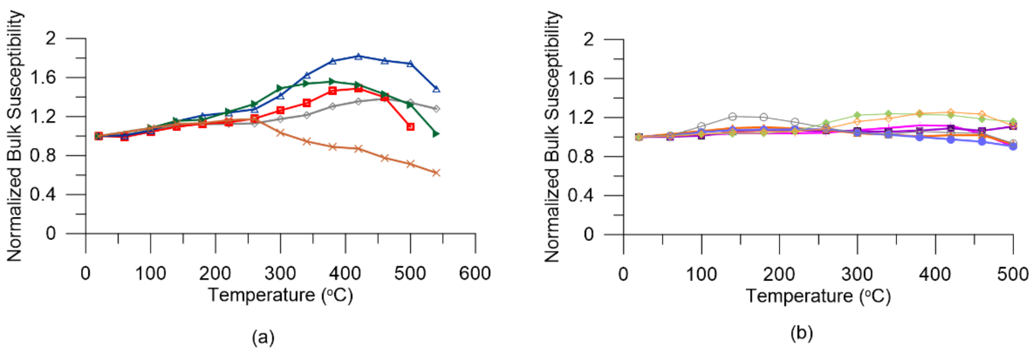

Figure 3 - Examples of samples with a) important magnetic susceptibility changes and b) stable thermal magnetic behaviour during heating.

3.2. Magnetic components analysis

The thermal demagnetization results have been represented using orthogonal vector plots (Zijderveld diagrams, Zijderveld, 1967) (Figure 4). Data have been elaborated using the PaleoMac (Cogné, 2003) software. From the 74 analysed specimens, 45 have been rejected either because of important mineralogical changes during heating or due to not clear interpretation of the Zijdelveld diagrams. The remaining specimens showed a two-magnetic components behavior, belonging to types C and D according to the classification made by Cioni *et al.* (2004) (Figure 4).

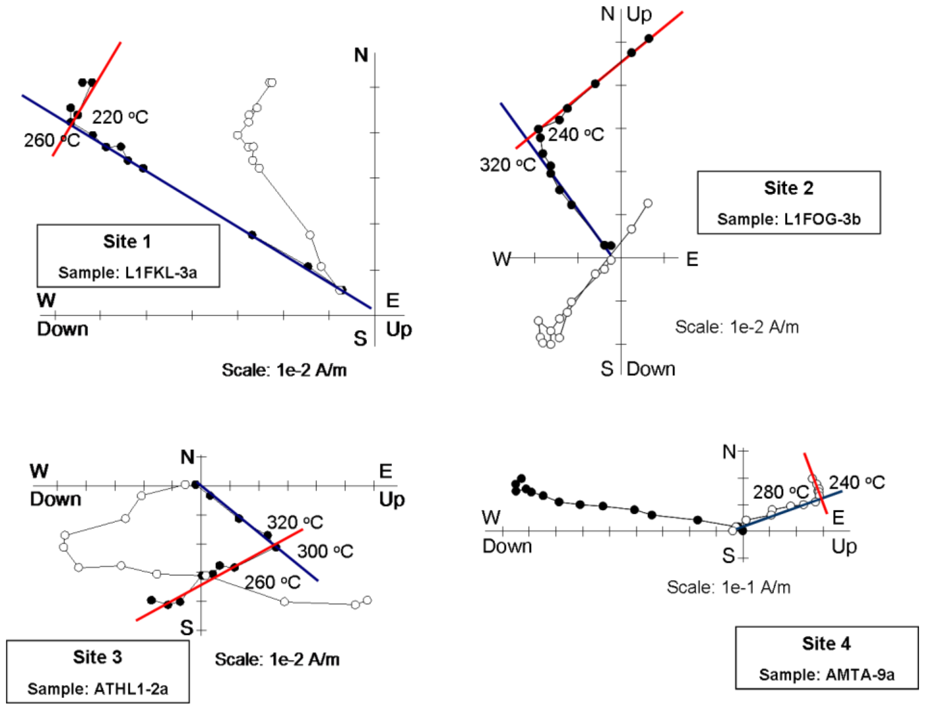

Figure 4 - Thermal demagnetization results represented in Zijderveld diagrams. Solid dot indicates declination; open dot indicates apparent inclination.

The deposition temperature of the pyroclastic deposit in which the lithic clasts were incorporated has been determined from the intersection of the two recognized magnetic components: the primary, high-temperature magnetic component corresponding to the initial magnetization of the clasts (before the Minoan eruption) and the secondary, low-temperature magnetic component acquired during the partial reheating of the clast when embedded in the pumice fall (blue and red lines in Figure 4). In the cases of curvature behaviour in the Zijderveld diagrams, the re-heating temperature has been determined taking into account the whole temperature interval between the lower-temperature where the curvature begins up to the first temperature of the high-temperature magnetic component (Tema *et al.*, 2013a). Even if this way the estimated temperature interval results rather wide, it however guarantees that the real deposition temperature would be included into this interval. The re-heating temperature for each site has been finally estimated from the maximum overlap of the re-heating temperatures determined from each studied specimen (Figure 5).

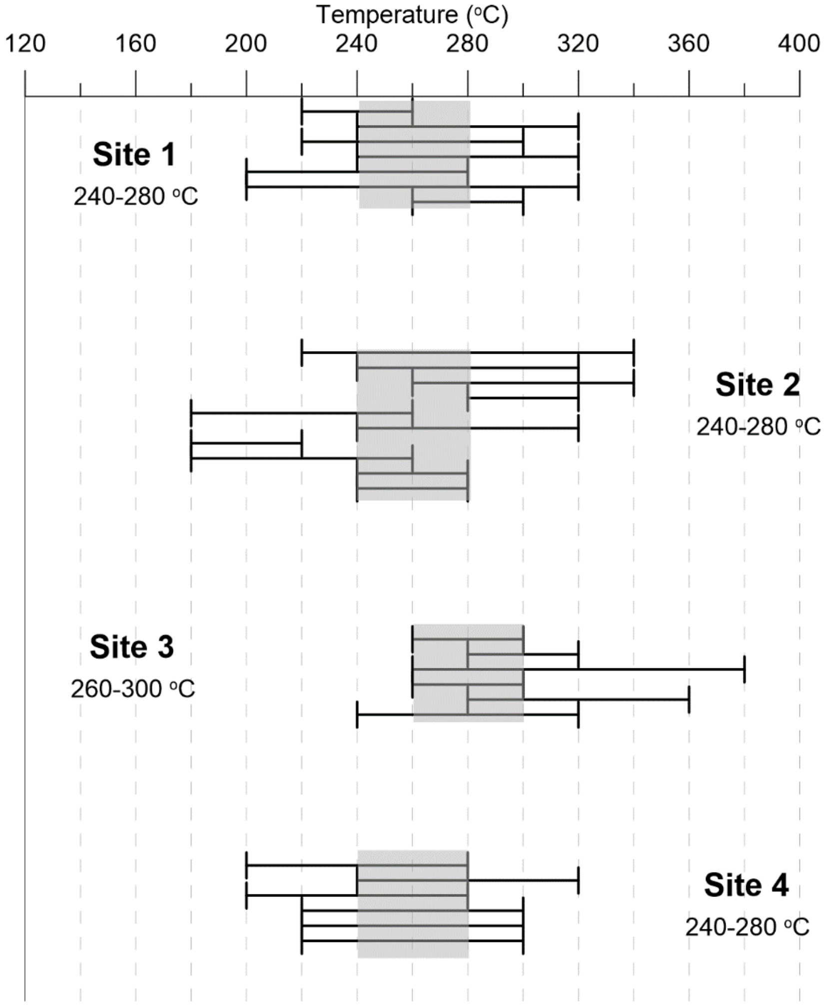

Figure 5 - Deposition temperature of the pyroclastic pumice fall at the four studied sites estimated by the maximum overlap of the re-heating temperatures at specimen level.

4. Discussion

The obtained results show that the temperature of the pumice fall, as registered by the lithic clasts embedded into the deposits from the archaeological site of Akrotiri and after the achievement of the thermal equilibrium between the cold lithics and the hotter pumice matrix, is generally ranging from 240ºC to 300ºC (Figure 5). Individual specimens, however, may show large temperature ranges occasionally varying from 180ºC to 380ºC, probably because of the different thermal history of each lithic clast and their unknown transportation path till their incorporation and deposition in the pumice fall deposits. Nevertheless, the 97 % of the accepted specimens show a common re-heating temperature interval of 240-280ºC and no important differences are noticed among the different sampling sites inside the Akrotiri settlement (Figure 5). These results are in good agreement with the results from lithic clasts selected from the Megalochori Quarry (Tema *et al.*, 2013a) that show temperatures in the 180-240ºC range while are higher than the temperatures obtained based on the study of ceramic fragments from the archaeological site of Akrotiri (Tema *et al.*, 2015), ranging from 130ºC to 200ºC. Such difference is probably due to the fact that the lithic clasts were embedded inside the hot pumice fall deposit while the ceramic fragments were lying over the building destruction lever and were re-heated only by the superficial contact with the overlying pumice fall deposit. The new temperature data presented here show that the pumice fall was still relatively hot when deposited inside the archaeological site and even if it interacted with the buildings often causing the collapse of roofs, it still remained hot with mean temperature around 260ºC.

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6. References

Aramaki, S. and 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.

Bond, A. and Sparks, R.S., 1976. The Minoan eruption of Santorini, Greece, *Journal of the Geological Society of London*, 132, 1-16.

Cioni, R., Gurioli, L., Sbrana, A. and 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, McGuire, W.G., Griffiths, D.R., Hancock, P.L. and Stewart, I.S., *eds*., *Geological Society Special Publication*, London, 171, 123-141.

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

Cogné, J.R., 2003. PaleoMac: a Macintosh application for treating palaeomagnetic data and making plate reconstructions, *Geochem. Geophys. Geosyst.*, 4(1), 1007, doi: 10.1029/2001GC000227.

Doumas, Ch., 1974. The Minoan eruption of the Santorini volcano, *Antiquity,* XLVIII, 110-115.

Downey, W.S. and Tarling, D.H., 1984. Archaeomagnetic Dating of Santorini Volcanic Eruptions and Fired Destruction Levels of Late Minoan Civilization, *Nature*, 309(5968), 519-523.

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

Heiken, G. and McCoy, F., 1984. Caldera development during the Minoan eruption, Thera, Cyclades, Greece, *J. Geophys. Res.,* 89, B 10, 8441-8462.

McClelland, E. and Druitt, D.H., 1989. Palaeomagnetic estimates of emplacement temperatures of pyroclastic deposits on Santorini, Greece, *Bull. Volcanol*., 51, 16-27, doi: 10.1007/BF01086758.

McClelland, E., Kondopoulou, D., Westphal, M. and Sophos, Ph., 1996. Palaeomagnetic estimation of emplacement temperatures of plinian airfalls on Santorini, Greece. *In*: Casale, R., Fytikas, M., Sigvaldasson, G. and Vougioukalakis, G., *eds*., The European laboratory volcanoes, *Proceedings of the 2nd workshop*, 2-4 May 1996, Santorini, Greece.

McCoy, F. and 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. and Navarro, C., 2010. Paleomagnetic determination of emplacement temperatures of pyroclastic deposits: an underutilised tool, *Bull Volcanol.*, 72, 309-330, doi: 10.1007/s00445-009-0324-4.

Porreca, M., Mattei, M., Mac Niocaill, C., Giordano, G., McClelland, E. and 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, doi: 10.1007/s00445-007-0176-8.

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

Sulpizio, R., Zanella, E. and 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. Volcanol. Geotherm. Res.*, 175, 494-500, doi: 10.1016/j.jvolgeores.2008.02.024.

Tema, E., Kondopoulou, D. and 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, doi: 10.1007/s11200-013-0601-8.

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

Tema, E., Zanella, E., Pavón-Carrasco, F.J., Kondopoulou, D. and Pavlides, S., 2015. Palaeomagnetic analysis on pottery as indicator of the pyroclastic flow deposits temperature: new data and statistical interpretation from the Minoan eruption of Santorini, Greece, *Geophys. J. Int*., 203, 33-47, doi: 10.1093/gji/ggv267.

Zanella, E., Gurioli, L., Pareschi, M.T. and 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. and Lanza, R., 2015. Temperatures of the pyroclastic density currents deposits emplaced in the last 22 kyr at Somma-Vesuvius (Italy). Geological Society, London, Special Publication: “The Use of Palaeomagnetism and Rock Magnetism to Understand Volcanic Processes”, 396, doi:10.1144/SP396.5.

Zijderveld, J.D.A., 1967. A.C. demagnetization of rocks: Analysis of results. *In: Methods in Palaeomagnetism*, Collinson, D.W., Creer, K.M. and Runcorn, S.K., *eds*., Elsevier, Amsterdam.