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**This is the author's manuscript**

*Original Citation:*

*Availability:*

This version is available <http://hdl.handle.net/2318/142474> since

*Published version:*

DOI:10.1007/s11200-013-0601-8

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# UNIVERSITÀ DEGLI STUDI DI TORINO

***This is an author version of the contribution published on:***

*Studia Geophysica Geodaetica*, Vol. 57, p.627-646, 2013, DOI:  
[10.1007/s11200-013-0601-8](https://doi.org/10.1007/s11200-013-0601-8)

***The definitive version is available at:***

<http://link.springer.com/article/10.1007/s11200-013-0601-8>

# **Palaeotemperature estimation of the pyroclastic deposit covering the pre-Minoan palaeosol at Megalochori Quarry, Santorini (Greece): Evidence from magnetic measurements.**

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## **Abstract**

Thermal remanent magnetization analyses were carried out on ceramic fragments and lithic clasts embedded in the first pumice fall deposits of the Minoan eruption. The aim of this study is to estimate the equilibrium temperature after deposition of these pyroclastic fall deposits and their thermal effect on the pre-Minoan surface. A total of 30 samples from 22 independent ceramic fragments and 20 samples from 14 lithic clasts have been studied. Samples were collected from the Megalochori Quarry, located at the southern part of Santorini island. Stepwise thermal demagnetization reveal that the ceramics were mostly re-heated at temperatures around 140-180 °C; in few ceramics a higher temperature component is also present, probably related to the original heating or the use of the ceramics before the eruption. Thermal demagnetization of the lithic clasts shows similar results with slightly higher re-

heating temperatures, around 180-240 °C. The estimated temperatures represent the equilibrium temperatures obtained after the deposition of the pumice fall and show that the pyroclastic fall deposits at a distance of around 6 km from the eruption vent maintained a temperature high enough to reheat the buried ceramics at temperatures around 140-180 °C.

## **1. Introduction**

Santorini is the most active volcano of the South Aegean volcanic arc and one of the world's most violent caldera volcanoes. It has a long history of strong eruptions started more than 650.000 years ago and has experienced at least 12 known large explosive eruptions during the past 250.000 years that triggered at least three or four caldera collapses (Druitt et al., 1989; 1999). Among these, the Minoan eruption that occurred in the Bronze Age, around 1613±13 BC (Friedrich and Heinemeier, 2009) is the last and the most famous event. It is considered as one of the largest plinian eruptions in recent time and is related to the destruction of the Cycladic culture and Minoan civilization in southern Aegean. The eruption produced a large volume of volcanic products that covered the whole island and changed its morphology burying all human settlements under metres of pyroclastic deposits.

Archaeological data indicate a rich and long history of human occupation of Santorini island that was particularly in flourish during the Bronze Age (Friedrich and Sigalas, 2009 and references therein). Archaeological excavation started around the end of '60s and brought into light a Bronze Age settlement, located at the southern part of the island close to the present-day village of Akrotiri. The large extent of the settlement, the elaborate drainage system, the sophisticated buildings with beautiful

wall-paintings, furniture and vessels, give proof of great development and prosperity. The whole village was totally buried by pumices and ashes of the Minoan eruption that destroyed it and at the same time preserved it up to nowadays just like a ‘Pompeii of the Late Bronze Age’ (Doumas, 1983).

Such archaeological sites in volcanic areas represent a precious and often unique source of data about the characteristics of catastrophic eruptions and the impact of the volcanic deposits on human settlements (Cioni et al., 2000; Gurioli et al., 2005). Among other physical parameters, the estimation of the deposition temperature of the volcanic products that came in contact and covered the ancient habitation levels can be of particular interest in order to better understand and assess the volcanic impact and hazard. Estimation of deposition temperature has long been addressed by measuring the thermal remanent magnetization (TRM) of both lithic and pumice fragments in pyroclastic deposits. This technique was first introduced by Aramaki and Akimoto (1957) and further developed and applied in several cases (e.g. Hoblitt and Kellogg, 1979; Kent et al., 1981; Downey and Tarling, 1984; McClelland and Druitt, 1989; Clement et al., 1993; Bardot, 2000; Cioni et al., 2004; Sulpizio et al., 2008; Porreca et al., 2008; Lesti et al., 2011). In a systematic study on Santorini, McClelland and Druitt (1989) used palaeomagnetic analyses of lithic clasts to estimate the emplacement temperatures of the Middle Pumice and Cape Riva pre-Minoan eruptions. In subsequent studies, Bardot et al. (1996) presented further palaeomagnetic results from the pyroclastic deposits of Santorini including also some data from lithic clasts of the four phases of the Minoan eruption. Bardot and McClelland (2000) and Bardot (2000) have further improved this methodology including discussion on the origin of the remanent magnetization of lithic samples from older eruptions of Santorini volcano. Recently this technique was extended by

involving also the study of human artefacts (tiles and pottery) embedded in pyroclastic density currents of the Pompeii 79 AD (Cioni et al., 2004; Zanella et al., 2007) and Pomici di Avellino 1800 BC (Di Vito et al., 2009) eruptions of Somma-Vesuvius.

In the present study, we focus our interest to the Minoan eruption using standard palaeomagnetic techniques in order to estimate the thermal effect of the Minoan volcanic products on the pre-Minoan habitation level. We systematically studied ceramic fragments that were lying on the surface of the pre-Minoan palaeosol and covered by the first eruption pyroclastic products (precursor tephra and the 1<sup>st</sup> major eruption phase), and lithic clasts embedded in the 1<sup>st</sup> phase pumice fall deposits. All samples are collected at Megalochori Quarry (36° 22' 00 N, 25° 25' 12 E), located 1.4 km SW from the homonymous village and around 6 to 7 km SSE from the inferred vent of the Minoan eruption. For the first time, Late Bronze Age ceramics from Santorini are used to estimate the deposition temperature of the Minoan products. The results obtained from the ceramics are compared with those from the lithic clasts presented in this study as well as those available from the literature.

## **2. Main characteristics of the Minoan eruption pyroclastic products**

The pyroclastic deposits formed during the Minoan eruption have been widely studied by various researchers (Bond and Sparks, 1976; Heiken and McCoy, 1984; 1990; Druitt et al., 1989; Sparks and Wilson, 1990; McCoy and Heiken, 2000). They are generally divided in a precursor tephra fall and four major stratigraphic phases (Druitt et al. 1989; Spark and Wilson, 1990; Heiken and McCoy, 1990) divided according to their characteristics and eruption mechanisms. A fine-grained, grey to

yellow ash layer of 1 to 4 cm found at the base of the Minoan pumice fall at several sites has been interpreted as an initial phreatic eruption that preceded the Minoan eruption and, coupled with earthquakes, could have been responsible for evacuation of the island before the main eruption (Heiken and McCoy 1984). This thin layer often contains imprints and molds of grass and ceramic fragments.

The first major eruption phase is a typical Plinian pumice fall that covered almost all the island with deposits which can locally reach 7 m (McCoy and Heiken, 2000). The deposit is composed of coarse pumice (0.5-20 cm) with less than 10% ash and lithic fragments in an open-framework structure (McCoy and Heiken, 2000). There is a coarsening of pumice sizes upward with an increasing content of lithic fragments that suggests an intensification of the eruption and depositional rates of tephra during this phase of activity (Bond and Sparks, 1976; Heiken and McCoy, 1984; McCoy and Heiken, 2000). Isopach maps, showing the total thickness of the first phase, indicate a vent position near or north of the present-day Kamani islands (Heiken and McCoy, 1984).

The second major eruption phase is characterized by surges and phreatomagmatic pyroclastic flows. It clearly represents a significant change in eruption character and vent emplacement. Pyroclastic surge deposits with planar and cross-stratification indicate phreatomagmatic activity and suggest unlimited access of water into the vent. The variation of the deposit thickness together with the direction of the pyroclastic flow and surges imply a second-phase vent located south of the first-phase (McCoy and Heiken, 2000). Significant topographic control is indicated by flow directions following the topographic landscape. Thick depositions are observed within large valleys of the pre-eruption landscape that in some cases reach up to 12 m at the southern part of the island.

The origin of the massive deposits that were formed during the third major eruption phase is quite controversial. Bond and Sparks (1976) interpreted the deposits as mud-flows, Pichler and Friedrich (1980) as ash-flow deposits and Heiken and McCoy (1984) considered them as phreatomagmatic deposits with multiple facies. These deposits are massive, poorly sorted mixtures of pumice and ash containing abundant lithic blocks with diameters up to 2 m. Lithic compositions are predominantly black, glassy, porphyritic dacites and red hyaloclastites characteristic of lavas and pyroclastics from Therasia and northern Thera (McCoy and Heiken, 2000). 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 and McCoy, 1984).

The deposits of the fourth eruption phase are a sequence of interbedded ignimbrites, lithic-rich base surge deposits, lithic-rich and ash-rich lahars and debris flows, with perhaps some co-ignimbrite ash-fall deposits (Bond and Sparks, 1976; Heiken and McCoy, 1984). They are mostly confined to coastal plains where they form sea cliffs of massive to stratified deposits. Clast size of both lithic and pumice fragments within the fourth-phase ignimbrites are considerably smaller than those found in the previous phase.

### **3. Deposition temperature estimation by palaeomagnetic methods**

Palaeomagnetic methods can be used to estimate the deposition temperature of pyroclastic deposits 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 and Druitt, 1989; Zanella et al., 2007; Paterson et al.

2010) and in some publications an analytical discussion on the reliability of the emplacement temperature estimates using palaeomagnetic methods is also included (Bardot and McClelland, 2000; Porreca et al. 2008; Lesti et al., 2011).

The method is based on the assumption that the lithic clasts found in the pyroclastic deposits were initially cold and were partially re-heated when incorporated in the hot mixture of ash and gases produced by a volcanic eruption. Such lithic clasts, probably coming from cold lavas of previous eruptions, contain magnetic minerals that carry a remanent magnetization acquired prior to the eruption. The remanent magnetization of individual magnetic grains depends on their blocking temperature  $T_b$  (temperature below which a magnetic mineral acquires its remanence) and varies according to their mineralogy, grain size and grain shape. In a natural sample that is an assembly of grains of various characteristics, all blocking temperatures from the Curie to room temperature are likely to exist (McClelland et al., 1996).

During a volcanic eruption, lithic clasts entrained from the floor, the roof or the walls of the magma chamber-conduit system, or eroded from the substrate, are often incorporated into pyroclastic deposits. If the pyroclastic deposits were emplaced above ambient temperature, the lithic clasts will have been heated during their incorporation into the deposit and subsequently cooled to ambient temperature in their present position. During heating, a portion of the original magnetization with unblocking temperatures ( $T_b$ ) less than or equal to the maximum temperature of the deposit will be lost and a new partial thermoremanent magnetization will be acquired, oriented along the Earth's magnetic field at the time of the deposition. According to this mechanism, the natural remanent magnetization (NRM) of a lithic clast will consist of two TRM components characterized by different blocking temperatures; an

original randomly oriented high temperature component and a new uniformly oriented low temperature component.

In an analogous way, ceramic fragments are characterized by 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 that involve 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). If the volcanic products were hot when deposited over the ceramic fragments, then once the thermal equilibrium between the hot pyroclastics and the cold ceramics is obtained, the ceramics will get partially demagnetized and will acquire a secondary low temperature magnetic component.

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 and Druitt, 1989) and/or a viscous remanent magnetization overprinting (VRM) due to a long time exposure to the ambient Earth's magnetic field (Bardot and McClelland, 2000). In the case of a CRM overprint, the chemical change may cause a complete replacement of the primary low- $T_b$  component (in this case no information about the deposition temperature can be retrieved) or only partially replace it, resulting to a curvature in vector plots between the two magnetization components. Porreca et al. (2008) suggested the investigation of the magnetic susceptibility variation with increasing temperature, in order to assess the possibility of significant alteration of the magnetic mineral assemblage during the thermal history of the samples. In the case of a VRM, its acquisition depends on the duration of the

exposure to an applied magnetic field and the temperature at which the exposure took place. In order to distinguish a partial TRM (pTRM) from a possible VRM, Bardot and McClelland (2000) used the magnetite nomograms proposed by Pullaiah et al. (1975) to determine a simple relationship between the blocking temperature of a VRM as a function of time for the relative short time interval over which explosive volcanism on Santorini occurred (approximately 300.000 years). The proposed function,  $T_b = 75 + 15\log(\text{acquisition time in years})$ , applied to the Minoan eruption indicates that low  $-T_b$  components with  $T_b \leq 130^\circ\text{C}$  could not be reliably distinguished between pTRMs or VRMs. For this reason in the present study, only temperatures determined by blocking temperatures higher than  $130^\circ\text{C}$  have been considered.

#### **4. Sampling and measurements**

Systematic sampling of ceramic fragments and lithic clasts has been carried out at Megalochory Quarry outcrops, located at the southern part of Santorini island (Fig. 1). Megalochory Quarry is situated about 6 km away from the inferred vent of the Minoan eruption, probably positioned somewhere between the Nea Kameni Island and the present Fira town (Heiken and McCoy, 1984; McCoy, 2009). This site was chosen as case study because it offers a complete section of the Minoan eruption volcanic products and the contact between the pre-Minoan palaeosol and the first pyroclastic deposits is clearly visible and approachable. Moreover, at the surface of the palaeosol, several pieces of ceramics have been found, completely covered by the first pumice fall and buried under metres of pyroclastic deposits. At the sampling section, situated at the northern part of the quarry, the thick of the pumice fall (1<sup>st</sup> phase) is around 2.5 metres followed by around 7 metres of surge and phreatomagmatic pyroclastic flows (2<sup>nd</sup> phase). According to archaeological research,

no human settlements or wall ruins have been found at that area. People probably transported these ceramics with them to places where they cultivated the earth in order to carry food or water.

A total of 22 ceramic fragments have been collected from the contact between the Pre-Minoan palaeosol and the products of the first pumice fall (Fig. 2). These 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 (Fig. 3a) that probably belonged to some vases or plates for domestic use, being on the palaeosol at the moment of the eruption. Together with the ceramics, 14 lithic clasts from the first 50 cm of the pumice fall that covered the palaeosol have been also collected. Pumice lumps were avoided because they are generally less magnetized than lithic clasts, as discussed by McClelland and Thomas (1990). Large lithics (diameter > 10 cm) were also avoided as they do not always achieve a uniform thermal equilibrium and in some cases a thermal gradient between the core and their external part that comes in direct contact with the hotter pyroclastic products may be noticed (Bardot, 2000). The collected lithics have dimensions between 1 to 6 cm (Fig. 3b) and were taken non-oriented. Accurate *in situ* orientation could not be obtained because of their small size and the very loose surrounding pumice matrix. A casual orientation line was marked on the samples at the laboratory for measurements purpose. Due to the small size of the ceramic fragments and lithic clasts, 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).

A total of 51 specimens (31 from ceramic fragments and 20 from lithic clasts) have been prepared and measured at the ALP- Alpine Laboratory of Palaeomagnetism (Peveragno, Italy). All specimens were stepwise thermally demagnetized using a TSD-2 Schonstedt furnace for heating/cooling and JR-5/JR-6 Agico spinner magnetometers for measuring the magnetic remanence. Thermal demagnetization started at 60 °C up to 620 °C, following temperature steps of 40 °C. Heating and cooling time was approximately 45 minutes each. Whenever twin specimens from individual samples were available, a second demagnetization group was carried out, starting this time from 80 °C and following again 40 °C step. After each step, bulk magnetic susceptibility was measured to detect possible mineralogical changes due to heating. The thermal demagnetization results were interpreted by principal component analysis using the Remasoft software (Chadima and Hrouda, 2006).

## **5. Magnetic mineralogy**

To assess the reliability of the re-heating temperatures estimated by palaeomagnetic techniques, we investigated the magnetic mineralogy of representative ceramic and lithic samples through the monitoring of the bulk magnetic susceptibility during the thermal demagnetization experiments, isothermal remanent magnetization (IRM) acquisition curves, alternating field (AF) demagnetizations of the NRM and saturation IRM (Lowrie and Fuller, 1971), and hysteresis loops. The magnetic mineralogy experiments were performed only on a limited number of samples because most of the available samples were used for the thermal

demagnetization experiments, and due to their small size only in few cases very small pieces of material remained for mineralogical experiments.

In order to estimate the thermal stability of the samples, the bulk magnetic susceptibility was measured at room temperature after each thermal demagnetization step with a KLY-3 Kappabridge (AGICO) at the ALP Palaeomagnetic laboratory. Most of the ceramic samples show a very stable behaviour and only negligible magnetic susceptibility variations with increasing temperature are observed (Fig. 4a). These results suggest that the ceramics are thermally stable and there is no evidence for important magnetic mineral transformations during heating. On the contrary, important changes on the susceptibility values can be noticed on the lithic clasts, mainly at temperatures higher than 260 °C (Fig. 4b). In these cases the acquisition of a secondary magnetization component of chemical origin (CRM) during deposition processes cannot be excluded and thus secondary components isolated at temperatures higher than 260 °C can be related to alteration of the primary magnetic mineralogy and therefore not reliably represent the re-heating temperatures. For this reason samples with important magnetic susceptibility changes have not been considered in the calculation of the final re-heating temperature estimation (e.g. samples MLF1-4, MLF1-8, MLF1-14).

Isothermal remanent magnetisation acquisition curves were performed on representative ceramic and lithic samples at the palaeomagnetic laboratory of Thessaloniki, Greece. Lowrie–Fuller experiments (Lowrie and Fuller, 1971) were also performed on ceramic samples: first their NRM was stepwise AF demagnetized and then an IRM was given by applying stepwise magnetic fields up to 1.2 T with an ASC pulse magnetizer. Finally, the saturation IRM (SIRM) was AF demagnetized and the normalized intensity curves were compared with the AF demagnetization of the

NRM. The IRM curves have similar behaviour for most of the studied samples (Fig. 5). They show that the saturation of the magnetisation is generally reached at low fields varying from 0.3 to 0.4 T indicating the presence of a low-coercivity mineral such as magnetite (with only exception the MLF1-5 sample where the presence of a high coercivity mineral is also observed). The normalized AF demagnetization curves ( $J/J_0$ , where  $J_0$  is the initial magnetization) of NRM and SIRM according to Lowrie-Fuller test (Fig. 6) show that NRM and saturation IRM have similar coercivity distribution, but NRM is slightly more stable, suggesting that the NRM is mainly carried by single-domain or pseudo-single domain grains (Lowrie and Fuller, 1971).

Hysteresis curves have been obtained for both ceramic and lithic samples with a Vibrating Sample Magnetometer (VSM-PAR 155) at the Physics Department of the University of Thessaloniki. The results obtained from representative ceramic fragments are illustrated in Fig. 7a. They show an important paramagnetic contribution (e.g. sample SMC-1), a mixture of ferromagnetic portions and paramagnetic grains (sample SMC-16), and dominance of a strong ferromagnetic phase (sample SMC-17). In some cases, the presence of secondary high coercivity phases, such as haematite is also observed (e.g. samples SMC-16 and SMC-17). For lithic clasts (Fig. 7b) a strong ferromagnetic phase is clear, obtaining saturation at fields lower than 400 mT.

## **6. Thermal demagnetization results and principal component analysis**

The thermal demagnetization results are interpreted using the normalized intensity decay curves that show the demagnetization path followed by each specimen and the orthogonal projection diagrams (Zijderveld, 1967) that show the number of remanence components and the temperatures at which they are cancelled (Fig. 8 and

Fig. 9). According to the demagnetization pattern, Cioni et al. (2004) classified the thermal behaviour of clasts in four groups (types A to D). Types A and B show one magnetization component: type A is characterised by blocking temperatures higher than the deposition temperature and therefore the TRM is not affected by the reheating; type B has blocking temperatures lower than the deposition temperature and consequently the primary TRM is completely erased during the reheating. Type C has a TRM that consists of two magnetization components with distinct blocking temperature spectra that are clearly distinguished in the Zijderveld diagram. This type is considered as the ideal sample behaviour for the determination of the deposition temperatures (Cioni et al., 2004). Finally, type D has also two components of magnetization but in this case they are not easily separated because of overlapping blocking temperature spectra or because of complicated demagnetization behaviour.

From the 51 specimens of ceramic fragments and lithic clasts studied here, 34 specimens provided reliable and well defined remanence directions classified as types C and D (Fig. 8 and Fig. 9 a,b). The rest of studied specimens were rejected either because showed important magnetic susceptibility variations versus temperature (see the Magnetic mineralogy paragraph) or because they showed type A or B behaviour (not distinguishable in our case as samples were not *in situ* oriented). Some of the rejected specimens had two components behaviour which however could not be reliably separated either because of a small angle between the two components or because of the accumulation of points at the first steps of demagnetization (e.g. Fig. 9c). These 17 specimens were not considered for the re-heating temperature estimation. The remaining 34 specimens (21 from ceramic fragments and 13 from lithic clasts) are characterized by two distinct magnetic remanence components.

Ceramic fragments showed a high temperature component acquired during their initial heating in a kiln and a low temperature component acquired during their partial re-heating caused by the covering hotter pyroclastic deposits. In most cases the two components were easily distinguished in the Zijderveld diagrams, showing a sharp change in direction (Fig. 8a and b). Three ceramic samples (6 specimens) have a three component magnetization; an initial characteristic remanent magnetization component which was acquired during the initial heating of the ceramics and which passes through the origin of the Zijderveld diagrams; a high temperature component indicating partial re-heating at elevated temperatures between 420 and 460 °C; and a low-temperature component caused by a final partial re-heating at lower temperatures between 180 and 220 °C (see Fig. 8c). The high temperature component observed in these ceramics may be interpreted as a magnetization component acquired during the use of the ceramics that often were utilized to prepare and cook food and for this reason were in contact with fire or heated in domestic furnaces.

The thermal demagnetization of the lithic clasts from the pumice fall that buried the ceramics shows similar results with a two-component behaviour (Fig. 9), even though in some cases the two magnetization components are not clearly distinguished or show overlapping unblocking temperatures spectra (Fig. 9b). This curved path between the two components can be caused by several factors such as mineralogical changes due to reheating that may introduce a chemical magnetization (CRM) overprint (McClelland-Brown, 1982), or due to a shift of the clast shortly after its deposition while still warm (e.g. due to pressure from the deposition of the subsequent pyroclastic products). As discussed by Cioni et al. (2004), understanding this magnetic behaviour often proves impossible mainly because in most cases lithic

fragments within a pyroclastic deposit have different lithologies and each of them may have a different and complicated thermal history.

The re-heating temperatures have been estimated separately for each individual specimen from the intersection point of the low- and high- temperature 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. In the cases of curvature behaviour in the Zijderveld diagrams, the re-heating temperature has been estimated taking into account the whole interval between the lower temperature where the curvature begins up to the first temperature of the high  $T_b$  component. 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 and McClelland, 2000). Estimated re-heating temperature intervals for each ceramic and lithic specimen based on the low-temperature magnetic component are illustrated in Fig. 10 and Fig. 11 respectively. For the ceramics, reheating temperatures vary from a minimum of 100 °C to a maximum of 260 °C while for the lithic clasts they are slightly higher varying from 140 °C to 280 °C. Taking into consideration that each ceramic fragment and especially each lithic clast may have different lithology, size, provenance and thermal history, the best estimation of the re-heating temperature of the ceramics and lithic clasts can be obtained from the maximum overlap range of the reheating temperature intervals of the individual fragments (Cioni et al., 2004). Following this technique we have estimated that all ceramic fragments show overlapping re-heating temperatures in the range of 140-180 °C (Fig. 10) while re-heating temperatures of the lithic clasts are included in the 180-240 °C range (Fig. 11).

## 7. Discussion and Conclusions

Estimating the deposition temperature of pyroclastic deposits can be important for understanding the dynamics of explosive eruptions and assessing the volcanic hazard in a certain area. It can contribute to the establishment of the thermal evolution of an eruptive phase or even the entire thermal history of an eruption. However, determining the deposition temperatures can be very complicated due to the various and complex factors that control the temperature of a deposit, such as the initial temperature of the mixture of hot gas and ejecta, the role of the air and/or water, the percentage of cold lithic fragments, the thickness of the deposit, the cooling rate etc (Paterson et al., 2010). Palaeomagnetic measurements of lithic clasts incorporated in the deposits and ceramic fragments covered by them can offer a potential estimation of the deposition temperatures but cannot control all the above parameters. Therefore reheating temperatures of lithic clasts can not always precisely represent the deposition temperature of the embedding volcanic unit (Cioni et al., 2004). Nevertheless they can still offer important information on the thermal effect of the pyroclastic products on the palaeo-surface on which they are deposited. In the case of Megalochory Quarry our results show that lithic clasts embedded in the first centimetres of the pumice fall reached thermal equilibrium with the rest of the deposit at temperatures around 180-240 °C and they re-heated the ceramics that were lying on the pre-Minoan palaeosol at temperatures around 140-180 °C.

The results obtained from the ceramics are generally in good agreement with those from the lithic clasts; lithic clasts however show slightly higher temperatures. We believe that the difference on these re-heating estimates can be related to the different thermal history and re-heating conditions that characterize these two types of samples. The ceramics were cold and they were spread on the cold palaeosol

background when covered by the volcanic products. They were then re-heated due to the overlying contact with the hot pyroclastic deposits. In a different way, lithic clasts were incorporated inside the whole hot pyroclastic products that apart from cold lithic clasts can also contain hot juvenile fragments. Whereas the cold fragments are re-heated by the heat they absorb from the deposit, the hot ones may convey heat to it, something that doesn't happen in the case of ceramics. However, this could be just one possible explanation and other factors may also cause this small difference on the re-heating temperatures registered by ceramics and lithics, such as differences on their magnetic properties and mineralogy.

The re-heating temperatures obtained in this study are compared with the temperature estimations from previous studies on lithics from the Minoan eruption of Santorini. McClelland and Thomas (1990) investigated the emplacement temperatures of the four phases of the Minoan eruption collecting pumice and lithic clasts from three sites. Regarding the 1<sup>st</sup> phase, they studied samples from two sites (Thera and Oia quarries, located in central and northern part of the island respectively) and obtained a wide range of emplacement temperatures that vary from 150 °C to 350 °C, with the maximum distribution around 250-300 °C. This within-site variability was explained by variations in initial temperatures of the lithics before they were incorporated into the deposit. Some lithic material may have been considerably hotter than the final equilibrium temperature of the deposit, and so will have cooled down to the equilibrium deposit temperature after transport, and will record a sample emplacement temperature greater than the average equilibrium temperature. On the other hand, initially colder clasts will heat up to the average equilibrium temperature, and only become remagnetized on subsequent cooling. The minimum temperature recorded by the individual lithic fragments should be therefore considered as the best

estimate of the deposit's temperature (McClelland and Thomas, 1990). McClelland et al. (1996) have 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 the estimated temperatures vary from 130 to 250 °C at site level. These temperatures are in good agreement with the reheating temperatures estimated by the lithic clasts in this study.

No literature data for deposition temperatures of the Minoan deposits based on ceramic fragments are available, and the new results from Minoan pottery presented here are the only ones obtained up to now. Our results show that ceramic fragments covered and reheated by the Minoan deposits can reliably represent the equilibrium temperature between the cold palaeosol and the overlying hot pumice airfall. As shown in the previous paragraph, ceramic fragments, compared to the lithic clasts, present two important advantages: 1) They have a similar thermal history which is usually well known. All the ceramics were lying on the palaeosol surface and were cold when the first volcanic products buried them. Their pTRM was therefore acquired only after the deposition of the hotter volcanic products and subsequent cooling. 2) They are thermally stable and no important mineralogical changes should have been occurred during their re-heating. This is probably due to the manufacture technology of the ceramics that often involves heating at high temperatures. In these cases, the secondary magnetisation component can be reliably interpreted as a pTRM and suspicion about secondary components of CRM origin is negligible. For these reasons, we consider that pottery can be more reliable re-heating temperature recorder in respect to the lithic clasts that usually are characterized by unknown and complicated heating, transporting and deposition history. In the future, it would be therefore interesting to extend this study, in collaboration with the archaeologists, in

order to study the re-heating temperatures of ceramic fragments distributed at different distances from the inferred vent of the Minoan eruption to obtain a spatial distribution of the thermal effects of the Minoan volcanic products on the pre-Minoan habitation level.

### **Acknowledgments**

Dr. Gerasimos Papadopoulos and the students A. Papadopoulos and G. Nikolaidis are highly acknowledged for assistance during a preliminary sampling campaign. The archaeologist Ms. Magia Efstathiou from the KA' Ephorate of Prehistoric and Classical Antiquities is warmly thanked for useful discussion and sampling permission. Assoc. Prof. Konstantinos Efthimiadis is sincerely thanked for performing the hysteresis measurements and for precious help with their interpretation. Dr. Elena Zanella is acknowledged for data interpretation assistance and for constructive comments on an early version of the manuscript. E. Tema acknowledges a post-doc fellowship from the Greek State Scholarship Foundation (IKY).

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## Figure captions

Fig. 1. Santorini island map and location of the Megalochori Quarry (red dot). The star represents the presumed position of the Minoan eruption's inferred vent.

Fig. 2. Megalochori Quarry: a) General view of the sampling site; b) Contact between the pre-Minoan palaeosol and the pyroclastic pumice fall of the first Minoan eruption phase; c) Detail of the palaeosol surface and the pumice fall.

Fig. 3. Studied samples: a) Part of the studied ceramic fragments and b) lithic clasts.

Fig. 4. Variations of the bulk magnetic susceptibility after each heating-cooling circle during stepwise thermal demagnetization for a) ceramics and b) lithic clasts.

Fig. 5. Normalized isothermal remanent acquisition curves for representative a) ceramic and b) lithic samples.

Fig. 6. Lowrie-Fuller experiments for representative ceramic samples.

Fig. 7. Hysteresis curves for samples from a) ceramics and b) lithic clasts.

Fig. 8. Stepwise thermal demagnetization results expressed as vector plots (left), intensity decay curves (center) and equal area projections (right) for selected ceramic fragments that show a) and b) a clear two-magnetic components behaviour; c) three magnetic components behaviour.

Fig. 9. Stepwise thermal demagnetization results expressed as vector plots (left), intensity decay curves (center) and equal area projections (right) for selected lithic clasts that show a) two components of magnetization that are easily separated; b) two components of magnetization with curved intersection path; c) possibly two magnetization components that however are not easily separated and therefore samples with such behaviour have not been used for the determination of the reheating temperatures.

Fig. 10. Evaluation of the deposition temperature of the pyroclastic pumice fall that covered the pre-Minoan palaeosol at Megalochory Quarry based on the overlap of individual ceramic fragments reheating ranges.

Fig. 11. Evaluation of the deposition temperature of the pyroclastic pumice fall that first deposited at the Megalochory Quarry based on the overlap of individual lithic clast reheating ranges.

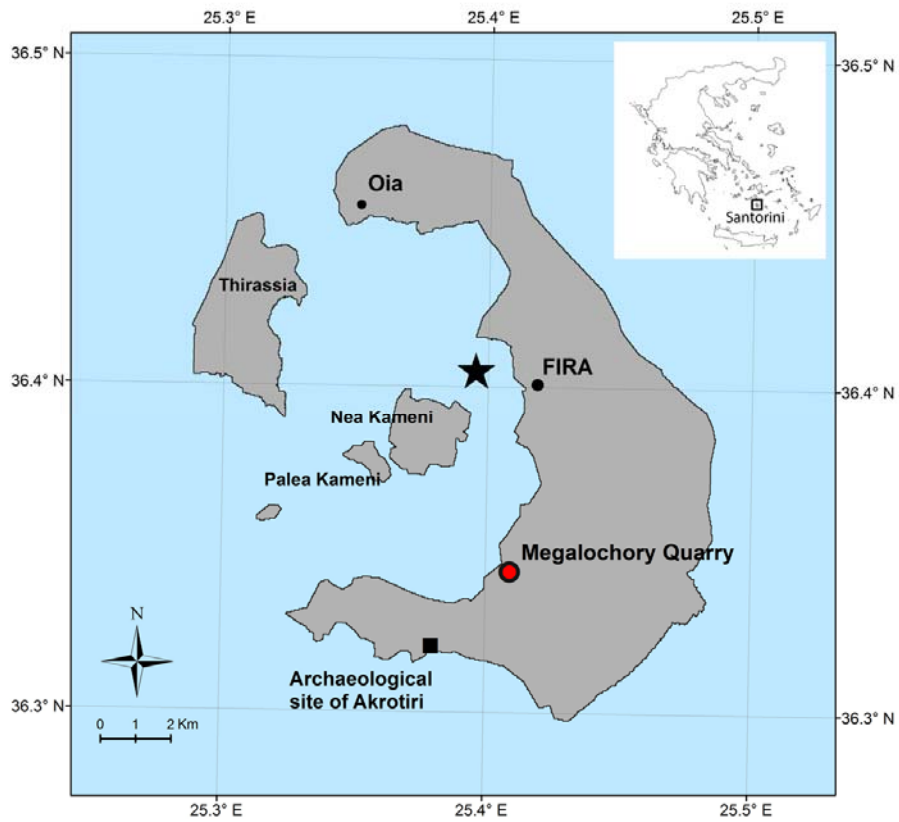


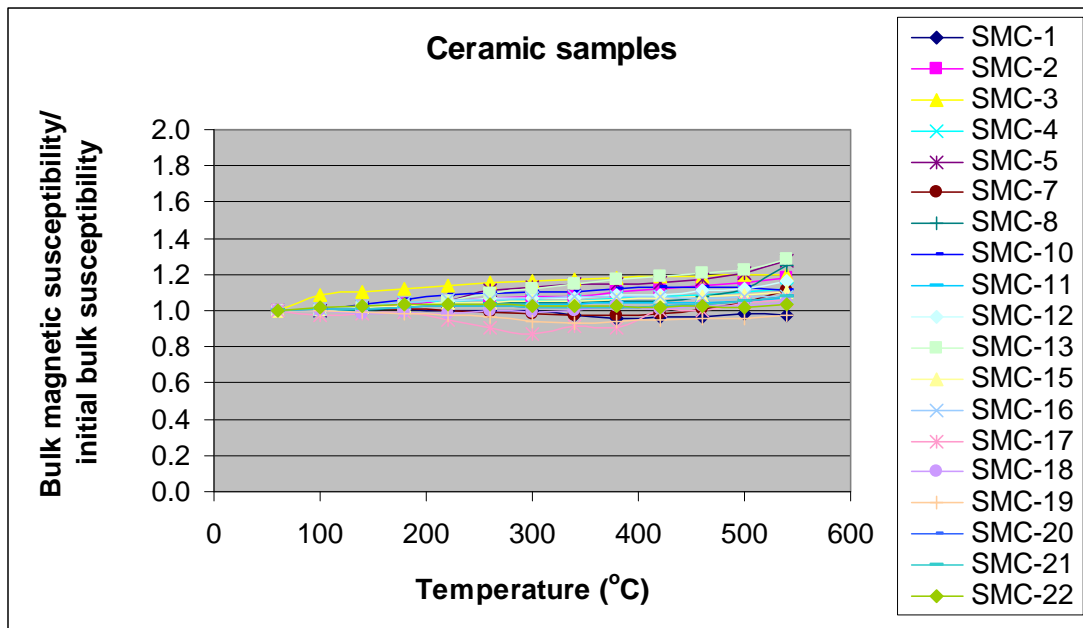
Fig. 1



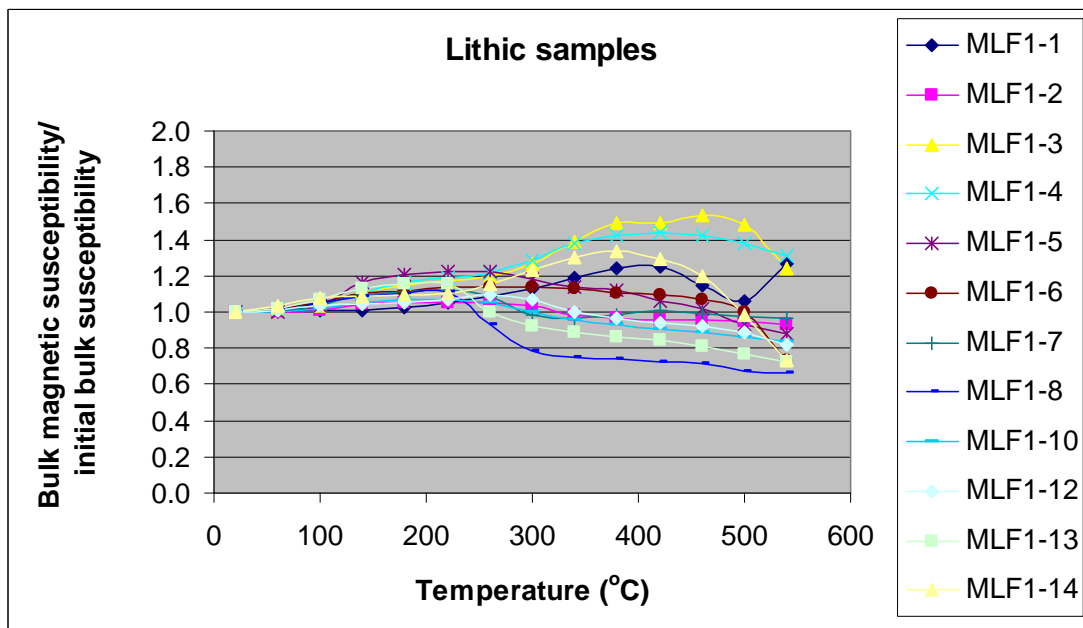
Fig. 2



Fig. 3

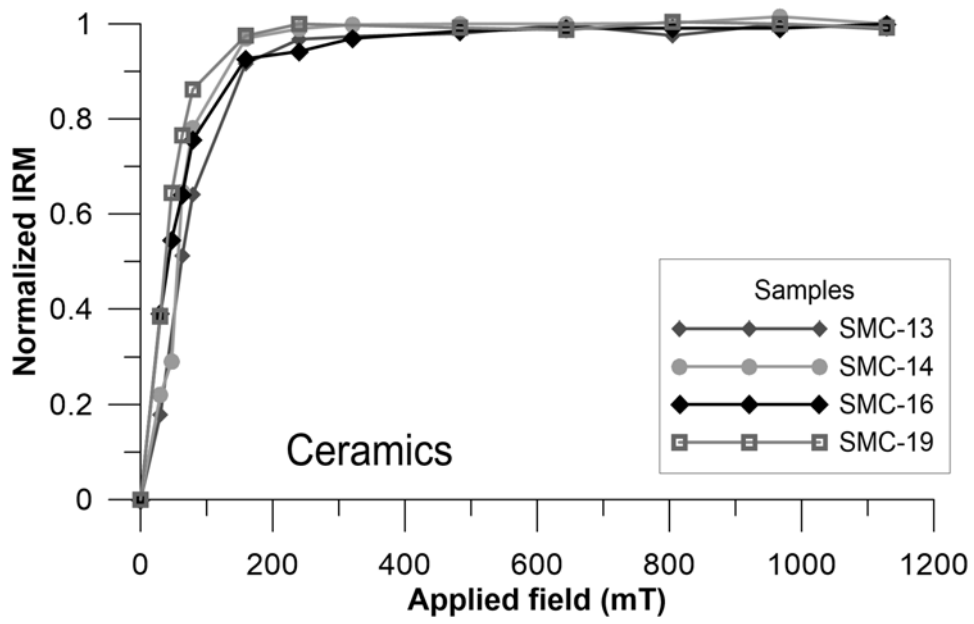


(a)

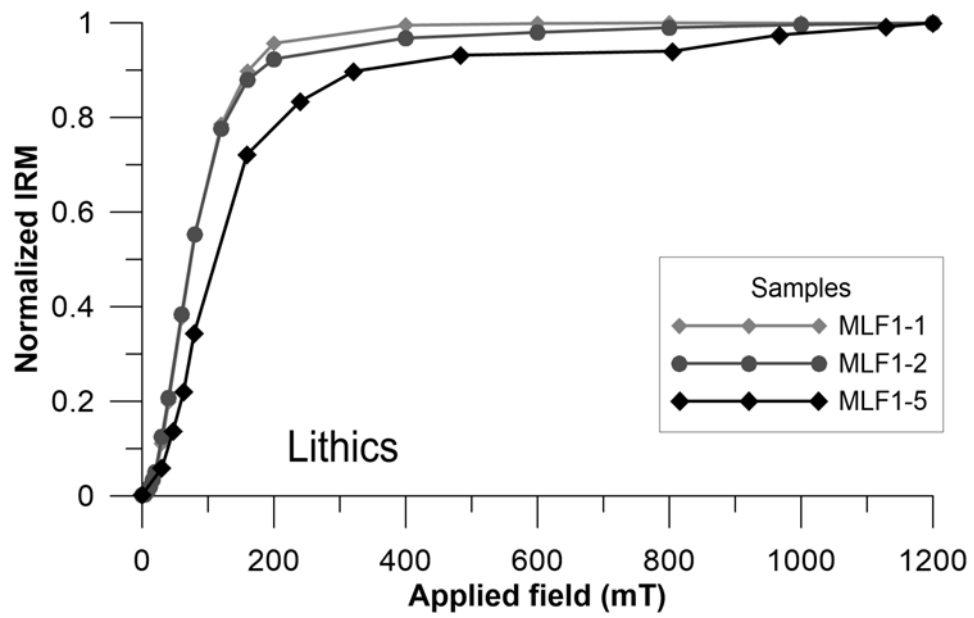


(b)

Fig. 4



(a)



(b)

Fig. 5

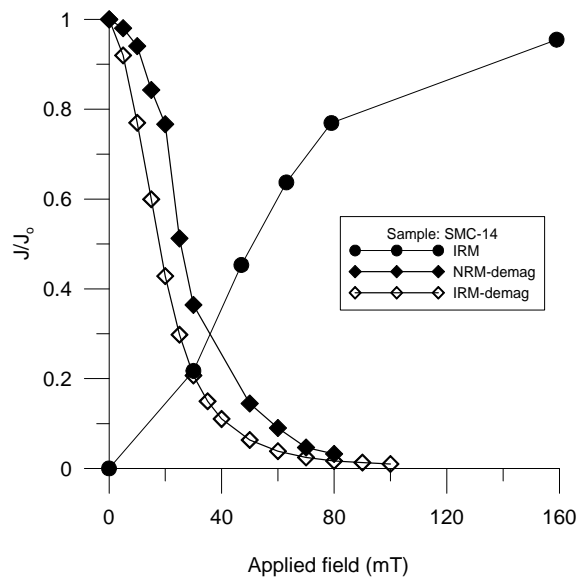
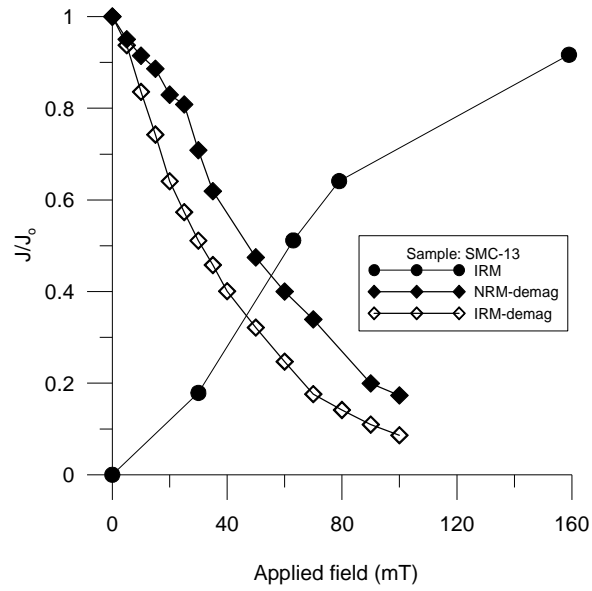
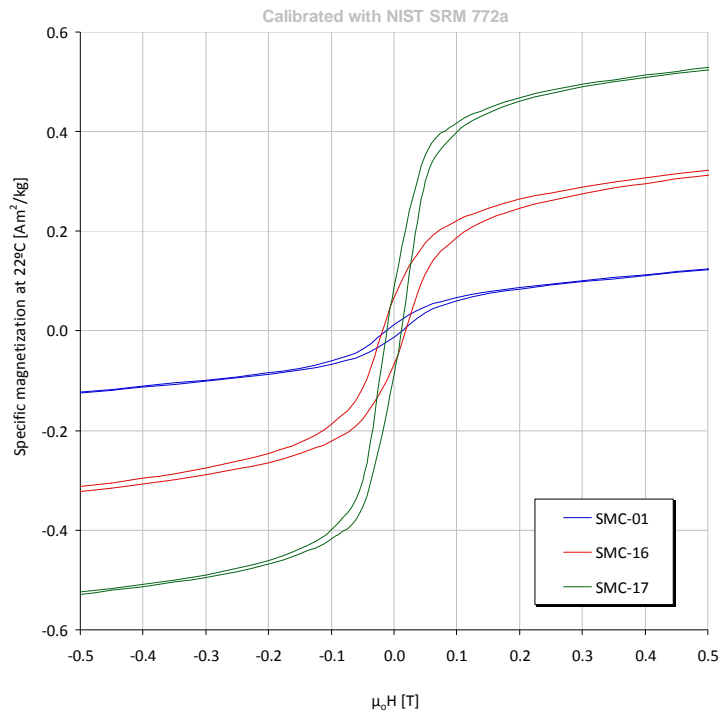
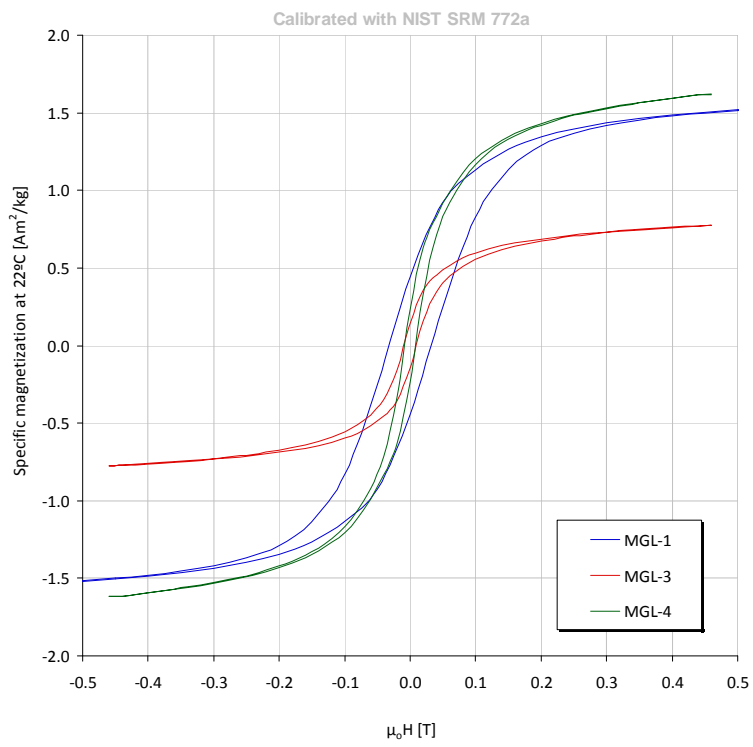


Fig. 6



(a)



(b)

Fig. 7

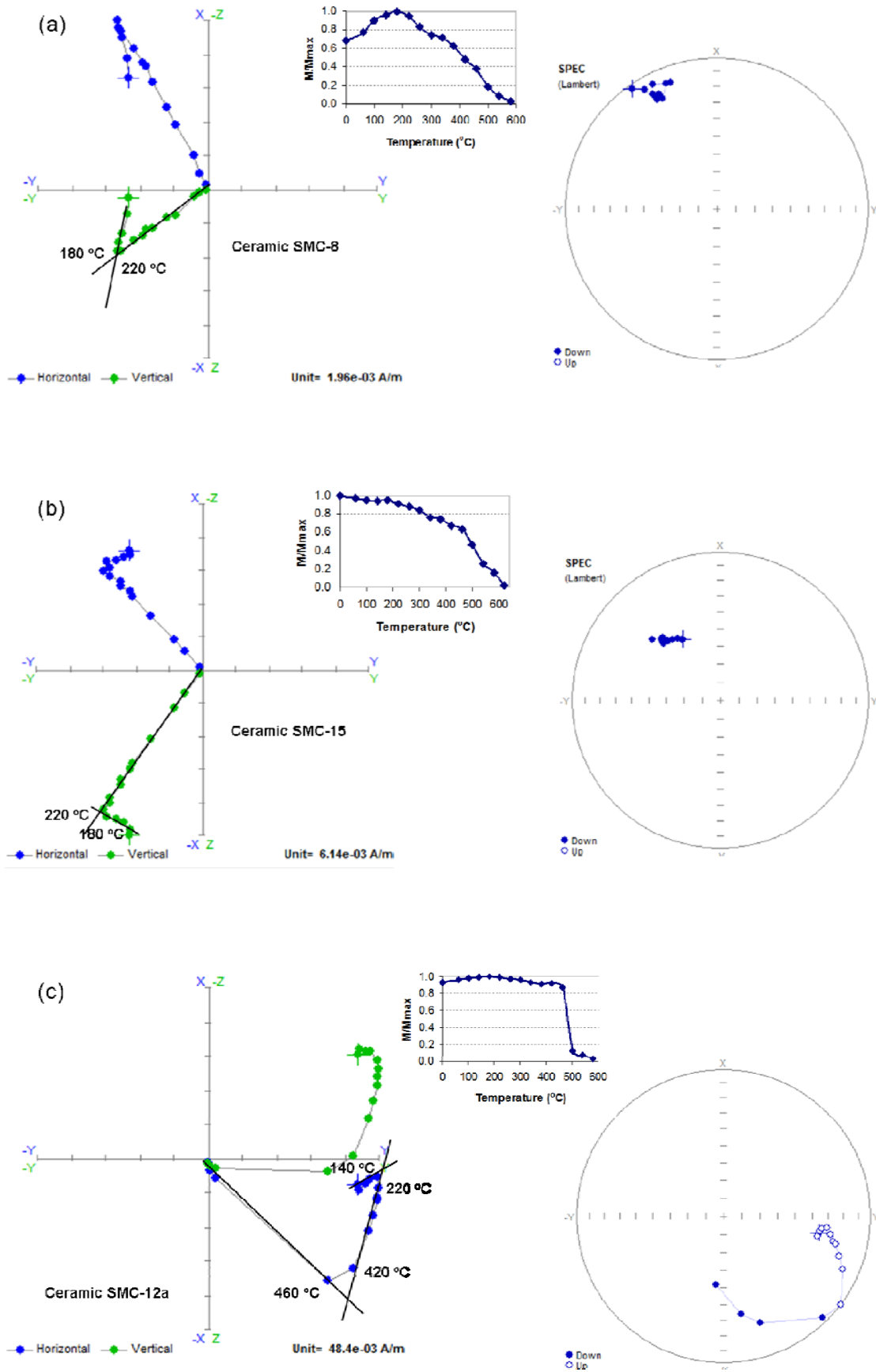


Fig. 8

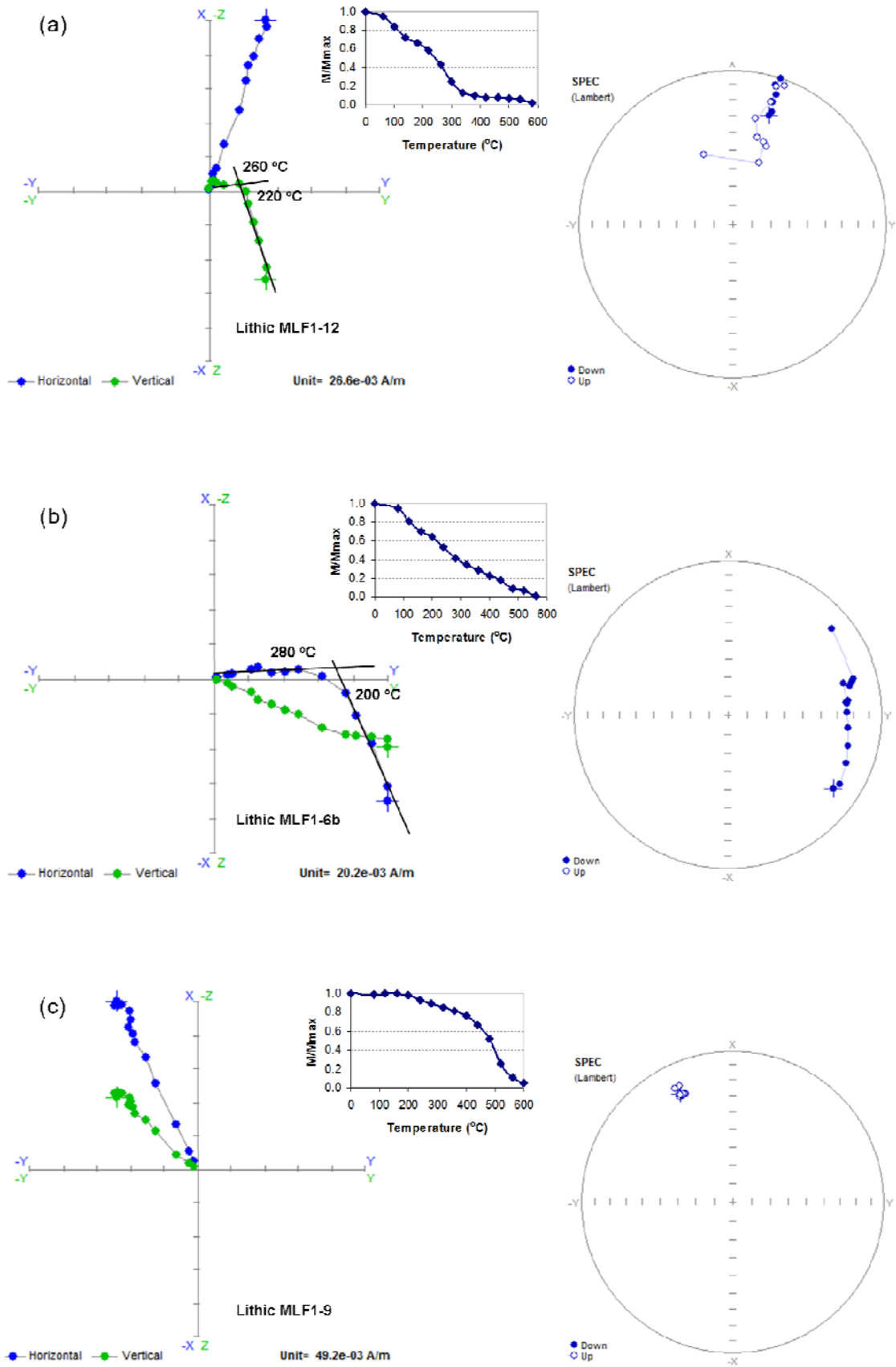


Fig. 9

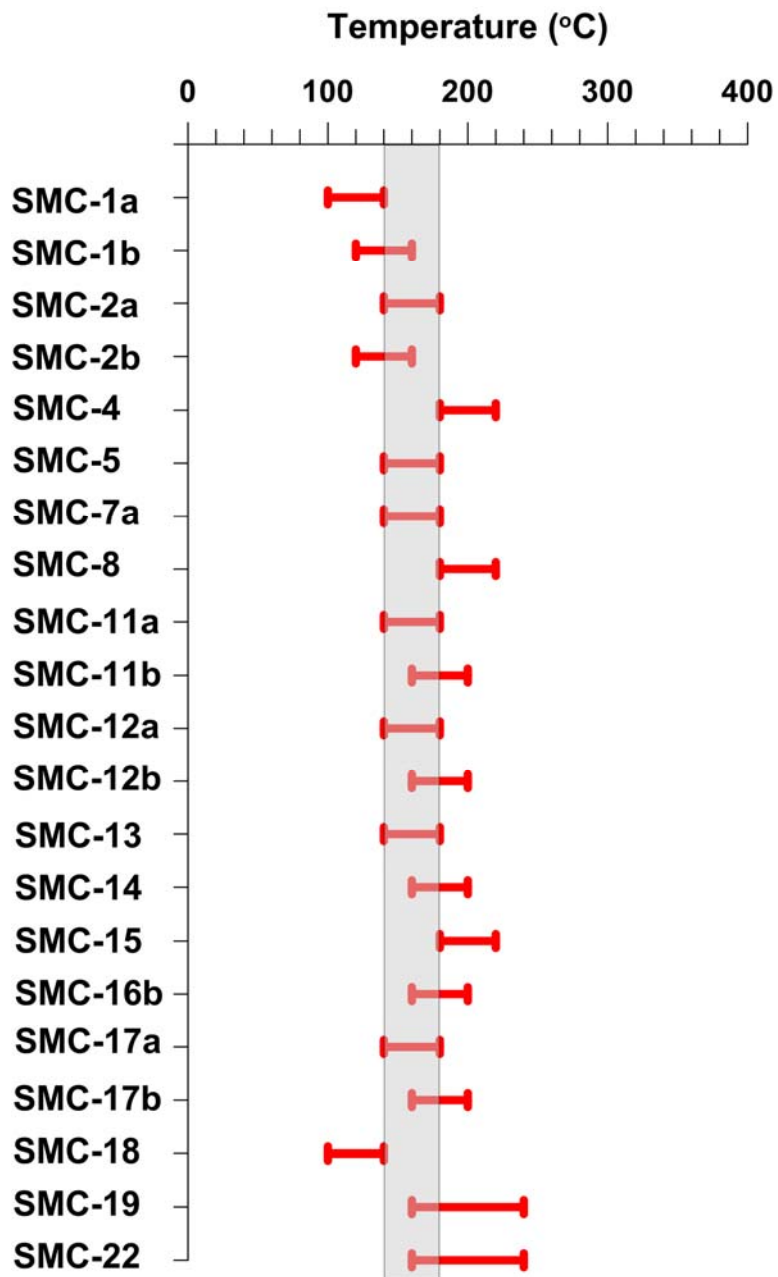


Fig. 10

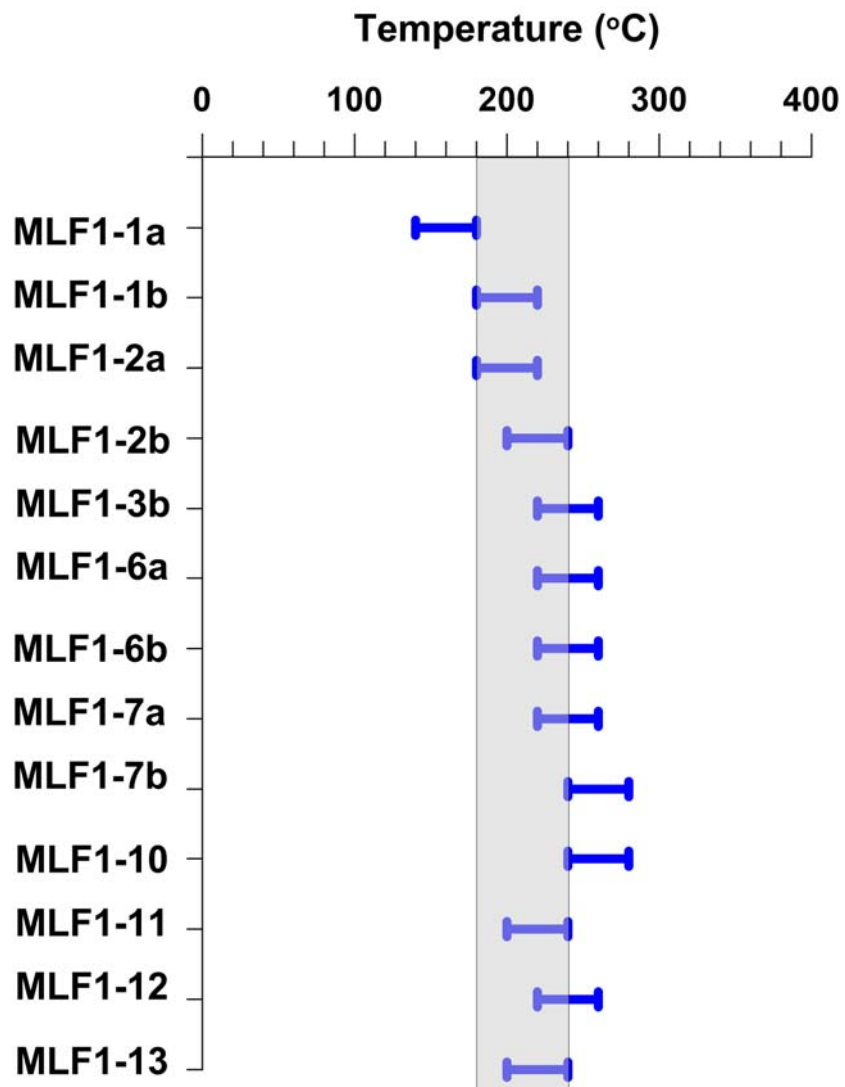


Fig. 11