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Highlights:

- Archeointensity analysis performed on Early Byzantine ceramics unearthed in Greece
- 5 new high quality archeointensity data obtained using the Triaxe protocol
- Geomagnetic field intensity increase observed in the Balkans from 4th to 7th C.

Keywords:

Archeomagnetism; Archeointensity; Secular variation; Greece; Early Byzantine period; Pottery

Abstract

We report on five new archeomagnetic field intensity data obtained in Greece from groups of pottery fragments precisely dated to between the middle of the fourth century and the beginning of the seventh century CE. These potsherds were unearthed on the islands of Thasos (Northern Greece) and Delphi (Central Greece). Their dating is primarily ensured by typo-morphological arguments, combined with archeological and historical constraints. Archeointensity measurements were performed using the Triaxe protocol, which involves continuous magnetization measurements at high temperatures and which allows us to overcome the thermoremanent magnetization anisotropy and cooling rate effects. Magnetic mineralogy measurements such as low-field magnetic susceptibility versus temperature and thermal demagnetization of three orthogonal IRM components have identified magnetite with possible impurities as the main carrier of the magnetization. The new data range from 52.0μT to 61.5μT after reduction to Thessaloniki and show an increase in geomagnetic field intensity in Greece during the Early Byzantine period. They appear in good agreement with previous intensity results satisfying a set of quality criteria and obtained in a region of 700 km around Thessaloniki, therefore incorporating data from Bulgaria, Greece and South Italy. This study is part of an ongoing effort to better constrain the evolution in geomagnetic field intensity in the Balkans over the past few millennia, with potential use for dating in archeology. The rapid intensity variations documented here during the Early Byzantine period are clearly of interest in this respect.

1 Introduction

Archeomagnetic data constitute a valuable source of information on the Earth's magnetic field variations during the last few millennia. Data compilations from all over Europe, where the discipline has flourished over the last few decades, have resulted in the construction of robust databases and the computation of secular variation curves for several regions including France (Gallet et al., 2002; Hervé et al. 2013a,b; Genevey et al., 2016), Germany (Schnepp and Lanos, 2005), Italy (Tema et al., 2006, 2013) and the UK (Zananiri et al., 2007) among others. There are, however, usually more directional than intensity data available, a feature related to the time-consuming and complicated protocols required to determine the archeointensity, together with the frequently high rate of failure.

Numerous archeomagnetic investigations conducted within the last forty years in the Balkans have resulted in a particularly well-documented secular variation of the Earth's magnetic field, with a complete, though not continuous, recovery of the geomagnetic behavior (i.e. both in direction and in intensity) over the past eight millennia. This largely relies on datasets obtained in Bulgaria, where the compilation of archeomagnetic results has recently been updated (Kovacheva et al., 2014), and includes full vector data, obtained exclusively from in-situ burnt structures.

Archeomagnetic studies were initiated in Greece, in the 80's (Thomas, 1981; Walton, 1984; Aitken et al., 1989) and in contrast to the general overview in Europe, there is more archeointensity than directional data. Nevertheless, the quality of several Greek archeointensity data has often been criticized (for a review see De Marco et al., 2008a) while several newly acquired results (Spatharas et al., 2011; Tema et al., 2012; Fanjat et al., 2013; De Marco et al., 2014) have supplemented the database with reliable input. As a result, the main trends of the geomagnetic field secular variation in the Balkans can now be used for the dating of baked clay structures of uncertain age. Several examples exist in the literature where archeomagnetic dating results are successfully compared with thermoluminescence or radiocarbon data and archeological constraints (Aidona and Kondopoulou, 2012; Tema et al., 2015; Kondopoulou et al., 2015).

In spite of its great potential, the precision of archeomagnetic dating in the Balkans is still limited by the dispersion seen in the data, which suggests that some of the published results are biased and/or their uncertainties underestimated (e.g. Pavón-Carrasco et al., 2014). As a consequence, the detailed recovery of the geomagnetic fluctuations in this region, although an achievable target given the richness of its archeological and historical heritage, still requires the acquisition of new, high-quality, data with a precise control of age. The present study is part of this effort.

We report on five new archeointensity data obtained from groups of ceramics unearthed in Greece on the islands of Thasos and Delphi, two historical excavation sites of the French School at Athens (Péntazos and Picard, 1992; Jacquemin, 2000; Mulliez, 2011; Muller and Mulliez, 2012). These ceramics are precisely dated to the Early Byzantine period, between the 4th and the 7th centuries CE. We will see that this time interval proves to be particularly interesting for both geomagnetic and archeological dating purposes as it was characterized by significant and rapid geomagnetic field intensity fluctuations.

2 Archeological collection

Our archeological collection is composed of six groups of ceramic fragments, three of them collected at Thasos (40.7°N, 24.6°E) and the other three at Delphi (38.5°N, 22.5°E; Fig. 1a). We underline that these groups were selected among the large amount of ceramic material unearthed from these two major archeological sites. The accuracy and reliability of the dating (an uncertainty of 100 years was fixed as a limit) and the precise knowledge of the location of the ceramic production site were a pre-requisite for our sampling in addition to considerations regarding the clay paste and the atmosphere of heating/cooling.

At Thasos, a joint project of the French School at Athens (represented by the University of Lille - UMR Halma - and the National and Kapodistrian University of Athens) and the Greek Ministry of Culture (represented by the Ephorate of antiquities of Kavala-Thasos) has brought to light a Late Roman/Early Byzantine urban villa called *DOM5* (for the latest excavation report see Blondé et al., 2014). This villa was built at the end of the 4th/ beginning of the 5th century CE and was destroyed no later than 619/620 CE. This date is attested to by numerous coins dated to 619 CE found in the destruction layers of the villa, whereas no later coins have been discovered. From the 5th century to its abandonment, the status of the villa had evolved from a luxurious *domus,* with the construction of private baths during the 5th or 6th century, to a more modest use after ca. 570 CE that saw a rearrangement of the house.

The three studied groups of pottery fragments were discovered in various occupation or dump layers of the villa. Each group is not associated to a single stratigraphic unit or context but in fact comes from different parts of the villa. The temporal homogeneity and the dating of the groups are, however, ensured by the typo-morphology of the fragments. Two of them belong to well-known and broadly distributed types of a famous Asia Minor production of Late Roman *Terra Sigillata* or *Phocaean Red Slip* ware (LI03 and LI04 groups, Fig. 1b; Hayes, 1972, LRC ware) with, for each group, one well-known shape selected (Table 1). The typo-chronology for the LRC ware was derived from the identification and classification of ten specific forms (and their variants) of this production and from their discovery in a number of archeological locations of the Eastern Mediterranean, which provided closed and well-dated (particularly from coins) contexts (Hayes, 1972, 1980). This type of production was widely distributed in the Eastern Mediterranean region from the 4th to the 7th century CE and its provenance was identified at the region of Phocaea (38.7°N, 26.8°E) in Asia Minor (for the workshops see Hayes, 1980; Empereur and Picon, 1986; Mayet and Picon, 1986). We underline that its recognition on archeological sites is largely used as a dating marker together with other imported fine wares such as the African Red Slip Ware (Hayes, 1972; Bonifay,

2004) or Late Roman D Ware (Hayes, 1972). We note that group LI03 includes also a few potsherds retrieved from the southern sector of the *Agora* of Thasos, identified as the *Macellum* (Marc, 2008; Excavations carried out by the French School at Athens). These fragments display the characteristic shape of the LI03 group, i.e. the 3C form dated to the second half of the 5^{th} century.

The third group from Thasos is composed of potsherds identified as *Central Greek Painted Ware* (LI05 group; Hayes, 1972; Pétridis, 1997, 2009). The classification and dating of this production rely also on cross-data obtained on different archeological dated contexts from consumption sites among which we may cite Argos, Athens, Delphi, Thessaloniki or even more distant sites such as Abu Mena in Egypt and Constantinople. Its production site was identified at Nea Anchialos (39.3°N, 22.8°E) in Thessaly (Fig.1a, Pétridis, 1997, 2009)

Late Roman/Early Byzantine remains were unearthed at Delphi as early as the end of the 19^{th} century but they had not received the attention they deserved (Pétridis, 1997). The restarting of excavations of Late Roman/Early Byzantine layers at Delphi in the 1990's by the French School at Athens allowed the uncovering of two artisanal districts with evidence of pottery activity. The first, dated to the second half of the 4^{th} century is located close to the *Gymnasium* of ancient Delphi, while the second, that was precisely dated by coins and imported pottery between 590 and 620 CE, is located South East of the *Peribolos*, in a place once occupied by the so-called *South-Eastern Villa* (Déroche et al., 2014). These excavations revealed a ceramic production of good quality, with a large corpus of shapes, covering the needs of a local and regional clientele (Pétridis, 2010). The two younger groups, referred to as DEL01 and DEL02, are associated with the *South-Eastern Villa* area. They were found in pottery deposits located close to the kilns and were identified as ceramic wasters (Fig. 1c). The dating interval is first constrained by stratigraphical arguments. The workshop indeed settled over a villa whose abandonment as a habitation unit is dated at about 580 CE by coins and imported ceramics. A *half follis* of Maurice struck in 588/589 CE, which was discovered in one of the structures of the workshop further helps to date the beginning of its activity. This activity stopped some thirty years later as evidenced by coins all dated before 620 CE and imported vessels (in particular by African Red Slip Wares), none of which can be dated to after 620 CE. Finally, the dating also relies on the hypothesis of the capacity and lifetime of the deposit (Pétridis, 2010). We note that the two groups were named differently to distinguish between fragments of pottery bases and fragments of pottery lips. They however come from exactly the same context and share the same age. Therefore their intensity results will be discussed together.

The last group from Delphi (DEL03) is from a large ensemble of ceramic fragments discovered in a shop, possibly a workshop, in the North-Eastern corner of the *Roman Agora*. The fragments were in fact used to fill-in the space after its partial destruction, probably due to the earthquake of July 21, 365 CE (Petridis, 2010). This devastating seism was described by the historian Ammianus Marcellinus (330-395) in his *Res gestae* and was felt throughout the eastern Mediterranean region (Guidoboni et al., 1994). The dating of the DEL03 ensemble is constrained by imported *terra sigillata* wares and reinforced by the study of the coins found in this context (most of them belonging to the Constantinian dynasty). All the fragments examined belong to the local production, which has already been an object of both a chemical and a petrographic analysis (see Kouzéli in Pétridis, 2010). We note that these combined experiments of XRF, XRD, and thin section observations allowed the distinction of two clay-paste groups with as a common feature their high content in iron oxides (Fe_2O_3) with a percentage of 7.90%.

3 Archeointensity measurements

Our analyses aim at recovering the intensity of the ancient geomagnetic field recorded by ceramics during their manufacture, more precisely during their cooling in the kilns. This information is recorded through the acquisition of a Thermo-Remanent Magnetization (TRM) whose direction is parallel to that of the ambient Earth's magnetic field and whose moment is proportional to its intensity. When ceramics are removed from the kiln, the information on the geomagnetic direction is lost, while that of the intensity is retained and may be retrieved.

The main principle of the archeointensity measurements is to replace the Natural Remanent Magnetization (NRM) recorded by the fragments by a new TRM acquired in known field conditions (direction and intensity). In this study the archeological artifacts were analyzed using a tailored experimental protocol designed for the Triaxe magnetometer (Le Goff and Gallet, 2004). The Triaxe protocol derives from the method of Thellier and Thellier (1959). Its originality relies on the fact that the magnetization measurements are performed continuously at high temperatures. This protocol was described in detail in previous publications (e.g. Le Goff and Gallet, 2004, Gallet and Le Goff, 2006; Gallet et al., 2014) and only a concise overview is given below.

The entire sequence of measurements is achieved within a little more than 2 hours and is performed on one specimen of 1 cm in length and with a thickness/diameter depending on the shape of the potsherd. It involves 4 successive steps:

- Step 1: Almost complete demagnetization of the NRM up to a high temperature referred to as T2, here comprised between 450 °C and 530 °C depending on the fragments.
- Step 2: The specimen is cooled to a low temperature referred to as T1 (set to 150 °C) and again heated to T2 in order to measure the temperature dependence of the spontaneous magnetization of the small fraction of the NRM remaining above T2.

- Step 3: Acquisition of a TRM by cooling the specimen from T2 to T1. Its direction is precisely set parallel to that of the NRM. The intensity of the applied field is also chosen to be close to the expected one.
- Step 4: Demagnetization of the newly acquired laboratory TRM between T1 and T2.

For each temperature Ti running from T1 to T2 by steps of ~5 °C, the R'(Ti) parameter is computed (Le Goff and Gallet, 2004). This parameter is given by the ratio between the NRM and TRM fractions demagnetized between T1 and Ti multiplied by the intensity of the laboratory field. A mean intensity value is finally estimated at the specimen level from the averaging of all R'(Ti) values. When a secondary magnetization component partly overprints the original TRM, the R'(Ti) values are then computed between a higher temperature T1' and T2, i.e. the temperature range where the original TRM is reliably isolated.

In the Triaxe protocol, it is worth stressing that the laboratory field is applied so that the direction of the new TRM is parallel to that of the NRM. This allows us to overcome the TRM anisotropy effect, which originates from the stretching of the clay during the manufacture of the object (e.g. Aitken et al., 1981). Furthermore, it has been experimentally and repeatedly observed on archeological artifacts of different types and origins that the intensity data obtained using the R'(Ti) parameters took into account the cooling rate effect (Le Goff et Gallet, 2004; Genevey et al., 2009; Hartmann et al., 2010; Genevey et al., 2016). We briefly recall that this effect is related to the dependence of the TRM acquisition on the cooling rate (e.g. Fox and Aitken, 1980) and to the fact that there is generally a large difference between the original cooling rate, during which the original TRM/NRM is recorded in the kiln and the cooling rate applied for the laboratory TRM acquisition (e.g. Genevey et al., 2008).

4 Rock magnetism investigations

Possible alteration due to heating was first investigated through susceptibility measurements performed from 50 °C up to ~500-525 °C, i.e. on the temperature range used for intensity determinations. Only pottery fragments showing reversible heating and cooling susceptibility curves were retained for further analyses (Fig. 2a,b,c,d). For these selected fragments, a second series of susceptibility measurements were carried out up to ~680 °C. For the *Terra Sigillata* produced at Phocaea (LI03 and LI05) and for the *Central Greek Painted Ware* production (LI04), the heating at higher temperature induced a strong alteration of the magnetic mineralogy, with higher susceptibilities observed on the cooling curves, most probably originating from the formation of new magnetite (Fig. 2f,g). These results highlight the advantage of investigating the magnetic mineral stability on the same temperature range as the one used for the intensity determinations rather than on a wider temperature interval. In the latter case, this would have led to the rejection of these three groups of pottery fragments. In contrast, the ceramics from Delphi appear more stable upon heating (Fig. 2e,h). Whatever the production, the heating susceptibility curves usually exhibit two inflexion points, at low (200-300 °C) and medium-high temperatures (450-550 °C).

The magnetic mineralogy of this collection was further investigated through the thermal demagnetization of three-axis Isothermal Remanent Magnetization (2 T, 0.4 T, and 0.2 T) acquired in three perpendicular directions (Lowrie, 1990). These experiments were carried on two to four fragments per group among those that provided reliable intensity results. In most fragments, they show the predominance of a magnetic phase, likely from the magnetite family (with possible impurities), of low coercivity (<0.2 T) and with unblocking temperatures below 550 °C (Fig. 3). Another phase characterized by low unblocking temperatures (200-250 °C) and high coercivity is also systematically observed, but in various proportions (Fig. 3). The very same phase has been widely documented in archeomagnetic studies, while its clear identification remains an open question (McIntosh et al., 2007, 2011). Finally, a small fraction of hematite is also observed, which, we note, was not detected from the susceptibility measurements (Figs. 2,3). In summary, the magnetic mineralogy hence appears as a combination of magnetite (in majority), a mineral of low-unblocking temperatures (200-250°C) and high coercivity (>2T), and a small fraction of hematite. Such a combination is in fact rather common in baked clay archeological artifacts (e.g. Hartmann et al., 2010; Genevey et al., 2016).

5 Intensity Results

In addition to the required stability of the magnetic mineralogy constrained by susceptibility measurements, a set of selection criteria was applied on the archeointensity data in order to only retain the most reliable results. These criteria are the same as those used in our previous investigations using the Triaxe protocol (e.g. Genevey et al., 2009, 2013; Hartmann et al., 2011; Gallet et al., 2014). These criteria aim to test the quality of the intensity determinations at the specimen level, with analyses strictly performed on the same temperature range where the primary TRM was reliably isolated. Over this temperature interval, the slope of the R'(Ti) values must be of less than 10% and must concern more than 50% of the magnetization fraction with an unblocking temperature larger than T1 (or T1', K% parameter; Supplementary Table S1; Gallet et Le Goff 2006). At the fragment level, two to three specimens were analyzed and the results must agree to within 5%. Finally, at least three fragments are required to define a mean value at the group level and its standard deviation must be of less than 10% and 5 μT.

A total of 63 specimens from 23 fragments were successfully analyzed and used to derive five new archeointensity values encompassing the Early Byzantine period in Greece (Table 1 and supplementary Table S1). All retained intensity determinations were reported at the specimen level in Fig. 4, with one panel per group. For each group, an example of thermal demagnetization is also presented in Fig. 4. These diagrams illustrate the different behaviors observed; that is, for part of the fragments, two components of magnetization observed above 150°C (Fig. 4b,f,j) and an intensity determination performed on the temperature range where the primary component was isolated (Fig. 4a,e,i). The thermal demagnetization of the other fragments revealed only one component of magnetization above 150 °C (Fig. 4d,h) and the intensity determination therefore concerned the entire temperature range above T1 (Fig. 4c,g). The percentage of success is relatively low, between 33% and 50%, on the understanding that this percentage relates to the number of fragments whose magnetic moment was strong enough to be measured on the Triaxe (supplementary Table S1). For these fragments, the main causes of rejection were either related to their unstable magnetic mineralogy upon heating, or because the slope of the R'(Ti) values was too strong over the temperature range where the TRM was isolated, or because it was not possible to reliably isolate this primary magnetization component (i.e. the magnetization acquired during the manufacturing of the artifacts).

The five new intensity results are reported in Fig. 5, together with a selection of intensity results available inside a region of 700 km around Thessaloniki (see below). These new data are well defined with standard deviations between 1% and 5% of the corresponding means, the latter ranging from 52.0 μT to 61.5 μT after reduction to Thessaloniki (Table 1). They clearly show an increase of the geomagnetic field intensities in the Balkans between the middle of the 4th century and the beginning of the 7th century CE.

6 Discussion

Archeomagnetism has largely been developed in the Balkan Peninsula, in particular through the numerous archeomagnetic studies carried out in Bulgaria since the late seventies

(Kovacheva et al., 2014 and references therein) and with the development of this discipline in Greece over the past fifteen years (Spatharas et al., 2000; De Marco et al, 2008a,b; Aidona and Kondopoulou, 2012; De Marco et al., 2014 among others). Regarding intensity, the available dataset allows a description of the geomagnetic variations over nearly the past eight millennia, making it, together with the one from the Middle East (Gallet et al., 2015), one of the longest archeomagnetic records.

The Balkan archeointensity dataset for the past three millennia was evaluated by Pavón-Carrasco et al. (2014), who underlined the rather small percentage of results satisfying modern quality criteria (see also the discussion in Tema and Kondopoulou, 2011). Taking advantage of the recent update of the Bulgarian archeomagnetic database (Kovacheva et al., 2014), we explore here again the Balkan results available for the first millennium CE, which is the period of interest of our study. The quality criteria considered below are those used in our previous studies conducted in Western Europe (e.g. Genevey et al., 2016) and can be summarized as follows. We only retain the data obtained using the original and derived versions of the method of Thellier and Thellier (1959) or the original method of Shaw (1974). The mean intensity must be defined by at least three independent values and the associated error must ≤ 15% of the corresponding mean. The TRM anisotropy effect must be taken into account for objects generally regarded as particularly anisotropic, such as pottery and tiles. The data respecting these criteria are reported in Fig. 5a. In this figure, a distinction was also made between the data whose reliability was further constrained by partial-TRM checks (pTRM-checks; solid symbols), allowing to better control the magnetic mineralogy stability on heating of the studied fragments, and the data with no such stability test (empty symbols).

As a whole, Fig. 5a shows a rather large variability of the archeointensity results. When the data are close in age, this scatter may, in some cases, raise questions about their accuracy, either regarding their experimental determinations or their dating. This is particularly the case for the data belonging to the first four centuries CE (see below). However, taken as a whole, the data support the occurrence of rapid and large intensity variations during the first millennium CE. For the Early Byzantine period, all results converge to indicate a significant increase in intensity from the 4th century CE until about the first half of the 7th century. Our new data are in good agreement with this evolution (Fig. 5a). A relative minimum in intensity is then observed around the transition between the 7th and 8th century CE, the intensity increasing again afterwards. It is interesting to note that a similar evolution was recently documented in Western Europe (Gómez-Paccard et al., 2012, Genevey et al., 2016), even though the fluctuations appear to be more intense in Eastern Europe.

The use of the pTRM-checks as a selection criterion has a strong impact for the time interval covering the first four centuries CE (compare Fig. 5a and b). For instance, there is at present no result constrained by pTRM-checks available for the period between the end of the second century CE and the end of the third century CE (Fig. 5b). Using only the most reliable archeointensity data obtained over Europe, Pavón-Carrasco et al. (2014) developed an archeomagnetic field model which predicts for the Balkans a decrease in intensity during the first three centuries followed, as previously mentioned, by an increase during the Early Byzantine period (Fig. 5b). Our new result dated to the second half of the 4th century (DEL03) is in good agreement with this trend, and so it is with two precisely dated results obtained in southern Italy (Tema et al., 2013). We note however that a few recent data (Spatharas et al. 2011; Kondopoulou et al. 2015), whose dating remains poorly defined, and which were not retained to derive the archeomagnetic field model A of Pavón-Carrasco et al. (2014), could also support the occurrence of rapid variations during the 4th century.

Although our new results appear to agree with the trend in intensity fluctuations, they seem to be systematically lower than the other mentioned data, in particular for the 5th and 6th centuries (Fig 5b). It is noteworthy that the Bulgarian data are not corrected for the cooling rate effect, which, when taken into account, usually tends to decrease the intensity values. This issue was discussed in Kovacheva et al. (2014) who acknowledged that this effect might indeed affect intensity values, at least for the data obtained on bricks. In Fig. 5b, the Bulgarian data are reported with different symbols depending on the type of analyzed objects (i.e. with a distinction between bricks, kilns, baked clays and baked soils). A cooling rate correction of a 5% decrease was applied on the Bulgarian data obtained from bricks, which represent the majority of the dataset for the 5th and 6th centuries (Fig. 5c), the other data remaining unchanged. Such a correction is a reasonable educated guess (e.g. Genevey et al., 2008), although we recognize that the cooling rate effect may in fact vary from one object to another. Clearly a 5% decrease of the Bulgarian intensity values would improve their agreement with our new results (Fig. 5c). At this stage, however, the question of the exact cooling rate correction factors required for the Bulgarian data remains unresolved and any further discussion on the significance of possible shifts between different datasets would require a systematic evaluation of the cooling rate effect for all data.

In spite of the complexity described above, we further selected the data with age uncertainties of less than 100 years. This smaller dataset, that includes our five new archeointensity data, was used to derive a mean archeointensity variation curve spanning the first millennium using a sliding windows of 75 years shifted every 10 years (Fig. 5c). We emphasize the fact that this curve, presented with its 2-s envelope, provides a likely accurate picture of the present knowledge on the secular geomagnetic field intensity variations in the Balkans during the first millennium CE, as constrained by using only the most reliable regional data.

7 Concluding remarks

This study reports on 5 new archeointensity data obtained from Greek pottery fragments precisely dated to the Early Byzantine period. These data allow to better constrain a significant geomagnetic field intensity increase in the Balkans between the fourth and seventh centuries CE. Such a feature appears particularly well established, even though the Balkan archeointensity dataset is severely penalized by a large scatter in the available results. It is worth pointing out that our study highlights the great potential of precisely dated potsherds for archeomagnetism, which have been, surprisingly, rarely exploited until now in this broad area.

Beside its implication for the regional geomagnetic field behavior, i.e. with the occurrence of rapid, centennial-scale intensity variations, the Early Byzantine intensity increase may also have interesting implications for archeological purposes. Archeointensity analyses may indeed help in deciphering the duration of certain ceramic productions in the Balkans such as the production of the Late Roman *Phocaean Terra Sigillata,* which may have persisted during the 7th century. Such issues would clearly strengthen effective collaboration between archeologists and archeomagnetists.

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Figure Captions

Fig. 1. a) Location map of the Thasos and Delphi archeological excavations sites, where the analyzed groups of pottery were unearthed (yellow squares). For the imported vessels collected at Thasos (LI# groups), the production sites at Phocaea and Nea Anchialos are also indicated (same symbol). The blue dots correspond to the locations of previously published intensity results within 700 km around Thessaloniki and dated to the first millennium CE. b)

LI04 group – composed of 12 pottery fragments, unearthed during the excavations of the Late Roman/Early Byzantine villa *DOM5* at Thasos and Phocean Red Slip Ware, Hayes 1972 Form 10A. c) Kiln discovered at Delphi, Southeast of the *Peribolos* and pottery deposit filled in with the ceramic wasters, which provided the fragments from DEL01/02 group ©Déroche et al., 2014.

Fig. 2. K-T curves for four representative fragments among those providing reliable intensity results. Red and blue curves indicate the heating and cooling curves, with heating performed at first up ~500 °C (upper row), then, on new fresh powder, up to ~680 °C (lower row).

Fig. 3. Thermal demagnetization of orthogonal 3-axis composite IRM for six representative fragments among those, which provided reliable intensity results.

Fig. 4. Archeointensity determination for the different studied pottery groups and examples of thermal demagnetization diagram. In the left panels, each curve represents the intensity analysis for one specimen over the temperature interval where the primary TRM was reliably isolated. Open (closed) symbols refer to the inclinations (declinations) in the orthogonal vector diagrams. Note that the Triaxe protocol provides measurements every 5 °C and that only a subset of the data (every 25 °C from 150 °C up to the highest temperature) are reported in these diagrams.

Fig. 5. Geomagnetic intensity variations in the Balkans area for the first millennium CE. Comparison of our new data (pink crosses) with three successive selections of available archeointensity data obtained in the Balkans (Nachasova et al., 2007; De Marco et al., 2008a; Tema et al., 2009, 2012, 2013; Spassov et al., 2010; Spatharas et al., 2011; Tema and

Kondopoulou, 2011; Kovacheva et al., 2014; Kondopoulou et al., 2014, 2015). All data were first reduced at the latitude of Thessaloniki (40.6°N). a) Archeointensity results satisfying a set of quality criteria as described in the main text. Solid symbols correspond to the data obtained using pTRM-checks while open symbols refer to those obtained without such magnetic mineralogy test. b) Archeointensity obtained using pTRM-checks, with results from Bulgaria reported with different symbols depending of the artifacts analyzed. The red curve (with yellow error band at 95% of confidence) corresponds to the prediction of the archeomagnetic model A at Thessaloniki (Pavón-Carrasco et al., 2014). c) Archeointensity data obtained using pTRM-checks and whose age error is < 100 years. A 5% decrease accounting for the cooling rate effect was applied for the Bulgarian data obtained on bricks. The mean curve of the intensity variations, with its 2-σ envelope (blue curves) was computed using a sliding window of 75 years shifted every 10 years.

Table captions

Table 1. New archeointensity results.

N Frag. (n spec.): Number of retained fragments (specimen) to derive the mean intensity value. F±σF (μT): mean intensity value given with its standard deviation, F Thessaloniki (μT) : relocated intensity results to Thessaloniki latitude (40.6 °N).

Supplementary material:

Supplementary Table 1. Intensity results obtained at the specimen level.

"Tmin-Tmax" indicates the temperature interval used for the intensity determination. "F_{Lab}" is the intensity of the laboratory field used during the experiments. "K T1 (T1')" gives the percentage of the magnetization fraction with unblocking temperature larger than T1 (or T1') involved for the intensity determination while the "slope R' " is the slope of the R'(Ti) values over the Tmin-Tmax interval. F Triaxe is the intensity value at the specimen level. At the fragment level, the mean intensity value is given with its standard error (resp. standard deviation) when computed from two (resp. three) values. (N1/N2/N3)* indicates the number of collected fragments (N1), the number of fragments whose magnetization was strong enough to be measured on the Triaxe (N2) and the number of fragment retained for the computation of the mean intensity value (N3).

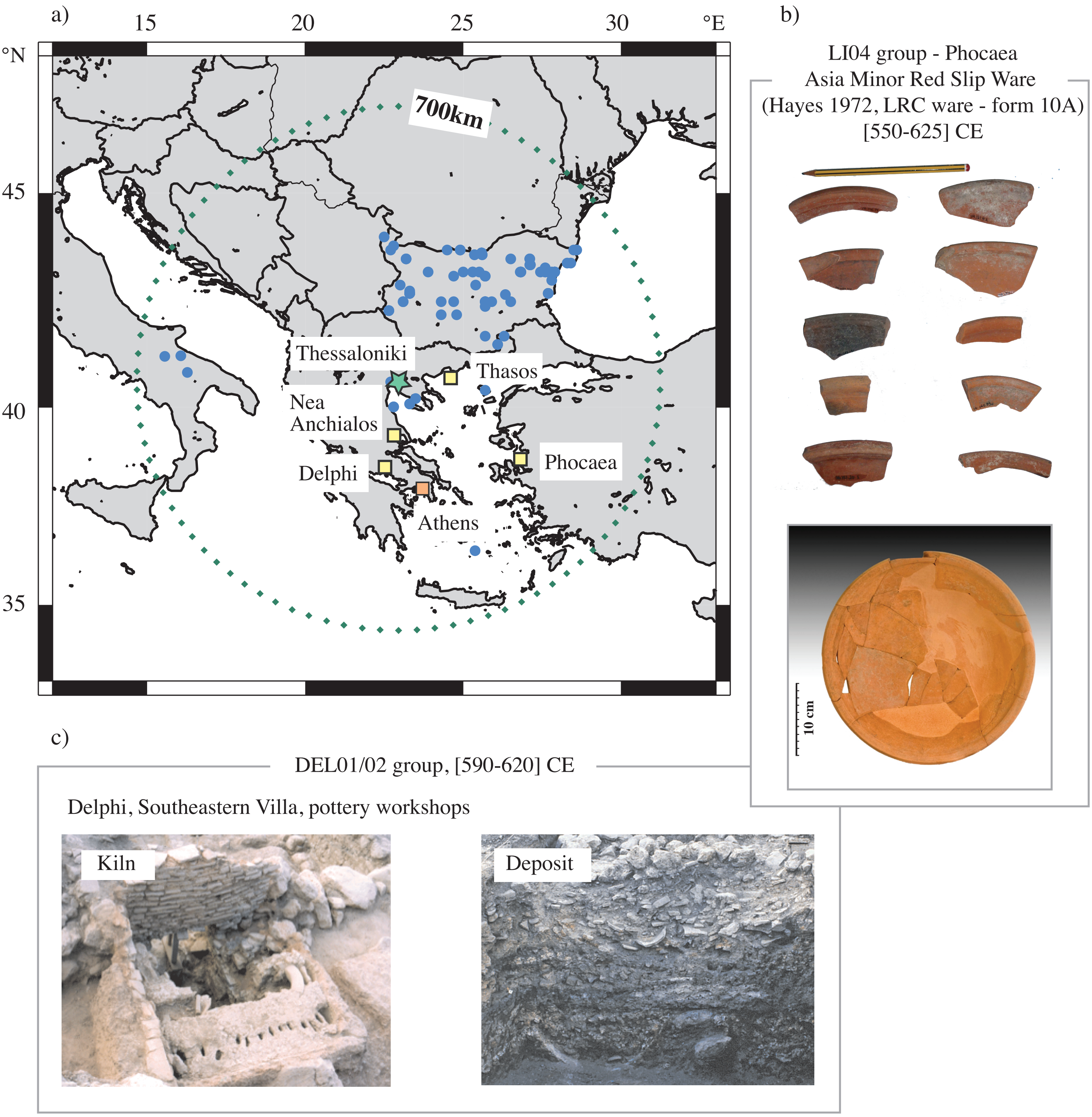

a)
15
20
25
30
°E
°N
45
40
35
700km
Thessaloniki
Thasos
Nea
Anchialos
Phocaea
Delphi
Athens
b)
LI04 group - Phocaea
Asia Minor Red Slip Ware
(Hayes 1972, LRC ware - form 10A)
[550-625] CE
10 cm
c)
DEL01/02 group, [590-620] CE
Delphi, Southeastern Villa, pottery workshops
Kiln
Deposit

Figure 1.

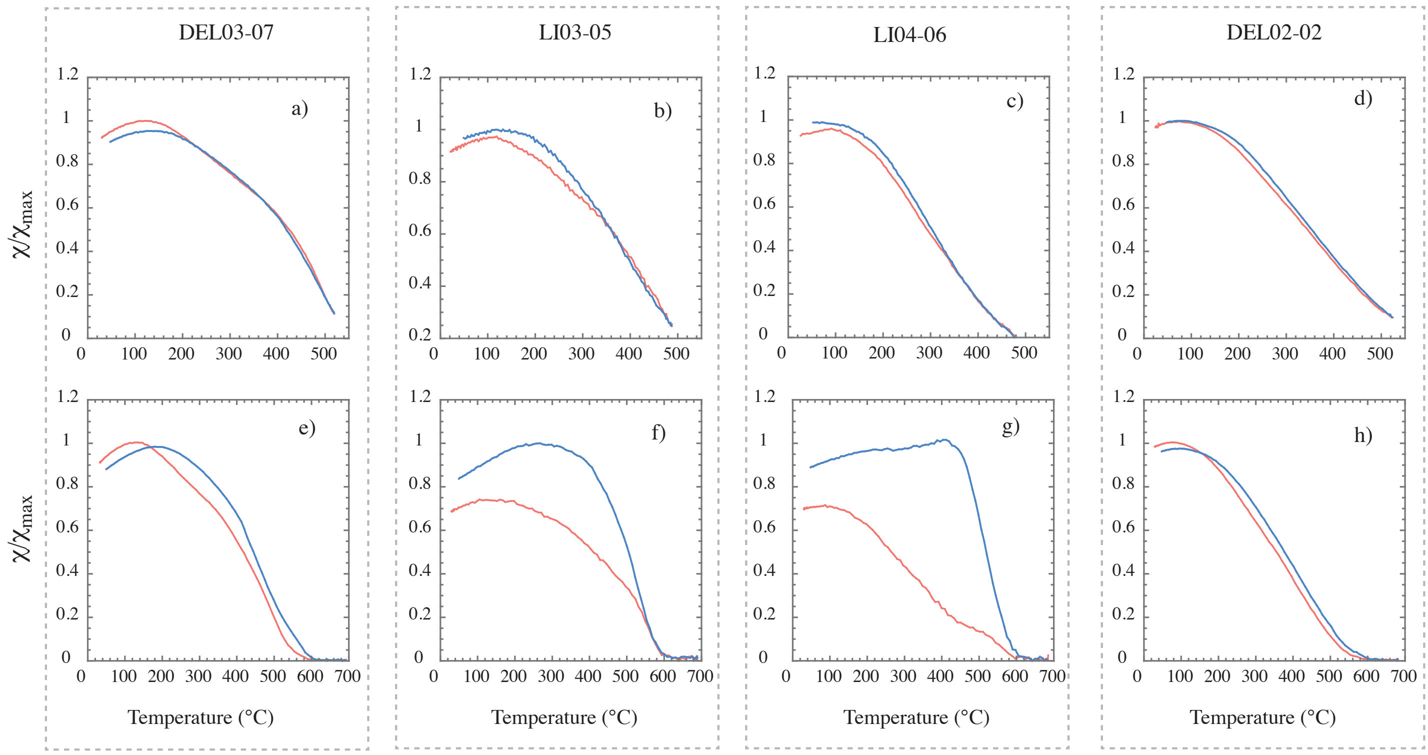
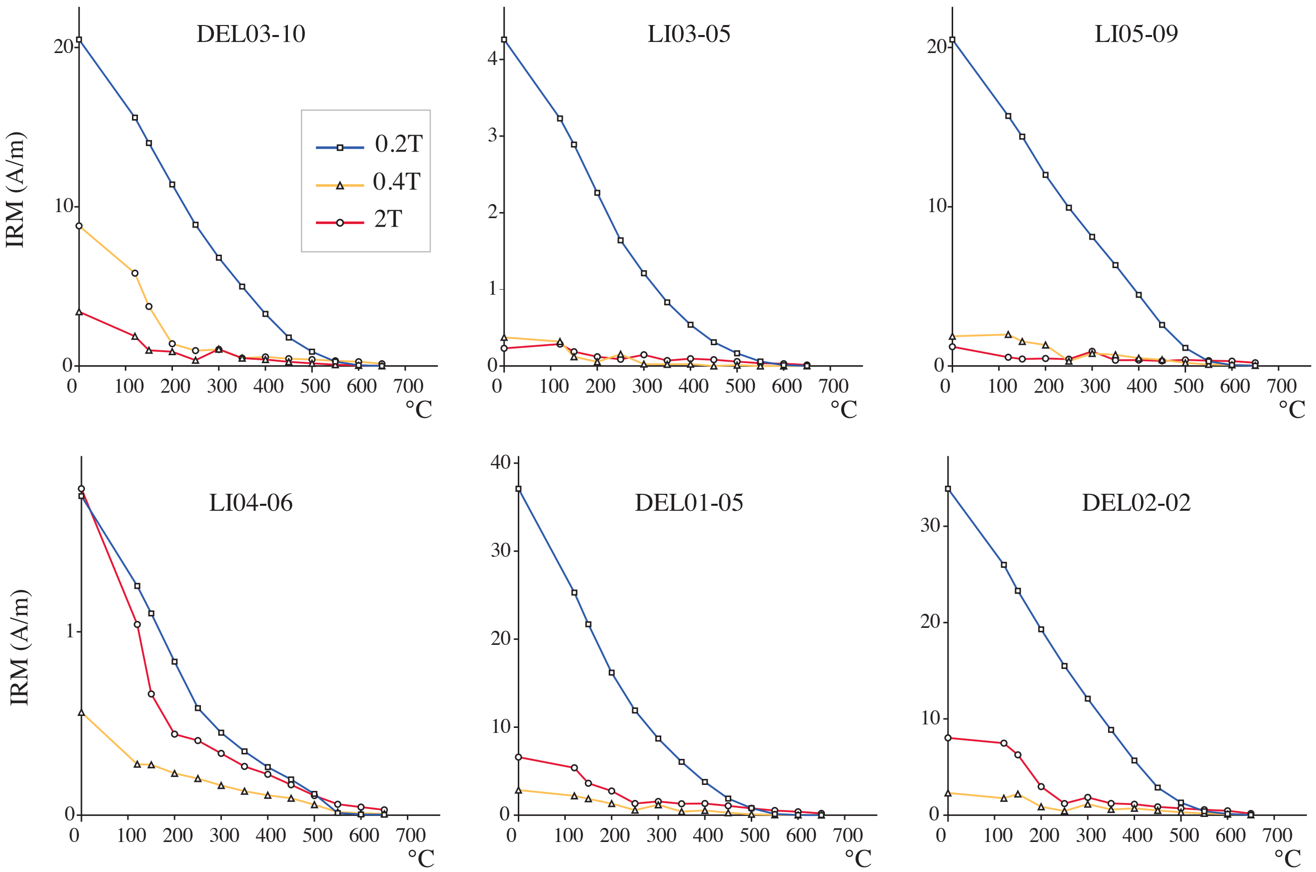

DEL03-07
LI03-05
LI04-06
DEL02-02
a)
b)
c)
d)
e)
f)
g)
h)
χ/χmax
Temperature (°C)

Figure 2.



DEL03-10
LI03-05
LI05-09
LI04-06
DEL01-05
DEL02-02
IRM (A/m)
°C
0.2T
0.4T
2T

Figure 3.

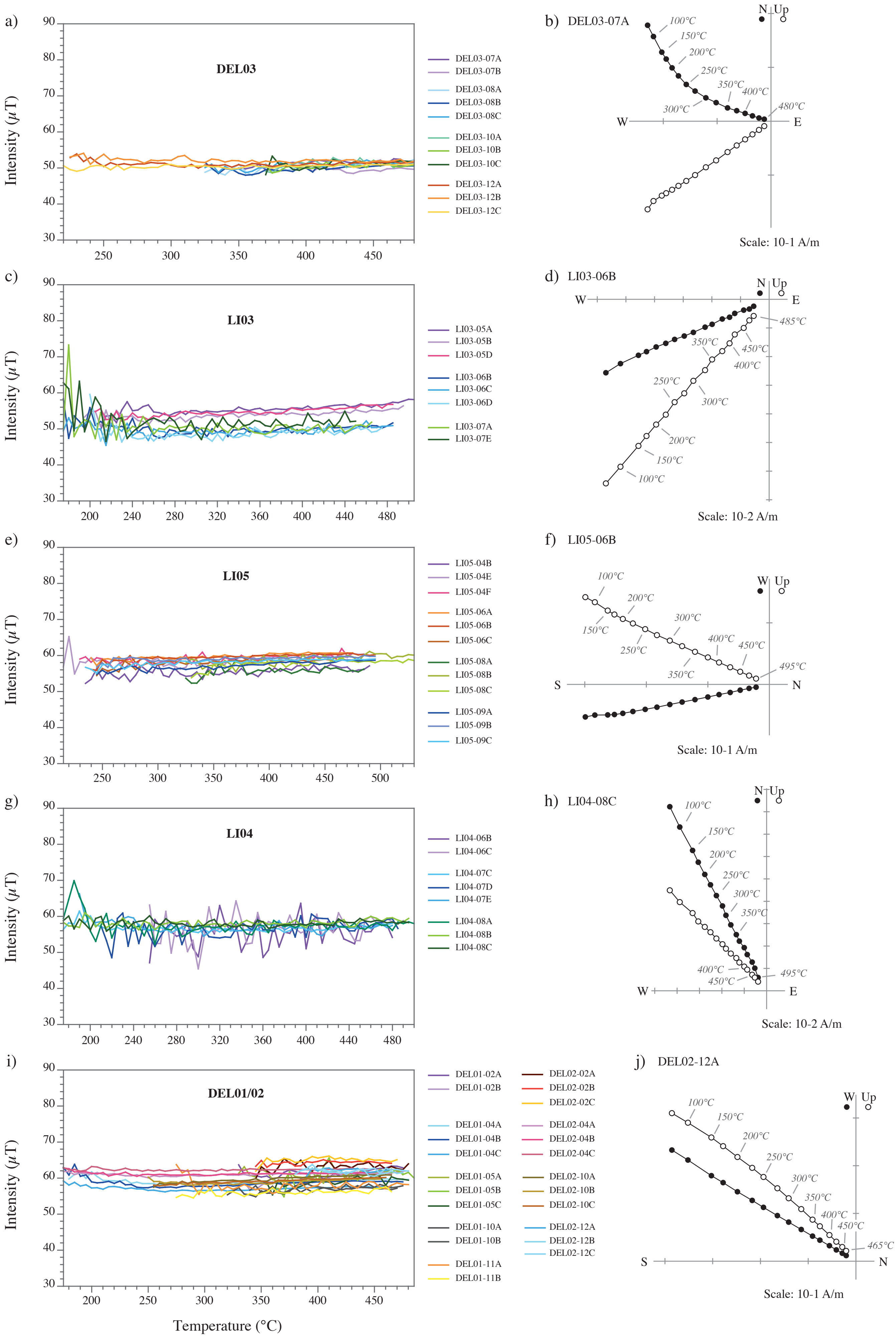
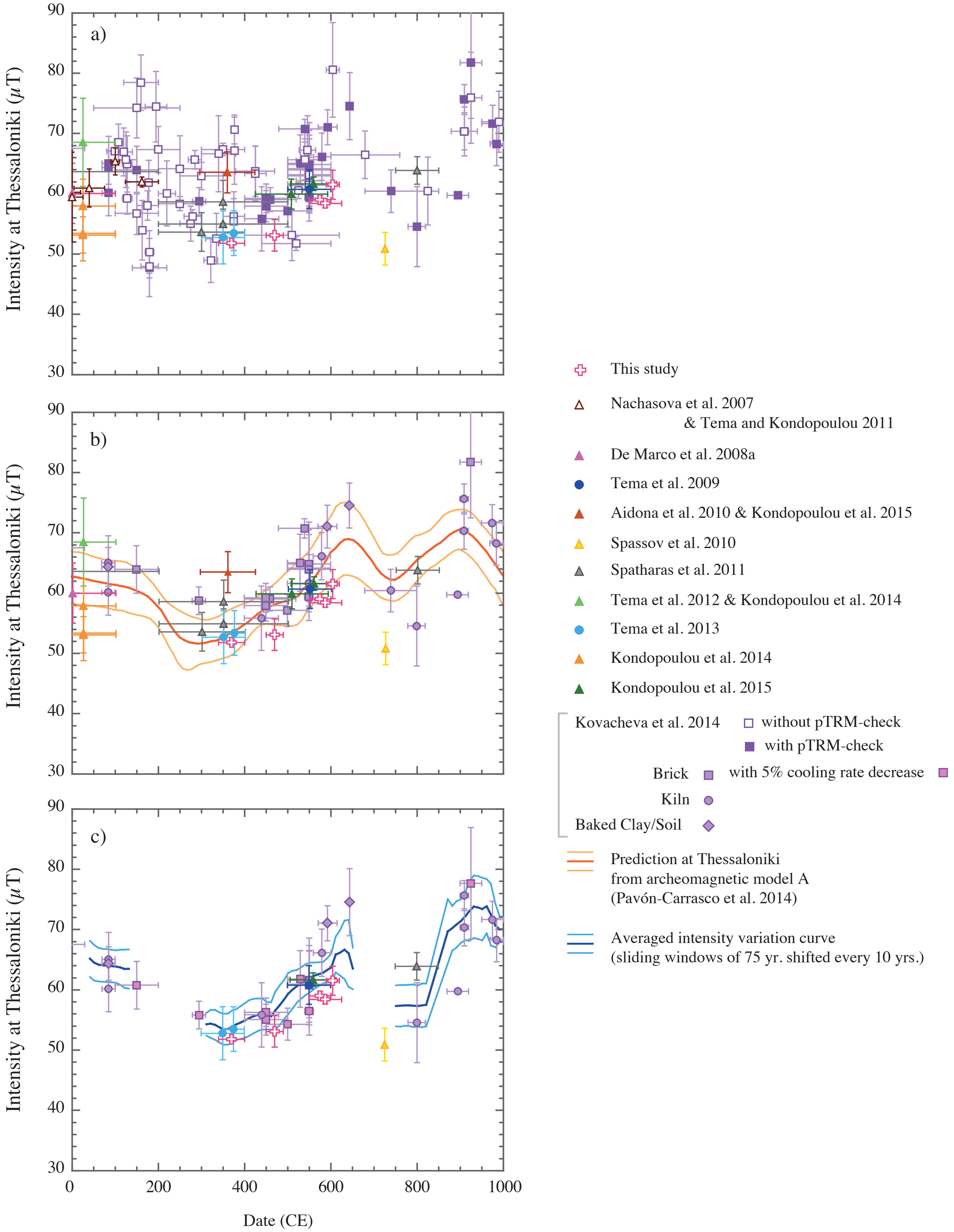

a)
DEL03
Intensity (μT)
DEL03-07A
DEL03-07B
DEL03-08A
DEL03-08B
DEL03-08C
DEL03-10A
DEL03-10B
DEL03-10C
DEL03-12A
DEL03-12B
DEL03-12C
b) DEL03-07A
N Up
W
E
100°C
150°C
200°C
250°C
300°C
350°C
400°C
480°C
Scale: 10-1 A/m
c)
LI03
LI03-05A
LI03-05B
LI03-05D
LI03-06B
LI03-06C
LI03-06D
LI03-07A
LI03-07E
d) LI03-06B
485°C
450°C
400°C
350°C
300°C
250°C
200°C
150°C
100°C
Scale: 10-2 A/m
e)
LI05
LI05-04B
LI05-04E
LI05-04F
LI05-06A
LI05-06B
LI05-06C
LI05-08A
LI05-08B
LI05-08C
LI05-09A
LI05-09B
LI05-09C
f) LI05-06B
W Up
S
N
100°C
150°C
200°C
250°C
300°C
350°C
400°C
450°C
495°C
Scale: 10-1 A/m
g)
LI04
LI04-06B
LI04-06C
LI04-07C
LI04-07D
LI04-07E
LI04-08A
LI04-08B
LI04-08C
h) LI04-08C
100°C
150°C
200°C
250°C
300°C
350°C
400°C
450°C
495°C
Scale: 10-2 A/m
i)
DEL01/02
DEL01-02A
DEL01-02B
DEL01-04A
DEL01-04B
DEL01-04C
DEL01-05A
DEL01-05B
DEL01-05C
DEL01-10A
DEL01-10B
DEL01-11A
DEL01-11B
DEL02-02A
DEL02-02B
DEL02-02C
DEL02-04A
DEL02-04B
DEL02-04C
DEL02-10A
DEL02-10B
DEL02-10C
DEL02-12A
DEL02-12B
DEL02-12C
Temperature (°C)
j) DEL02-12A
100°C
150°C
200°C
250°C
300°C
350°C
400°C
450°C
465°C
Scale: 10-1 A/m

Figure 4.



a)
b)
c)
Intensity at Thessaloniki (μT)
90
80
70
60
50
40
30
0
200
400
600
800
1000
Date (CE)
This study
Nachasova et al. 2007 & Tema and Kondopoulou 2011
De Marco et al. 2008a
Tema et al. 2009
Aidona et al. 2010 & Kondopoulou et al. 2015
Spassov et al. 2010
Spatharas et al. 2011
Tema et al. 2012 & Kondopoulou et al. 2014
Tema et al. 2013
Kondopoulou et al. 2014
Kondopoulou et al. 2015
Kovacheva et al. 2014
without pTRM-check
with pTRM-check
Brick
with 5% cooling rate decrease
Kiln
Baked Clay/Soil
Prediction at Thessaloniki from archeomagnetic model A (Pavón-Carrasco et al. 2014)
Averaged intensity variation curve (sliding windows of 75 yr. shifted every 10 yrs.)

Figure 5.

Table 1.

#Group	Age (CE)	Production site	Lat (°N)	Long (°E)	Archeological context/description	N Frag. (n Spec.)	F±σF (μT)	F Thessaloniki (μT)
DEL03	[340-400]	Delphi	38.5	22.5	Delphi - North-Eastern corner of the *Roman Agora* - (Units: AG90; AG91; AG92) - Local production	N=4 (n=11)	50.7±0.5	52.0
LI03	[450-490]	Phocaea	38.7	26.8	Thasos - *DOM5*, Area North of the *Artémision* & Southern sector of the *Agora*, *Macellum* - Asia Minor Red Slip Ware (Hayes 1972, LRC ware – form 3C) - Imported vessels	N=3 (n=8)	51.9±2.6	53.1
LI05	[550-600]	Nea Anchialos	39.3	22.8	Thasos - *DOM5*, Area North of the *Artémision - Central Greek Painted Ware* production - Imported vessels	N=4 (n=12)	58.1±0.7	59.0
LI04	[550-625]	Phocaea	38.7	26.8	Thasos - *DOM5*, Area North of the *Artémision*– Asia Minor Red Slip Ware (Hayes 1972, LRC ware - form 10A) - Imported vessels	N=3 (n=8)	57.1±0.8	58.4
DEL01/02	[590-620]	Delphi	38.5	22.5	Delphi - *South-Eastern Villa* area - Sector C30 (Unit TS95.15) - Local production	N=9 (n=24)	60.0±2.4	61.5

Fragment	Specimen	Tmin-Tmax (°C)	F Lab (μT)	K T1 (T1') (%)	Slope R' (%)	F Triaxe (μT)	F Triaxe mean value per fragment ± σF (μT)
DEL03 - Delphes - [340-400] A.D. - (12/11/4)*							
DEL03-07	DEL03-07A	350-480	55	83	5	51.3	50.4±0.9
	DEL03-07B	400-480	50	73	0	49.5	
DEL03-08	DEL03-08A	325-480	55	86	7	50.3	50.2±0.4
	DEL03-08B	325-480	50	85	4	49.8	
	DEL03-08C	325-480	50	86	5	50.6	
DEL03-10	DEL03-10A	370-480	55	71	4	51.1	50.9±0.3
	DEL03-10B	370-480	50	70	3	50.5	
	DEL03-10C	370-480	50	71	4	51.0	
DEL03-12	DEL03-12A	225-480	55	85	-1	51.1	51.2±0.9
	DEL03-12B	225-480	50	92	-2	52.1	
	DEL03-12C	220-480	50	86	-2	50.4	
LI03 - Phocée - [450-490] A.D. - (8/7/3)*							
LI03-05	LI03-05A	210-505	55	88	7	55.5	54.7±0.8
	LI03-05B	195-495	55	82	5	53.9	
	LI03-05D	205-485	55	76	6	54.7	
LI03-06	LI03-06B	175-485	55	76	-3	50.1	49.5±0.6
	LI03-06C	175-485	55	77	1	49.6	
	LI03-06D	200-475	55	76	-2	48.9	
LI03-07	LI03-07A	175-465	55	94	-6	50.7	51.5±0.8
	LI03-07E	175-450	55	86	-6	52.2	
LI05 - Nea Agchialos - [550-600] A.D. - (10/8/4)*							
LI05-04	LI05-04B	240-495	60	76	5	55.5	57.7±2.0
	LI05-04E	215-485	60	82	4	58.6	
	LI05-04F	230-475	60	79	4	59.1	
LI05-06	LI05-06A	240-475	60	75	4	59.8	59.1±1.0
	LI05-06B	240-495	60	83	5	59.5	
	LI05-06C	245-495	60	83	5	58.0	
LI05-08	LI05-08A	325-485	60	60	3	55.6	57.4±1.6
	LI05-08B	325-530	60	87	6	58.8	
	LI05-08C	330-530	60	88	6	57.7	
LI05-09	LI05-09A	245-495	60	85	6	57.2	58.1±1.0
	LI05-09B	245-495	60	85	3	59.1	
	LI05-09C	235-495	60	86	5	58.1	
LI04 - Phocée -[550-625] A.D. (10/9/3)*							
LI04-06	LI04-06B	260-485	60	68	-2	56.0	56.4±0.4
	LI04-06C	260-495	55	69	5	56.8	
LI04-07	LI04-07C	180-485	60	71	-1	56.8	56.9±0.3
	LI04-07D	210-485	55	79	7	56.6	
	LI04-07E	190-480	60	64	-5	57.2	
LI04-08	LI04-08A	175-500	60	93	-3	57.5	57.9±0.4
	LI04-08B	175-495	60	81	2	58.2	
	LI04-08C	175-495	55	81	0	58.1	
DEL01/02 - Delphes - [590-620] A.D. - (24/22/9)*							
DEL01-02	DEL01-02A	335-480	60	90	3	61.4	60.7±0.7
	DEL01-02B	335-480	60	88	9	60.0	
DEL01-04	DEL01-04A	180-480	60	86	0	59.1	58.3±1.1
	DEL01-04B	175-475	60	91	-1	58.7	
	DEL01-04C	175-465	60	87	0	57.1	
DEL01-05	DEL01-05A	335-480	60	79	2	61.1	60.2±1.1
	DEL01-05B	360-485	60	79	-7	60.5	
	DEL01-05C	355-480	60	77	5	59.0	
DEL01-10	DEL01-10A	325-475	60	84	3	56.6	57.0±0.4
	DEL01-10B	340-475	60	82	2	57.4	

DEL01-11	DEL01-11A	275-480	60	83	-1	58.1	57.1±1.1
	DEL01-11B	275-475	60	86	3	56.0	
DEL02-02	DEL02-02A	345-480	60	85	2	63.2	64.1±0.9
	DEL02-02B	345-465	60	82	1	64.2	
	DEL02-02C	345-470	60	79	2	65.0	
DEL02-04	DEL02-04A	175-465	60	96	1	61.0	61.5±0.7
	DEL02-04B	175-445	60	94	0	61.2	
	DEL02-04C	175-445	60	95	0	62.3	
DEL02-10	DEL02-10A	255-465	60	87	5	59.7	59.3±0.4
	DEL02-10B	250-455	60	86	2	59.0	
	DEL02-10C	255-460	60	85	4	59.3	
DEL02-12	DEL02-12A	390-465	60	64	0	62.3	62.1±0.3
	DEL02-12B	385-475	60	71	-2	61.8	
	DEL02-12C	380-480	60	71	0	62.3	