Determining the use of ancient ceramic artefacts through combined morphological and magnetic analyses: the case of Villa del Foro, Northern Italy

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Abstract

Even though multidisciplinary approaches are widely used for the investigation of archaeological findings, magnetic analyses are still little exploited and only rarely applied to the determination of ancient artefacts use. Here, we present the results of a combined archaeological, morphological and magnetic study carried out on the ring-shape clay artefacts found in large quantities at the protohistoric site of Villa del Foro (Alessandria, Northern Italy). The shape and significant number of such artefacts make their archaeometric investigation very interesting to understand the technological conditions of their production and use. A morphological investigation carried out on 640 fragments showed inhomogeneity in their dimensions, colour, form, and clay refinement. Magnetic measurements show thermal stability after heat treatment up to around 500-600 ^{o}C, while further heating at higher temperature introduces some magnetic mineralogy changes. Thermal demagnetization of the samples generally shows a strong and stable thermal remanent magnetization. In few cases, a clear secondary component is present, suggesting partial re-heating or displacement at temperatures ranging from 200 ^{o}C to 450 ^{o}C. The results obtained indicate that the investigated ring-shaped artefacts were baked during their manufacture at temperatures of at least 600 °C. The archaeomagnetic investigation does not show any systematic evidence for magnetic components related to cooking activities and it is therefore suggested that the rings were used as weight looms and baked only during their production procedures. Such pilot study can be used as reference for the identification and study of similar objects found in other archaeological sites worldwide.

Keywords: Archaeomagnetism, rock-magnetism, morphology, baked clay, weight loom, Iron Age

Introduction

Each year, archaeological excavations bring to light countless human remains, relics and artefacts, and archaeologists are asked to interpret the meaning of these finds in order to give answers about their origin, technology, and functionality and offer information about when and by whom they were made and used. Sometimes, such answers may be easily given by the findings themselves; in other cases, the questions that arise are much more than the answers that can be given. This is especially important for structures, artefacts, and findings whose function or use have been lost over time or where there are no written records or further evidence to help their interpretation.

Nowadays, multidisciplinary approaches are widely applied to the investigation of archaeological findings, including the contribution of various scientific and laboratory techniques. Well-established methods such as e.g. radiocarbon dating, chemical analysis, microscopic investigations, and many others, are often used for the chronological identification, analysis and better understanding of an archaeological site and/or artefact. Nowadays, experimental techniques are continuously evolving and increasingly applied to cultural heritage problems, mainly related to the provenance, use and technology of archaeological artefacts like pottery and other baked clay artefacts. Among them, archaeomagnetism is a very promising but still under-utilized technique. Even though during the last decades it has been increasingly used as a dating tool (Herries et al. 2008; Tema et al. 2013; Batt et al. 2017; Casas and Tema 2019; Tema et al. 2019) or as ancient heating temperature indicator (Spassov and Hus 2006; Rasmussen et al. 2012; Kostadinova-Avramova et al. 2018; Jordanova et al. 2018; Tema and Ferrara 2019), its great potential on pottery use studies is still very little exploited (Francés-Negro et al. 2019).

In this study we present a combined archaeological, morphological and archaeomagnetic study of the characteristic ring-shaped clay artefacts found in large quantities at the Iron Age site of Villa del Foro, in Northern Italy. The principal objective was to investigate the thermal history of these artefacts through the analysis of their natural remanent magnetization (NRM) and the investigation of magnetic mineralogical changes during laboratory heating. Furthermore, such analyses integrated with the morphological characteristics of the studied material and the archaeological context of the site are used to identify the functionality of these artefacts, particularly interesting and curious due to their large dimensions and noteworthy quantities. The potential of the combined archaeomagnetic and rock magnetic measurements in the investigation of the use of ancient baked clay artefacts is also investigated and discussed.

Materials and methods

Archaeological site and materials

The archaeological site of Villa del Foro (44° 53' 18'' N, 8° 32' 01'' E) is situated at Alessandria Province, in Northern Italy (Fig. 1a). It is dated between the sixth and the first half of fifth century BC (Venturino Gambari et al. 2010) and it has been excavated since the middle '80s of the last century. Several excavation campaigns brought to light large quantities of features and materials, including kilns and firing structures, ceramics, metal items, as well as large quantities of broken and badly fired pottery (Giaretti et al., in press). Such findings together with several pits, wells and other water management structures, suggest that the area was used as a structured workshop for multiple manufacturing activities, including the production of semi-finished and finished metal, pottery, and clay artefacts (Venturino Gambari 1993; Venturino Gambari et al. 2017). Many traces of firing activities *in loco*, or in proximity to the combustion structures, as well as the presence of different types of locally produced pottery and metal ornaments and tools (Cicolani, in press) further confirm the use of the site as a production workshop, offering evidence for a special differentiation of the production activities too.

Among the various findings, the ring-shape clay artefacts found in large quantities mainly during the 2007-2008 excavation campaign, are of particular interest. Such rings are distributed between different trenches, inside fills of cuts identified either as firing structures or as waste pits. Most of them were found inside the backfilling of a firing structure (US2087-2091) that consists of two communicating chambers filled with ash and carbonaceous remains (Fig. 1b). They present a characteristic "donut" shape with diameters that range from 17 to 20 cm and weight between 1.5 and 1.9 kg (Fig. 1c). A total of 640 ring fragments have been analyzed, belonging to 230 single individuals. A minimum of 125 individuals come from the US2087-2091 firing structure alone.

In literature, large ring-shaped clay artefacts have been variously interpreted as kiln supports, cooking stands, or loom weights (Zamboni, in press). The quantities and dimensions of the Villa del Foro specimens and their stratigraphic association with firing structures found in the site may therefore advance several possible hypotheses that need to be further investigated. For this purpose, we have analyzed the technological and morphological characteristics of the Villa del Foro clay rings as well as their magnetic behavior and thermal stability through archaeomagnetic and rock magnetic analyses. To our knowledge, this is the first archaeomagnetic study carried out on this kind of artefacts and our results aim to provide the first reference database for the identification of similar objects in the future.

Methods

A total of 640 ring fragments were selected and macroscopically examined to determine their technical and morphological characteristics. Such analysis included the measurement of their outer and inner diameter, height and weight, observation of the clay matrix, and identification of variations in color (external and internal parts), vegetable inclusions and external characteristics. Among these fragments, 31 were selected for archaeomagnetic analysis. The selected samples come from different rings and were chosen after a macroscopic examination of the pieces; when possible, the upper surface of the rings was identified, assuming that the rings were horizontally placed during their manufacture or last heating with their flat surface downwards. On the assumed upper surface of the rings, small arrows were incised to keep evidence of such surface during the archaeomagnetic measurements. From each fragment, at least two specimens of around 1 cm^3 volume were cut and inserted in non-magnetic plastic palaeomagnetic cubes of standard dimensions (2 cm x 2 cm x 2 cm), fixed with white non-magnetic plasticine. Moreover, small pieces with mass < 50 mg were also cut for magnetic mineralogy experiments. In total, more than 80 specimens were prepared and analyzed.

The magnetic analyses were performed at the Alpine Palaeomagnetic Laboratory (ALP-CIMaN, Peveragno, Italy) and the Istituto Nazionale di Ricerca Metrologica (INRIM, Torino, Italy) and preliminary results are reported in a volume dedicated to the archaeological site of Villa del Foro (Tema et al., in press). The magnetic susceptibility versus temperature curves were measured at the Ivar Giæver Geomagnetic Laboratory (IGGL, Oslo, Norway). The magnetic mineralogy was investigated through the acquisition of Isothermal Remanent Magnetization (IRM) curves, Lowrie (1990) experiments and hysteresis curves. IRM curves were obtained by applying stepwise increasing applied fields up to 1 T with an ASC Pulse magnetizer (ASC Scientific), and the remanent magnetization was measured with a JR6 Spinner magnetometer (AGICO). A composite IRM was imparted applying first a maximum 1.6 T, then a medium 0.5 T and finally a minimum 0.1 T magnetic field along three orthogonal axes of representative samples, respectively. Stepwise thermal demagnetization was then performed to investigate the contribution of hard-, medium- and soft-magnetic component (Lowrie 1990). Hysteresis loops and heating/cooling curves reporting the magnetic moment versus temperature were measured with a Lakeshore 7400 Vibrating Sample Magnetometer (VSM) equipped with a thermo-resistance oven operating in inert Argon atmosphere. Small samples (mass < 100 mg) were heated and cooled down at room temperature, while their magnetic moment was continuously measured. Several heating-cooling cycles were performed at stepwise increasing maximum temperatures, up to 700 ^{o}C, under a constant field intensity of 0.2 T. The magnetic susceptibility versus temperature was also measured for representative samples with a MFK1-FA Kappabridge equipped with a CS-4 furnace (AGICO) up to 700 ^{o}C. The anisotropy of the magnetic susceptibility was investigated with a KLY3 Kappabridge (AGICO) to detect preferential orientation of the clay grains during the artefacts' production. Finally, the NRM of the samples was thermally demagnetized with a TD-48 SC (ASC Scientific) furnace in several steps of 20 or 40 ^{o}C, up to a maximum temperature varying from 560 to 640 ^{o}C at which all samples were completely demagnetized. After each heating-cooling step, the bulk magnetic susceptibility at room temperature was measured to detect possible magnetic mineralogy changes occurred during the laboratory heating and to obtain information about the equivalent maximum firing temperatures of the rings (Rasmussen et al. 2012; Jordanova et al. 2019).

Results

Technological and morphological characteristics

The average external diameter of the clay rings of Villa del Foro is around 17-20 cm, with a significant cluster around 18-19 cm (extreme peaks of 15 and 22 cm). The internal diameters indicate concentrations between 6.5 and 9 cm (rare peaks of 5 and 10 cm). The heights vary depending on the section, which could be irregularly slenderer or flattened but are generally comprised between 5 and 6.8 cm (concentrations between 5.6 and 6.4 cm). The section varies from specimen to specimen, with both circular and oval shapes (Fig. 2): the central hole, always axial, often presents an oval profile with gaps between the two axes around 1 or 2 cm. In the best-preserved specimens, the weight is considerable, ranging between 1.5 and 1.9 kg (in most cases around 1.8 kg).

The clay rings were locally produced at Villa del Foro with a silty or silt-clay matrix, rich in microcrystalline calcite, both fine and coarse grained. The clay was probably drawn from the natural deposits of the local substrate from which they incorporate part of the limestone fraction as well as more rare ferrous nodules. The clay body is prepared with the addition of a substantial part of vegetable inclusions (from 5 to 30%, on a macroscopic observation) showing thin porosity and an elongated shape. In the specimens with a lower percentage of plant inclusions, the structure is rather lumpy, concentric towards the center and more massive near the surfaces. The manufacturing process took place starting from a simple clay ring roughly worked and left to dry on one side, where it is observable a slight flattening and traces of detachment from an irregular surface (probably a not structured working surface). Specimens of greater thickness (especially those with sub-rectangular sections) are characterized by two overlapping and compressed clay ‘donuts’. In general, the finishing of the surfaces is rather raw and handmade. In some cases, two parallel elongated impressions, made before the drying and of unclear interpretation, are present on the external side of the ring (Fig. 1c and Fig. 2).

The most frequent colors of the surfaces resulting from the production process are mainly tending to shades of beige (10YR 7/3) and pale brown (10YR 6/3), less frequently light brown (7.5YR 6/4), and reddish yellow (7.5YR 6/6; 5YR 6/6), with occasional purplish halos, according to Munsell Color (2009). Sometimes thermal alterations, such as black heart, superficial oxidations, inhomogeneous colors, as well as few episodes of vitrification, are observed, probably caused by organic inclusions, differences in the initial clay matrix and/or inaccurate conduction of firing process. The overall impression is that of a homogeneous yet coarse production, with some differences in the clay bodies and the final products perhaps due to inaccurate decantation and firing processes.

A morphological analysis of the clay rings from Villa del Foro confirms the hypothesis of a consistent and rough production not much interested in aesthetic aspects (Zamboni, in press). If we look at the differences between the profiles (circular torus or elliptical) and between the sections (regular sub-quadrangular, sub-quadrangular with irregular margins, sub-rectangular, flattened), they appear more the result of a rapid and inaccurate modeling process than a precise craftsman’s choice. A further confirmation comes from the observation that in various cases, the sections differ from one point to another of the same sample. Keeping this in mind and without strict typological purposes, the most common shape of clay rings in Villa del Foro is the sub-quadrangular section (128 individuals, corresponding to 56% of the total). A widespread variant with regular edges can be distinguished (72 individuals). A greater irregularity of the internal margin is observed in 21 specimens, while in a third variant, quite consistent (30 individuals), the upper external margin appears rounded. In few cases, the section is sub-quadrangular with one of the internal margins raised and pointed. A second group (57 specimens, 25% of individuals) is recognizable by a sub-rectangular section: in only one case the margins are well shaped, while the norm is that of an irregular section. A rarer, flattened section (42 individuals, 19% of the total) characterizes a third group, while the rounded section is rather underrepresented.

Rock-magnetic and archaeomagnetic results

Magnetic mineralogy

Magnetic minerology experiments were performed on several casually selected fragments from different rings. The IRM acquisition curves obtained are almost identical for all the samples studied, getting completely saturated at applied field intensities of 0.2-0.4 T, indicating the presence of a low coercivity mineral (Fig. 3a). Thermal demagnetization diagrams of a composite IRM obtained from eight different rings are also very similar between them and further confirm the dominance of the soft magnetic fraction, while the medium and hard coercivity components are generally negligible (Fig. 3b). Hysteresis loops measured for three rings are almost identical after the correction for dia- and paramagnetic contributions, characterized by low coercivity values of 5-10 mT (Fig. 3c). The magnetic saturation is reached at field intensity of around 0.4 T. Magnetic susceptibility versus temperature curves up to 700 ^{o}C obtained on 3 samples indicate Curie temperature of around 520-580 ^{o}C (Fig. 3d). These magnetic mineralogy results point to the presence of magnetite and/or Ti-magnetite as the main carriers of the remanent magnetization.

Magnetic anisotropy

The anisotropy of low field magnetic susceptibility was measured on 40 specimens, coming from 20 independent ring fragments. The results show a well-developed magnetic fabric with the minimum axes (k_3) of the AMS ellipsoid being perpendicular to the flat surface of the rings, while the intermedium (k_2) and maximum anisotropy (k_1) axes lie on the horizontal plane (Fig. 4a). The mean degree of anisotropy ($P= k_1/k_3$) is P= 1.049, with a minimum value of P_{min}=1.031 and a maximum of P_{max}=1.105. The mean magnetic lineation ($L= k_1/k_2$) is L= 1.014 and the mean magnetic foliation ($F=k_2/k_3$) is F= 1.035 while there is no preferential ellipsoid shape; the data are dispersed in both prolate and oblate areas in the T -P plots (Fig. 4b), where T is the shape parameter (Jelinek, 1981). The well-developed magnetic fabric observed in these artefacts is in very good agreement with previous results on tiles and bricks, confirming that the strain applied during their shaping tends to orient the magnetic grains included in the clay mixture parallel to the flat surface (Tema 2009).

Thermomagnetic analysis and ancient firing temperatures

Magnetic moment vs temperature curves, obtained after continuous heating-cooling cycles at increasing temperatures carried out on four rings, show generally stable thermal behavior up 500-600 ^{o}C (Fig. 5). The heating-cooling curves are almost completely reversible up to heating at 600 ^{o}C. However, further heating at a temperature of 700 ^{o}C seems to introduce some mineralogical changes, as after this temperature the heating-cooling curves are not completely reversible (blue curves in Fig. 5). The magnetic susceptibility vs temperature curves obtained after heating at 700 ^{o}C also show irreversible path (Fig. 3d), confirming that most probably some chemical alteration took place at temperatures higher than 600 ^{o}C. Based on these results, it seems that although samples could have experienced different heating conditions (temperature, duration, atmosphere), their equivalent ancient firing temperature was however higher than ~ 500-600 °C. All samples have lost their magnetization at temperatures ~ 560-580 °C, indicating the prevalence of magnetite-type magnetic carrier.

These results are also confirmed by the variation of the magnetic susceptibility measured at room temperature after each heating step during the stepwise thermal demagnetization (Fig. 6). The magnetic susceptibility variation and the calculated first derivative squared following Rasmussen et al. (2012), show that all samples have a magnetically stable behaviour up to almost 600 ^{o}C, while magnetic mineralogy variations, if any, occur at temperatures higher than 580-620 ^{o}C (Fig. 6). Based on these results, the rings were probably heated at temperatures of around 600 ºC to 700 ºC, temperatures compatible with their firing in a kiln.

Stability of the Natural Remanent Magnetization (NRM)

Stepwise thermal demagnetization carried out on 62 specimens (two specimens for each of the 31 studied rings) shows that most of the samples are characterized by a strong and stable remanent magnetization and their Characteristic Remanent Magnetization (ChRM) component is easily isolated from the Zijderveld diagrams (Fig. 7). In almost all samples, a small secondary component, presumably of viscous origin, is also noticed but it is easily eliminated during the first steps of the thermal demagnetization. On the contrary, in some samples a clear and strong secondary magnetic component is observed. Such component cannot be ascribed to a viscous origin (generally observed at temperatures < 200 ºC), but it is most probably acquired during a partial secondary re-heating of the samples or due to their displacement during cooling. Among the 62 thermally demagnetized specimens, 36 specimens (coming from 19 independent rings) show one single magnetic component (Fig. 7 a,b), 16 specimens (coming from 8 rings) show a clear secondary magnetic component isolated at temperatures that vary from 300 ºC to 460 ºC (Fig. 7 c,d) while for 4 rings it was not possible to reliably interpret the demagnetization path.

Discussion

The study of the clay rings of Villa del Foro allowed the appreciation of some aspects and problems linked to the characterization of this type of artefacts and the interpretation of their original use. Clay rings are quite common archaeological artefacts, traditionally interpreted as loom weights when characterized by small dimensions (generally less than 10 cm diameter). Nevertheless, to our knowledge, massive clay rings of large dimensions (diameters between 10 and 20 cm), with a large central hole, of sub-quadrangular, sub-rectangular or sub-circular profiles, rich in vegetable inclusions similar to those found at Villa del Foro are much rarer (Bazzanella and Mayr 2009). Few large rings are attested in northern and central Italy between the late Bronze Age and the Iron Age (Zamboni, in press). Most of them are found in Veneto and north-eastern Italian regions between the late second millennium BC (Final Bronze Age period) and the very beginning of the first millennium BC (Early Iron Age). They were mostly excavated within structured and nucleated centers such as Frattesina di Fratta Polesine, or Montagnana – Borgo S. Zeno (Panella 1998; Saracino and Maritan, 2012) and interpreted as loom weighs (also called 'taralli'). Comparisons have been found in Romagna and other central Italy regions, too (Zamboni, in press).

During the following centuries, a different type of clay ring is widespread in most of the pre-Roman cultures, including Veneto, the Po valley, and the Etruscan or Etruscanized regions. It is characterized by smaller dimensions (diameter less than 10 cm), a smaller central hole, and weights between 0.5 and 1 kg. During the Iron Age larger clay rings, similar to the mentioned Final Bronze Age prototypes, are only known in the western regions of northern Italy, namely the Golasecca area of present-day Lombardy and western Piedmont, and the Ligurian sphere both on the Tyrrhenian coast and the inlands (Zamboni, in press). From a comparative perspective, analogous large clay rings are known in several European regions across time, from protohistory to the Medieval period (e.g., Médard 2000; Mårtenson et al. 2009; Rogers 2007), and mainly interpreted as loom weights allegedly related to the need of a greater number of threads or working wider and heavier fabrics. Other authors, nevertheless, argue that they are more likely to be interpreted as pot stands used in cooking hearths (e.g., Grahek 2016; Nin 2003).

The large size and the significant quantities of the clay rings found at Villa del Foro make their interpretation less straightforward. Contextual, morphological and traceological analyses show that the characteristics of these rings are not those traditionally attributed to loom weights. Clear evidence of firing and the often carbonized interiors seen in the cross sections of representative rings

(Reboldi 2016) suggest their connection to firing procedures and could advance hypothesis of their use as cooking stands or firing supports.

Thermomagnetic analyses confirm that the Villa del Foro rings were fired, with estimated firing temperatures of around 600-700 ^{o}C. Such firing may have occurred either during the production of the rings, confirming that they were baked and not just sun dried, either during their use. Thermal demagnetization of the natural remanent magnetization of a selection of rings, independently of their typology, shows in almost all cases a strong and stable remanent magnetization further confirming that the rings were fired. Apart from a small overprint of most probably viscous origin, 8 from the 31 studied rings show a clear and well-defined secondary magnetic component too, isolated at a temperature range of around 240-460 ^{o}C. Such secondary magnetic component is indicative of a secondary heating at temperatures 300-400 ^{o}C (360 ^{o}C as defined by the best examples e.g. Fig. 8 c,d), or of a displacement of the rings from their initial firing position while still hot (~360 ^{o}C).

Even though the studied rings belong to casually different morphological typologies, no connection among type and magnetic behavior was observed. This suggests that the ring's morphology does not define neither their production conditions nor the final use of the artefacts. Moreover, it is interesting to notice that the magnetic inclination, even if it is only approximately estimated since the rings were not in-situ oriented, is in some cases negative (i.e. upward aligned) suggesting that the surface initially identified as the base of the rings according to the macroscopical observations, was not the same during the secondary partially re-heating of the samples. Most probably, the secondary magnetic component was acquired in a casual position, suggesting that during their cooling or subsequent use, the position and standing side of the rings was not important.

Investigating the various hypotheses regarding the use of the baked rings, the results of the magnetic analysis can offer some very helpful insights. If the rings were used as loom weights, they would be expected to have been heated only once during their production in big kilns. Inside the firing chamber of ancient protohistoric kilns for ceramics, like those found in Villa del Foro, temperatures could be as high as 900-1000 °C based on experimental archaeology evidence (Venturino Gambari et al. 2017) and therefore the baked rings would have acquired one single and stable component of magnetization during their cooling at room temperature. This hypothesis agrees well with the magnetic behavior observed in the majority of the studied fragments that are characterized by only one component of magnetization. On the contrary, if the rings were used as food cooking supports, that means that they would have been heated several times in much lower temperatures (cooking temperatures could be estimated around 200-300 ºC), they should have recorded a systematic secondary component. This hypothesis could be partially compatible with the behavior observed in 8 rings that showed a secondary magnetic component (that could have been acquired during cooking) but not with the single component behavior of the rest of the rings studied. Moreover, using the rings as a cooking or firing supports implies that they would be always used with their flat surface horizontally placed, used as a base. In that case, we would expect to find always a positive magnetic inclination value for the secondary magnetic components (even if its exact value cannot be calculated as the artefacts are not any more in the original position they had during their last heating/cooling).

Combining the morphological and magnetic analyses ~~results~~, it seems plausible that the Villa del Foro baked clay rings consist of an ~~example~~ ensemble of large loom weights. The secondary magnetic component observed in few rings seems better explained by the discard of few rings (maybe broken or damaged) from the kiln while still hot rather than their systematic and repeated partial reheating due to cooking activities. The main characteristic of these weights was to support a larger number of threads (Grömer 2016), thus reducing the number of loom weights and perhaps leading to wider and heavier fabrics, such as carpets or wool blankets, allegedly reminiscent of previous late Bronze Age fashion styles.

Conclusions

Even though loom weights are interesting and often abundant archaeological artefacts, they are little studied so far from an archaeometric point of view. Most of the available literature is focused on petrographic, mineralogical and chemical analysis while, to our knowledge, no rock-magnetic and archaeomagnetic investigation on such artefacts is available so far. Our study shows that magnetic analysis can offer important information regarding the thermal history of such clay artefacts and together with archaeological, morphological and technological evaluations can provide evidence about their production and use. Such analysis applied in the case of the large clay rings found at the Iron Age archaeological site of Villa del Foro indicates that the studied rings were fired at temperatures of at least 500-600 ºC. These results are in very good agreement with the temperatures estimated based on petrographic analysis of loom weights from other archaeological sites (e.g. Saracino and Maritan 2012). Moreover, the absence of systematic secondary components in most of the studied artefacts suggests that their use was not related to food cooking activities, further supporting the archaeological hypothesis of their use as loom weights. In this framework, the productive site of Villa del Foro seems to provide the surrounding Iron Age dwelling sites with different products, including a large quantity of loom weights, apart from pottery, metal ornaments and weaving tools such as spindle whorls. The new obtained magnetic results can be used as reference data for comparison of future results obtained from similar clay artefacts, not only from Italy but from other European sites too. This study further aims to underline the potential of magnetic analysis in the investigation of the technology and use of ancient baked clays.

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Figure captions

Fig. 1 a) Map of Italy with the localisation of the Villa del Foro archaeological site (Alessandria, Northern Italy; b) Photo of the kiln US 2087-2091, where most of the clay rings were found; c) Photos of representative clay rings from Villa del Foro.

Fig. 2 Drawings of main typologies of clay rings found at Villa del Foro, as classified based on the morphological analysis.

Fig. 3 a) Isothermal remanent magnetization curves up to 1 T; b) Thermal demagnetization of three orthogonal IRM components; c) Hysteresis loop corrected for the para/diamagnetic contribution; d) Magnetic susceptibility vs temperature curve up to 700 ^{o}C.

Fig. 4 a) Equal-area projection of the principal axes of the anisotropy of magnetic susceptibility ellipsoid; b) Shape parameter vs anisotropy degree plot.

Fig. 5 Magnetic moment vs temperature curves obtained after successive heating-cooling cycles at increasing final temperatures (heating = continuous line; cooling = dashed line)

Fig. 6 Examples from the experimental determination of the maximum firing temperatures of representative rings based on the magnetic susceptibility variation (Rasmussen et al. 2012). Bulk magnetic susceptibility vs temperature (left); Magnetic susceptibility normalized to the initial value (at 120 ^{o}C) vs temperature (middle); the first derivative of magnetic susceptibility squared vs temperature (right).

Fig. 7 Thermal demagnetization results plotted in Zijderveld diagrams (left) and intensity decay curves (right) for representative samples. a,b) Samples with a single magnetic component; c,d) Samples showing a clear, well-defined secondary magnetic component.

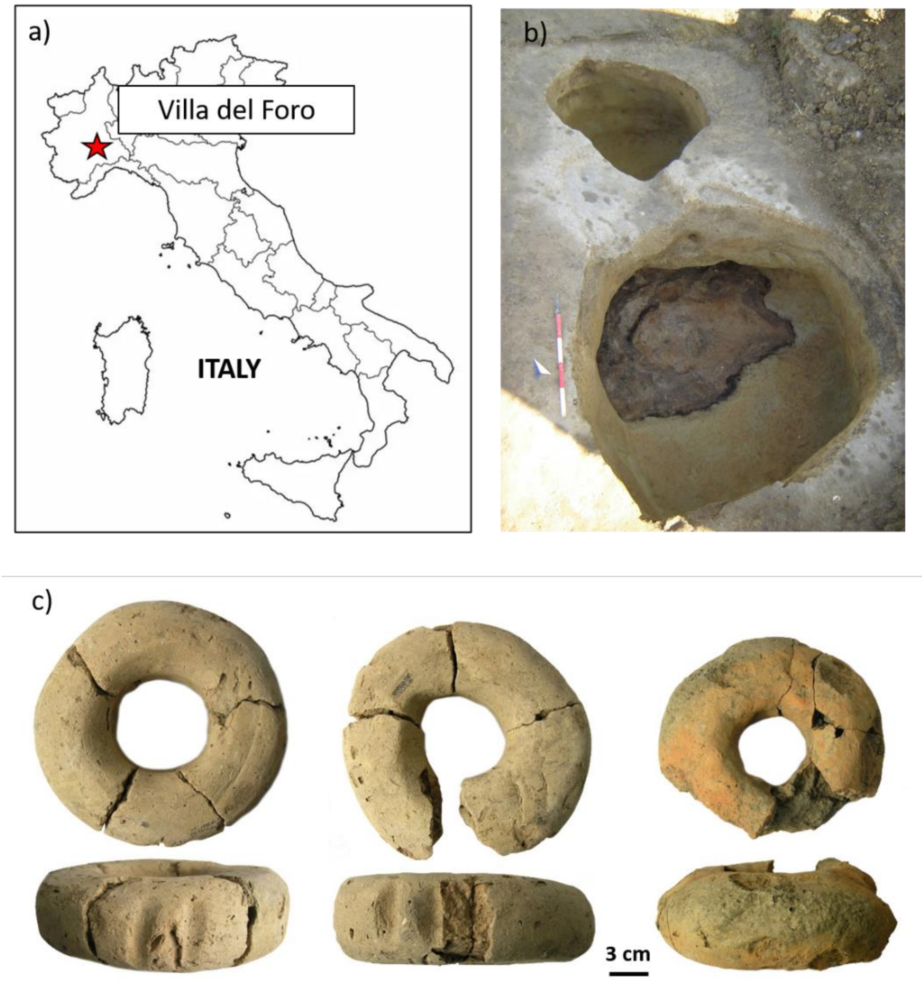

Fig. 1

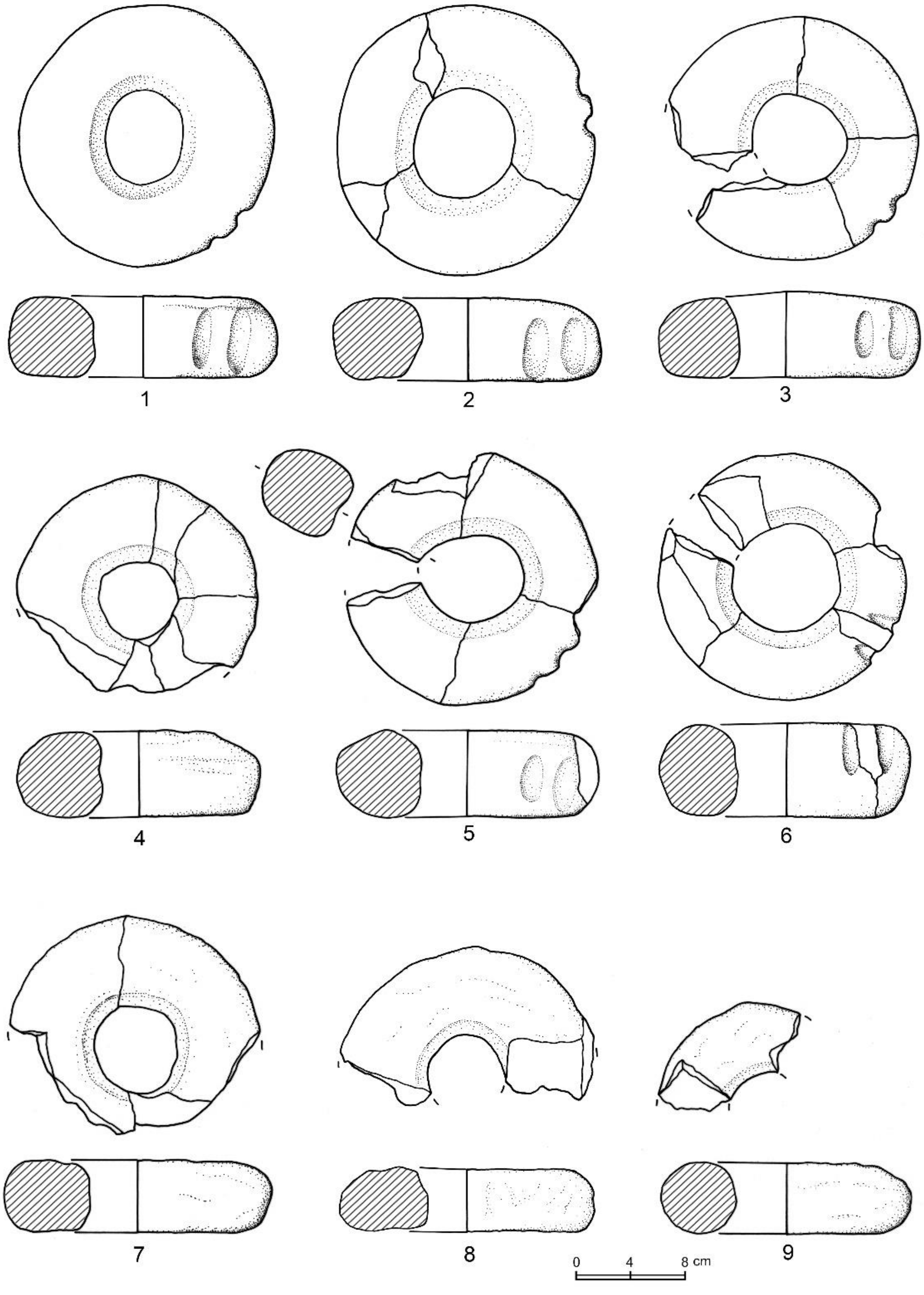

Fig. 2

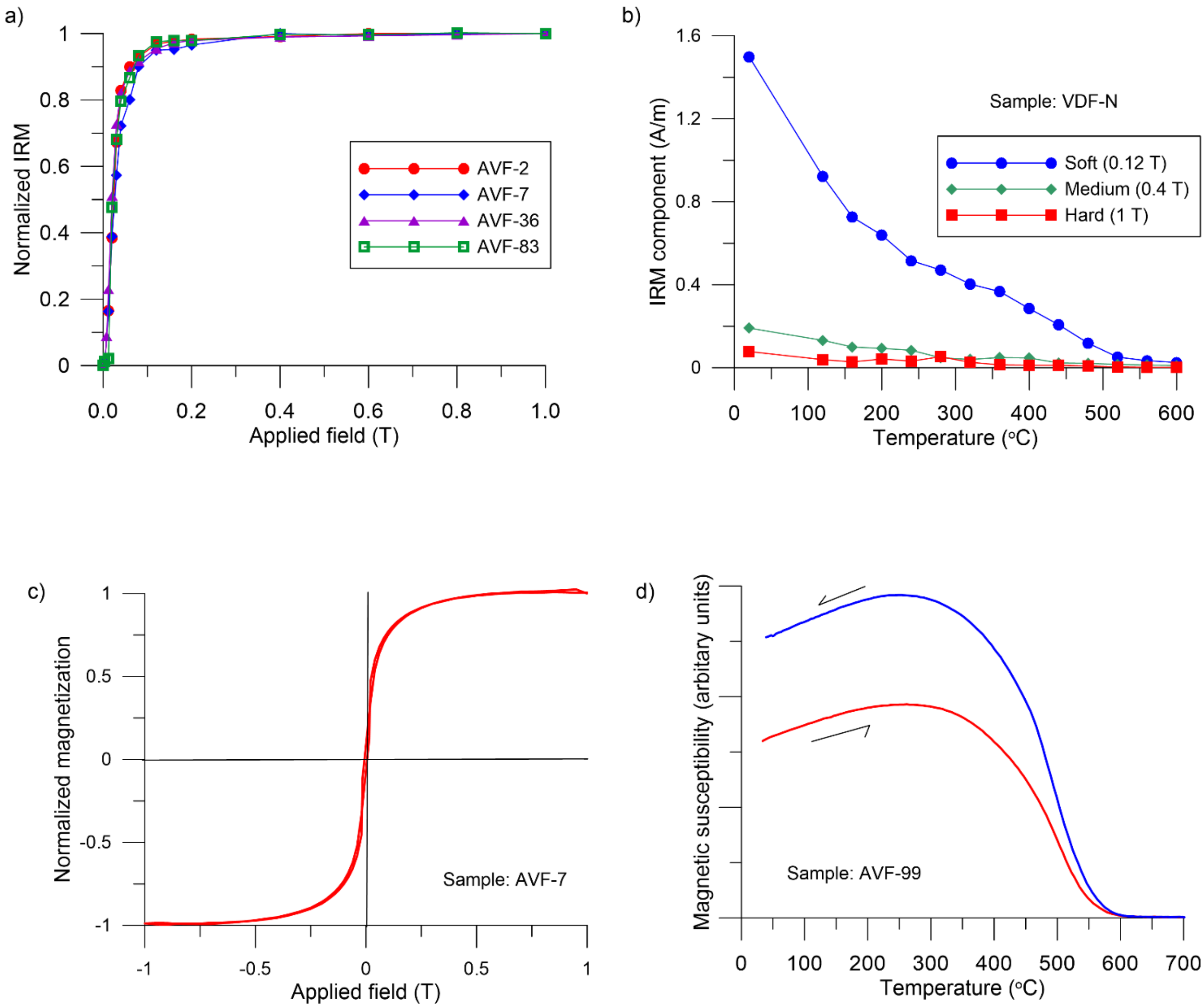
a)
Normalized IRM
Applied field (T)
AVF-2
AVF-7
AVF-36
AVF-83
b)
IRM component (A/m)
Temperature (°C)
Sample: VDF-N
Soft (0.12 T)
Medium (0.4 T)
Hard (1 T)
c)
Normalized magnetization
Applied field (T)
Sample: AVF-7
d)
Magnetic susceptibility (arbitary units)
Temperature (°C)
Sample: AVF-99

Fig. 3

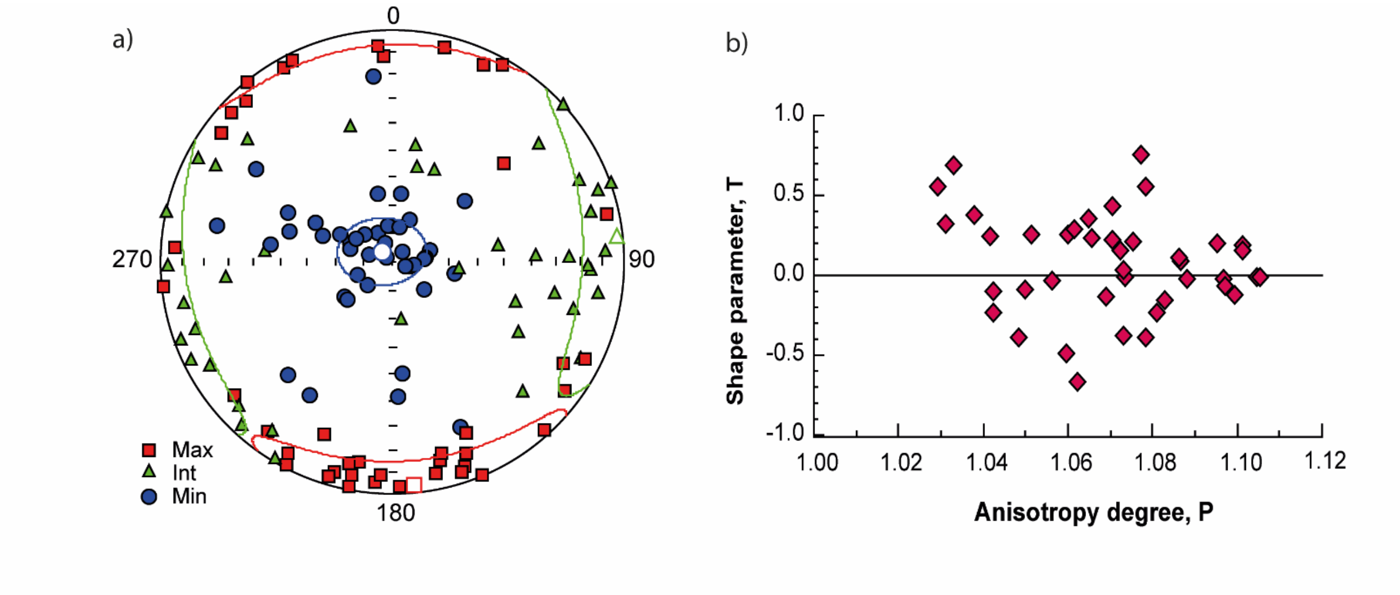
a)
0
90
180
270
Max
Int
Min
b)
Shape parameter, T
1.0
0.5
0.0
-0.5
-1.0
1.00
1.02
1.04
1.06
1.08
1.10
1.12
Anisotropy degree, P

Fig. 4

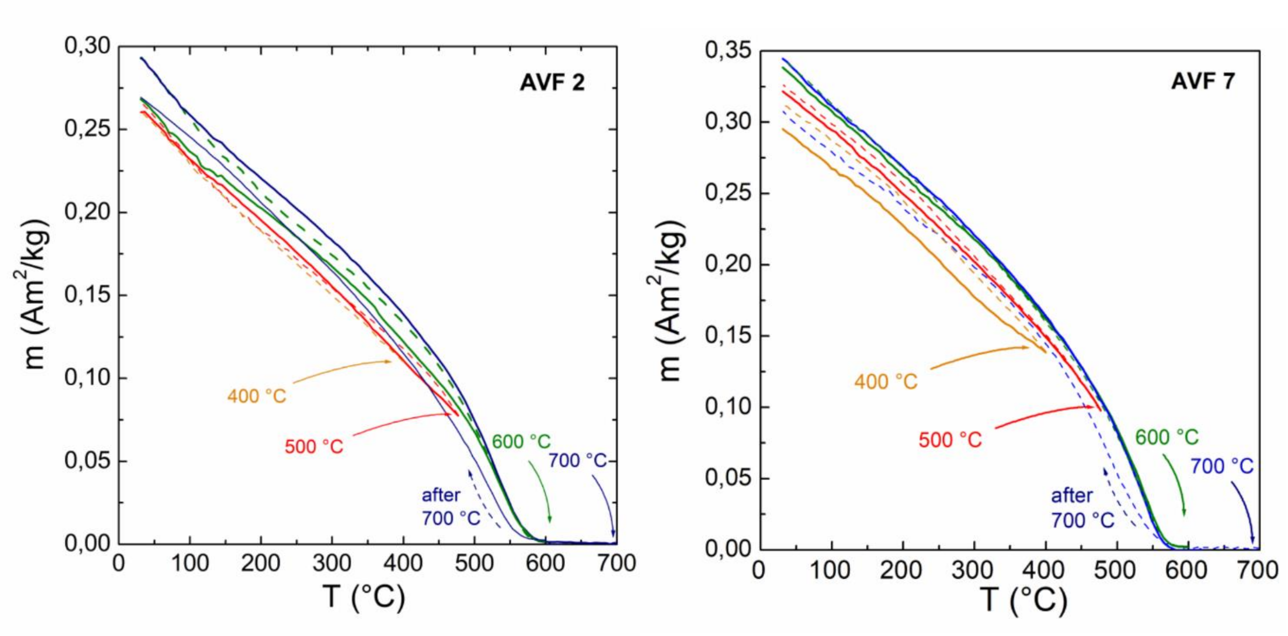
AVF 2
m (Am²/kg)
T (°C)
400 °C
500 °C
600 °C
700 °C
after
700 °C
AVF 7
m (Am²/kg)
T (°C)
400 °C
500 °C
600 °C
700 °C
after
700 °C

Fig. 5

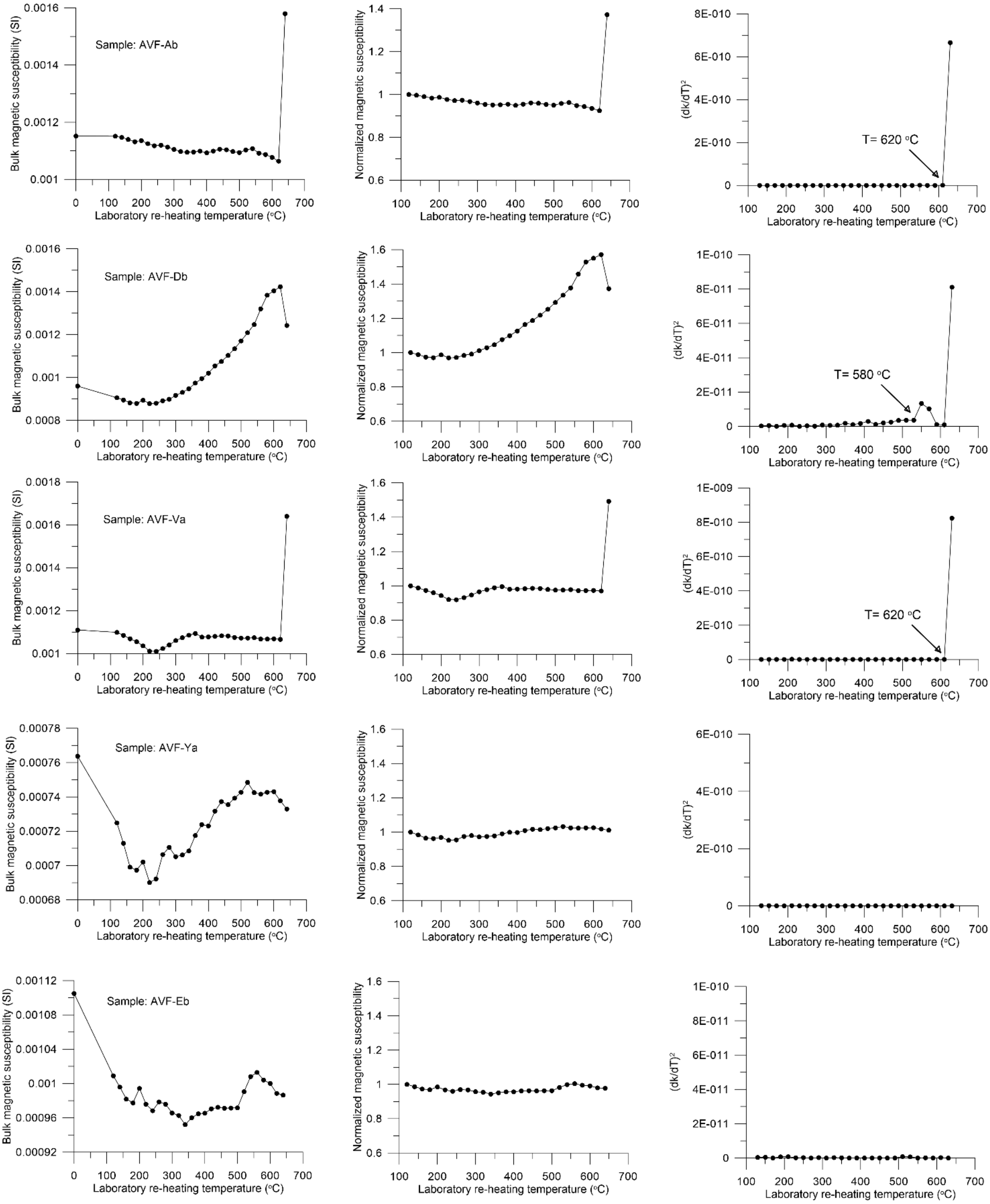
Sample: AVF-Ab
Sample: AVF-Db
Sample: AVF-Va
Sample: AVF-Ya
Sample: AVF-Eb
Bulk magnetic susceptibility (SI)
Normalized magnetic susceptibility
(dk/dT)²
Laboratory re-heating temperature (°C)
T= 620 °C
T= 580 °C
T= 620 °C

Fig. 6

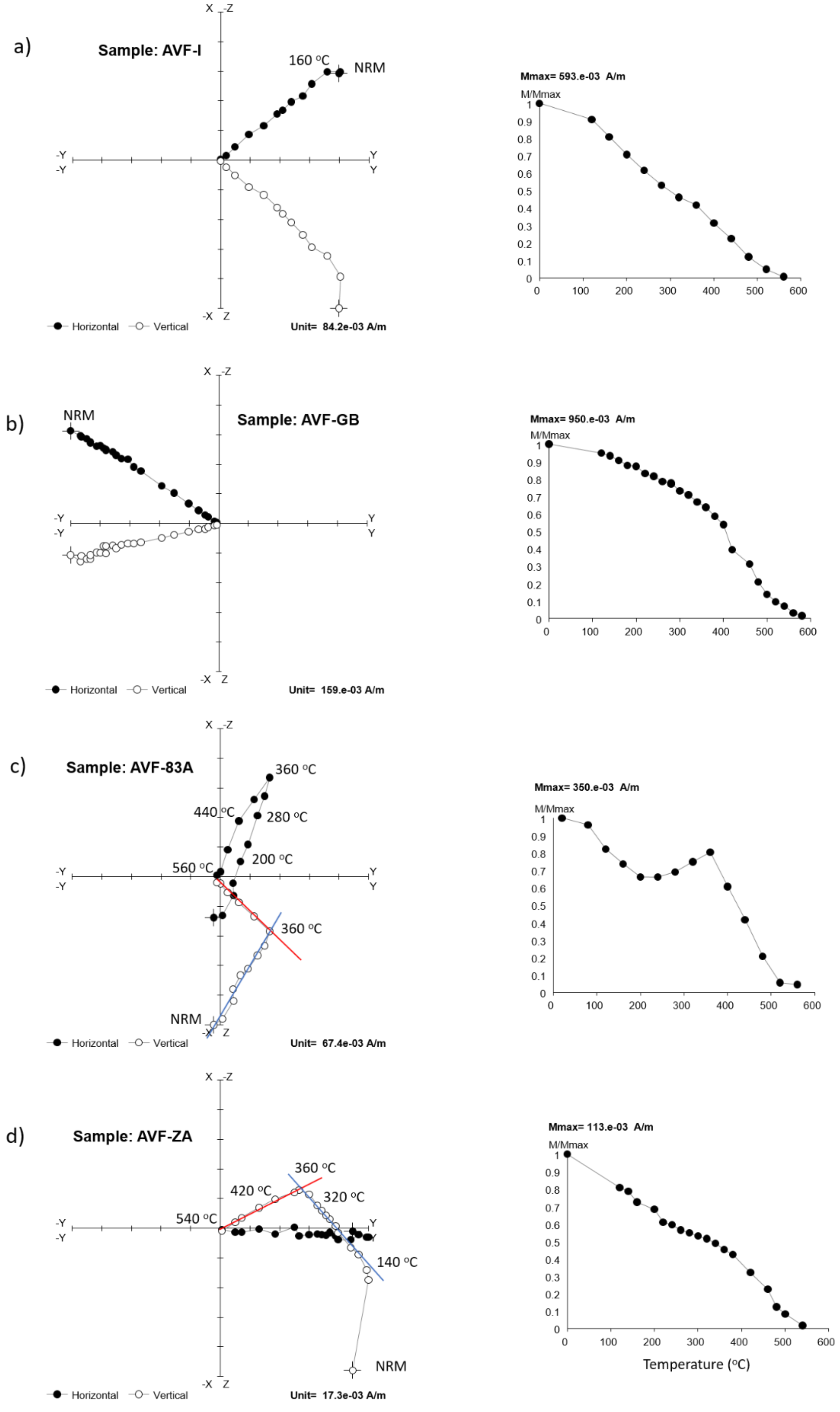
a)
Sample: AVF-I
160 °C
NRM
Horizontal
Vertical
Unit= 84.2e-03 A/m
Mmax= 593.e-03 A/m
M/Mmax
b)
Sample: AVF-GB
NRM
Unit= 159.e-03 A/m
Mmax= 950.e-03 A/m
c)
Sample: AVF-83A
360 °C
440 °C
280 °C
200 °C
560 °C
360 °C
NRM
Unit= 67.4e-03 A/m
Mmax= 350.e-03 A/m
d)
Sample: AVF-ZA
360 °C
420 °C
320 °C
540 °C
140 °C
NRM
Unit= 17.3e-03 A/m
Mmax= 113.e-03 A/m
Temperature (°C)

Fig. 7