Is it possible to identify temporal differences among combustion features in middle palaeolithic palimpsests? The archaeomagnetic evidence: a case study from level O at the Abric Romaní rock-shelter (Capellades, Spain).

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Abstract

Archaeomagnetic dating is probably one of the most known applications of magnetic methods to archaeology but there are others still underutilized and of particular interest to Palaeolithic archaeology. Here, we report a novel application of archaeomagnetism as a technique to determine temporal diachronies among combustion features from the same surface within palaeolithic palimpsests. The approach is based on the subtle directional changes of the Earth´s magnetic field through time (secular variation, SV) and on the ability of burned materials to record such variations under certain conditions. Three middle palaeolithic hearths from level O (ca. 55 ka BP) at the Abric Romaní rock-shelter (NE Spain), were archaeomagnetically investigated. The studied surface (black homogeneous carbonaceous facies), recorded the magnetic enhancement produced by fire with a tenfold increase in concentration-dependent magnetic parameters in the uppermost centimetre with respect to its unburned or deeper counterparts. Pseudo-single domain (PSD) Ti-low titanomagnetite was identified as the main remanence carrier. The irreversibility of thermomagnetic curves suggests that these samples did not undergo enough high temperatures as to record a full thermoremanence (TRM). Additionally, the occasional occurrence of maghaemitized magnetite is interpreted as an indication of a thermochemical remanent magnetization

(TCRM), making these samples unsuitable for absolute palaeointensity determinations. Two well-defined (α95 < 5º) and statistically indistinguishable archaeomagnetic directions were obtained with their mean directions within their respective confidences circles at the 95 % level. The lack of directional changes and the similarity in the magnetic properties suggest that these hearths recorded simultaneously or closely confined in time the Earth´s magnetic field direction at the time of cooling. These results agree well with archaeological evidence which indicates a synchronic occupation of this activity area. The possibility of determining temporal differences among combustion features in prehistoric sites arises as a promising tool in palimpsest dissection studies and may help to reconstruct occupation patterns of prehistoric groups. The practical limits of the method are discussed as well as its potential to identify post-depositional mechanical alteration processes.

Keywords: archaeomagnetism, diachrony, hearth, middle Palaeolithic, Neanderthals, secular variation.

1. Introduction

One of the major topics in current archaeological research focuses on palimpsest dissection in Middle Palaeolithic sites. Understanding the way in which Neanderthal groups organised their living space in caves and rock-shelters largely depends on defining precisely the spatial and temporal relationships of artifacts, ecofacts and other features (Henry 2012). Middle Palaeolithic palimpsests usually consist of occupational surfaces with multiple combustion structures, densely stratified, often partially overlapping and containing many lithic and faunal remains defining domestic activity areas (Vaquero and Pastó 2001; Bailey 2007, Henry 2012). Their degree of complexity is variable depending on the number, type and size of remains as well as their spatial distribution (Bailey 2007). However, the key issue is the difficulty to isolate and quantify individual episodes of activity preserved in these occupational surfaces and establish temporary relationships between them.

Beyond the variety of natural or cultural processes involved in the formation of palimpsests (see Henry 2012), multiple post-depositional processes may act distorting and even destroying the archaeological record. This complicates the interpretation of the timing and use of these hearth-related assemblages resulting in the so-called “palimpsest problem” (e.g. Bailey 2007; Henry 2012; Machado et al. 2013, 2015). Over recent years, dissection of palimpsests is being performed through combined analysis of raw material units (RMUs), faunal and lithic refits, archaeostratigraphy, tooth microwear analysis (e.g. Machado et al. 2013, 2015; Chacón et al. 2015; Rivals et al. 2009a; Vaquero et al. 2015) and high resolution geoarchaeological techniques such as soil micromorphology, FTIR, etc. (e.g. Miller et al. 2013; Mallol et al. 2013; Cabanes et al. 2010). These approaches are providing valuable information to reconstruct site formation processes and the dynamics of occupation of Mousterian groups.

The interpretation of these contexts especially through spatial analysis requires excavation areas wide enough to cover spatial variability. The study of spatial arrangement of hearths, lithic and faunal remains has revealed how Neanderthals' use of space and hearth function changed through time. This has been shown by the studies carried out at different levels in the Abric Romaní rock-shelter, NE Spain (e.g.: Pastó et al. 2000; Vallverdú et al. 2005, 2010; Vaquero et al. 2004, 2012a,b; Rosell et al. 2012a,b) and other middle Palaeolithic sites such as Tor Faraj (Henry 2012) or Payre (Moncel et al. 2007; Rivals et al. 2009a), among others.

Some activities as lithic tool recycling by later occupations also imply time which needs to be determined (Vaquero et al. 2004, 2015; Machado et al. 2015). In the field one usually observe an amalgam of overlapping elements difficult to differentiate both at the spatial and temporal scale. They may appear contemporaneous based on macroscopic field observations but may also represent multiple "short-term" occupations (e.g. Vallverdú et al. 2005; Rivals et al. 2009a; Machado et al. 2013;Sánchez-Hernández et al. 2014) or alternatively, longer ones (e.g. Thiébaut et al. 2009; Rivals et al. 2009b; Vaquero et al. 2012a). Establishing the contemporaneity among material remains and hearths is a difficult task and much of the problem lies in the degree of resolution of the techniques available. Therefore, exploring methodological options which can be used as temporal markers using single occupation episodes as the basic analytical unit (Machado et al. 2015; Chacón et al. 2015) and determine their degree of contemporaneity are main goals in palimpsest research.

Here, we report an application of archaeomagnetism as a technique to determine whether different hearths exposed on a living floor were burned in the same moment or conversely, were separated in time (synchronous *vs.* diachronous). Our hypothesis is that if several mean archaeomagnetic directions are obtained from various hearths from the same surface and they are different (statistically distinguishable), it could be assumed that they were carried out in temporally distinct moments being therefore not synchronous. This information is of great value to reconstruct the occupation patterns of

Neanderthal groups and it has been tested studying several hearths from level O (ca. 55 ka BP) at the Abríc Romaní rock-shelter. The technique also allows assessing mechanical post-depositional alteration processes in cave fires (Carrancho et al. 2012), so their primary position is also evaluated as a tool to study living floor´s integrity. The archaeological implications and limits of the method are discussed.

2. Materials and methods

2.1 Abric Romaní rockshelter. Sampled materials

The Abric Romaní site (41º 32´ N; 1º 41´ E; 280 m above sea level) is located in the town of Capellades, 50 km west of Barcelona, NE Spain (Fig. 1a-b). The site is rockshelter opened in a travertine cliff called "Cinglera del Capelló", in a karst landscape at the west bank of the Anoia river. The stratigraphic sequence consists of 20 m of well-stratified travertine platforms dated by U-series and radiocarbon analysis to between 40 and 70 ka BP (Vaquero et al. 2013). The archaeological levels (at least 25) appear interbedded between the travertine platforms and correspond to periods of low or no water inside the rock shelter. Except level A which belongs to the Aurignacian, all of the archaeological units correspond to the Middle Palaeolithic and fifteen levels (from level B to P) have been excavated (Fig. 1c).

The site is particularly suited for palimpsest dissection analyses for its multidisciplinary excavation methodology and because is a sedimentary context of high-resolution. The mean sedimentation rate for the entire sequence is estimated around 0.6 cm/yr (Bischoff et al. 1988). The Abric Romaní has an outstanding archaeological record with thousands of lithic artefacts, faunal and palaeobotanical remains and even wood implements (Carbonell and Castro-Curel, 1995). However, the site is particularly known for being a key site to study prehistoric fire with almost 200 combustion activity areas excavated (Vallverdú et al. 2010). Every combustion activity area is recorded following a detailed field-based description (see Vallverdú et al. 2012). It comprises sedimentary facies analyses including measurements of geometry, size and thickness of every combustion feature. *In situ* combustion structures are identified by rubified sediment overlain by mixtures of carbonaceous and ash facies. Carbonaceous facies are carbon-rich sediments which are classified as "heterogeneous" if unburned and burned sedimentary components are mixed or as "homogeneous" if the matrix exhibits uniform thermal modification with > 40 % in charcoal content (Vallverdú et al. 2012)

The hearths studied here correspond to level O dated by means of U-series at around 55 ka BP (Bischoff et al., 1988; Vaquero et al., 2013). It was excavated between 2004 and 2011 over an area of about 271 m^2 with almost thirty combustion structures identified (Gabucio et al. 2014; Fig. 2). Most of them are simple and flat although some display concave or basin-like forms. This study focused on the domestic activity area O10 (grid squares UW/51-53; Fig. 3), a hearth-related assemblage with a dense concentration of lithic and faunal remains, many of them with evidences of calcination (Chacón et al. 2015; Gabucio et al. 2014). At the time of sampling, a dark homogeneous carbonaceous surface (~ 3 m length) and amorphous geometry was observed. According to field observations, at least three different combustion focuses were distinguished by the archaeologists. Following their guidelines, three oriented hand-blocks were collected using Plaster of Paris from each one of the three combustion focuses. In the lab, the hand-blocks were consolidated in Ethyl silicate and left to dry during 4 weeks and subsequently subsampled taking special care of sample depth. A total of 50 cubic (10 cm^3) specimens were obtained (Table 1).

2.2. Methods

All palaeomagnetic and rock-magnetic analysis were carried out at the laboratory of Palaeomagnetism of Burgos University (Spain). The natural remanent magnetization (NRM) was measured using a 2G SQUID magnetometer (noise level 5×10^{-12} Am^2). Low-field susceptibility was measured with a KLY-4 Kappabridge (AGICO, noise level 3×10^{-8} S.I.) at room temperature initially and after each thermal demagnetization step to monitor possible magneto-chemical alterations. The NRM directional stability was analysed by stepwise progressive alternating field (AF) and thermal (TH) demagnetization. AF demagnetization was performed in 23 steps up to a maximum peak field of 100 mT with the 2G magnetometer AF demagnetization unit. TH demagnetization was carried out in 15 steps up to 585 ºC with a TD48-SC (ASC) thermal demagnetizer. Characteristic Remanent magnetization (ChRM) directions were calculated by linear regression of the component that linearly converges towards the origin of the orthogonal NRM demagnetization plots using the Remasoft software (Chadima et al 2006). Mean directions and associated statistical parameters were calculated using Fisher´s (1953) statistics.

In addition, different rock-magnetic analyses were carried out in order to identify the main remanence carriers and their domain structure. By using a Variable Field Translation Balance (MM_VFTB) progressive isothermal remanent magnetization (IRM) acquisition curves, hysteresis loops (± 1 T), backfield coercivity curves and thermomagnetic curves up to 700 ºC in air were performed on representative sample (~ 450 mg) for each hearth. Curie point determination was done following the two-tangent method of Grommé et al. (1969) and hysteresis parameters –corrected for the dia/paramagnetic contribution– were calculated using the RockMag Analyzer software (Leonhardt 2006).

3. Results

3.1. Magnetic properties

The content of ferromagnetic minerals (*s.l.*) among the studied samples is rather variable. Many samples are characterized by noisy diagrams whereas others –mostly restricted to the uppermost cm- are sufficiently interpretable as to characterize their magnetic properties. Fig. 4(a-c) illustrates some representative examples of thermomagnetic curves, all corresponding to samples from the 1st upper cm. The intensity of magnetization varies up to 2 orders of magnitude and all curves show irreversible behaviour. All heating curves contain a phase with a Curie point (T_C) estimated between 530 ºC and 580 ºC indicating that Ti-low titanomagnetite is the main magnetization carrier (Fig. 4a-c). Occasionally, a phase with T_C extending to 600 – 610 ºC was also identified (Fig. 4a), which might be related with slightly oxidized magnetite (magnetite partially maghaemitized). Some samples also display inflections in the range of 350 – 370 ºC (Fig. 4a), probably due to maghaemite inverting to less magnetic haematite during heating or a highly isomorphous substituted spinel phase. The occurrence of ferromagnetic sulphides cannot be ruled out but, to the best of our knowledge, is very rare in burned archaeological materials. In other cases, an increase in magnetization is observed from 360 ºC indicating the creation of magnetite probably from the transformation of some paramagnetic mineral (Fig. 4b). Moreover, secondary magnetite is also created as revealed by the increase in magnetization in most cooling curves (Fig. 4a-b). Overall, these results indicate that most of these samples did not experience heating temperatures as high as those used in this experiment (700 ºC). Otherwise, they would be much more reversible.

IRM progressive acquisition curves (not shown here) are almost saturated around ~ 150 – 200 mT, indicating that the remanence is carried by a low-coercivity ferromagnetic mineral. Hysteresis measurements revealed that the samples are characterized by low coercive fields (Bc = 5.5 - 14.25 mT). The remanent coercivities (Bcr), determined separately from the backfield curves, vary between 18 and 40 mT. Hysteresis ratios range from $0.10 < M\mathrm{rs}/M\mathrm{s} < 0.21$ and $2.20 < B\mathrm{cr}/B\mathrm{c} < 3.80$ which according to Dunlop (2002) theoretical mixing lines indicates the dominance of pseudo-single domain (PSD) magnetite particles (Fig. 5).

In order to study the variation of magnetic properties in depth, one of these hearths (GV4) was subsampled every cm (Fig. 6). The intensity of magnetization decreases almost an order of magnitude below the uppermost cm as shown in the thermomagnetic curves (Fig. 6a-c-e) and their corresponding hysteresis loops (Fig. 6b-d-f). This indicates that the 1st cm was the most heated and below that depth, the samples are noisier and magnetically weaker. This would be in accordance with the colour variation from blackish at the top to yellowish at the base. A three point smoothing was applied to the thermomagnetic curves in order to make them more amenable to interpretation. A single phase with a T_C of around 585 – 600 ºC was observed pointing to Ti-low titanomagnetite as the main carrier showing traces of maghaemitization.

3.2 Archaeomagnetic directions

Initial natural remanent magnetization (NRM) values range from 6.03×10^{-6} to 6.78×10^{-8} Am^{2}kg^{-1} whereas magnetic susceptibility (MS) oscillates between 2.08×10^{-8} and -3.09×10^{-9} m^{3}kg^{-1}. 38 % of samples showed initial diamagnetic (negative) MS values, indicating that the concentration of ferromagnetic minerals is poor. The highest values for both parameters correspond to the uppermost (1st cm) superficial samples in agreement with the results observed in the micro-profile in depth (Fig. 6).

The NRM stability of the studied samples is quite reproducible among samples from the GV3 and GV4 hearths. However, GV2 samples exhibited anomalous behaviours as explained below. After removal of a small secondary component (< 15 mT or 250 ºC), AF demagnetization diagrams are mostly defined by a stable single component of normal polarity almost demagnetized at 100 mT (Fig. 7a-c). In the case of TH demagnetization, the ChRM direction was determined between 250 – 300 ºC and 585 ºC

(Fig. 7b-d). In contrast, samples from GV2 hearth are very heterogeneous. Some specimens show a univectorial and stable normal polarity component (Fig. 8a) while others display multicomponent structure of magnetization with anomalous directions (Fig. 8c-d). Most likely, this behaviour reflects some type of mechanical reworking of the sediment after burning. The mean archaeomagnetic directions determined from each hearth and their corresponding associated statistics are shown in Fig. 9 and Table I, respectively.

4. Discussion

The purpose of this study is not the use of archaeomagnetism as dating method. Standard archaeomagnetic dating requires of regional secular variation curves (SVCs) composed of well-dated and high-quality (TRM) data describing the Earth´s magnetic field variations through time. Dating is obtained by comparing the direction and/or intensity determined from an archaeological site with the SVC available for the territory and period concerned. In Europe for example, most SVCs “only” cover the last 2-3 millennia (e.g. Gallet et al. 2002; Schnepp and Lanos 2005; Gómez-Paccard et al. 2006; Tema et al. 2006; Zananiri et al. 2007) and exceptionally some records reach the last 8 ky (Kovacheva et al. 2014; Tema and Kondopoulou 2011, Carrancho et al. 2013). However, we are dealing here with mid-Palaeolithic hearths of ~ 55 ky and there is not any SV record for this chronology. Our approach is based on the comparison of the mean archaeomagnetic directions obtained from different hearths exposed in the same archaeological surface. If these fireplaces were burned at different times (enough time to distinguish directional variations of magnetic north -order of decades or more-), different or statistically distinguishable mean directions should be recorded providing empirical evidence of diachrony. The interpretation is not so straightforward since several factors come into play. The age of these hearths is within the normal polarity Bruhnes Chron (last ~780 ka), so all *in situ* samples should display northward directions. This means that comparison between directions is based on small (few degrees) directional changes. Accuracy in sampling orientation and lab analysis is important as errors may imply significant scatter and high statistical uncertainties. Sometimes is the intrinsic samples’ behaviour which prevents a proper interpretation either by difficulties isolating the ChRM direction or due to mineralogical alterations. Available SV records for the last millennia for mid latitudes as the Iberian Peninsula (Gómez-Paccard et al. 2006), show that magnetic declination fluctuates within a dispersion range of approximately ± 20º of the present field and inclination between 40º to 65º in an chaotic, not predefined pattern and more importantly, with varying SV rates. That is, the field varies rapidly at certain times and slowly in others. We are aware that it is tempting for archaeologists to look for evidence of temporal differences between multiple combustion features from the same surface. However, for the given reasons, the comparison of different mean directions from the same occupational surface cannot be directly interpreted in terms of duration.

The studied fireplaces all show similar magnetic properties with PSD Ti-low titanomagnetite as main remanence carrier. NRM intensities are quite variable with the highest values constrained to the uppermost cm. It should be kept in mind that the original substrate where the hearths were carried out was travertine, mostly composed of carbonates and very poor in ferromagnetic (*s.l.*) minerals. That explains why below the 1st cm -the most heated part- the magnetic signal is weak with noisy diagrams due to a dominant diamagnetic behaviour. Two out of the three studied hearths have yielded well-defined geomagnetic field directions, with good statistical parameters ($\alpha95 < 5º$) and low scatter in the stereograms (Fig. 9 and Table 1). Samples from GV3-4 hearths displayed a stable, normal polarity ChRM component indicating that they successfully recorded the Earth´s magnetic field direction at the time of cooling. On the contrary, some type of mechanical disturbance (e.g. trampling, bioturbation) affected GV2 hearth after burning since most of its samples exhibit multicomponent NRM behaviour and anomalous directions. The usefulness of the palaeomagnetic technique to assess post-depositional alteration processes in cave fires has already been demonstrated (Carrancho et al. 2012).

Ideally, archaeomagnetic studies are carried out on *in situ*, well-heated archaeological materials carrying a thermal remanent magnetization (TRM). TRM is by far the most efficient recording mechanism of geomagnetic field variations. However, if the material does not reach temperatures high enough to record a full TRM (e.g. > 580 °C, magnetite *Tc*; Dunlop and Özdemir, 1997) or reheatings at mild temperatures occur, a partial thermoremanent magnetization (pTRM) might be recorded partially overlapping the original magnetization. The pTRM would record the Earth´s magnetic field direction of the last heating, but we did not find evidence of it here. Alternatively, mineralogical alterations as phase changes or grain growths may also imply the acquisition of secondary magnetizations. Such changes may occur simultaneously to the cooling process resulting in a thermochemical remanent magnetization (TCRM) or time after burning through weathering or analogous processes, resulting in a chemical remanent magnetization (CRM). Both are difficult to discriminate but the key question is whether the direction recorded is actually representative of the Earth´s magnetic field at the time of cooling (TRM or TCRM) or in contrast, was acquired at a later time (CRM).

The irreversibility of thermomagnetic curves indicates that the samples are not physically and chemically stabilized because they alter during laboratory heating up to 700 ºC. This suggests that they did not reach high temperatures as to record a full TRM. In principle, this would contradict taphonomic results that indicate evidences of calcination in most bone remains from this area (O10) (Gabucio et al. 2014). Temperatures over 600 ºC are required to achieve bone calcination according to experimental evidence (Shipman et al. 1984; Mentzer 2009; Théry-Parissot 2002). The archaeomagnetic samples come from the black homogeneous carbonaceous facies which was in process of excavation when samples were collected. Gabucio et al. (2014) suggested that bones were used as fuel and possibly it might have produced ashes that at the time of sampling were already removed. In any case, thermomagnetic results do not support high temperature heatings in this carbonaceous facies.

The lack of directional changes among samples from GV3-4 hearths along with a remarkable similarity in magnetic properties, suggests that the remanence-carrying minerals formed simultaneously recording the Earth´s magnetic field direction at the time of cooling. Apart from showing stable and univectorial NRM demagnetization plots, these samples display a tenfold increase in NRM intensities in comparison with their unburned (or deeper) counterparts. This reinforces the idea that the NRM is a TCRM. The occasional occurrence of maghaemitized magnetite is suggestive of oxidation, equally implying a chemical or thermochemical NRM origin depending on when it took place. The difficulty of proving which one is responsible of the remanence is the underlying problem. Optical and/or electron microscopy analysis might be useful to this matter and it will be the scope of an upcoming paper. It is generally accepted that CRM due to maghaemitization of SD-size (or small PSD) titanomagnetite grains appears to parallel the original TRM (Dunlop and Özdemir 1997). In contrast, in larger (MD) grains or when the mineral comes from a multiphase oxidation reaction (e.g.

intergrown of maghaemite-haematite particles) the field acting during oxidation may influence the CRM direction either deviating from the primary direction or lying in an intermediate direction of no palaeomagnetic significance (Dunlop and Özdemir 1997 and references therein). Given the directional and rock magnetic results obtained that is not our case. If burning and oxidation are closely confined in time, which is likely in natural materials as cave fires (e.g.: Carrancho et al. 2009; Kapper et al. 2014), the interpretation of directions would be valid because of the thermochemical nature of the NRM. Since the TCRM is acquired during initial cooling, directional fidelity is out of doubt (Dunlop and Özdemir 1997) but not so the intensity. One of the prerequisites for absolute paleointensity determinations is that the primary magnetization must be a TRM. Therefore, these materials are not suitable to that aim.

Further evidence on the possibility of a TCRM record was demonstrated in an experimental hearth recreation under controlled field and temperature conditions (Carrancho and Villalaín, 2011; Calvo et al. 2012). Different mechanisms of magnetization were simultaneously recorded depending on the temperatures achieved on surface: TCRM in the periphery (~ 300 ºC) *vs.* a TRM in the centre of the hearth (> 600 ºC). Interestingly, both types of samples showed univectorial NRM demagnetization plots, reproducible directions between them and similar unblocking desmagnetization spectra as those obtained here.

Here, very similar directions were obtained for GV3 and GV4 hearths (Table 1) with their mean directions within their respective error ellipses at 95 % confidence level (Fig. 10). This implies that both directions are statistically undistinguishable pointing out that they are synchronous or were burned in a short time interval. At this point caution should be regarded because, strictly speaking, synchrony is very difficult to prove if not impossible. First, because of the difficulties to determine the NRM mechanism as discussed above; second, because SV is a repetitive looping motion through time defining ribbons often overlapping previous segments of the curve, resulting in directions repeated at different times. This means that it is possible to obtain similar directions corresponding to different times. This ribbonlike nature of SVCs is visible in all available records from Europe and elsewhere and it occurs on scales ranging from decades to centuries (e.g. Gallet et al. 2002; Schnepp and Lanos 2005; Gómez-Paccard et al. 2006; Tema et al. 2006; Zananiri et al. 2007; Hagstrum and Blinman 2010;

Lengyel et al. 2011). It is unlikely, however, that these hearths were reused in time intervals separated for example by centuries. Unfortunately, the lack of chronological resolution required (at a year timescale), prevents to verify it. What is beyond doubt is that they are not clearly diachronic because even accepting the possibility of a CRM acquired time after the last heating (rock-mag data point out to a TCRM), the direction is so similar that magnetization recording had to occur simultaneously or closely confined in time.

The strongest argument in this regard is possibly provided by the archaeological evidence which according to faunal and lithic refits, archaeostratigraphic projections and tooth wear analysis (Chacón et al. 2015; Gabucio et al. 2014) suggest a synchronic occupation. It is true, however, that the existence of an interstratified unburned level in the 010 area also indicates diachrony (Chacón et al. 2015), but our samples correspond to a single surface not related with this interstratified level. Taken together, it is the sum of all evidence, including the magnetic one, which points out to the contemporaneity of these hearths. In a similar case study, Sternberg and Lass (1997) obtained two mean directions 15.6º apart, from two mid-palaeolithic hearths from unit XIII in Kebara cave, Israel. Assuming a SV rate of 0.05 – 0.15º yr^{-1} by comparison with the American Southwest, they inferred a temporal difference between both hearths of 100 – 310 yr. Such degree of resolution is promising considering that both directions are significantly different from each other, but caution should be regarded inferring temporal differences because of the variable rate of SV. Moreover, a CRM origin of the NRM could not be completely discarded in that case. A similar result to our study is that of Eighmy and Hathaway (1987), who compared different data sets with mean directions less than five degrees apart and substantial overlapping ranges in polar projections, concluding that differences less than 50 to 100 years (depending on the rate of directional change) cannot be confidently established. Such precision is difficult to achieve and in this study, the angular distance between both means (2.1º) plus their respective α_{95} is 9.9º, which is similar. Even with the very acceptable statistic obtained we are in the practical limits of the method and it does not support establishing short term temporal inferences of less than a few decades.

Taphonomic and spatial patterning analyses carried out at Abric Romaní indicate that post-depositional alterations are not common at area O10 (Chacón et al. 2015).

However, it does not exclude that localized processes such as for example trampling, might have locally disturbed this facies after heating as the anomalous results from the GV2 hearth indicate. On the contrary, GV3-4 hearths preserve their original position in spite of coming from the same burned surface as GV2. This means that post-depositional reworking (not identified macroscopically in the field) affected only partially to this surface without compromising the integrity of the archaeological record.

To sum up, Palaeolithic palimpsest studies have reached maturity thanks in part to the advent of new methodological approaches to which archaeomagnetism should be now integrated. It has been demonstrated how archaeomagnetism may help to identify (or reject) diachronic occupations from the record of the ancient Earth´s magnetic field direction on burned features. Even with its limitations, identifying temporal distinctions (diachrony) is always of high value in palimpsest dissection and is a promising tool to reconstruct ancient Neanderthal settlement patterns.

5. Conclusions

The archaeomagnetic and rock-magnetic study carried out on three middle palaeolithic hearths from the Abric Romaní rock-shelter (Level O; ca. 55 ka BP) lead to the following conclusions:

- The studied surface (black homogeneous carbonaceous facies), recorded the magnetic enhancement produced by fire with a tenfold increase in NRM intensity in the uppermost centimeter, with respect to its unburned or deeper counterparts. PSD Ti-low titanomagnetite was identified as the main remanence carrier. The lack of reversibility of thermomagnetic curves suggests that the samples did not reach high temperatures as to record a full TRM. The occasional occurrence of maghaemitized magnetite points out to a thermochemical remanent magnetization (TCRM), although a CRM cannot be completely ruled out. On the basis of the directional and rock magnetic data obtained we interpreted the remanence as a TCRM acquired upon cooling, so directional fidelity is out of doubt.

-Two well-defined ($\alpha95 < 5º$) and statistically indistinguishable archaeomagnetic directions were obtained with their mean directions within their respective error ellipses at the 95% confidence level. The lack of directional changes and the similarity in the magnetic properties suggest that these hearths recorded simultaneously the Earth´s magnetic field direction at the time of cooling. Synchrony cannot be empirically demonstrated but the directions obtained are so similar that they do not indicate diachrony, in agreement with archaeological evidence.

- Some type of mechanical post-depositional alteration process not previously identified in the field, reworked one the hearths studied (GV2) after burning. It was identified by unstable, multicomponent NRM demagnetization plots and anomalous directions in most of its samples.

- The variable rate of change of SV and the practical limit of the method itself do not support establishing short term temporal inferences on duration between burning episodes (less than few decades). Archaeomagnetic data combined with archaeological information may help to evaluate the degree of contemporaneity (within the limits discussed) and reconstruct occupation patterns of prehistoric groups in palimpsests.

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References

Bailey, G., 2007. Time perspectives, palimpsests and the archaeology of time. Journal of Anthropological Archaeology 26, 198-223.

Bischoff, J., Julià, R., Mora, R., 1988. Uranium-series dating of the Mousterian occupation at the Abric Romani, Spain. Nature 332, 68–70.

Blunier, T., Brook, E.J., 2001. Timing of millennial-scale climate change in antarctica and greenland during the last glacial period. Science 291, 109-112.

Cabanes, D., Mallol, C., Expósito, I., and Baena, J., 2010. Phytolith Evidence for hearths and Beds in the late Mousterian occupations of Esquilleu cave (Cantabria, Spain). Journal of Archaeological Science 37, 2947-2957

Calvo-Rathert, M., Carrancho, Á., Stark, F., Villalaín, J.J., Hill M., 2012. Are burnt sediments reliable recorders of geomagnetic field strength? Quaternary Research, 77, 326–330.

Carbonell, E., and Castro-Curel, Z., 1992. Palaeolithic Wooden Artefacts from the Abric Romaní (Capellades, Barcelona, Spain). Journal of Archaeological Science 19 (6), 707-719.

Carrancho, A., Villalaín, J., Angelucci, D., Dekkers, M., Vallverdú, J. and Vergès, J.M., 2009. Rock-magnetic analyses as a tool to investigate archaeological fired sediments: a case study of Mirador cave (Sierra de Atapuerca, Spain). Geophysical Journal International, 179, 79–96

Carrancho, Á. and Villalaín, J.J., 2011. Different mechanisms of magnetisation recorded in experimental fires: Archaeomagnetic implications. Earth and Planetary Science Letters 312, 176-187.

Carrancho, Á., Villalaín, J.J., Vergès, J.M., Vallverdú, J., 2012. Assessing postdepositional processes in archaeological cave fires through the analysis of archaeomagnetic vectors. Quaternary International 275, 14-22.

Carrancho, Á., Villalaín, J.J., Pavón-Carrasco, F.J., Osete, M.L., Straus, L.G., Vergès, J.M., Carretero, J.,M., Angelucci; D.E., González Morales, M.R., Arsuaga, J.L., Bermúdez de Castro, J.M., Carbonell, E., 2013. First directional European palaeosecular variation curve for the Neolithic based on archaeomagnetic data. Earth and Planetary Science Letters 380, 124 – 137.

Chacón, M.G., Bargalló, A., Gabucio, M.J., Rivals, F. and Vaquero, M., 2015. Neanderthal Behaviors from a Spatio-Temporal Perspective: An Interdisciplinary Approach to Interpret Archaeological Assemblages. In: Conard, N. J., Delagnes, A. (Eds.), Settlement Dynamics of the Middle Paleolithic and Middle Stone Age, Vol. IV. Tübingen Publications in Prehistory. Kerns Verlag, pp. 253-294.

Chadima, M. and Hrouda, F., 2006. Remasoft 3.0 a user-friendly palaeomagnetic databrowser and analyser. Travaux Geophysiques XXVII, 20–21.

Day, R., Fuller, M., Schmidt, V.A., 1977. Hysteresis properties of titanomagnetites - grain size and compositional dependence. Physics of the Earth and Planetary Interiors 13, 260-267.

Dunlop, D.J., 2002. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc). 2. Application to data for rocks, sediments, and soils. Journal of Geophysical Research 107 (B3), 1-15. doi:10.1029/2001JB000486

Dunlop, D., Özdemir, Ö., 1997. Rock Magnetism. Fundamentals and Frontiers. Cambridge Univ. Press, New York. 573 pp.

Eighmy, J.L., Hathaway, J.H., 1987. Contemporary Archaeomagnetic Results and the Accuracy of Archaeomagnetic Dates. Geoarchaeology 2(1): 49-61.

Fisher, R., 1953. Dispersion on a sphere. Proceedings Royal Society London A 217, 295-305.

Gabucio, M. J., Cáceres, I., Rosell, J., Saladié, P., and Vallverdú. J., 2014. From small bone fragments to neanderthal activity areas: the case of Level O of the Abric Romaní (Capellades, Barcelona, Spain). Quaternary International 330, 36-51.

Gallet, Y., Genevey, A., LeGoff, M., 2002.Three millennia of directional variation of the Earth's magnetic field in Western Europe as revealed by archaeological artefacts. Physics of the Earth and Planetary Interiors. 131, 81–89.

Gómez-Paccard, M., Chauvin, A., Lanos, P., McIntosh, G., Osete, M.L., Catanzariti, G., Ruiz-Martinez, V.C., Núñez, J.I., 2006. First archaeomagnetic secular variation curve for the Iberian Peninsula: comparison with other data from Western Europe and with global geomagnetic field models. Geochemistry, Geophysics, Geosystems, 7, Q12001. doi:10.1029/2006GC001476.

Grommé, C.S., Wright ,T.L., and Peck, D.L., 1969. Magnetic properties and oxidation of iron-titanium oxide minerals in Alae and Makaopuhi lava lakes, Hawaii. J. Geophys. Res., 74, 5277-5294.

Hagstrum, J.T., Blinman, E., 2010. Archeomagnetic dating in western North America: An updated reference curve based on paleomagnetic and archeomagnetic data sets. Geochemistry, Geophysics, Geosystems 11 (6), Q06009.

Henry, D.O., 2012. The palimpsest problem, hearth pattern analysis, and Middle Paleolithic site structure. Quaternary International 247, 246-266.

Kapper, K., Anesin, D., Donadini, F., Angelucci, D., Cavulli, F., Pedrotti, A. and Hirt, A., 2014. Linking site formation processes tomagnetic properties. Rock- and archaeomagnetic analysis of the combustion levels at Riparo Gaban (Italy). Journal of Archaeological Science, 41, 836–855.

Kovacheva, M., Kostadinova-Avramova, M., Jordanova, N., Lanos, P., Boyadzhiev, Y., 2014. Extended and revised archaeomagnetic database and secular variation curves from Bulgaria for the last eight millennia. Physics of the Earth and Planetary Interiors 236, 79-94.

Lengyel, S.N., Eighmy, J.L., Van Buren, M., 2011. Archaeomagnetic research in the Andean highlands. Journal of Archaeological Science 38, 147-155.

Leonhardt, R., 2006, Analyzing rock magnetic measurements: The RockMagAnalyzer 1.0 software. Computers & Geosciences, 32, 1420–1431.

Machado, J., Hernández, C.M., Mallol, C. and Galván, B., 2013. Lithic Production, Site Formation and Middle Palaeolithic Palimpsest Analysis: In Search of Human occupation Episodes at Abric del Pastor Stratigraphic unit IV (Alicante, Spain). Journal of Archaeological Science 40 (5): 2254-2273.

Machado, J., Mallol, C., and Hernández, C.M., 2015. Insights into Eurasian Middle Paleolithic Settlement Dynamics: The Palimpsest Problem. . In: Conard, N. J., Delagnes, A. (Eds.), Settlement Dynamics of the Middle Paleolithic and Middle Stone Age, Vol. IV. Tübingen Publications in Prehistory. Kerns Verlag, pp. 361-382 .

Mallol, C., Hernández, C.M., Cabanes, D., Sistiaga, A., Machado, J., Rodríguez, Á., Pérez, L. and Galván, B., 2013. The Black layer of Middle Palaeolithic combustion Structures. Interpretation and Archaeostratigraphic Implications. Journal of Archaeological Science 20, 2515-2537.

Miller, C. E., Goldberg, P. and Berna, F., 2013. Geoarchaeological investigations at Diepkloof rock Shelter, western cape, South Africa. Journal of Archaeological Science 40: 3432-3452

Mentzer, S. M., 2009. Bone as a fuel source: The effects of initial fragment size distribution. In I. Théry-Parisot, S. Costamagno, & A. Henry (Eds.), Gestion des Combustibles au Paleolithique et au Mesolithique: Nouveaux Outiles, Nouvelles Interpretations. UISPP Proceedings of the XV World Congress (Lisbon, 4–9 September 2006) (pp. 53–64). Oxford: Archaeopress (British Archaeological Reports International Series 1914).

Moncel, M. H., Chacón, M.G., Bouteaux, A., Julien, M.-A. and Patou-Mathis, M., 2007. Ocupación en abrigo durante el estadio isotópico 5: El nivel d del yacimiento de Payre (Ardèche, Francia). Gestión del territorio y actividades dentro del yacimiento. Trabajos de Prehistoria 64: 65-86.

Pastó, I., Allué, E., and Vallverdú, J. 2000. Mousterian hearths at Abric Romaní, Catalonia (Spain). In C. B. Stringer, R. N. E. Barton, & J. C. Finlayson (Eds.), Neanderthals on the edge: Papers from a conference marking the 150th anniversary of the Forbes' Quarry discovery, Gibraltar (pp. 59–67). Oxford: Oxbow Books.

Rivals, F., Moncel, M.H. and Patou-Mathis, M., 2009a. Seasonality and Intra-Site Variation of neanderthal occupations in the Middle Palaeolithic locality of Payre (Ardèche, France) using dental wear Analyses. Journal of Archaeological Science 36: 1070-78

Rivals, F., Schulz, E. and Kaiser, T.M., 2009b. A new Application of dental wear analyses: Estimation of duration of hominid occupations in Archaeological localities. Journal of Human Evolution 56, 329-39.

Rosell, J., Cáceres, I., Blasco, R., Bennàsar, M., Bravo, P., Campeny, G., Esteban-Nadal, M., Fernández-Laso, M.C., Gabucio, M.J., Huguet, R., Ibáñez, N., Martín, P., Rivals, F., Rodríguez-Hidalgo, A., Saladié, P., 2012a. A zooarchaeological contribution to establish occupational patterns at Level J of Abric Romaní (Barcelona, Spain). Quaternary International 247, 69-84.

Rosell, J., Blasco, R., Fernández-Laso, Mª.C., Vaquero, M. and Carbonell, E., 2012b. Connecting Areas: Faunal refits as a diagnostic Element to Identify Synchronicity in the Abric romaní Archaeological Assemblages. Quaternary International 252: 56-67

Sánchez-Hernández, C., Rivals, F., Blasco, R. and Rosell, J., 2014. Short, but repeated Neanderthal visits to Teixoneres Cave (MIS 3, Barcelona, Spain): a combined analysis of tooth microwear patterns and seasonality. Journal of Archaeological Science 49, 317-325.

Schnepp, E., Lanos, P., 2005, Archaeomagnetic secular variation in Germany during the past 2500 years. Geophysical Journal International 163, 479–90.

Shipman, P., Foster, G.F., Schoeninger, M., 1984. Burnt bones and teeth: an experimental study of colour, morphology, crystal structure and shrinkage. Journal of Archaeological Science 11, 307-325.

Sternberg, R. and Lass, E. H.E., 2007. An archaeomagnetic study of two hearths from Kebara Cave, Israel. In: (Ofer Bar-Yosef and Liliane Meignen, eds.), Kebara Cave, Mt. Carmel, Israel: The Middle and Upper Paleolithic Archaeology, Part I. American School of Prehistoric Research, Bulletin 49, Peabody Museum of Archaeology and Ethnology, Harvard University, Cambridge, 123- 130.

Tema, E., Hedley, I., Lanos, P., 2006. Archaeomagnetism in Italy: a compilation of data including new results and a preliminary Italian secular variation curve. Geophysical Journal International, 167, 1160–71.

Tema, E., Kondopoulou, D., 2011. Secular variation of the Earth's magnetic field in the Balkan region during the last eight millennia based on archaeomagnetic data. Geophysical Journal International 186, 603–614.

Théry-Parisot, I., 2002. Fuel management bone and wood during the lower Aurignacian in the Pataud Rock Shelter Lower Palaeolithic, Les Eyzies de Tayac, Dordogne, France. Contribution of experimentation. Journal of Archaeological Science 29, 1415-1421.

Thiébaut, C, Meignen, L. and Lévêque, F., 2009. Les dernières occupations moustériennes de Saintcésaire (Charente-Maritime, France): Diversité des techniques utilisées et comportements économiques pratiqués. Bulletin de la Société Préhistorique Française 106 (4), 691-714.

Vallverdú, J., Allué, E., Bischoff, J. L., Cáceres, I., Carbonell, E., Cebriá, A., et al., 2005. Short human occupations in the Middle Palaeolithic level I of the Abric Romaní rock-shelter (Capellades, Barcelona, Spain). Journal of Human Evolution, 48, 157–174.

Vallverdú, J., Vaquero, M., Cáceres, I., Allué, E., Rosell, J., Saladié, P., Chacón, Mª.G., Ollé, A., Canals, A., Sala, R., Courty, M.-A. and Carbonell, E., 2010. Sleeping activity area within the site structure of Archaic human groups: Evidence from Abric Romaní Level N combustion activity areas. Current Anthropology, 51(1), 137–145

Vallverdú, J., Alonso, S., Bargalló, A., Bartrolí, R., Campeny, G., Carrancho, Á., et al., 2012. Combustion structures of archaeological level O and Mousterian activity areas with use of fire at the Abric Romaní rockshelter (NE Iberian Peninsula). Quaternary International, 247, 313–324

Vaquero, M. and Pastó, I., 2001. The definition of spatial units in Middle Palaeolithic Sites: The hearthrelated assemblages. Journal of Archaeological Science, 28 (11), 1209–1220.

Vaquero, M., Rando, J.M., Chacón, G., 2004. Neanderthal spatial behavior and social structure: hearth-related assemblages from the Abric Romaní middle Palaeolithic site. In: Conard, N.J. (Ed.), Settlement Dynamics of the Middle Paleolithic and Middle Stone Age, vol. 2. Kerns Verlag, Tübingen, pp. 367-392.

Vaquero, M., Chacón, M.G., García-Antón, M.D., Gómez, R., Martínez, K., Cuartero, F., 2012a. Time and space in the formation of lithic assemblages: the example of Abric Romaní Level J. Quaternary International 247, 162-181.

Vaquero, M., Chacón, M.G., Cuartero, F., García-Antón, M.D., Gómez de Soler, B., Martínez, K., 2012b. The lithic assemblage of level J. In: Carbonell, E. (Ed.), High

Resolution Archaeology and Neanderthal Behavior. Time and Space in Level J of Abric Romaní (Capellades, Spain). Springer, Dordrecht, pp. 189-311.

Vaquero, M., Allué, E., Bischoff, J.L., Burjachs, F., Vallverdú, J., 2013. Environmental, depositional and cultural changes in the Upper Pleistocene and Early Holocene: the Cinglera del Capelló sequence (Capellades, Spain). Quaternaire 24 (1), 49-64.

Vaquero, M., Bargalló, A., Chacón, M.G., Romagnoli, F., Sañudo, P., 2015. Lithic recycling in a Middle Paleolithic expedient context: Evidence from the Abric Romaní (Capellades, Spain). Quaternary International 361, 212-228.

Zananiri, I., Batt, C. M., Lanos, P., Tarling, D. H., and Linford, P., 2007, Archaeomagnetic secular variation in the UK during the past 4000 years and its application to archaeomagnetic dating, Physics of the Earth and Planetary Interiors, 160 (2), 97–107.

Figure captions

Fig. 1 (a-b) Geographic location of Capellades (Barcelona, Spain) and major physiographical units in the NE Iberian Peninsula. Legend: Pi, Pyrenees; CE, Ebro Basin; Cpr, Pre-coastal ranges; P, Penedès graben; V, Vallès graben; CL, Coastal range; MP, Prades massif; Ll, Lleida; B, Barcelona; T, Tarragona. **(c)** Lithostratigraphic column of the Abric Romaní Coveta Nord profile. The stratigraphic column contains the temporal position of the archaeological level in accordance with the chronology of the basal boundaries of the Dansgaard-Oeschger events in the GISP2 temporal scale model (Blunier y Brook, 2001). Legend for the lithological column: 1, organomineral grey horizon; 2, red siliciclastic and calcitic silty sand; 3, yellow calcitic sand; 4, yellow tuffaceous-travertine gravel and calcitic sand; 5, platy gravels of crystallitic travertine and calcitic sand and silt; 6, speleothems; 7, cemented sands and travertines; 8, diastem; 9, paraconformity or erosive unconformity; 10, archaeological bed. Legend for the comment columns: a, rock-fall of travertine blocks and megablocks; b, letters of the archaeological beds; e, sedimentary sequences; d, the lower boundary chronology of the Dansgaard-Oeschger events in the temporal scale model of the GISP2 core (Blunier y Brook, 2001).

Fig. 2. Situation of combustion structures in Level O of Abric Romaní with indication of the studied area 010 (dashed line). “Pou Romaní” refers to a survey pit and the stratigraphic testimonial is an unexcavated area used as a stratigraphic profile. A

bimodal distribution of combustion structures in this level around 2.5 and 5.5 m from the wall of the rockshelter can be distinguished (see Vallverdú et al. 2012).

Fig. 3. Field record of combustion structure U-V / 50 - 53, which forms part of zone O10 (Chacón *et al.*, 2015), used to draw up the Abric lithofacies map and determine the microstratigraphy of Abric Romaní level O. Legend: 1, outline of the charcoal-rich deposits. 2, outline of the reddened deposits. a, reddened travertine sands and granules in stratified horizontal beds. b, travertine sands and granules in black stratified horizontal beds. c, travertine sands and granules in grey and whitish (milky) grey stratified horizontal beds. d, travertine sands and granules stratified in yellow horizontal beds. e, cemented sands and travertines stratified in yellow or red dome-shaped or horizontal beds. f, hearths sampled for archaeomagnetic analysis.

Fig. 4. (a-c) Representative thermomagnetic curves (magnetization *vs.* temperature) of three samples from the 1st centimeter of depth. Heating (cooling) cycles are plotted in red (blue) with their respective arrows. Sample code and magnetization intensity values are indicated.

Fig. 5. M_{rs}/M_s vs. B_{cr}/B_c logarithmic plot -Day diagram- (Day et al. 1977) of representative samples from the hearths studied. The dashed lines represent mixing curves taken from Dunlop (2002) for mixtures of single-domain (SD) with multidomain (MD) or superparamagnetic (SP) magnetite particles.

Fig. 6. Variation with depth of thermomagnetic curves (a-c-e) and their corresponding hysteresis loops (b-d-f) of the GV4 hearth subsampled every centimetre. Sample code, depth and magnetization intensity values are indicated for each panel. Magnetization intensity of heating cycles at 20 ºC is indicated in thermomagnetic curves. Hysteresis loops (± 1 T) are corrected for the dia/paramagnetic fraction and expressed on a mass-specific basis. The main hysteresis parameters and ratios are also included.

Fig. 7. Representative orthogonal NRM demagnetization plots, stereoplots and normalized decay intensity curves of samples from (a-b) GV3 and (c-d) GV4 hearths. Solid (open) circles show projections of vector endpoints onto the horizontal (vertical) plane. The intensity and sample code are indicated for each sample. A.F. (alternating field); TH (Thermal).

Fig. 8. (a-d) Representative orthogonal NRM demagnetization plots, stereoplots and normalized decay intensity curves of samples from GV2 hearth. Legend and symbols as in Fig. 7.

Fig. 9. Equal-area projections of all ChRM directions together with the mean direction and α95 for each of the studied hearths. See also Table 1.

Fig. 10. Equal-area projections with the mean directions obtained according to the legend. The area is blown-up on the left to denote how GV3 and GV4 mean directions are contained within their respective confidence circles. Stratigraphic sketch at the base showing the location of the hearths.

Figure 1

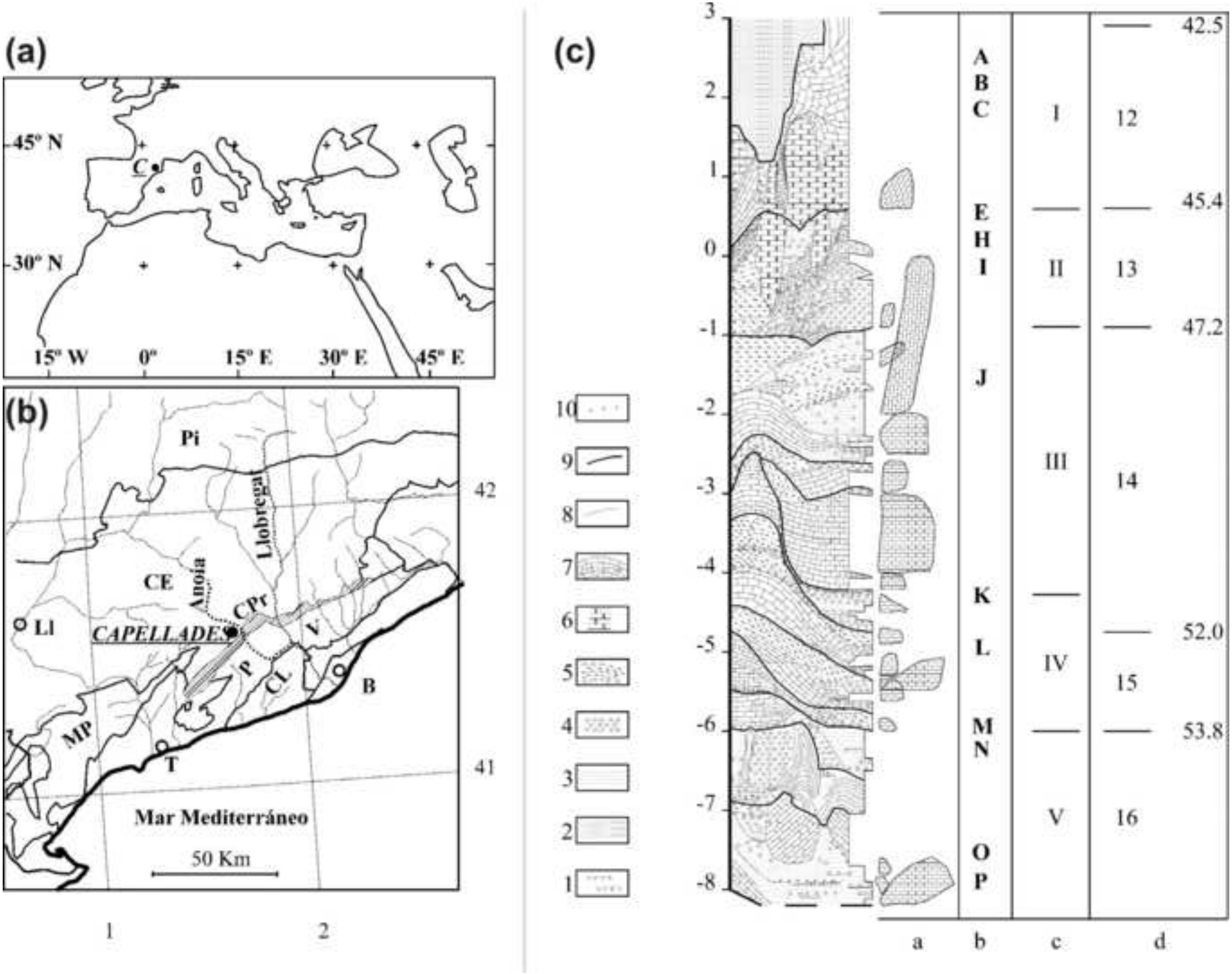
(a)
45° N
30° N
C
15° W
0°
15° E
30° E
45° E
(b)
Pi
Llobregat
42
CE
Anoia
CPr
Ll
CAPELLADES
V
P
CL
B
MP
T
41
Mar Mediterráneo
50 Km
1
2
(c)
10
9
8
7
6
5
4
3
2
1
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
A
B
C
E
H
I
J
K
L
M
N
O
P
I
II
III
IV
V
12
13
14
15
16
42.5
45.4
47.2
52.0
53.8
a
b
c
d

Figure 2

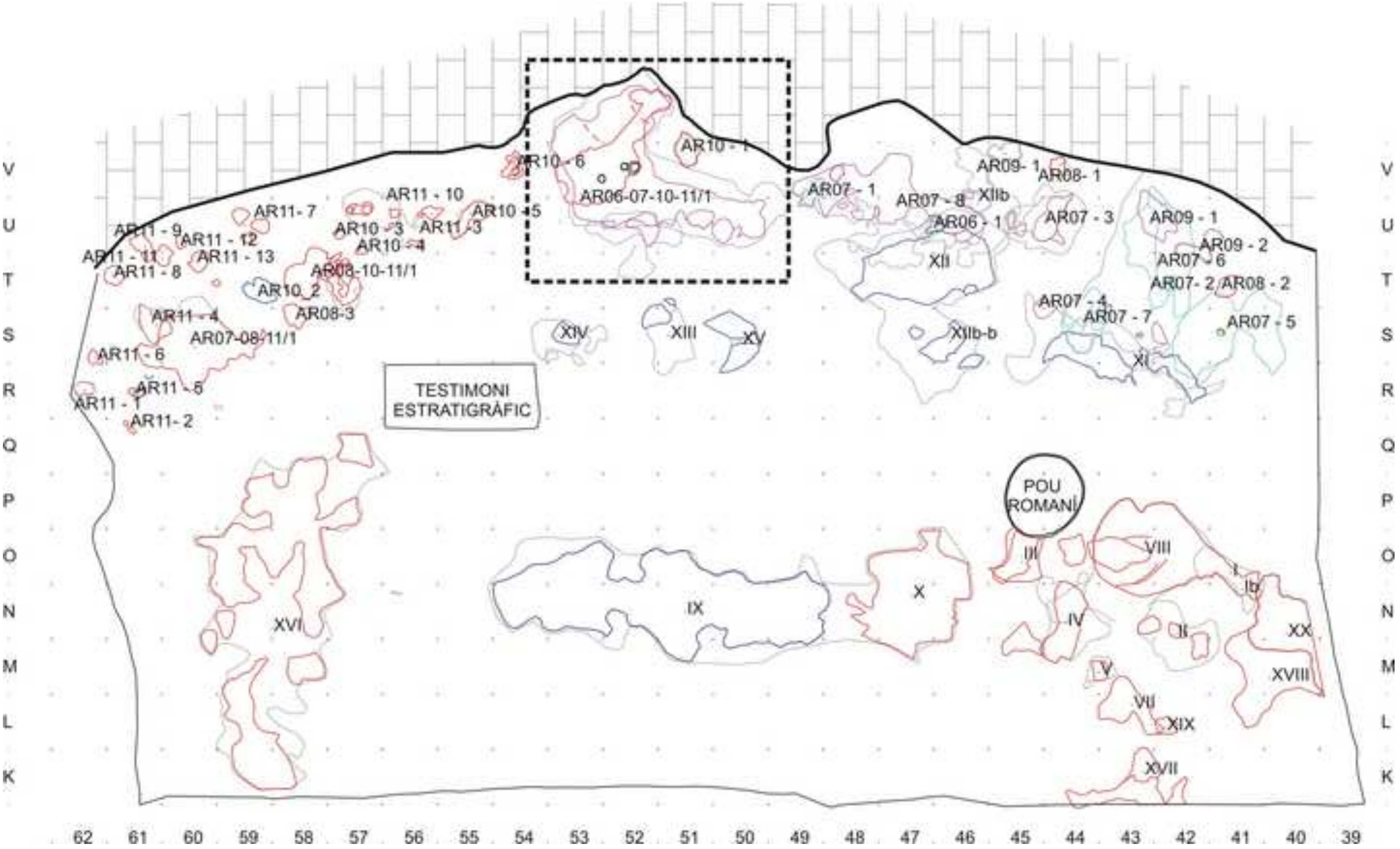
V
U
T
S
R
Q
P
O
N
M
L
K
AR10 - 6
AR10 - 1
AR06-07-10-11/1
AR11 - 10
AR10 - 5
AR11- 7
AR11 - 9
AR11 - 12
AR10 - 3
AR11 - 3
AR10 - 4
AR11 - 11
AR11 - 13
AR11 - 8
AR08-10-11/1
AR10_2
AR08-3
AR11 - 4
AR07-08-11/1
AR11 - 6
AR11 - 5
AR11 - 1
AR11- 2
TESTIMONI
ESTRATIGRÀFIC
XIV
XIII
XV
AR07 - 1
AR09- 1
AR08- 1
AR07 - 8
XIIb
AR06 - 1
AR07 - 3
AR09 - 1
AR09 - 2
AR07 - 6
XII
AR07- 2
AR08 - 2
AR07 - 4
AR07 - 7
AR07 - 5
XIIb-b
XI
POU
ROMANÍ
III
VIII
I
Ib
IX
X
XVI
IV
II
XX
V
XVIII
VII
XIX
XVII
62
61
60
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Figure 3

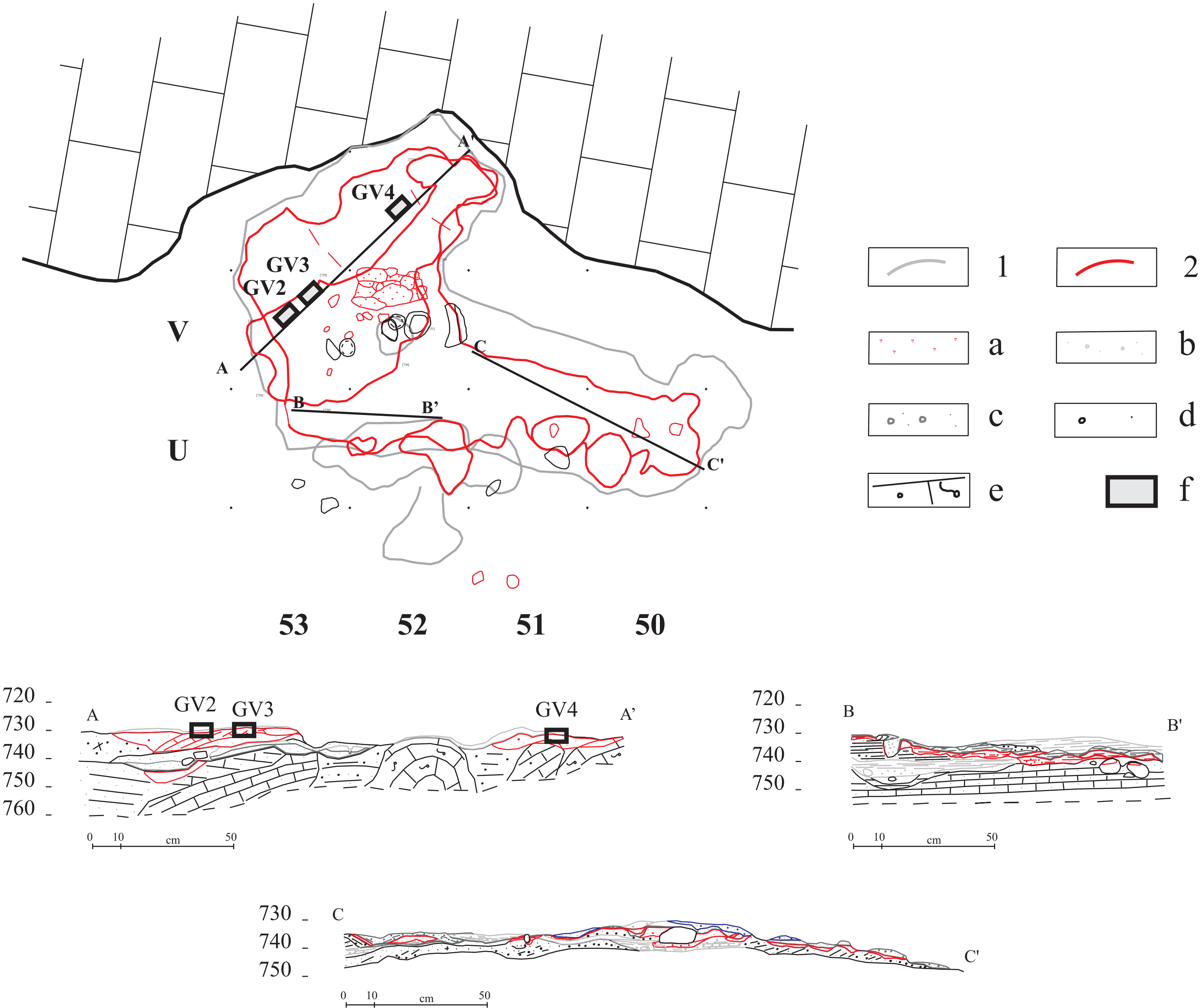
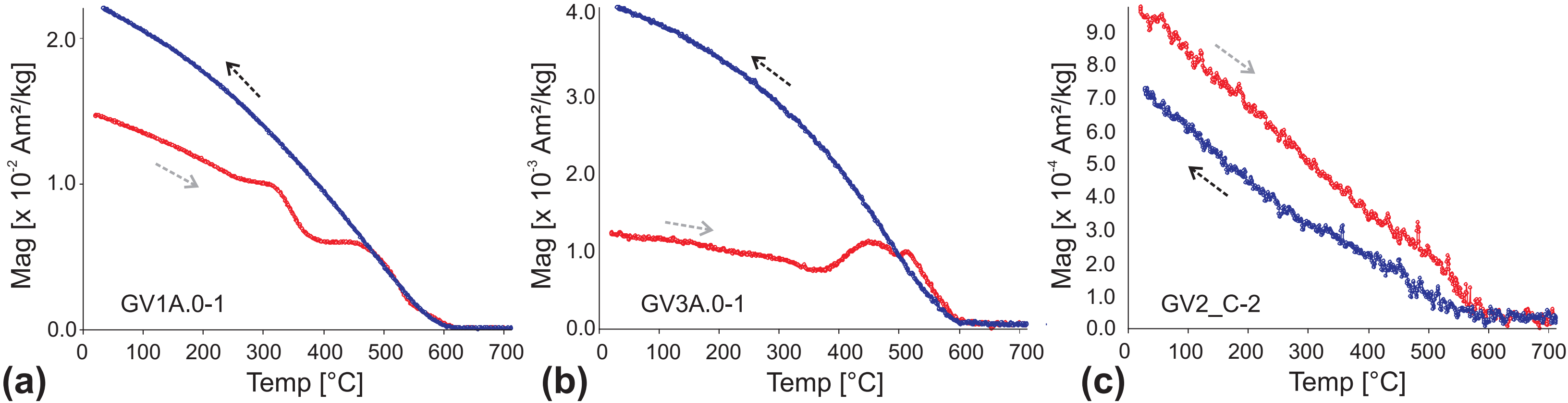
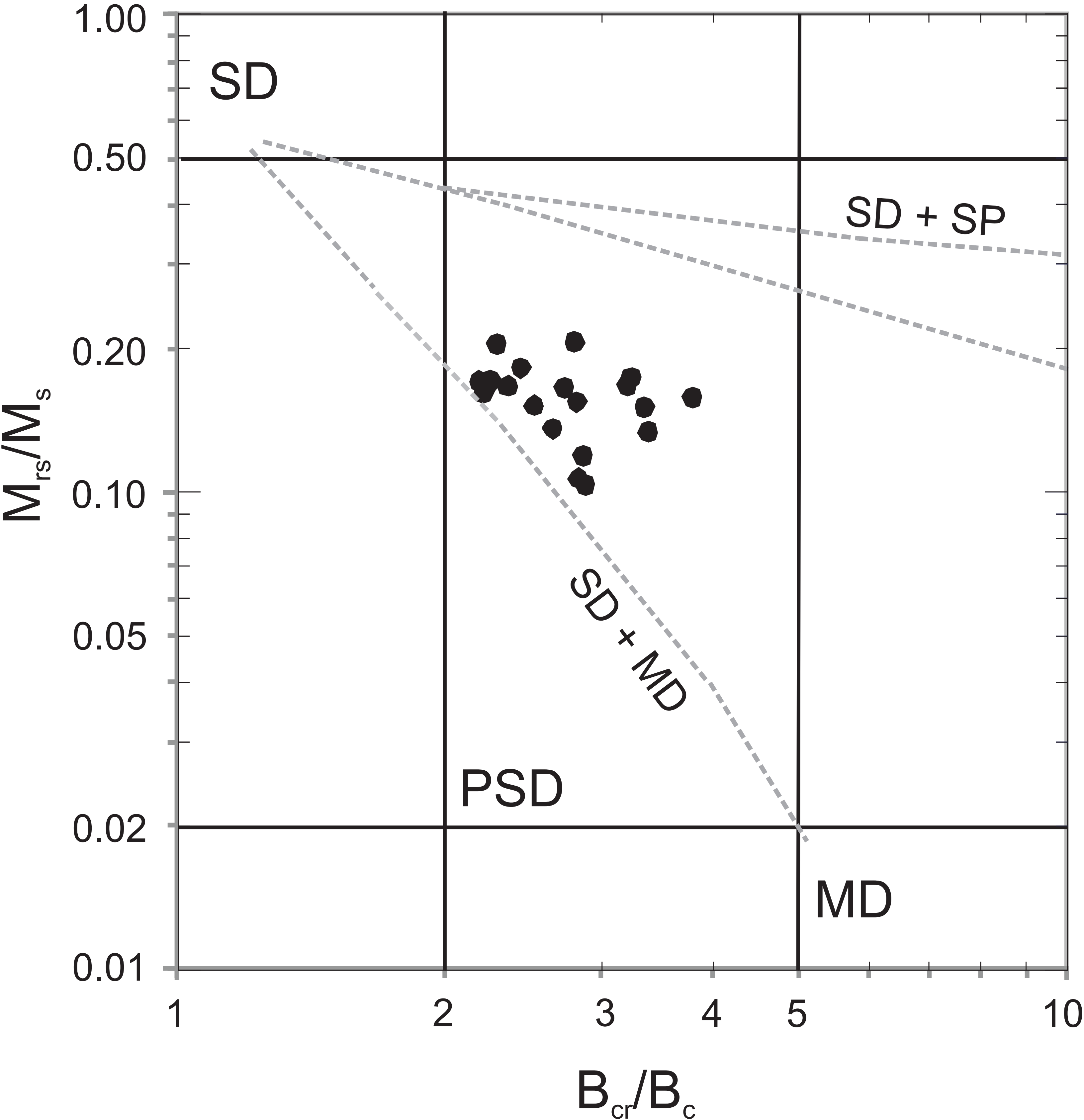

A'
GV4
GV3
GV2
V
A
C
B
B'
C'
U
53
52
51
50
1
2
a
b
c
d
e
f
720
730
740
750
760
A
GV2
GV3
GV4
A'
0
10
cm
50
720
730
740
750
B
B'
0
10
cm
50
730
740
750
C
C'
0
10
cm
50

Figure 4



Mag [x 10⁻² Am²/kg]
2.0
1.0
0.0
0
100
200
300
400
500
600
700
Temp [°C]
GV1A.0-1
(a)
Mag [x 10⁻³ Am²/kg]
4.0
3.0
2.0
1.0
0.0
0
100
200
300
400
500
600
700
Temp [°C]
GV3A.0-1
(b)
Mag [x 10⁻⁴ Am²/kg]
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
100
200
300
400
500
600
700
Temp [°C]
GV2_C-2
(c)

Figure 5



1.00
0.50
0.20
0.10
0.05
0.02
0.01
M_{rs}/M_s
SD
SD + SP
SD + MD
PSD
MD
1
2
3
4
5
10
B_{cr}/B_c

Figure 6

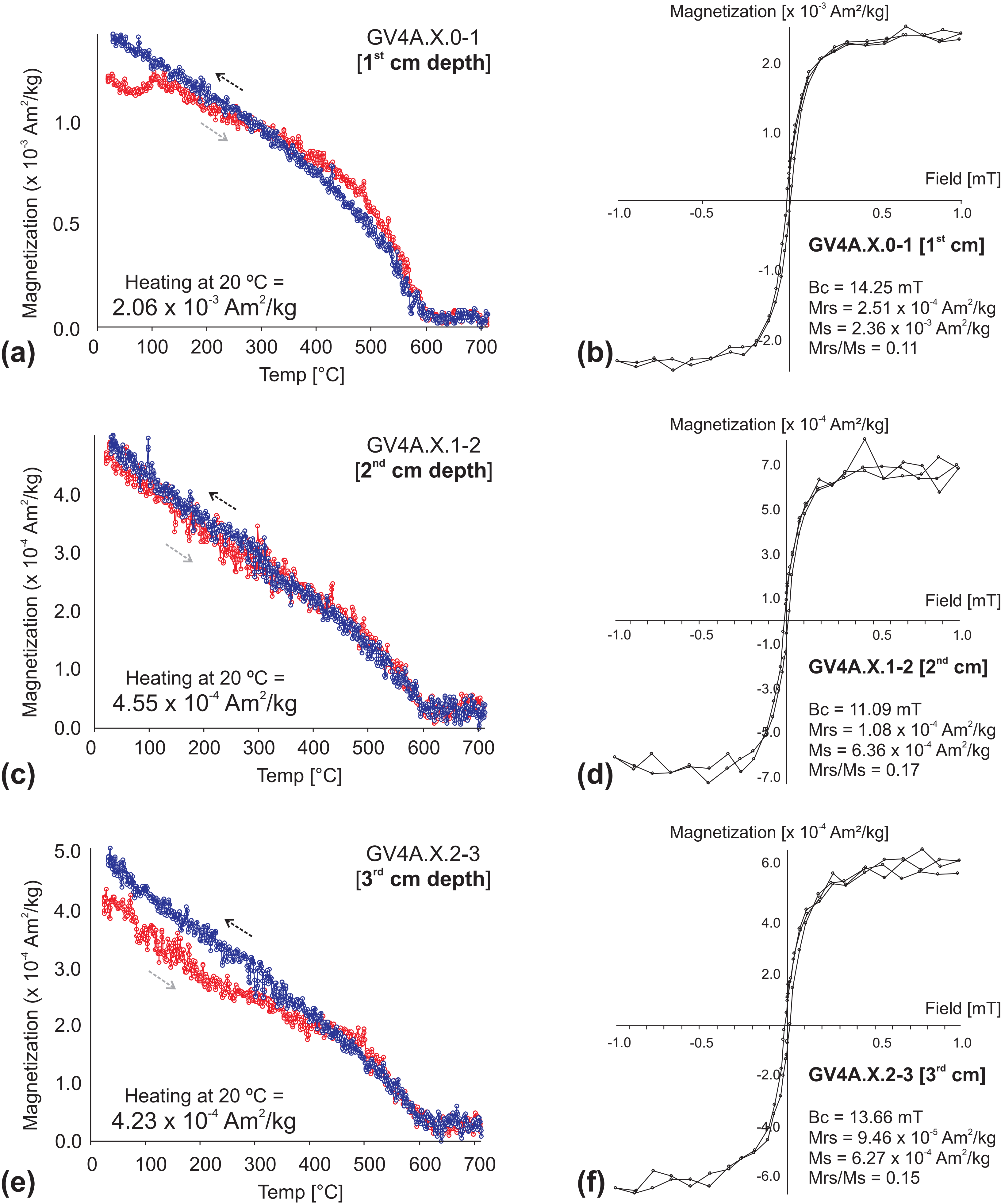
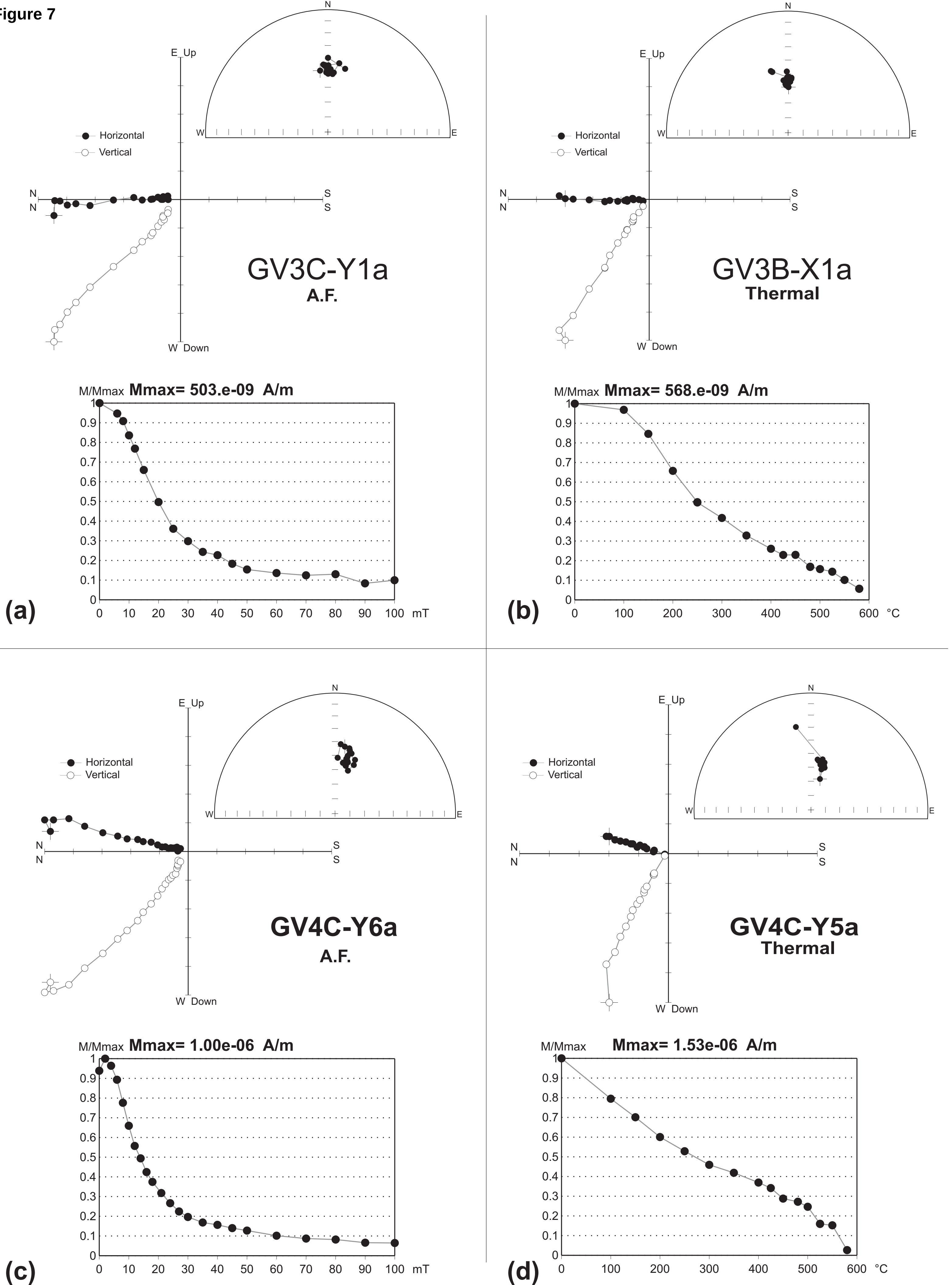

GV4A.X.0-1
[1st cm depth]
Magnetization (x 10-3 Am2/kg)
Heating at 20 ºC =
2.06 x 10-3 Am2/kg
0.0
0.5
1.0
0
100
200
300
400
500
600
700
Temp [°C]
(a)
Magnetization [x 10-3 Am²/kg]
Field [mT]
2.0
1.0
-1.0
-2.0
-1.0
-0.5
0.5
1.0
GV4A.X.0-1 [1st cm]
Bc = 14.25 mT
Mrs = 2.51 x 10-4 Am2/kg
Ms = 2.36 x 10-3 Am2/kg
Mrs/Ms = 0.11
(b)
GV4A.X.1-2
[2nd cm depth]
Magnetization (x 10-4 Am2/kg)
Heating at 20 ºC =
4.55 x 10-4 Am2/kg
0.0
1.0
2.0
3.0
4.0
0
100
200
300
400
500
600
700
Temp [°C]
(c)
Magnetization [x 10-4 Am²/kg]
Field [mT]
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
-7.0
-1.0
-0.5
0.5
1.0
GV4A.X.1-2 [2nd cm]
Bc = 11.09 mT
Mrs = 1.08 x 10-4 Am2/kg
Ms = 6.36 x 10-4 Am2/kg
Mrs/Ms = 0.17
(d)
GV4A.X.2-3
[3rd cm depth]
Magnetization (x 10-4 Am2/kg)
Heating at 20 ºC =
4.23 x 10-4 Am2/kg
0.0
1.0
2.0
3.0
4.0
5.0
0
100
200
300
400
500
600
700
Temp [°C]
(e)
Magnetization [x 10-4 Am²/kg]
Field [mT]
6.0
4.0
2.0
-2.0
-4.0
-6.0
-1.0
-0.5
0.5
1.0
GV4A.X.2-3 [3rd cm]
Bc = 13.66 mT
Mrs = 9.46 x 10-5 Am2/kg
Ms = 6.27 x 10-4 Am2/kg
Mrs/Ms = 0.15
(f)

Figure 7



GV3C-Y1a
A.F.
Horizontal
Vertical
E Up
W Down
N
S
W
E
M/Mmax
Mmax= 503.e-09 A/m
mT
(a)
GV3B-X1a
Thermal
Mmax= 568.e-09 A/m
°C
(b)
GV4C-Y6a
A.F.
Mmax= 1.00e-06 A/m
(c)
GV4C-Y5a
Thermal
Mmax= 1.53e-06 A/m
(d)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
0 10 20 30 40 50 60 70 80 90 100
0 100 200 300 400 500 600

Figure 8

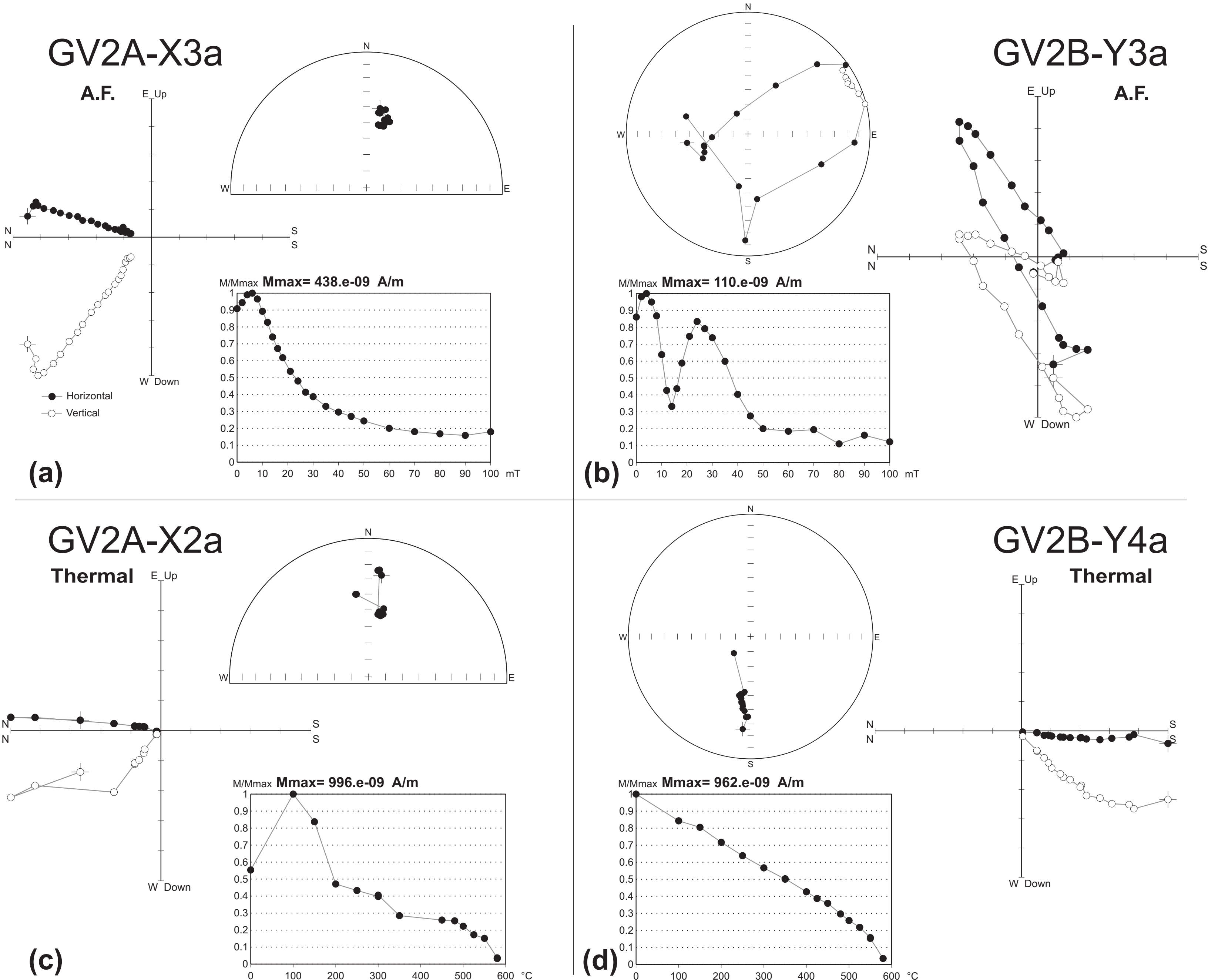

GV2A-X3a
A.F.
E Up
W Down
N
S
E
W
Horizontal
Vertical
M/Mmax Mmax= 438.e-09 A/m
0 10 20 30 40 50 60 70 80 90 100 mT
(a)
GV2B-Y3a
A.F.
Mmax= 110.e-09 A/m
(b)
GV2A-X2a
Thermal
Mmax= 996.e-09 A/m
0 100 200 300 400 500 600 °C
(c)
GV2B-Y4a
Thermal
Mmax= 962.e-09 A/m
(d)

Figure 9

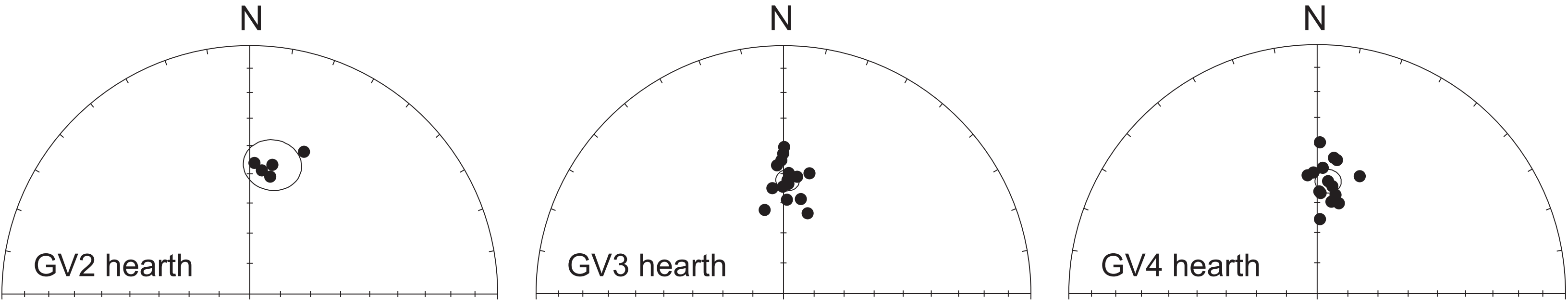


Figure 10

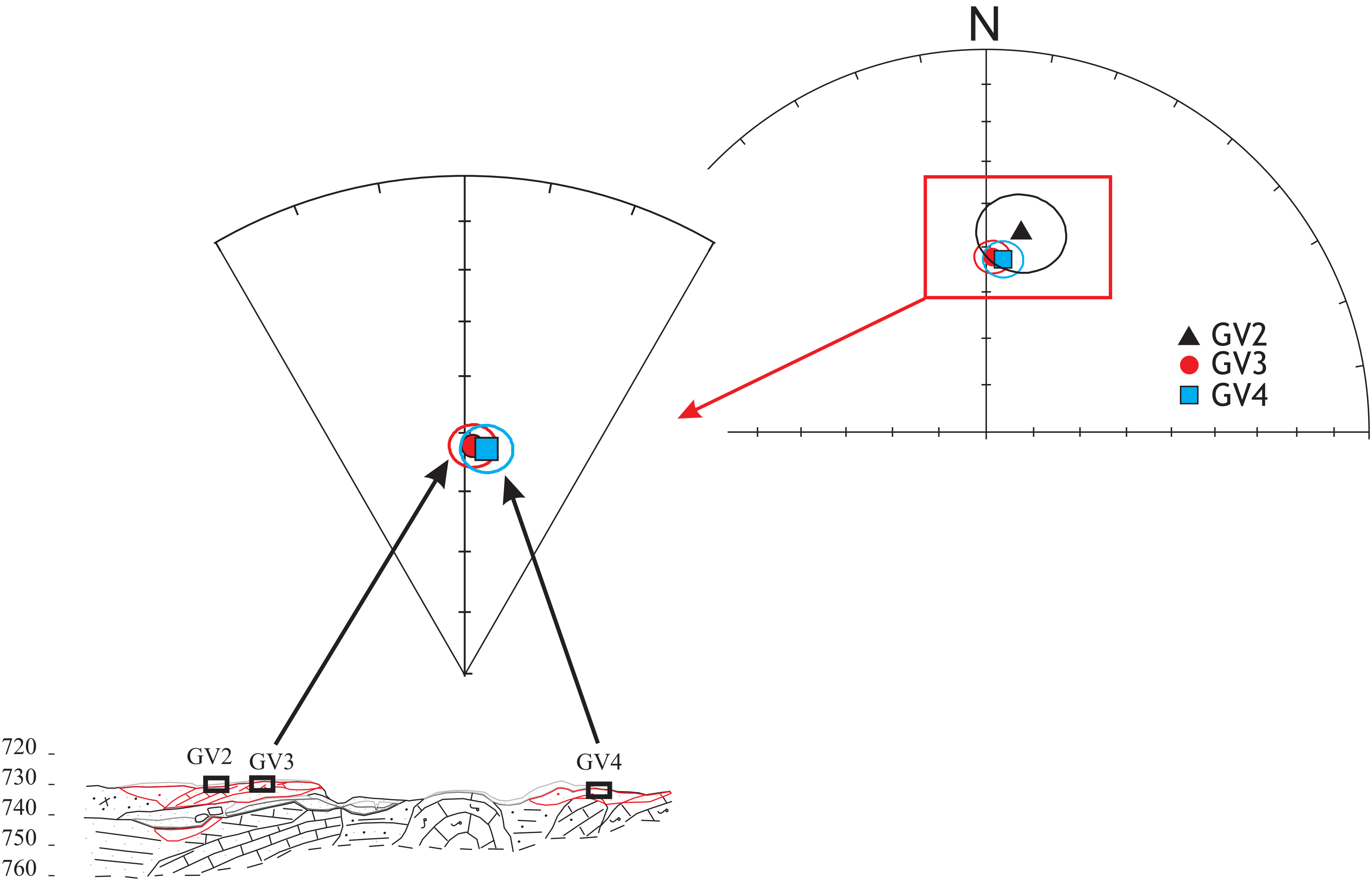


Table 1

Table 1. Archaeomagnetic directional results. From left to right: hearth code, N/N´(number of specimens considered to calculate the ChRM direction / number of specimens processed), Dec. (magnetic declination), Inc. (magnetic inclination), *k* (concentration parameter) and α95 (confidence limit of mean direction at the 95 % level, from Fisher statistics)

Hearth	N / N´	Dec.	Inc.	*k*	α95
GV2	4/10	10	46.1	107.8	8.9
GV3	15/19	2.1	52.2	109.8	3.7
GV4	14/21	5.6	52.6	97.0	4.1

Answers to reviewer´s comments

Please, find below detailed answers to every point raised by reviewer.

…

Some points may require more detailed explanation

- My major concern is the interpretation of possible existence of thermochemical remanent magnetization in some samples. I invite to authors do discuss in great details whether the creation of TCRM may affect the primary directions. This is very important point since some very fine changes in archaeodirections are interpreted by the authors as the result of variation of geomagnetic declination and inclination.

The question is not if the record of a TCRM affects the primary direction. A TCRM is a type of remanence acquired simultaneously during cooling below the Curie temperature, so the directional record of the Earth´s magnetic field is totally trustworthy (Dunlop and Özdemir 1997: 409). The problem here is to prove whether the remanence is actually a TCRM or a CRM. A CRM acquired time after the last burning may distort the prior TRM direction. In single-phase oxidation processes such as the magnetite to maghaemite oxidation (or maghaemitization), particularly for single-domain or small PSD grains, is generally accepted that the CRM inherits or preserves the original TRM direction (see Dunlop and Özdemir and references therein). For larger (MD) grains or multiphase oxidation processes (e.g. intergrown of maghaemite-haematite from titanomagnetite) the field acting during oxidation may influence the CRM direction even lying in intermediate directions of no palaeomagnetic significance (cf. Heider and Dunlop 1987). Clearly, that is not our case because we have no evidence of haematite intergrowns in these samples. We only observed occasionally traces of maghaemitization or partially maghaemitized magnetite. These explanations are quite hard for an archaeological audience but the basic ideas are included in the discussion to help understanding. Anyway, directional fidelity in a TCRM is absolutely out of doubt as we claim because it is acquired during initial cooling and the field does not change. This is briefly explained in the main text (see pages 9 and 10).

- The authors argue that 'The irreversibility of thermomagnetic curves… may indicate the creation of TCRM rather than a TRM (thermoremanent magnetization). This is probably wrong since many other factors (and not only occurrence of TCRM) may cause the irreversibility observed on continuous thermomagnetic curves.

Yes, the reviewer is right. The lack of reversibility does not necessary imply a TCRM. This may be caused by many other reasons such as variations in magnetic domains, changes in the topology of the sample, phase alterations induced by heating (e.g.: transformation of paramagnetic minerals, phyllosilicates or even other ferromagnetic minerals). In any case, the irreversibility of thermomagnetic curves cannot be used as criterion to recognize a TCRM. It has been modified in the text accordingly (see abstract and conclusions).

- The ideal case of archaeomagnetic investigation on burned features consists to determine absolute intensity together with archaeodirections. Please discuss in more details why these samples are unsuitable for such experiments (classical Thellier or Multispecimen approach)?

That’s true. The ideal situation is to determine the full geomagnetic vector including both directions (declination and inclination) and archaeointensity values. However, the success rate in palaeointensinty experiments is usually very low (< 30 %) because the materials often do not fulfill the necessary requirements. These are that the remanence must be preferably carried by non-interacting single domain (SD) particles (particularly true for the Thellier method; no so critical for the multispecimen method), the sample must exhibit a high thermomagnetic reversibility and above all, the primary direction must be a thermoremanence (TRM).

First, the studied materials are pseudo-single domain (PSD) magnetite particles, implying that they contain a mixture of single-domain and multidomain particles. However, the domain state is not so critical depending on the palaeointensity method used. Reliable data can be obtained with the multispecimen method regardless of the dominant domain state. In the Thellier method, the presence of multidomain particles is a problem, because it generates concave “Arai” diagrams.
Second, these samples do not show a high thermomagnetic stability given the irreversibility of thermomagnetic curves. It strongly indicates that they do not carry a full TRM because probably they did not undergo very high temperature heating. The lack of evidence suggesting a TRM as the primary remanence makes these samples unsuitable material for absolute palaeointensity analysis. This is already indicated in the main text (page 10).

- Domain state estimation using room temperature hysteresis parameters in terms of the plot of magnetization ratio vs coercivity ratio has no resolution for most of natural rocks and burned archaeomagnetic materials.

Based on the experimental study of the chemically well-identified synthetic titanomagnetites, Day (1977) proposed an empiric relation between the domain structure and the hysteresis parameters, which has been widely used in research papers in paleo and rock-magnetism. However, natural rocks, almost always plot on the pseudo-single-domain behavior judging from their hysteresis parameter values. This is true for this study too. Please use Dunlop's (2002) interface to discriminate between hysteresis ratios and their relationship with the domain sate.
The hysteresis parameters of this collection were already represented in the Day plot including the mixing theoretical curves of Dunlop (2002) for mixture of single-domain (SD) with multidomain (MD) or superparamagnetic (SP) magnetite particles (see Fig. 5). It is indicated in the legend of Fig. 5. The hysteresis results are also discussed in the main text (end 2nd paragraph page 6).