Three archaeomagnetic applications of archaeological interest to the study of burnt anthropogenic cave sediments

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Abstract

Recent archaeomagnetic studies carried out on Mid- to Late Holocene burnt anthropogenic cave sediments have shown that under certain conditions, these materials are suitable geomagnetic field recorders. Archaeomagnetic analyses carried out on these contexts constitute a rich source of information not only for geophysical purposes -in terms of reconstructing the variation of Earth's magnetic field in the past- but also from the archaeological point of view, for example by archaeomagnetic dating. Here, we report three different archaeomagnetic applications to the study of burnt cave sediments: (i) archaeomagnetic dating; (ii) determining palaeotemperatures and (iii) assessing post-depositional processes. The first case study is a dating attempt carried out on a Late Holocene (Bronze Age) burnt level from El Mirador Cave (Burgos, Spain). Using the directional European secular variation curve, several dating intervals were obtained for the last burning of this combustion feature. Considering the archaeological evidence and the independent radiometric (^{14}C) dating available the possible ages obtained are discussed. This is the first archaeomagnetic dating obtained in these contexts so far. The second case study is an application of the method to determine the last heating temperatures reached by the carbonaceous facies of these fires. Stepwise thermal demagnetization of oriented samples can be used to quantitatively estimate heating temperatures. An intermediate normal polarity component interpreted as a partial

thermo-remanence (pTRM) with maximum unblocking temperatures of 400 – 450 ºC was systematically identified, revealing the last heating temperatures experienced by this facies. These temperatures were confirmed with partial thermomagnetic curve experiments. Finally, archaeomagnetic analyses on a partially bioturbated burning event were performed in order to evaluate until what spatial extent the burnt sediments were affected by post-depositional mechanical alteration processes. For each case study, the archaeological implications are discussed highlighting the potential of archaeomagnetic methods to retrieve archaeological information.

Keywords: Fumiers, Holocene, Thermoremanent magnetization, Secular variation, Ashes, Bronze Age.

1. Introduction

Since the pioneering work of Brochier (1983a,b), the study of Holocene burnt anthropogenic cave sediments has experienced considerable progress. A great number of archaeological excavations as well as the increasing amount of data provided by disciplines such as soil micromorphology (Angelucci et al 2009; Boschian 1997; Macphail et al. 1997), palaeobotany (Rasmussen 1993; Delhon et al. 2008; Cabanes et al. 2009) or zooarchaeology (Martín et al. 2014; Rowley-Conwy 1998) among others, is yielding valuable information about the formation and use of these deposits. Archaeomagnetism has emerged as one of these lines of research. Although it has a long tradition in Earth sciences its application in prehistoric archaeology is still sporadic and its potential to retrieve archaeological information remains underutilized.

Broadly speaking, archaeomagnetism deals with the study of the record of the Earth´s magnetic field direction and/or intensity changes in the past in burnt archaeological materials. Most archaeological materials contain small amounts of ferromagnetic minerals (*s.l.*), such as magnetite or haematite. When heated to high temperatures (> 500 – 600 ºC) and subsequently cooled these minerals acquire a remanent (permanent) magnetization parallel to the ambient magnetic field. Under several conditions this information may be very stable over long periods of time and used in a wide variety of applications, among which dating is likely the most known. However, given their versatility, magnetic methods can provide valuable information ranging from determining palaeotemperatures (e.g., Brown et al. 2009), ash sourcing (Church et al. 2007) or assessing the degree of preservation in archaeological cave fires (e.g., Carrancho et al. 2012). This paper provides a review of some of these applications specifically applied to anthropogenic cave sequences.

These stratigraphic sequences usually contain multiple burning events generated by the periodic burning of organic material (e.g., vegetal remains and dung) produced by livestock penning (Angelucci et al. 2009). Their preservation state is usually good, are generally well-dated by independent methods (namely radiocarbon) and have a broad geographical distribution throughout the Mediterranean region (Angelucci et al. 2009). Therefore they constitute a great source of archaeomagnetic data and the information obtained has both geophysical and archaeological interest. The main goal of this article is to highlight the potential of magnetic methods to answer archaeological questions through three different applications. The first is a dating attempt of a firing event from El Mirador Cave (Spain) using the recently designed directional European Secular Variation (SV) curve for the Neolithic (Carrancho *et al*. 2013). The second is a methodological application to determine the last heating temperature undergone by these fires. The third consists on evaluating to what extent a burning event might be affected by post-depositional processes. The archaeological and archaeomagnetic implications of these cases studies will be discussed as well as the limits of each application.

2. Materials and methods

2.1 Sites

The studied materials correspond to samples from Neolithic, Chalcolithic and Bronze Age burning events exposed in the Holocene stratigraphies of El Mirador and Portalón de Cueva Mayor caves (Sierra de Atapuerca, Burgos) and El Mirón Cave (Cantabria, Spain; Fig. 1a). For detailed information on the archaeology, stratigraphy and chronology of these sites the reader is referred to Straus and González Morales (2012), Carretero et al., (2008) and Vergès et al. (2008; this volume). These fires generally contain a grey/white ash facies of variable thickness (2-10 cm) over a thin (~ 2 cm) black carbonaceous subjacent facies.

2.2 Sampling

Archaeomagnetic sampling was carried out with the aid of a non-ferromagnetic cylindrical tube which incorporates a built-in orientation system specifically designed for soft (unlithified) lithologies (Carrancho et al. 2013). Its main advantage is that it allows a precise geographical orientation of the samples besides being minimally invasive. The tube is pressed against vertical profiles where the burnt facies outcrop. After the azimuthal reading, the sediment is carefully inserted in cylindrical plastic boxes (Ø 16.5 mm, 17 mm length; volume of about 3.6 cm^3) and stored in cold conditions (3-4 ºC) until measurement to avoid chemical alterations. Samples for thermal (TH) demagnetization of the natural remanent magnetization (NRM) were oriented by the same means and introduced into home-made plaster cubes (Carrancho 2010). These contain a cylindrical hole with the same dimensions and volume as the plastic capsules in order to keep the sample in fixed position. The NRM of the plaster cubes is at least two orders of magnitude less than the sample´s magnetization. Details of the number and type of samples collected for each case study are given below.

2.2.1 Case study 1 (archaeomagnetic dating)

A burning event (Ci1) from El Mirador Cave (42º 20´ 58´´ N, 03º 30´ 33´´ W; Sierra de Atapuerca, Burgos, Spain) was intensively sampled for archaeomagnetic dating purposes (Fig.1a-b). The archaeostratigraphic unit where Ci1 is located (MIR103 – Sector 100) has a ^{14}C (AMS) dating (sample code: Beta – 339094) obtained from a charcoal fragment with a 2σ dating interval of 1510 to 1410 cal. BC (3190 +/- 30 BP). Archaeological evidence is limited to few pottery remains suggesting a possible Bronze Age for the MIR103 unit. The objective here was to obtain an archaeomagnetic date of the last heating of this event using the directional European SV curve (Carrancho et al. 2013). The Ci1 burning event is composed of an ash and a carbonaceous facies. The ashes are white on top and reddish brown on the bottom with a total thickness of about 15 cm. Just beneath, a dark carbonaceous (~ 2 cm) facies is preserved delimiting the surface where burning occurred (Fig. 1). At the top of the lower level, just at the base of the burning event, a burrow can be observed that may have partially affected the structure. A total of 29 oriented samples (22 ashes and 7 carbonaceous samples) were collected following the sampling procedure described in section 2.2.

2.2.2 Case study 2 (estimating palaeotemperatures)

The samples analysed in this case study are representative carbonaceous samples from 6 different Holocene burning events from El Mirador, El Portalón and El Mirón Cave (Spain). They were previously studied along with hundreds of burnt samples in the design of the first directional European PSV curve for the Neolithic (Carrancho et al. 2013). The objective is to show how the identification of partial thermal remanent magnetizations (pTRMs) permits the quantitative estimation of the last heating temperature in the carbonaceous facies. The validity of this approach was verified carrying out thermomagnetic curve analyses on bulk (unoriented) sample from this facies and studying their degree of reversibility (section 4.2). The sampling procedure was the same as described in section 2.2.

2.2.3 Case study 3 (assessing post-depositional processes)

In order to test the reliability of the palaeomagnetic method to determine to what extent the mechanical reworking might have affected an anthropic cave fire, an archaeomagnetic study of a Late Holocene burning event from El Portalón Cave (Burgos, Spain; map of Fig. 1a) is reported. This burning event contains a white ash facies (~ 10 cm) over a ~ 2 cm dark carbonaceous facies both partially altered by an ancient burrow (Fig. 8). The colour and texture of ashes on the right side of the burning event are somewhat mixed, suggesting that some kind of mechanical reorganization might have occurred. In contrast, the ashes of the central and left part are pure white ashes seemingly *in* situ. This event was intensively sampled collecting 24 oriented samples of both facies (18 ashes and 6 carbonaceous samples). The archaeomagnetic mean direction obtained has been reported by Carrancho et al. (2013). Nevertheless, the objective here is to describe what magnetic features display *in situ* samples compared to those that are reworked. These results will allow testing the criteria established in a similar case study (Carrancho et al. 2012) as well as evaluating the degree of alteration that the structure might have suffered.

2.3 Laboratory methods

All analyses were performed in the laboratory of palaeomagnetism of Burgos University (Spain). The measurement of the natural remanent magnetization (NRM) was carried out with a 2G SQUID magnetometer (noise level 5×10^{-12} Am^2). Low-field magnetic susceptibility at room temperature was measured with a KLY-4 susceptometer (AGICO, noise level 3×10^{-8} S.I.). The NRM directional stability was analysed by stepwise progressive alternating field (AF) and thermal (TH) demagnetization. AF demagnetization was carried out in 18–20 steps up to maximum fields of 100–120 mT with the 2G magnetometer AF demagnetization unit. TH demagnetization was performed using a TD48-SC (ASC) thermal demagnetizer in 15-17 steps up to 660 ºC. The Characteristic remanent magnetization (ChRM) direction of every specimen was determined by principle component analysis (PCA; Kirschvink, 1980) including at least four demagnetization steps (usually five or more).

In order to study further the ferromagnetic mineralogy present, different rock-magnetic experiments were carried out with a variable field translation balance (MM_VFTB). These comprised progressive isothermal remanent magnetization (IRM) acquisition curves, hysteresis loops (± 1 T), backfield curves and thermomagnetic curves up to 700 ºC in air. These analyses were undertaken on representative bulk sample (~ 400 mg) both on ash and carbonaceous samples. Curie temperatures of Js-T curves were determined using the two-tangent method of Grommé et al. (1969). Saturation magnetization (M_s), remanence saturation magnetisation (M_{rs}) and coercive field (B_c) were calculated from hysteresis loops after subtracting the paramagnetic contribution. In combination with the coercivity of remanence (B_{cr}) determined from the backfield curves, the domain state distribution was analysed in the Day diagram (Day et al. 1977; Dunlop 2002).

3. Case 1: Archaeomagnetic dating

3.1. Background

Archaeomagnetic dating is based on two fundamental phenomena. First, the ability of ferromagnetic minerals (*s.l.*) to acquire a remanent magnetization when heated and subsequently cooled from high temperatures parallel with and proportional to the geomagnetic field. This mechanism of magnetization is known as thermoremanent magnetization or TRM and is characteristic of structures such as ovens, kilns and hearths. Second, the Earth´s magnetic field undergoes subtle variations in direction and intensity on a timescale of 10^2-10^3 years on a regional scale. These fluctuations are known as secular variation (SV) and are reproducible for regions no bigger than 500-600 km of radius (Lanos 2004). Over recent years great efforts have been undertaken to derive regional SV curves for different regions, particularly in Europe. These master curves are composed of directional and/or intensity data of the Earth´s magnetic field obtained from previously well-dated burnt archaeological materials (and occasionally also from lava flows). With some exceptions in Eastern Europe (Tema and Kondopolou 2011; Kovacheva et al. 2014), most European SV curves cover the last 2-3 millennia

(Gallet et al., 2002; Gómez-Paccard et al., 2006; Marton and Ferencz, 2006; Schnepp and Lanos 2005, 2006; Tema et al., 2006; Zananiri et al., 2007).

Standard archaeomagnetic dating works on the basis of comparing the mean direction and/or intensity determined from a site with the SV curve available for the region and period concerned. Many archaeomagnetic dating examples are reported in the literature using directional, intensity data or both combined (e.g., Casas et al. 2007; Ech-Chakrouni et al. 2013). The more archaeomagnetic data added to these regional SV curves the better defined they will be, thus improving the dating technique. More recently, archaeomagnetic dating using geomagnetic field models has become feasible. For instance, the SCHA.DIF.3K European regional model (Pavón-Carrasco et al. 2009) based exclusively on archaeomagnetic directional and intensity data for the last 3 millennia, directly predicts the geomagnetic field at the site of interest even for regions where no SV curve is available. This avoids any eventual relocation error which has been proved to introduce significant errors (Casas and Incoronato 2007). There are also global models for longer periods (e.g., Pavón-Carrasco et al. 2010; Korte and Constable, 2005; Korte et al., 2011) but not suited for archaeomagnetic dating because they include sedimentary data that smooth the geomagnetic field variations through time. Also, new software has been developed to carry out archaeomagnetic dating using various SV models (Pavón-Carrasco et al. 2011).

Archaeomagnetic dating has a typical range of error of a few centuries although there are good examples reaching dating resolution of a few tens of years as the one reported from an early 18th century brick kiln by Casas et al. (2007). This depends on several factors such as sampling or analytical errors, inconsistent behaviour of the material or the rate of variation of the Earth´s magnetic field. However, dating applicability of the method depends on the length and completeness of the SV curve for the region concerned. The longest and systematic archaeomagnetic records for the last 8 ky exist for Eastern Europe (Tema and Kondopolou 2011; Kovacheva et al. 2014) but that is not the case for Western Europe as mentioned before. Current efforts aim to temporally and geographically extend SV records using well dated, *in situ* archaeomagnetic materials.

Recent studies carried out on Mid to Late Holocene burnt anthropogenic cave sediments from the Iberian Peninsula (Carrancho et al. 2009, 2012, 2013) and Central Europe

(Kapper et al. 2014a,b) have allowed the extension to mid-Holocene times of the archaeomagnetic database and the dating technique. These authors showed how under certain conditions reliable archaeomagnetic directions can be obtained from these materials. As multiple burning events are usually present in these archaeological sequences, various archeomagnetic data (spanning a time period in the range of hundreds to thousands of years) can be obtained from a single site. Combining 26 new directions obtained from Neolithic, Chalcolithic and Bronze Age burnt levels from three caves in Spain with the existing archaeomagnetic database for Eastern Europe (Korte et al. 2011; Kovacheva et al., 2009), a directional European SV curve for the Neolithic exclusively based on archaeomagnetic (TRM) data was published (Carrancho et al. 2013). Although new results are being reported (e.g., Hervè et al. 2013a,b), archaeomagnetic data for times prior to around 1000 BC in Western Europe are rather scarce. Burnt anthropogenic cave sediments emerge thus as a new geomagnetic field recorder with a great potential both for geophysical and archaeological purposes.

3.2 Results and discussion

3.2.1 Magnetic properties

Natural remanent magnetization values are between 4.08 x 10^{-5} and 8.27 x 10^{-4} Am^2kg^{-1} whereas low-field magnetic susceptibility values oscillate between 6.42 x 10^{-7} and 4.78 x 10^{-6} m^3kg^{-1}. The highest values for both parameters correspond to the ashes indicating a major concentration of ferromagnetic minerals in this facies. The Koenigsberger ratio ([Qn = NRM/(χH) (*cf* . Stacey 1967)]) where χ is the magnetic susceptibility and H is the local geomagnetic field strength, yielded values between 1.6 and 19.6. These values agree well with others reported for similar materials (Carrancho et al. 2009, 2012; Kapper et al. 2014a,b) and indicates that the NRM is of thermal origin.

The rock magnetic experiments carried out allowed characterizing the magnetic mineralogy, domain state and thermal stability. The IRM acquisition curves are almost saturated at fields of 150 – 200 mT indicating that they are dominated by a low-coercivity mineral (Fig. 2). A small fraction of a high-coercivity mineral (up to 5-10 % of the SIRM or Saturation of IRM at 1T), most probably haematite, seems also to be present. However, its contribution to the magnetization is not significant. The Curie temperatures (T_C) determined from thermomagnetic curves performed on selected samples are around 580 ºC indicating the dominance of magnetite in both facies (Fig.

3). Occasionally, T_{CS} of up 615 ºC have been observed in some reddish brown ashes pointing out that stable maghaemite might also be present (Fig. 3b). The occasional presence of maghaemite has been already observed in this type of fire (e.g., Carrancho et al. 2009; 2013) and it would imply a thermochemical remanent magnetization (TCRM), making such specimens unsuitable for absolute archaeointensity determinations. The high thermomagnetic reversibility of ashes is noteworthy, particularly the white one (Fig. 3a). Conversely, carbonaceous specimens exhibit much lower thermomagnetic reversibility producing secondary magnetite on cooling (Fig. 3c). This indicates that they underwent lower heating temperatures as is explained in more detail in case study 2 (section 4).

3.2.2. NRM directional stability and archaeomagnetic dating

Fig. 4 (a-f) illustrates representative NRM orthogonal demagnetization diagrams of both facies and the stereographic projection with all the individual Characteristic remanent magnetization (ChRM) directions determined. All specimens show a secondary viscous component of normal polarity easily removable in the first steps of the magnetic cleaning (< 10 – 15 mT or < 200 – 250 ºC) particularly evident in carbonaceous specimens (Fig. 4d-e). The NRM stability of the ashes is defined by a stable, high intensity normal polarity component almost demagnetized at 80–100 mT decaying univectorially towards the origin (Fig. 4a-b). AF demagnetized carbonaceous specimens exhibit also a single component (Fig. 4d) or occasionally two-component magnetizations partially overlapping. In the latter case, these specimens were not considered to calculate the ChRM direction.

Three out of 5 specimens sampled for TH demagnetization of the NRM broke during laboratory analyses. The two remaining specimens (Fig. 4c and e) correspond to an ash and a carbonaceous specimen, respectively. The ChRM direction in the ash was determined between 250 ºC to 580-600 ºC. The ChRM direction in the carbonaceous specimen was defined between 250 ºC and 450 ºC, reflecting a partial thermo-remanent magnetization (pTRM) likely caused by moderate heating that this facies underwent. This is consistent with the irreversible thermomagnetic behaviour of this facies (e.g., Fig. 3c) as is more detailed in section 4 (case study 2). AF demagnetization is adequate to determine successfully the ChRM direction because the main remanence carrier is a low-coercivity mineral.

Carrancho et al. (2013) established various quality selection criteria to identify anomalous behaviours and determine the reliability of these structures to obtain archeomagnetic directions. These are: (i) presence of all the sedimentary facies for each burning event (ashes over underlying carbonaceous facies); (ii) Koenigsberger (Q_n) ratio values > than 1 indicating a stable thermoremanence (TRM) or a partial TRM; (iii) absence of any indication of mechanical alteration in the sediments (e.g., mixed or truncated facies), and (iv) a majority of demagnetisation diagrams with univectorial NRM among the ashes. Following these criteria, 8 specimens were rejected for the calculation of the mean archaeomagnetic direction (the three broken specimens excluded). These specimens have the lowest NRM intensities, Q_n ratios < 1.0 and anomalous directions or multicomponent demagnetization diagrams. As it is discussed further in case study 3 (section 5), all these features are indicative of some type of post-depositional reworking. It is worth mentioning that most rejected specimens come from parts close to the burrow, which are potentially affected by reworking (Fig. 1). The mean direction obtained (Fig. 4f) has a Declination = 20.1º; Inclination = 56.5º; k = 63.3; α_{95} = 4.4º, according to Fisher (1953) statistics.

Probability density functions of possible dates for declination and inclination were obtained comparing the results with the directional European PSV curve (Carrancho et al. 2013) at the site coordinates using the archaeomagnetic dating tool of Pavón-Carrasco et al. (2011). The probability functions were combined to obtain the most probable dating solutions at 95% confidence level (Fig. 5). Four different dating intervals were obtained: 2256 – 2143 BC; 2061 – 1888 BC; 1651 – 1520 BC and 1081 – 1000 BC. The first two intervals can be discarded because they are inconsistent with the Bronze Age context for this unit. The last one is within the bounds of possibility and with the largest statistical probability but is out of the radiocarbon date range (1510 - 1410 yr BC) by more than three centuries. The one which best agrees with the radiocarbon dating is the 1651 – 1520 BC interval, although slightly sooner than indicated by radiocarbon date. In any case it is consistent with a Middle-Late Bronze Age for the MIR103 unit.

The archaeomagnetic dating reported does not improve the accuracy of radiocarbon dating for this case study although both are archaeologically consistent. Beyond that, thanks to the recently developed European PSV curve (Carrancho et al. 2013), is already possible to date with archaeomagnetism *in situ* burnt archaeological materials from Western Europe for these older periods. Much remains to be done in order to improve and extend back in time the archaeomagnetic dating technique but the potential of these materials for both geophysical and archaeological purposes is indisputable.

4. Case 2: Estimating heating temperatures

4.1. Background

Determining the temperature at which a burnt archaeological remain was heated in the past is a topic of interest for archaeologists. This information is interesting because on the one hand, it may help to reconstruct the technological conditions under which a combustion structure was carried out. On the other hand, it has also geochronological implications since other dating methods (e.g., thermoluminescence or TL) require a minimum heating temperature in the materials to be dated in order to obtain reliable results (e.g., Mercier et al. 1995). Therefore, determining this information with other techniques is archaeologically valuable.

Magnetic methods are not new to this aim and different approaches have been proposed. Linford and Plaztman (2004) proposed a method to estimate heating temperatures applying a linear unmixing model based on the correlation observed between the maximum exposure temperature recorded in experimentally burnt sediments and the hysteresis properties. Hrouda et al. (2003) used progressive susceptibility *versus* temperature measurements as palaeotemperature indicator quantifying magnetomineralogical changes induced during laboratory heating. In essence, this approach does not differ substantially from that proposed by Spassov and Hus (2006). These authors performed several rock magnetic analyses on Roman kiln samples and tested the results with a thermal conductivity model. In both cases, the basic assumption relies on the fact that if a sample was heated in the past to a given temperature, it should not show mineralogical alterations when heated again until that temperature under similar conditions in the laboratory. A similar approach using the reversibility of thermomagnetic curves combined with other rock magnetic measurements and petrographic and dielectric analyses was tested on prehistoric potsherds from Venezuela by Rada-Torres et al. (2011).

Here we use an alternative approach based on the stepwise thermal demagnetization of the NRM of oriented samples. Many prehistoric fireplaces do not reach temperatures high enough (600 – 700 ºC) to acquire a full TRM. In theory, any archaeological material heated to temperatures below the Curie temperature (T_C) of the ferromagnetic mineral present (e.g., magnetite T_C: 580 ºC; Dunlop and Özdemir 1997) is able to record the Earth´s magnetic field direction on cooling through the acquisition of a partial thermal remanent magnetization (pTRM). Regarding the carbonaceous facies of burnt anthropogenic cave sediments, this pTRM will partially reset the original magnetization recorded by the substrate which is supposed to be a depositional remanent magnetization or DRM recorded before any previous heating. Thus, two components of magnetization should be distinguished and progressive TH demagnetization of the NRM can be used to isolate both components. The highest temperature step at which the low temperature component is still present defines the last heating temperature.

Progressive TH demagnetization has been widely used in volcanic studies to distinguish emplacement mechanisms and the temperature of emplacement of pyroclastic flows, lithic clasts and other volcanic products (e.g., Kent et al. 1981; Bardot and McClelland 2000, Cioni et al. 2004; McClelland et al. 2004; Porreca et al. 2007). Its application to various archaeological materials of different age has also been investigated (e.g., Gose et al. 2000; Brown et al. 2009; Herries 2009). However, to our knowledge, this method has not been yet tested in burnt anthropogenic cave sediments.

4.2. Results and discussion

Figure 6(a-f) illustrates representative examples of TH demagnetization diagrams of the NRM from carbonaceous samples from different Holocene burning events from El Mirador, Portalón and El Mirón Cave (Spain; Fig. 1). These burning events have previously been studied for archaeomagnetic purposes (Carrancho et al. 2013). However, the objective here is to illustrate how the identification of pTRMs permits the estimation of the last heating temperature in the carbonaceous facies of these fires.

After removing a low temperature component probably of viscous origin (< 150 – 200 ºC), an intermediate component of normal polarity between 200 – 250 ºC and 400 – 450 ºC is systematically observed (Fig. 6a-f). Finally, a high temperature (HT) component can also be distinguished between about 400 – 600 ºC. The estimation of the ancient heating temperature is based on identifying the maximum unblocking temperature (max T_{UB}) of the pTRM. This is at about 400 - 450 ºC where the intermediate magnetization component switches the direction (highlighted with grey ellipses in Fig. 6).

The fact that the intermediate magnetization component (pTRM) lies along the Earth´s magnetic field direction showing normal polarity is the basic principle of this technique. The HT component is of normal polarity and predates the pTRM component. It represents the Earth´s magnetic field direction originally recorded by the archaeological surface during its formation and on which subsequently the burning took place. The remanence associated to the HT component would be detrital (DRM). During the heating, a portion of its original remanence with unblocking temperatures (T_{UBS}) less than or equal to the maximum temperature heating underwent by the carbonaceous facies (*ca*. 400-450 ºC; Fig. 6) was replaced by the pTRM acquired on cooling. Under the proviso that the materials remains undisturbed (*in situ*) after burning, the progressive TH demagnetization of the NRM may yield the heating temperature. Occasionally we have observed that the HT component is randomly oriented (e.g., Fig. 6f). This might be explained if before heating, the substrate was for whatever reason reworked (e.g., some kind of intentional preparation of the surface). Such reworking would necessarily be produced before heating because the pTRM direction is northward and again showing max T_{UB} between 400 – 450 ºC. We are currently trying to reproduce this effect experimentally in order to verify this hypothesis.

The palaeomagnetic estimation of the heating temperature in carbonaceous samples requires that the intermediate magnetization component is of thermal origin. If it results from another mechanism of magnetization such as viscous remanent magnetization (VRM) or chemical remanent magnetization (CRM) the temperature assessment may be erroneous. In “geologically” young materials like these (~ 5-2 ky BC) and considering that the main carrier is PSD magnetite, the intermediate component with max T_{UB} of about 400 – 450 ºC is highly unlikely to be due to a viscous overprint. That is not compatible with the time-temperature nomograms for magnetite (Pullaiah et al. 1975). The possibility of a CRM is more difficult to prove because it can be derived from the formation of a new magnetic phase or the growth or shape change of a pre-existing one (Dunlop and Özdemir 1997). These are preliminary data and further experiments are being carrying out in order to verify it. It should be noted, however, that Q_n ratio values of all carbonaceous samples but one (Fig. 6f), are over unity suggesting a pTRM origin of the magnetization. This has been tested with partial thermomagnetic curve experiments as we outline below.

Partial thermomagnetic curves of a carbonaceous sample adjacent to the specimen P2-01 (Fig. 6b) were carried out in order to study its thermomagnetic reversibility following Hrouda´s et al. (2003) method to estimate palaeotemperatures. A complete thermomagnetic curve of this sample is irreversible (heating and cooling cycles do not coincide) when heated up to 700 ºC (Fig. 7a). In order to study at which temperature step magnetic alteration begins, partial thermomagnetic runs were carried out on another (sister) powdered sample (~ 350 mg) in 50 ºC incremental steps from 200 ºC to 550 ºC (Fig. 7b-h). As expected, the heating and cooling cycles exhibit high reversibility until 400 - 450 ºC (Fig. 7b-f). However, when the sample is heated in the laboratory over 500 ºC (Fig. 7g-h), the magnetization during the cooling cycle considerably increases because mineralogical transformations take place (formation of secondary magnetite). Consequently, the sample loses its thermomagnetic reversibility. This alteration can be quantitatively estimated as $A_{30} = 100\ (j_{30} - J_{30})/\ J_{30}$, where j_{30} and J_{30} are the magnetization on the cooling and heating curves at 30 ºC, respectively (Hrouda et al 2003). In this case study, the alteration starts at 450 – 500 ºC, reaching a maximum at 550 ºC (Fig. 7i). These results agree well with the maximum T_{UB} temperatures determined for the carbonaceous sample P2-01 (Fig. 6b) and are a solid indication that the intermediate magnetization component is a pTRM.

As far as the ashes are concerned, these most likely reached temperatures over 600 – 700 ºC, which has been shown in our previous studies (Carrancho et al. 2009; 2012, 2013). Ashes from this type of fire are characterized by high NRM intensities (one order of magnitude higher than carbonaceous or more), Q_n ratios > 1, stable and univectorial NRM demagnetization diagrams and full reversibility in thermomagnetic curves. The thermomagnetic curves of the ashes shown in Fig. 3a-b (case study 1) are a good example of this kind of behaviour. This is logical since ashes are the last residue of combustion and the underlying carbonaceous facies represents the fire-altered topsoil on which the fire was performed. The carbonaceous facies do not differ substantially from the “black layer” studied by Mallol et al. (2013) in Middle Palaeolithic and experimental fires. In essence, both are blackened layers rich in charcoal remnants and organic matter. Our heating temperatures determined with paleomagnetic analyses are very similar to those reported by Mallol et al. (2013) from a series of actualistic fire experiments. Canti and Linford (2000) also reported temperatures of around 400 ºC on the substrate beneath ashes exceeding 800 ºC and Carrancho and Villalaín (2011) and Calvo-Rathert et al. (2012) monitored temperatures of around 350 ºC in the peripheral surface of an experimental fire. More dramatic colour changes could be seen depending on the original mineral composition and burning conditions. According to Mallol et al. (2013), the duration of heating and the amount of fuel used seem to be less important factors in the formation and preservation of this blackened layer as is the presence of organic matter. Indeed, burning of organic matter is necessary to promote the formation of magnetite under prevailing reducing conditions (Carrancho et al. 2009). In any case, the palaeomagnetic evidence presented here indicates that this facies systematically underwent heating temperatures up to 400 – 450 ºC.

The application of this method differs depending on the nature of the archaeological material studied. In contrast to sediments as studied here, rocks commonly located around archaeological fireplaces have their previous (geological) magnetization. In such a case, an eventual pTRM should also record normal polarity if the rocks are *in situ*. However, HT component should exhibit a random direction corresponding to the original remanence acquired during the rock´s genesis. Good examples of this are published using experimental and archaeological materials (e.g., Gose 2000; Herries 2009). The usefulness of the palaeomagnetic method for determining heating temperatures in burnt anthropogenic cave sediments is certainly of high value for the archaeologists.

5. Case study 3: Assessment of post-depositional processes

5.1 Background

Identifying potential syn/post-depositional processes in archaeological cave fires and evaluating their degree of alteration is relevant because if these processes are severe enough, there are significant implications for the cultural interpretation of a site. Depending on the degree of alteration, these processes can cause displacement or dispersion of artefacts within the stratigraphy over distances of millimetres to centimetres or even meters. Other effects involve fragmentation of bone and lithic remains, mixing of burnt and natural sedimentary components and in the most extreme cases, the complete homogenization of the sediment. The implications of these processes are not only cultural but also chronological. Some authors have noted the importance of collecting samples for thermoluminiscence (TL), optical stimulated luminescence (OSL) and electron spin resonance (ESR) dating from undisturbed areas showing the least evidence of mineralogical change (e.g., Mercier et al. 1995; Bateman et al. 2007). The measurements of the radiation dose-rates can be seriously affected and not accurately reflect the dose-rates prevailing in the past. It is easy to understand the significant consequences derived from the correct assessment of the degree of alteration caused by these processes in terms of establishing a reliable age determination.

Regardless of whether the responsible agent is anthropogenic, biogenic or geogenic (see Goldberg and Sherwood 2006 for a good synthesis), syn/post-depositional processes in cave fires can be generally grouped as physical and/or chemical. The latter imply mineralogical changes and diagenesis in general. Particularly, ash diagenesis from archaeological cave fires has been extensively studied over recent years with diverse techniques such as soil micromorphology, Fourier transform Infrared spectrometry (FTIR), geochemistry or scanning electron microscopy, among others (e.g., Weiner et al. 1993; 2002; Karkanas 2010; Bull and Goldberg 1985). Particularly interesting are some studies carried out on Middle Palaeolithic sites establishing a diachronic sequence of diagenetic alteration of calcite, the major component of wood ashes (e.g., Schiegl et al. 1996; Weiner et al. 1993, 2002). However, burnt anthropogenic cave sediments (and combustion features in general) are susceptible not only to diagenesis but also to reworking. That is, mechanical disturbances of the burnt sedimentary facies. Mechanical reworking of cave fires has been traditionally addressed through simple macroscopic or field observations. The absence of some of the facies composing these fires (rubefied sediment, charcoal and ashes), absence of their lateral continuity or mixing of burnt and unburnt material are the main criteria used. Recently, Mentzer (2014) detailed a comprehensive description of the main features characteristic of reworked combustion structures both at macro and microscale. The palaeomagnetic technique has been recently proposed to evaluate mechanical post-depositional processes in archaeological cave fires (Carrancho et al. 2012). This case study aims to test the reliability of the method determining to what extent the mechanical reworking might have affected a partially bioturbated Late Holocene burning event from El Portalón Cave (Burgos, Spain; Fig. 8).

5.2. Results and discussion

Representative examples of NRM demagnetization diagrams corresponding to ashes from different parts of the structure are shown in Fig. 8. Thermal demagnetization of a carbonaceous specimen from this event is shown in Fig. 6a (P3-16; Fig. 8) and whose characteristics are reported in section 3.2.2 (case study 2).

The NRM demagnetization diagrams of specimens to the right side of the burrow (Fig. 8a-b) exhibit an anomalous and unstable directional behaviour. Q_n ratio values are not greater than 1 and initial magnetization intensities (NRM_0) are one order of magnitude lower than those from pure white ashes. On the contrary, NRM demagnetization plots to the left of the burrow (Fig. 8c-d) are defined by a stable single palaeomagnetic component, around 10 times more magnetic than carbonaceous samples, displaying high Q_n ratio values and reproducible directions among them. The main magnetic carrier is a low-coercivity mineral as the normalized decay intensity plots indicate. According to thermomagnetic curves this mineral is low-Ti titanomagnetite or partially maghaemitized magnetite with Curie temperatures of around 580 ºC – 600 ºC (Fig. 9a-c). Maghaemite might be responsible of the inflection observed at about 310 ºC in Fig. 9b, although it could also be due to change of grid structure.

Even when these structures were partially affected by bioturbation, it is still possible to evaluate whether mechanical reworking extends beyond the visual alteration originally observed in the field in order to exclude those samples for calculating the mean archaeomagnetic direction. The quality selection criteria established by Carrancho et al. (2013) to obtain a reliable mean direction in these fires are related to the following factors: (i) a good preservation of the structure (presence of all the sedimentary facies for each burning event, meaning ashes over underlying carbonaceous facies), (ii) the intensity of the burning with regard to the quantity of fuel employed (ash thickness) and (iii) an efficient record of the magnetization (Koenigsberger ratio values greater than 1 and a majority of demagnetization diagrams with univectorial NRM among the ashes).

The results in this study are very similar to those reported by Carrancho et al. (2012) where the magnetic behaviour of two different burning events from El Mirador cave (one strongly bioturbated and other apparently *in situ*) was analysed and compared. It is evident that samples showing anomalous magnetic behaviour were reworked by the effect of bioturbation. However, the interesting fact as this case shows is that adjoining areas to the bioturbation may also suffer from reworking and in many cases this effect cannot be easily distinguished in the field. Although in this case it did not imply movement of archaeological remains in the stratigraphy (fumiers are usually not rich in archaeological materials), special care must be taken during the excavation of these fires. Archaeostratigraphic 3D projections of coordinated artefacts (e.g., pottery, lithic remains) can be particularly useful for a proper archaeological interpretation.

From the magnetic point of view, a useful parameter with regard to TRM preservation is the Q_n ratio. Koenigsberger values for this collection are between 1 and 7.3 (Fig. 10) whereas two out of three samples with values < 1 correspond to ashes from the reworked side (e.g., Fig. 8b). The other is a carbonaceous sample. On the basis of these results, the relationship between the *in situ* nature of the structure and the preservation of the TRM is obvious. Mechanical reworking promotes the disorganization of the magnetic moments of the ferromagnetic grains reducing the remanence but maintaining the bulk magnetic susceptibility. As this parameter does not depend on the orientation of the magnetic grains (excluding the anisotropy), the direct consequence is that the TRM is lost and Q_n values become considerably reduced. Moreover, the multicomponent NRM structure of reworked samples is also indicative of alteration along with lower magnetization values. Carrancho et al. (2012) have described the importance of combining these analyses with macroscopic field observations such as determining the lateral continuity of the facies, absence of sedimentary mixtures, etc.

No significant differences in terms of magnetic composition or domain state variation are observed between *in situ* and reworked ash samples from the rock magnetic experiments carried out. The backfield ratios obtained oscillates between 15.79 and 22.94 mT without distinctive differences between both types of samples. The hysteresis ratios obtained range from 0.116 < Mrs/Ms < 0.170 and 2.645 < Bcr/Bc < 4.380 (Fig. 11a), indicating a pseudo-single domain (PSD) state for the magnetite grains, which suggests that the granulometric distribution of both the *in situ* and reworked ashes is quite similar. This homogeneity in magnetic properties can also be observed in the representative hysteresis loops shown in Fig. 11(b-c) and similar results were reported in analogous studies (Carrancho et al 2009, 2012; Kapper et al. 2014a,b).

Summarizing, it is of primary importance for archaeomagnetic dating purposes to determine the *in situ* nature of a cave fire if only directional analyses are carried out. Magnetic orientation for archaeointensity determinations is not indispensable, although the material cannot be disaggregated. For archaeologists, the concept of "*in situ*" does not necessary mean the same as for archaeomagnetists. The latter look for burnt materials that preserve exactly the same position as they had when cooled. Any post-depositional movement, no matter how minimal, may have significant effects in the archaeomagnetic results. Archaeologists usually consider that a combustion feature remains *in situ* as long as artefacts or sediments do not experience significant stratigraphic movements which may compromise the cultural interpretation of the record. Using the above guidelines and when possible combining this information with that provided by other disciplines (e.g., micromorphology and FTIR) is the best way to infer the primary or secondary position of an archaeological combustion feature.

6. Conclusions

Three applications of archaeo- and rock magnetism to the study of burnt anthropogenic cave sediments have been reported in the following case studies: (i) archaeomagnetic dating; (ii) estimating palaeotemperatures and (iii) evaluating post-depositional processes.

Case study 1: A mean archaeomagnetic direction was obtained from a burning event at El Mirador Cave. Its comparison with the directional European SV curve yielded several dating intervals. According to archaeological evidence, the most likely date of the last burning was 1651 – 1520 yr BC (95 % of confidence), slightly older than an independent radiocarbon date from this unit but both are archaeologically consistent. The agreement of the two dating methods reveals the potential of anthropogenic burnt cave sediments as geomagnetic field recorders as well as the possibility to be dated by archaeomagnetism. These data represent the first archaeomagnetic dating obtained in this type of materials.

Case study 2: Stepwise thermal demagnetization of the NRM of oriented carbocaneous samples is a useful method to estimate the last heating temperature. These samples show an intermediate palaeomagnetic component of normal polarity that we interpret as a pTRM with maximum unblocking temperatures of 400 – 450 ºC, representing the last heating temperature. These temperatures agree well with those obtained from partial thermomagnetic analyses.

Case study 3: The archaeomagnetic analysis of a burning event partially bioturbated allowed to obtain a comparative characterization of the magnetic behaviour of *in situ* samples against reworked samples. The latter showed low NRM intensities (at least one order of magnitude), Q_n ratios < 1 and multicomponent nature of NRM along with anomalous directions. Mechanical reworking extends beyond the deformation which one can visually identify in the field. Therefore, special care must be taken when excavating these features in order to interpret correctly the primary position of the materials.

As a concluding remark, archaeomagnetic analyses on burnt anthropogenic cave sediments have a great potential not only from the geophysical point of view (reconstructing directional and/or intensity changes of geomagnetic field in the past) but also for archaeological purposes. We encourage our colleagues to work on this type of materials promoting multidisciplinary collaboration.

Acknowledgments

This work was funded by the Spanish Ministry of Economy and Competitiveness (MINECO projects CGL2012-32149 and CGL2012-38481). Special gratitude is devoted to the archaeological teams involved in the excavation of these sites by their efforts and much help in field work.

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Figure captions:

Figure 1

(a-b) Photographs showing the studied burning event with the location of the samples. The plan and section view of Mirador Cave showing the survey pit where Ci1 is located (sector 100). The location of the three caves studied is shown in the map: 1, 2 (El Mirador and Portalón Caves, Sierra de Atapuerca, Burgos) and 3 (El Mirón Cave, Cantabria).

Figure 2

Four normalized progressive isothermal remanent magnetization (IRM) acquisition of representative ash and carbonaceous samples from the Ci1 burning event. Maximum field = 1 T.

Figure 3

(a-c) Representative thermomagnetic curves (magnetization *vs*. temperature) of two ashes and a carbonaceous sample from Ci1 burning event (El Mirador Cave). Heating (cooling) cycles are plotted in red (blue) with their respective arrows. Sample code, facies and magnetization intensity values and the T_C are indicated.

Figure 4

(a-f). Representative orthogonal NRM demagnetization plots from the Ci1 burning event. Solid (open) circles show projections of vector endpoints onto the horizontal (vertical) plane. The sample code, facies, intensity (NRM_0), Koenigsberger (Q_n) ratio and normalized demagnetization spectra are shown for each sample. AF = alternating field; TH = thermal. (f) Equal area projection of all ChRM directions with the mean direction and α_{95} confidence circle. N = number of samples; Dec = declination; Inc = inclination; k = precision parameter and α_{95} = semi angle of confidence.

Figure 5

Probability-of-age density functions (95 % of confidence) obtained for the Ci1 burning event with the Matlab tool from Pavón-Carrasco et al. (2011) for declination and inclination values using the European directional secular variation curve (Carrancho et al. 2013).

Figure 6

(a-f) Orthogonal NRM demagnetisation plots of representative carbonaceous samples from different burning episodes of (a-b) El Portalón cave, (c-d) El Mirón cave and (e-f) El Mirador Cave. Symbols are as in Fig. 4. The final steps of the diagrams are blown up to denote the presence of a high-temperature component. The maximum unblocking temperatures (max T_{UB}) of the partial thermoremanent magnetization (pTRM) are within grey ellipses indicating the heating temperatures. Dec (declination) and Inc (inclination) of the pTRM component are shown for each diagram.

Figure 7

(a) High-temperature thermomagnetic curve up to 700 ºC of the carbonaceous sample P2-22 (sister sample of P2-01; Fig. 5b) from El Portalón Cave. (b-h) Progressive thermomagnetic curves in 50 ºC incremental steps from 200 ºC to 550 ºC carried out on additional sample from P2-22 specimen. The starting magnetization intensities (heating values at 30 ºC, J_{30}) are indicated for each graph. Symbols are as in Fig. 3. (i) Histogram showing the variation in the alteration index of individual heating/cooling runs of P2-22 sample following Hrouda´s et al. (2003) method.

Figure 8

Representative orthogonal NRM demagnetization plots of a partially bioturbated burning event from El Portalón Cave. (a-b) Diagrams of two ashes showing anomalous behaviour. Note how ashes from the right part of the photo are somewhat mixed. (c-d) Diagrams of two ashes from the central-left part (in situ). Symbols are as in Fig. 4 and 6. See section 5 for explanation.

Figure 9

(a-c) Representative thermomagnetic curves (magnetization *vs*. temperature) of two ashes and a carbonaceous sample from P3 burning event (El Portalón Cave). Symbols are as in Figure 3.

Figure 10

Natural remanent magnetization (NRM) *vs*. bulk magnetic susceptibility (S.I.) showing lines of constant Koenigsberger ratio (Q_n) between 0.1 and 100 for the P3 burning event samples (see legend).

Figure 11

(a) Day-Dunlop logarithmic plot (M_{rs}/M_s *vs*. H_{cr}/H_c) plot of representative *in situ* and reworked ash samples from P3 burning event (Fig. 8). The dashed lines represent mixing curves taken from Dunlop (2002) for mixtures of single-domain (SD) with multidomain (MD) or superparamagnetic (SP) magnetite particles. (b-c) Two representative hysteresis loops of an *in situ* and a reworked ash, respectively, showing main hysteresis parameters.

Figure 1
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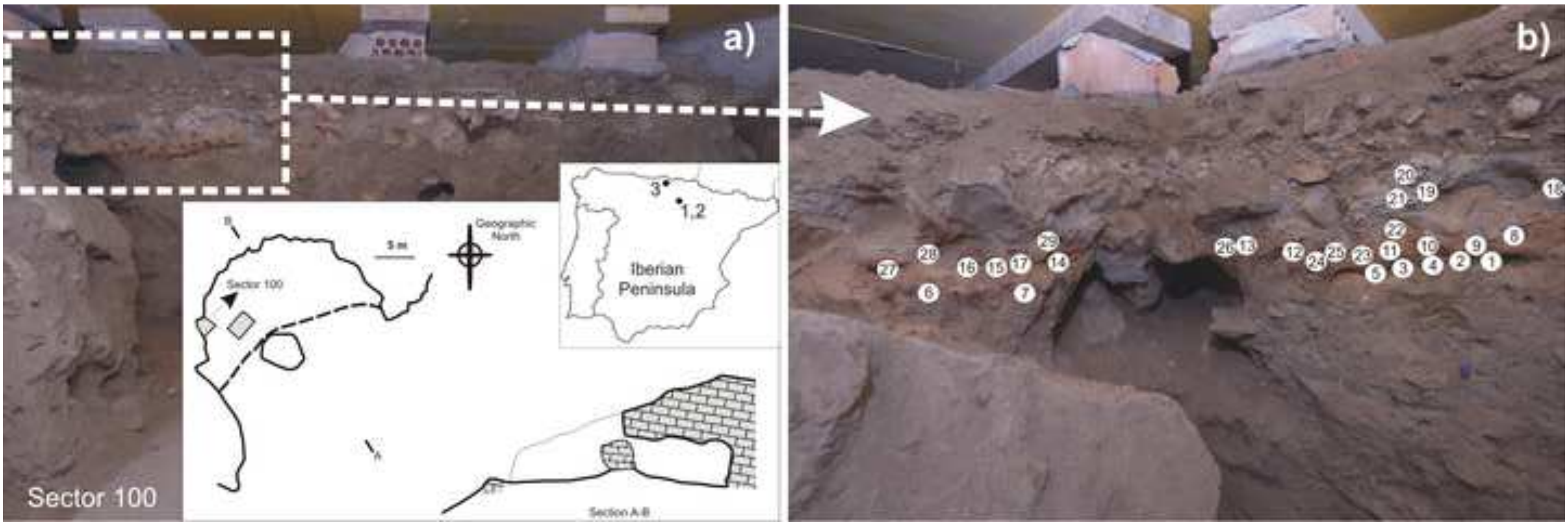
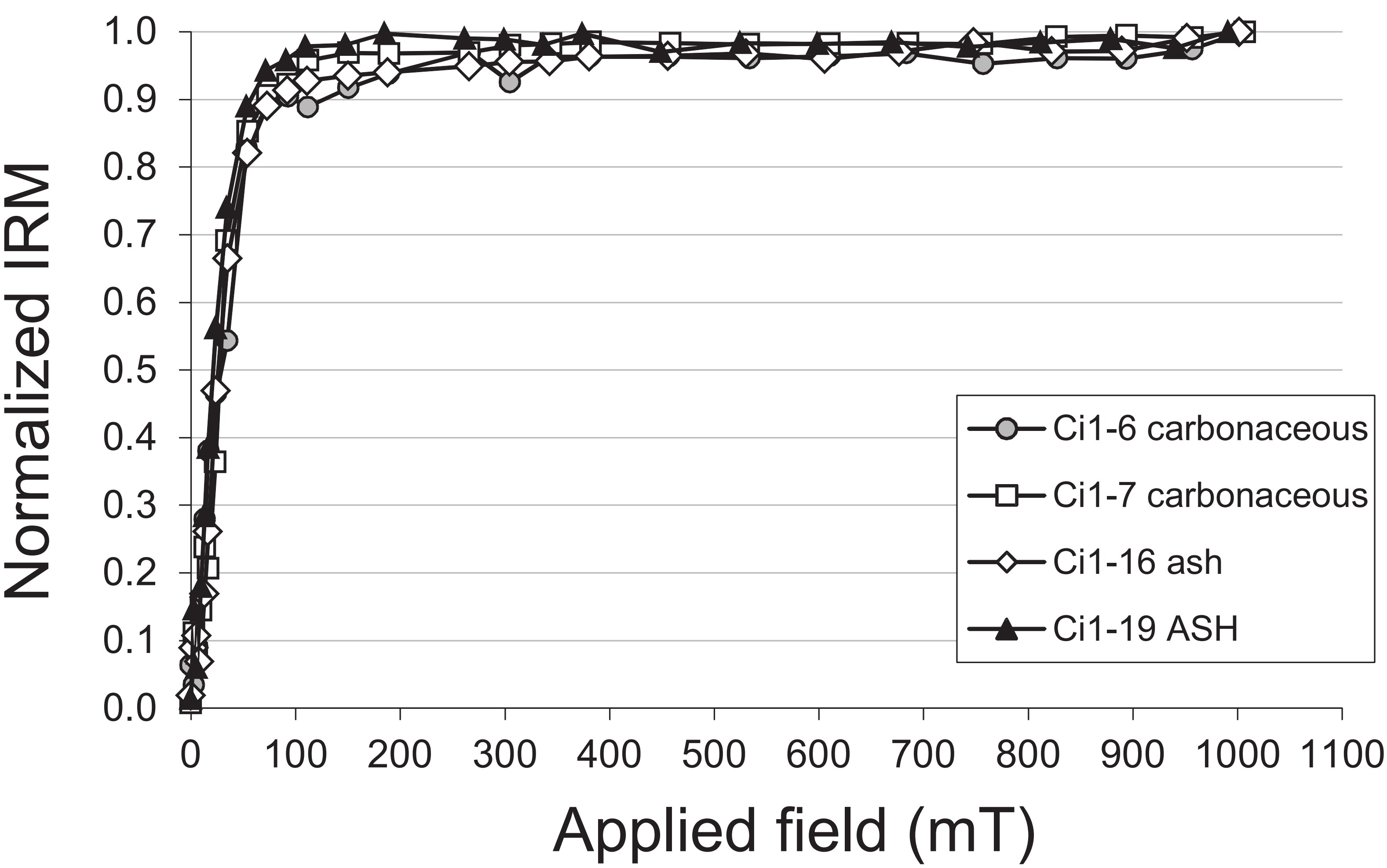


Figure 2



Normalized IRM
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
500
600
700
800
900
1000
1100
Applied field (mT)
Ci1-6 carbonaceous
Ci1-7 carbonaceous
Ci1-16 ash
Ci1-19 ASH

Figure 3

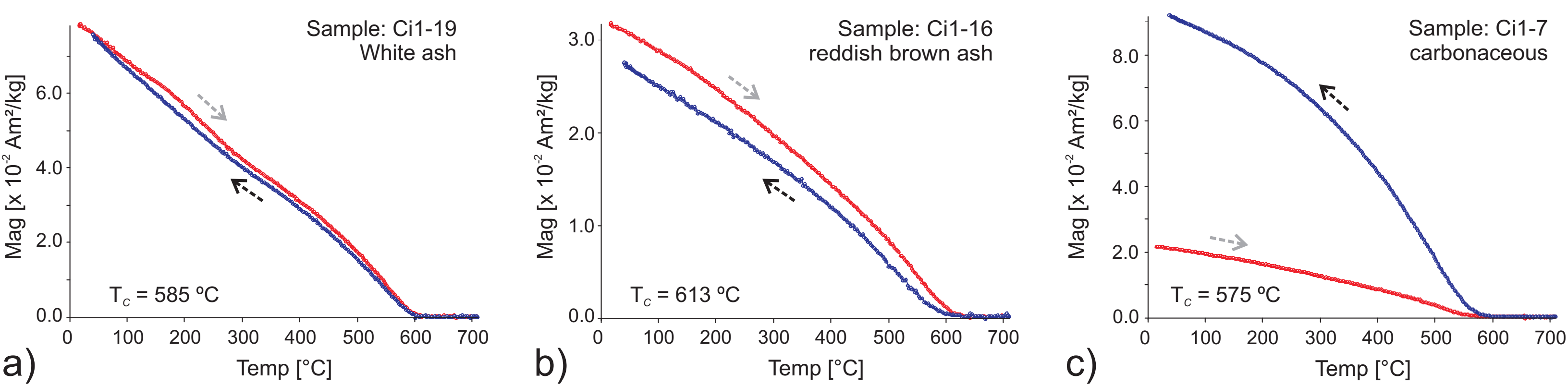
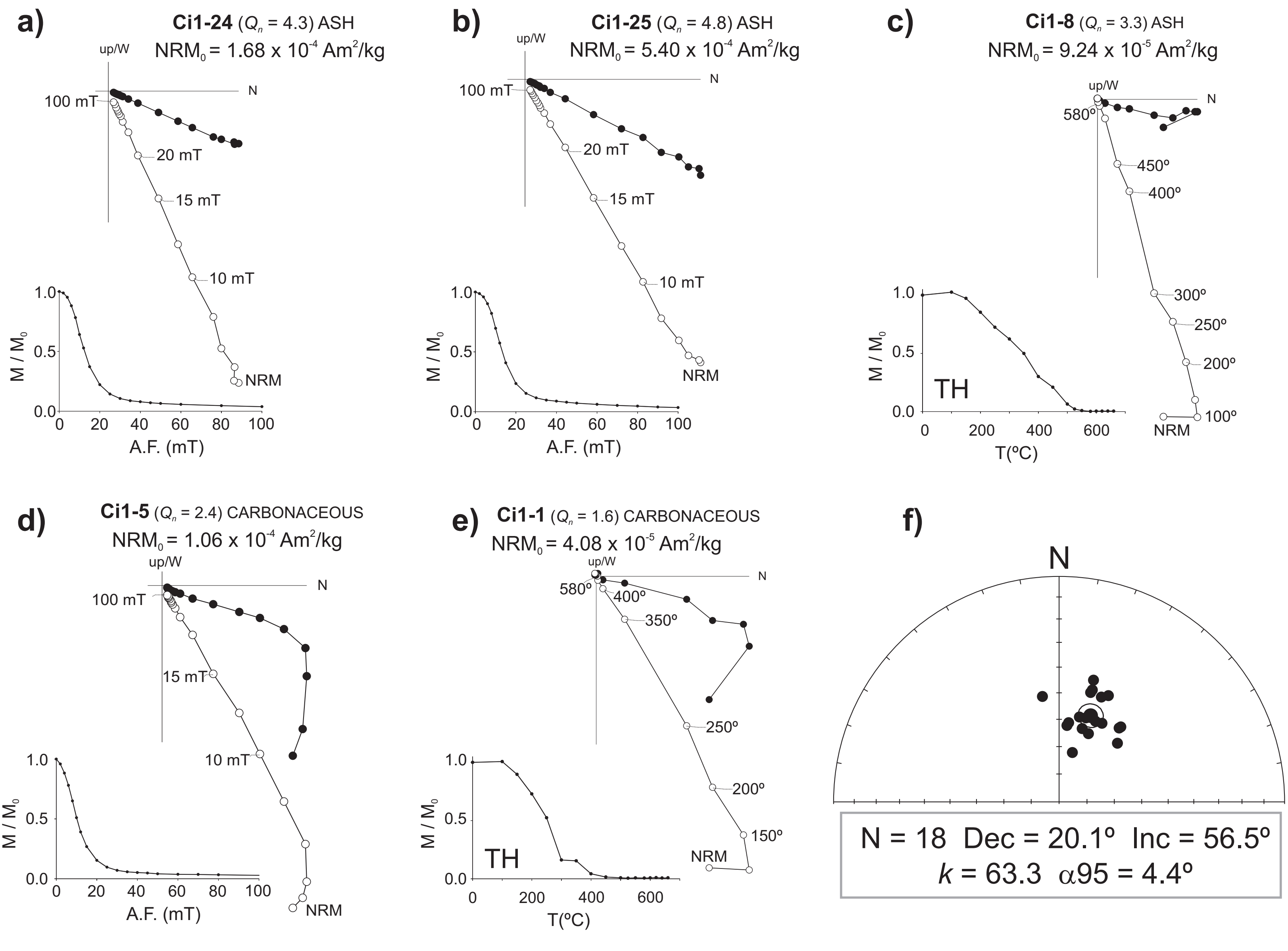

Sample: Ci1-19
White ash
T_c = 585 ºC
Mag [x 10^-2 Am²/kg]
Temp [°C]
a)
Sample: Ci1-16
reddish brown ash
T_c = 613 ºC
Mag [x 10^-2 Am²/kg]
Temp [°C]
b)
Sample: Ci1-7
carbonaceous
T_c = 575 ºC
Mag [x 10^-2 Am²/kg]
Temp [°C]
c)

Figure 4



a)
Ci1-24 (Q_n = 4.3) ASH
NRM$_0$ = 1.68 x 10^{-4} Am^2/kg
up/W
N
100 mT
20 mT
15 mT
10 mT
NRM
M / M$_0$
A.F. (mT)
b)
Ci1-25 (Q_n = 4.8) ASH
NRM$_0$ = 5.40 x 10^{-4} Am^2/kg
up/W
N
100 mT
20 mT
15 mT
10 mT
NRM
M / M$_0$
A.F. (mT)
c)
Ci1-8 (Q_n = 3.3) ASH
NRM$_0$ = 9.24 x 10^{-5} Am^2/kg
up/W
N
580º
450º
400º
300º
250º
200º
100º
NRM
TH
M / M$_0$
T(ºC)
d)
Ci1-5 (Q_n = 2.4) CARBONACEOUS
NRM$_0$ = 1.06 x 10^{-4} Am^2/kg
up/W
N
100 mT
15 mT
10 mT
NRM
M / M$_0$
A.F. (mT)
e)
Ci1-1 (Q_n = 1.6) CARBONACEOUS
NRM$_0$ = 4.08 x 10^{-5} Am^2/kg
up/W
N
580º
400º
350º
250º
200º
150º
NRM
TH
M / M$_0$
T(ºC)
f)
N
N = 18 Dec = 20.1º Inc = 56.5º
k = 63.3 α95 = 4.4º

Figure 5

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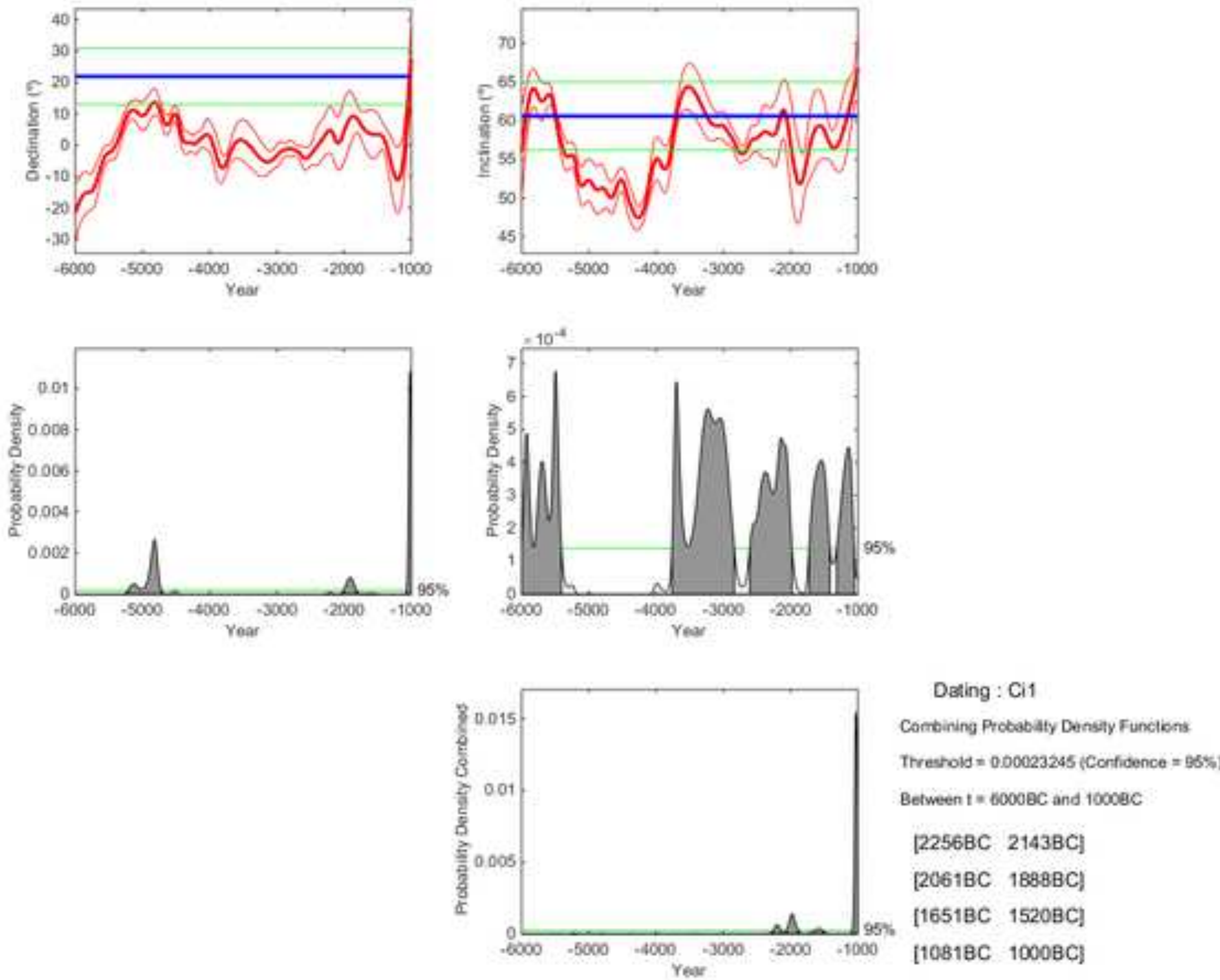
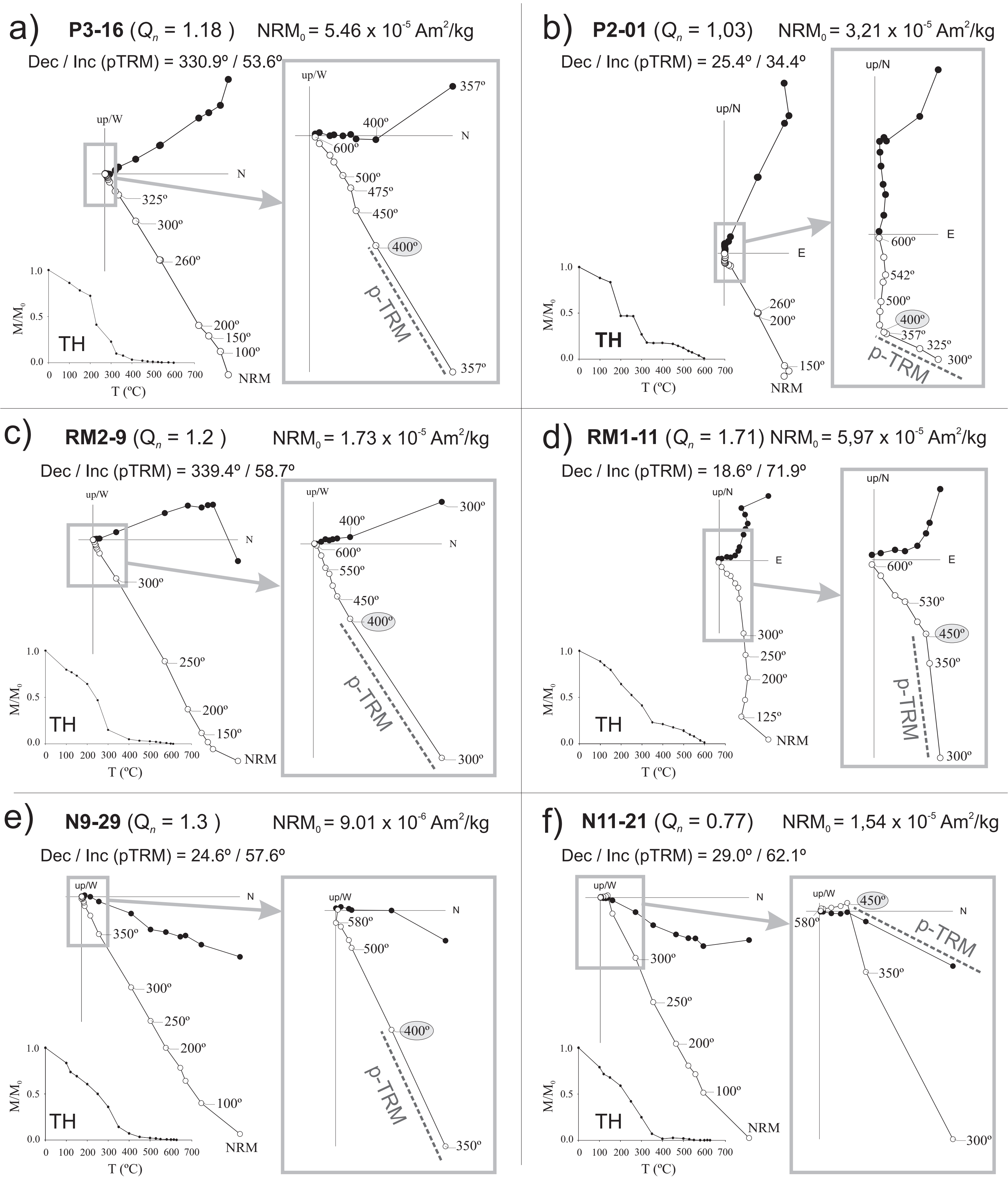
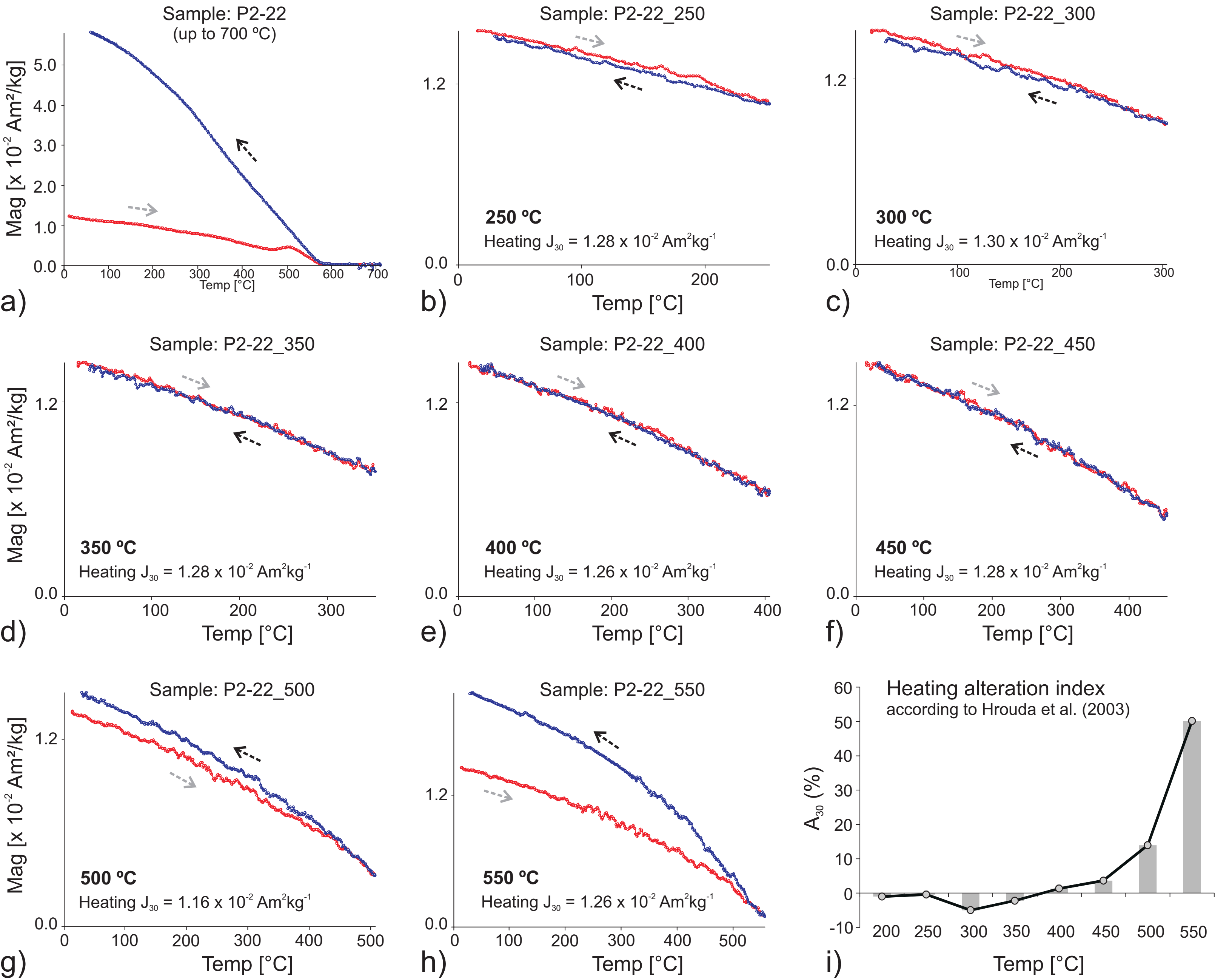


Figure 6



a) P3-16 (Q_n = 1.18) NRM$_0$ = 5.46 x 10^{-5} Am^2/kg
Dec / Inc (pTRM) = 330.9º / 53.6º
b) P2-01 (Q_n = 1,03) NRM$_0$ = 3,21 x 10^{-5} Am^2/kg
Dec / Inc (pTRM) = 25.4º / 34.4º
c) RM2-9 (Q_n = 1.2) NRM$_0$ = 1.73 x 10^{-5} Am^2/kg
Dec / Inc (pTRM) = 339.4º / 58.7º
d) RM1-11 (Q_n = 1.71) NRM$_0$ = 5,97 x 10^{-5} Am^2/kg
Dec / Inc (pTRM) = 18.6º / 71.9º
e) N9-29 (Q_n = 1.3) NRM$_0$ = 9.01 x 10^{-6} Am^2/kg
Dec / Inc (pTRM) = 24.6º / 57.6º
f) N11-21 (Q_n = 0.77) NRM$_0$ = 1,54 x 10^{-5} Am^2/kg
Dec / Inc (pTRM) = 29.0º / 62.1º
up/W
up/N
N
E
NRM
p-TRM
TH
M/M$_0$
T (ºC)

Figure 7



Sample: P2-22
(up to 700 ºC)
Mag [x 10⁻² Am²/kg]
Temp [°C]
a)
Sample: P2-22_250
250 ºC
Heating J30 = 1.28 x 10-2 Am2kg-1
b)
Sample: P2-22_300
300 ºC
Heating J30 = 1.30 x 10-2 Am2kg-1
c)
Sample: P2-22_350
350 ºC
Heating J30 = 1.28 x 10-2 Am2kg-1
d)
Sample: P2-22_400
400 ºC
Heating J30 = 1.26 x 10-2 Am2kg-1
e)
Sample: P2-22_450
450 ºC
Heating J30 = 1.28 x 10-2 Am2kg-1
f)
Sample: P2-22_500
500 ºC
Heating J30 = 1.16 x 10-2 Am2kg-1
g)
Sample: P2-22_550
550 ºC
Heating J30 = 1.26 x 10-2 Am2kg-1
h)
Heating alteration index
according to Hrouda et al. (2003)
A30 (%)
i)

Figure 8

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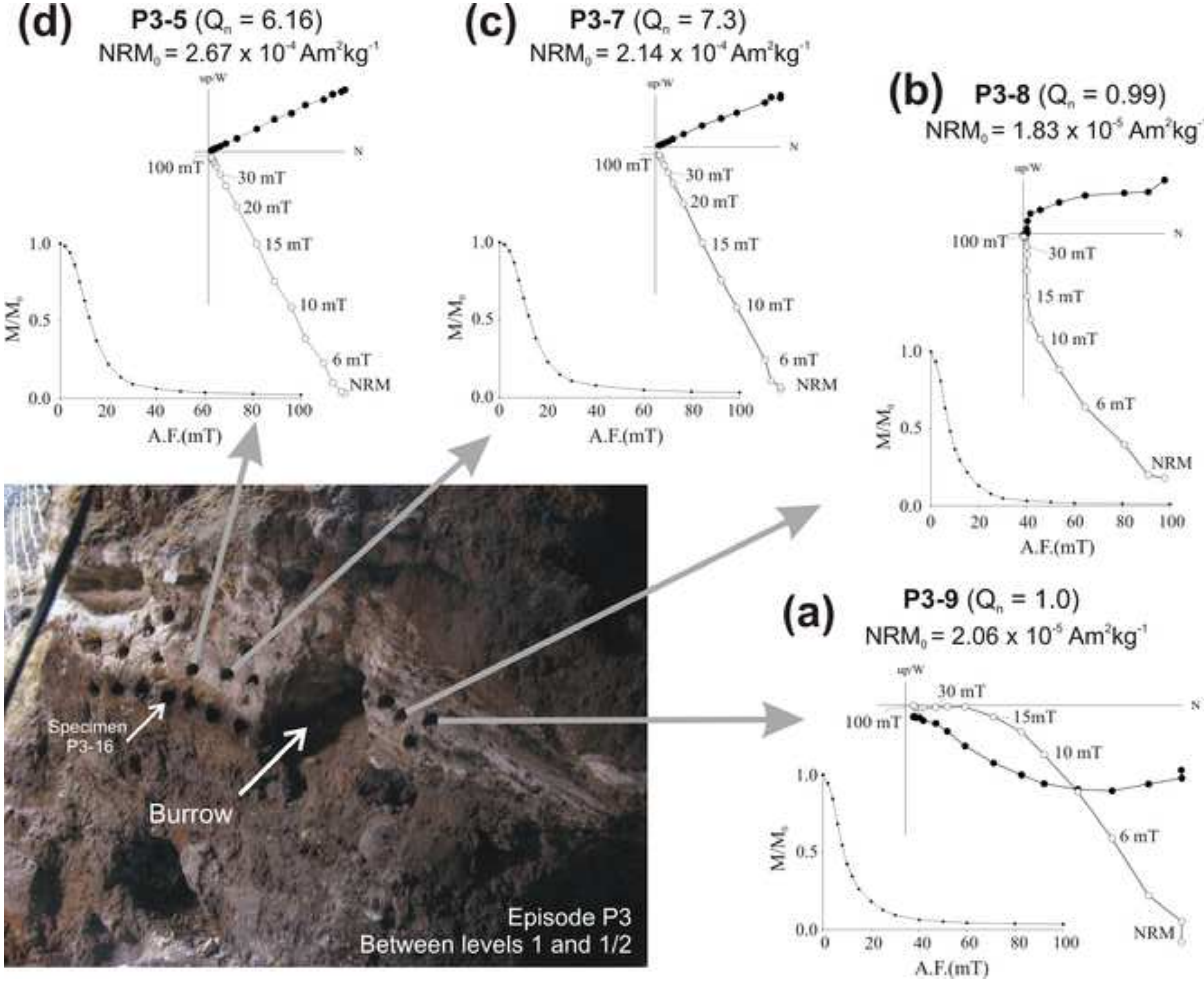
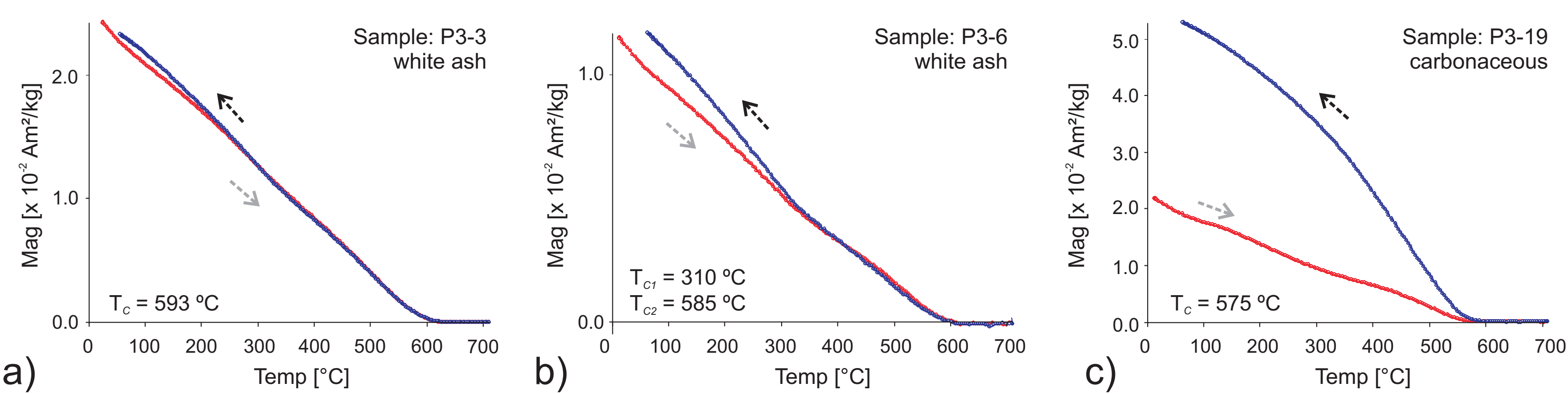
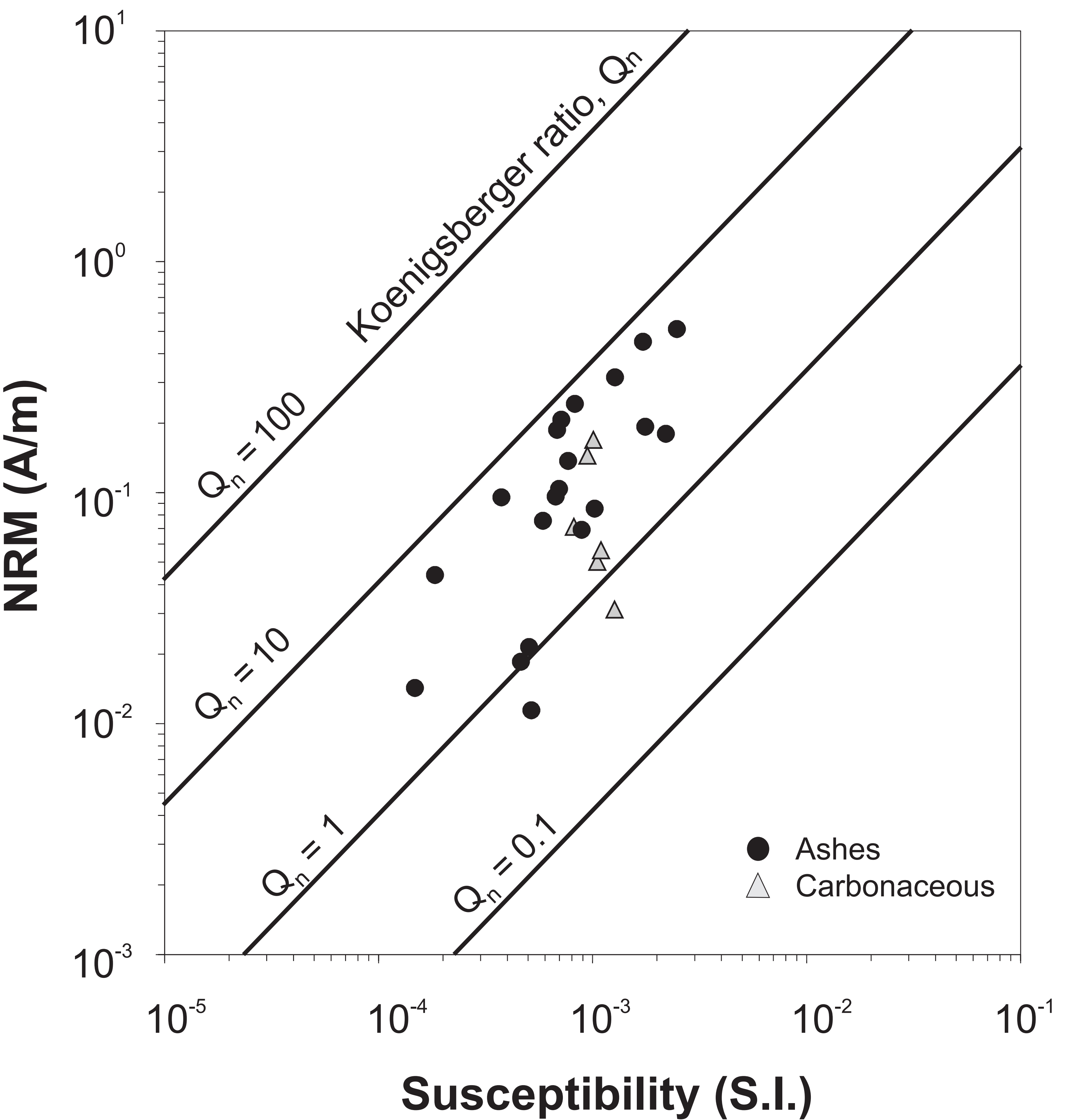


Figure 9



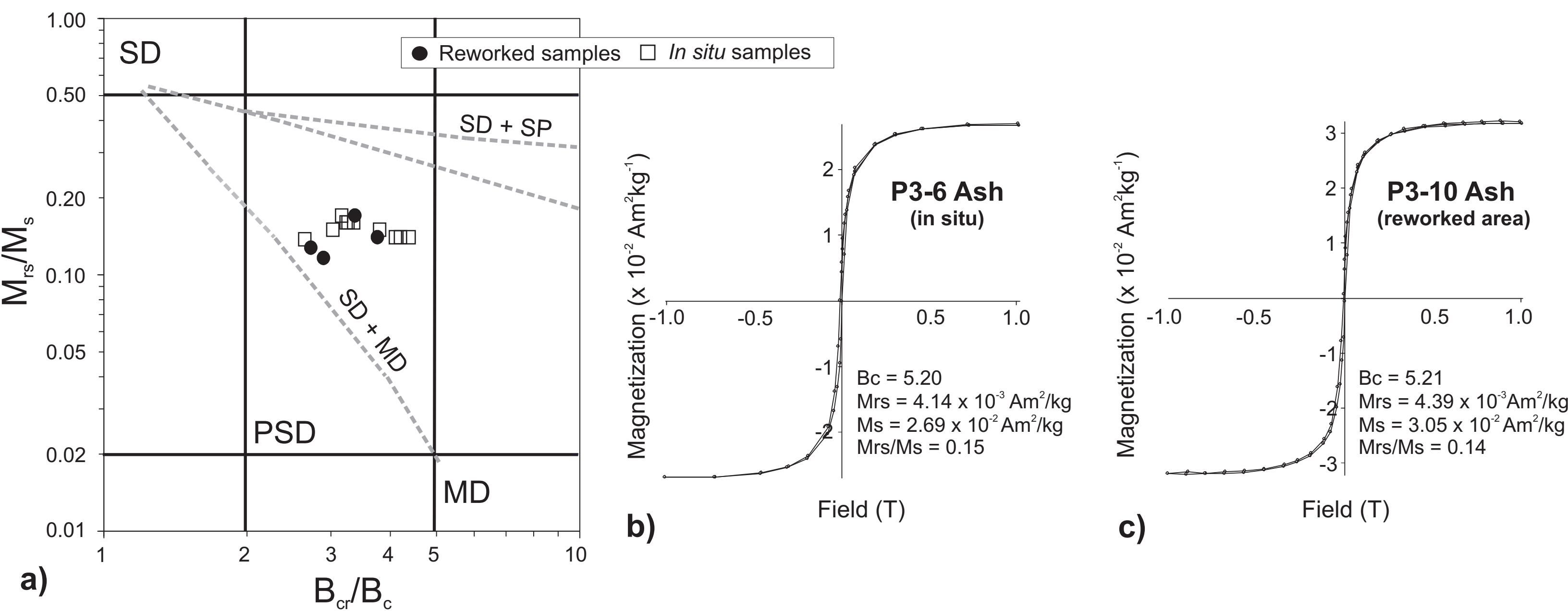
Sample: P3-3
white ash
T_C = 593 ºC
Mag [x 10⁻² Am²/kg]
Temp [°C]
a)
Sample: P3-6
white ash
T_{C1} = 310 ºC
T_{C2} = 585 ºC
Mag [x 10⁻² Am²/kg]
Temp [°C]
b)
Sample: P3-19
carbonaceous
T_C = 575 ºC
Mag [x 10⁻² Am²/kg]
Temp [°C]
c)

Figure 10



NRM (A/m)
Susceptibility (S.I.)
Koenigsberger ratio, Qn
Qn = 100
Qn = 10
Qn = 1
Qn = 0.1
Ashes
Carbonaceous
10^1
10^0
10^-1
10^-2
10^-3
10^-5
10^-4
10^-3
10^-2
10^-1

Figure 11



1.00
0.50
0.20
0.10
0.05
0.02
0.01
SD
Reworked samples
In situ samples
SD + SP
SD + MD
PSD
MD
M_{rs}/M_s
1
2
3
4
5
10
B_{cr}/B_c
a)
Magnetization (x 10^{-2} Am^2kg^{-1})
P3-6 Ash
(in situ)
Bc = 5.20
Mrs = 4.14 x 10^{-3} Am^2/kg
Ms = 2.69 x 10^{-2} Am^2/kg
Mrs/Ms = 0.15
Field (T)
b)
Magnetization (x 10^{-2} Am^2kg^{-1})
P3-10 Ash
(reworked area)
Bc = 5.21
Mrs = 4.39 x 10^{-3} Am^2/kg
Ms = 3.05 x 10^{-2} Am^2/kg
Mrs/Ms = 0.14
Field (T)
c)

***Detailed Response to Reviewers**

Detailed answers to reviewers' comments:

Reviewer #1: I have uploaded an annotated copy of the manuscript. The English needs work.
Corrections indicated by reviewer 1 have been introduced in the new version along with those complementary from reviewer 2. English has been carefully reviewed. Further details below.

I find that with three applications to sediments from four caves, with two caves being used for two applications, the possible significance is obscured by the complicated combination of application and sites.
The aim of this work is not to report data from specific sites, but rather show three different methodological applications to the study of burnt anthropogenic cave sediments. We simply report data from the sites that we have studied, which are three, not four. Sample provenance, age and nature are explained with enough detail for each case study. In any case, some sections and sub-sections within the manuscript have been reorganized, following also requirements of reviewer 2. Details are appended below.

The way of presenting three applications, with three sets of backgrounds, materials, methods, and results, is also confusing. Case 1 has no Methods or Results sub-sections. Case 2 has no Sampling or Methods sub-sections. Case 3 combines Sampling and Methods sub-sections.
This point was also been pointed out by ref. 2. We have followed the reviewers´ indications to reorganize the manuscript. Sampling details for the three cases studied are now in section 2.2 (sampling). All methodological details are indicated at section 2.3 (laboratory methods). Results for case 1 are in section 3.2.

The results of each individual application are not too compelling. Application1 gives just one archaeomagnetic date, even though many more samples were available. Then, application 3 is very similar to what was reported on in Carrancho et al. (2012), but on different samples, and without a particularly interesting result.
We really think that these results are interesting and convincing. Application 1 is the first archaeomagnetic dating carried out on this type of materials, what is already interesting. The range of uncertainty obtained is not ideal (although it does not depend on the number of specimens analysed), but the result is coherent with archaeological data and it is well justified. The case study 3 (post-depositional processes) is indeed methodologically similar to that reported by Carrancho et al. (2012), but that argument is no cause for criticism. The idea is to demonstrate in other case study the applicability of the method. This information may not be very relevant from the geophysical point of view but for the archaeologists it is interesting. The case study 2 (palaeotemperatures) provides useful information to reconstruct the technological conditions under which these burning events were carried out and in addition, it is also relevant for geochronological studies as we outline below. Moreover, it is methodologically interesting since it was tested (and verified) with two different magnetic methods.

Although the authors claim the potential significance for archaeology, they do not specifically indicate why their results, especially for applications 2 and 3, are in fact significant.-
Please, see answers above.

Specific comments to the PDF file (Reviewer #1):

General comment to the Editor: Suggestions of Ref. 1 about reorganizing the different sections have been followed. Minor changes or idiomatic corrections have been also introduced. Please, find below detailed answers to the most important specific questions raised by ref. 1. The location of the answers in the main text is indicated with respect to the page numbering of the new PDF.

2. Materials and methods

2.2 Sampling

Following also suggestions of reviewer 2 details about sampling for the three case studies are now integrated in this section.

- **Page 3, last paragraph: What do you mean by home-made?** (Regarding the use of plaster cubes for thermal demagnetization experiments). It means that the cubes were manufactured by ourselves. A reference about it has been added: Carrancho 2010.
- **Page 3, last paragraph: Doesn't the plaster dehydrate and crack apart during heating?** Thermal demagnetization of the NRM was a very time-consuming process requiring much effort to restore the specimens after every heating step applying plaster or eventually alumina cement. Cracking did not necessarily imply complete disaggregation of all specimens, although unfortunately three of them broke (said in 2nd paragraph, section 3.2.2). Recently we have started using quartz-cups to carry out thermal experiments.

- **Page 4, (section 2.2.1; sampling of case study 1): The date is not correctly reported: see** http://www.c14dating.com/publication
It has been corrected accordingly, including sample code and conventional radiocarbon age. We have also corrected the delta sign by the sigma one (it was a mistake): 2σ

- **Page 4, (section 2.2.1; sampling of case study 1): The location map should be cited earlier. Is the quality of the map good enough?**
The first cite to Fig. 1 in the main text has been checked and map quality has been improved, indicating also the location of the three caves studied (Fig. 1a).

3. Case 1: Archaeomagnetic dating

3.1. Background

- **Page 6, last paragraph: "***Archaeomagnetic dating has a typical accuracy of a few hundred years…***" (Ref.1: accuracy refers to precision? ca. +/- 100 years?)**
This sentence has been modified to facilitate its understanding. Now it reads: "*Archaeomagnetic dating has a typical range of error of a few centuries…*"

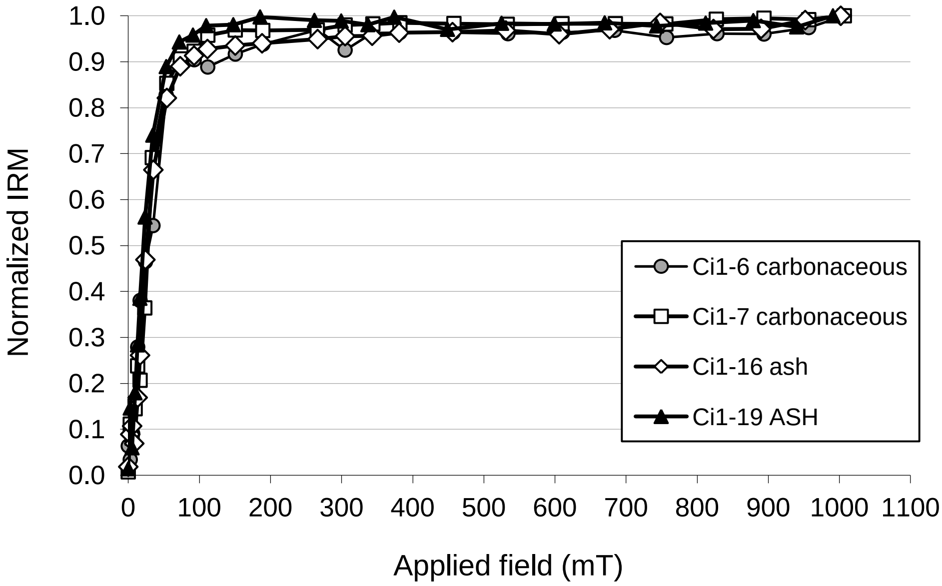
3.2. Results and discussion

3.2.1 Magnetic properties

- **Page 7 (1st paragraph section 3.2.1):** *"…These values agree well with others reported for similar materials (Carrancho et al. 2009, 2012; Kapper et al. 2014a,b) and indicates that the NRM is of thermal origin". **Ref.1:*** **do you mean that a strong NRM suggests a TRM rather than a possible DRM or CRM?**
We don´t say that. In burnt archaeological materials, high NRM values are expected if ferrimagnetic minerals (magnetite or maghaemite) are formed. These are the most magnetic minerals so if their concentration is increased by fire, the NRM will automatically increase. The NRM basically depends on the type and concentration of ferromagnetic minerals (*s.l.*). However, we were not taking about the NRM but the Koenigsberger ratio, Q_n. What is really indicative of a TRM is a high Q_n ratio (> 1 and preferably higher). The Q_n ratio provides a quick estimate of the 'efficiency' of the NRM acquisition mechanism based on the relationship between the induced and the remanent magnetization. Q_n ratio values for Ci1 event are between 1.6 and 19.6 (1st paragraph, section 3.2.1) and also visible in examples of Fig. 4. Q_n ratios values for case study 3 are mostly comprised between 1 and 10 (Fig. 10).

Other evidences given in the manuscript indicating a TRM origin of the NRM are reversible thermomagnetic curves (Fig. 3a and Fig. 9a) or univectorial NRM demagnetization diagrams (Fig. 4a-c or Fig. 8c-d) for ashes. Carbonaceous samples underwent lower heating temperatures (*ca*. 400-450 ºC) recording pTRMs (case study 2). This is well justified in the manuscript.

- **Page 7, last paragraph: "***A small fraction of a high-coercivity mineral (up to 5-10 %), most probably haematite, seems also to be present*". **Ref. 1: % of what, and how determined?**
  It refers to the relative contribution (%) of this phase to the total IRM or SIRM (Saturation of IRM at 1T). It´s now indicated. It is haematite because goethite should exhibit much higher coercivity. The percentage is easily quantified from the normalized IRM progressive acquisition curves. Please, see below the new figure 2 with four normalized progressive IRM acquisition curves for two carbonaceous samples and two ashes from Ci1 event. They are almost saturated at 150-200 mT. It is explained in the main text (2nd paragraph, section 3.2.1)



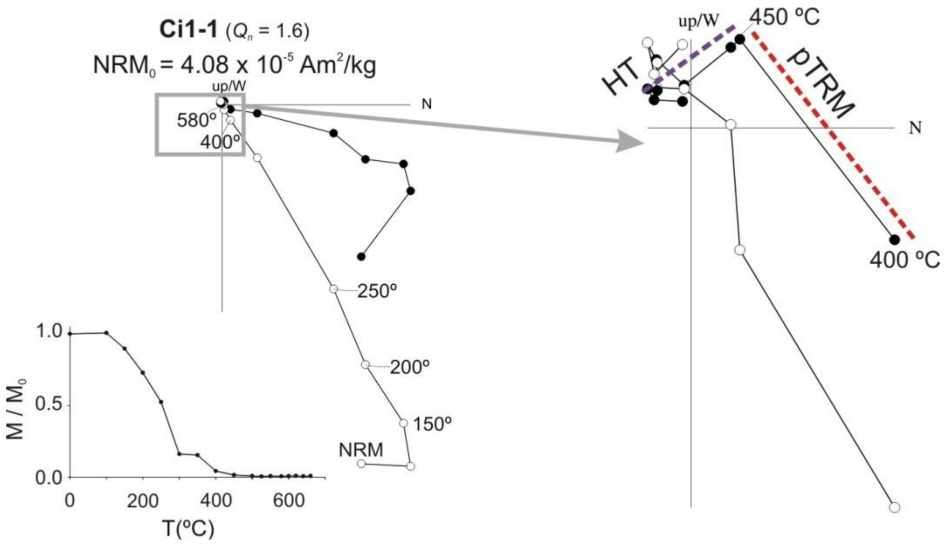
3.2.2. NRM directional stability and archaeomagnetic dating

- **Page 8, 1st lines section 3.2.2: "***Fig. 3 (a-f) illustrates representative… and the stereographic projection with all the individual Characteristic remanent magnetization (ChRM) directions determined*. **Ref. 1: was PCA used?**
  Yes, it is now indicated in the text (section 2.3 – laboratory methods) as well as its respective reference (Kirschvink 1980).

- **Page 8, end of 1st paragraph section 3.2.2:** *"AF demagnetized carbonaceous samples exhibit also a single component (Fig. 3d)".* **Ref. 1: Fig. 3d does not show a single component**
  Now is Fig. 4d. It shows a single component if the secondary low-coercivity (viscous) component is not considered as we explain 4-5 lines before in the main text:
  "*All samples show a secondary viscous component of normal polarity easily removable in the first steps of the magnetic cleaning (< 10 – 15 mT or < 200 – 250 ºC) particularly evident in carbonaceous samples (Fig. 4d-e).***"**

- **Page 8, 2nd paragraph section 3.2.2:** *"The ChRM direction in the carbonaceous specimen was defined between 250 ºC and 450 ºC, reflecting a partial thermo-remanent magnetization (pTRM) likely caused by moderate heating that this facies underwent"*
  Ref. 1: I don't see in the diagram why the upper limit is 450° and not higher
  Please, see in the figure below and amplification of the high temperature component (HT; dashed purple line) of specimen shown in Fig. 4e. The pTRM component is shown in a red dashed line. It can be observed how the component changes the direction around 450 ºC. For space limits and to avoid a saturation of this figure we didn´t include it. Moreover, this is one of the few examples where the HT component has an anomalous (not northward) direction as it happens in Fig. 6f. In case study 2, when taking about carbonaceous samples we give an explanation to this behaviour (end of 3rd paragraph of section 4.2). However, for the purpose of

this case study (archaeomagnetic dating considering the pTRM as the ChRM direction in this specimen), a maximum unblocking temperature of 450 ºC is well justified.



Ref. 2 suggest to write this: **"This sample is demagnetized by about 450 degrees reflecting moderate heating that this facies underwent"**
Sorry, but we do not agree with this statement. At 450 ºC the specimen is not completely demagnetized. Otherwise, there should not be a HT component from approximately 450 – 600 ºC as is the case (see figure above). The change in direction at around 450 ºC shows the last heating temperature undergone by this specimen as ref. 2 claims, but it does not mean that it is demagnetized at 450 ºC. The meaning is different.

- **Page 9, end of 1st paragraph:** *"…that most rejected specimens come from the nearest parts potentially affected by the burrow (Fig. 1)"*. **Ref: nearest to what?**
  Ok, the sentence has been rewritten to make it clearer.

- **Page 9, last paragraph section 3.2.2:** *"that it is already possible to date with archaeomagnetism burnt archaeological features from Western Europe*. **Ref. 1 suggests to change "features" by "sediments"**
  Instead of "sediments" which is much more specific, we write "materials", referring to any *(in situ)* burnt archaeological material including also sediments (e.g., kilns, ovens, hearths, etc.).

4. Case 2: Estimating heating temperatures

4.1. Background

- **Pages 9-10, 1st paragraph section 4.1:** *"One of the topics that traditionally have most attracted the attention of archaeologists is to know the temperature at which burnt archaeological remains were heated in the past*". **Ref. 1: this statement is an exaggeration**
  The topic is interesting but we have lowered down the tone of the statement. We have also included in this 1st paragraph a better explanation of the archaeological interest that determining ancient heating temperatures may have (requested by Ref. 1; see below).

- **Page 10, 3rd paragraph section 4.1:** *"Regarding burnt anthropogenic cave sediments, this pTRM will partially reset the original magnetization recorded by the substrate and two components of magnetization should be distinguished"*. **Ref. 1: I am not clear on what the two heating/magnetization events were. Or is this a DRM of sediments and a pTRM overprint?**

It is the second case and a comment has been included to improve understanding. The substrate on which the fire is performed has its original magnetization, which must be a DRM (before any heating event). Once this substrate is heated to mild temperatures (*ca.* 350 – 450 ºC), a pTRM is recorded partially overprinting the original magnetization. This happens in the carbonaceous facies as case study 2 shows and it is specifically explained in 3rd paragraph of section 4.2.

4.2. Results and discussion

- **Pages 9-10, 1st paragraph section 4.1:** (about the archaeological significance of estimating temperatures) **Ref.1: can you explain why this is of archaeological interest?**
It is now better explained in the main text (1st paragraph, section 4.1). This information may help to reconstruct the technological conditions under which a specific combustion structure was carried out. It´s not the same if a hearth was heated until 200 ºC than if it reached 700 ºC in terms of intensity, quantity of fuel employed, etc. Moreover, it has geochronological implications. Dating methods as for example, thermoluminiscence (TL) require a minimum heating temperature in the materials to be dated in order to obtain reliable results. Heatings to very low or insufficient temperatures may imply unsuccessful results. The original sentence in section 4.2 has been shortened to avoid excessive repetitions.

- **Page 11, last paragraph (section 4.2): Ref.1: I do not think you have given a clear explanation of what events are represented by the HT and MT components. Are they two heating events? What caused the two heatings? How do they differ in time? Why are the component declinations so different?**
Explanatory note: HT (High temperature) and MT (middle temperature or pTRM).
Are they two heating events? What caused the two heatings? We didn´t say in any place that they represent two different heating events. This is explained with detail in this paragraph of the main text and also in 2nd paragraph of section 4.1 (and also two questions above in this document). However, some comments have been included in the main text:

"The fact that the intermediate magnetization component (pTRM) lies along the Earth´s magnetic field direction showing normal polarity is the basic principle of this technique. The HT component is of normal polarity and predates the pTRM component. It represents the Earth´s magnetic field direction originally recorded by the archaeological surface during its formation and on which subsequently the burning took place. The remanence associated to the HT component would be detrital (DRM). During the heating, a portion of its original remanence with unblocking temperatures (T_{UBS}) less than or equal to the maximum temperature heating underwent by the carbonaceous facies (ca. 400-450 ºC; Fig. 6) was replaced by the pTRM acquired on cooling. Under the proviso that the materials remains undisturbed (in situ) after burning, the progressive TH demagnetization of the NRM may yield the heating temperature…"

-**How do they differ in time?** (*the palaeomagnetic components*) Sorry, but we cannot answer to that. We only know that they are different, because they recorded different directions (always north). The only exception is Fig. 6f which has a HT component with an anomalous direction. The most plausible explanation is that the surface on which this fire took place experienced for whatever reason some type of mechanical reorganization of the particles (e.g., intentional preparation of the surface). Otherwise, the direction of the HT component should be northward as the other examples (Fig. 6a-e). This is said in the last 6 lines of 3rd paragraph of section 4.2. In any case, estimating the time between both components is highly speculative.

Why are the component declinations so different? Please, see previous answer. They are different because the Earth´s magnetic field changed governed by the process of secular variation (SV), the basis of archaeomagnetism. Directional differences among specimens are logical since each panel correspond to a different burning event.

- **Page 12, end 2nd paragraph (section 4.2):** *"Q_n ratio values of all samples but one (Fig. 5f), are over unity suggesting a TRM or a p-TRM origin of the magnetization".* **Ref.1: Q=1 is not very high and does not convince me this is a TRM**

This has been answered before (1st question, section 3.2.1). Burnt anthropogenic cave sediments are novel materials for archaeomagnetism and the few studies available report Q_n ratio values mostly comprised between 1 and 10, with the highest values in ashes and the lowest in carbonaceous samples (see Carrancho et al. 2009, 2012, 2013; Kapper et al. 2014a,b). See also Fig. 4 and 10 of this manuscript. We claim that carbonaceous samples recorded a pTRM in the thermal demagnetization diagrams and Q_n ratios > 1 might be an indication of it, so the sentence has been modified accordingly. Results from partial thermomagnetic curves and reversibility experiments (Fig. 7) are also a proof of it, as we justify in the next paragraph of the main text.

- **Page 12, last paragraph (section 4.2):** *"…partial thermomagnetic runs were carried out on a sister powered sample…"* **Ref.1: What does sister powered mean? You mean another, powdered sample?**
Yes, another powdered sister sample. It is now indicated.

- **Page 12, end of last paragraph (section 4.2):** *"This alteration can be quantitatively estimated (see Hrouda et al 2003) and starts at 450 – 500 ºC…* **Ref.1: do you want to make a quantitative estimate?**
It´s done and shown in fig. 6i. In addition, more details are added following indications of ref. 2.

- **Page 13, middle of 1st paragraph (section 4.2):** *"Canti and Linford (2000) also reported temperatures of around 400 ºC beneath fires exceeding 800 ºC and…"*. **Ref.1: 400° beneath 800°? What do you mean?**
The sentence has been modified to make it clearer. 400 ºC refers to the substrate and 800 ºC to the ashes.

- **Page 13, end of last paragraph (section 4.2):** *"The usefulness of the palaeomagnetic method for determining heating temperatures in burnt anthropogenic cave sediments is certainly of high value for the archaeologists"*. **Ref.1: Why is it? You haven't clarified what these temperatures represent.**
This is now better explained in the main text (1st paragraph section 4.1).

5. Case study 3: Assessment of post-depositional processes

5.1 Background

- **Page 14, middle of last paragraph:** *"…establishing a diachronic sequence of diagenetic alteration of calcite, the major component of wood ashes"*. **Ref.1: is calcite the major component of wood ash??**
Yes, it is. This is well known and there are many papers published (e.g., Schiegl et al. 1996, Weiner et al. 1993, 2000). These are cited.

5.2 Results and discussion

- **Page 15, end 2nd paragraph (section 5.2):** *"…given the inflection at intermediate temperatures of Fig. 8b…"* **Ref.1: More specific temperature range**
Ok, it is included. This sentence was modified also following requirements of Ref. 2.

- **Page 15, end 3rd paragraph (section 5.2):** *"…(iii) an efficient record of the magnetization…"*. **Ref.1: what does "efficient" mean?**
It means that the magnetization was recorded efficiently, in a quick and trustworthy way. It does not require further explanation.

- **Page 16, 2nd paragraph:** *"…and two out of the three samples with values < 1 correspond to ashes from the reworked side (e.g.: Fig. 7b). The other is a carbonaceous sample. On the basis of these results, the relationship between the in situ nature of the structure and the preservation* *of the TRM is obvious.”*. **Ref.1: I would not say that 2 out of 3 makes for an obvious relationship**

2 out from 3 samples may not be a particular statistically robust result. However, what is particularly interesting is the relationship between their location (right side of the burrow, in the bioturbated zone) and their low Q_n ratio values, always < than 1. That´s not a coincidence and we observed the same behaviour in the bioturbated event studied by Carrancho et al. (2012). We really think that there is relationship between low Q_n ratio values (< than 1) and reworked samples. Furthermore, that relationship is complemented by the other features described (e.g., high intensity, univectorial NRM diagrams, reproducible directions among specimens). It is explained with enough detail in that paragraph.

- **Page 16, 1st lines last paragraph (section 5.2):** *“This is critical for directional analyses but not so much for absolute archaeointensity determinations since magnetic orientation is not indispensable*”. **Ref. 1: but if a material is disaggregated, it will not give a valid paleointensity**
  That´s right. For directional analyses orientation is critical, not so for archaeointensity analyses. Archaeointensity can only be performed on compact (not disaggregated) samples, mainly because of the numerous heatings steps required. The sentence has been modified.

- **Last paragraph page 16 / 1st paragraph page 17:** *“For archaeologists, the concept of “in situ” does not necessary mean the same as for archaeomagnetists”*. **Ref. 1: so what does it mean for archaeologists?**
  A sentence explaining it has been included.

6. Conclusions

- **Page 17: “***As a concluding remark, archaeomagnetic analyses on burnt anthropogenic cave sediments have a great potential ... but also for archaeological purposes”* **Ref. 1: Where in this paper are those archaeological purposes made explicit?**
  We have reported three different applications of archaeological interest (archaeomagnetic dating, estimating palaeotemperatures and assessing post-depositional alterations). For example, they are explicitly mentioned in the abstract and in the last paragraph of the introduction: “*The main goal of this paper is to highlight the potential of magnetic methods to answer archaeological questions through three different applications…, etc.”*.
  Certainly, they provide valuable information for “archaeological purposes”.

Specific comments to the PDF file (Reviewer #2):

Minor changes suggested by reviewer 2 complementary to those from reviewer 1 have been introduced. Please, find below detailed answer to the most important questions.

Abstract (Ref. 2): *“This is the first archaeomagnetic dating obtained in these contexts so far”.*
Reviewer 2 suggests to remove this sentence. We prefer to maintain it because is true and highlights the relevance of the dating attempt carried out in the case study 1.

1. Introduction

- **Page 2, last line 1st paragraph:** *“…its application in prehistoric archaeology is still sporadic and its potential to retrieve archaeological information remains underutilized.”* Referee 2 suggests changing “remains underutilized” by “is mainly focused on archaeomagnetic dating”.
  Archaeomagnetic dating in prehistoric materials has been barely used because available secular variation curves only reach the last 2-3 millennia. Furthermore, there isn´t any archaeomagnetic dating specifically carried out on these materials yet. For these reasons we leave the comment.

2. Materials and methods

2.1 Sampling

- **Pages 3-4:** *"...As three different case studies with different applications are reported, specific details of sampling and laboratory analysis will be given in each one of them".* **Ref. 2: I would add this information here in this sub chapter rather than in 3 separate subchapters, in order not to distract from the case studies**

  Following suggestions of both reviewers, section 2.2 now includes sampling details for each case study. Sampling subsections in the previous version (3.1.2 and 3.3.2) are now removed.

2.2.1 Case study 1 (previous section 3.1.2)

- **Page 4, section 2.2.1:** *"...The ashes are white on top and reddish brown on the bottom with a total thickness of about 15 cm".* **Is it also ash if it is reddish brown? Or could it also be a thermally altered part?**

  It is certainly a thermally altered facies but we considered it as ashes (distinguishing the colour) because they are directly above the underlying carbonaceous facies, which represents the substrate upon which the heating took place. The similarity in the magnetic properties between white and brown ashes from Ci1 event in terms of magnetic carrier, mineral magnetic concentration as well as domain state is a clear indication that they underwent high temperature heating as expected in ashes. It can be observed in Fig. 2 (IRM curves), Fig. 3a-b (thermomagnetic curves) and Fig. 4 (NRM demagnetization diagrams).

2.3Laboratory methods

This information previously given in other sections in the first version is now reported here.

3.1 Background

- **Page 6, end 2nd paragraph (section 3.1):** *"...but not suited for archaeomagnetic* dating *because they include sedimentary data that smooth the geomagnetic field variations through time"* **Ref. 2: This depends on the time period. Besides, a record of lake sediments might not be wrong, but only smoothed.**

  Yes, the reviewer is right but if the record is smoothed (and is well known that sedimentary data from lakes or marine sequences produces that effect), it is not suited for archaeomagnetic dating. It can be used for correlating sequences, but not for dating. The consensus within the archaeomagnetic community is that the design of secular variation curves must be done with materials carrying a thermoremanence (TRM). For this reason we leave the statement.

- **Page 7, first line:** *"...that is not the case for Western Europe as mentioned before".* **Ref. 2 suggest: whereas for Western Europe the longest record reaches back only XXXX years.**

  It is said at the end of the 1st paragraph of this section 3.1: *"...most European SV curves cover the last 2-3 millennia...".* We leave it to avoid repetitions.

3.2.1 Magnetic properties

Representative examples of IRM acquisition curves are now in the new Fig.2.

- **End page 7 / beginning page 8:** *"The Curie temperatures (TC) determined from thermomagnetic curves performed on selected samples are around 580 ºC indicating...".* **Ref. 2: please add error range.**

  Curie temperatures were calculated with the two-tangent method of Grommé et al. (1969). It´s now included in the main text (2nd paragraph, section 2.3). The Curie point is determined projecting onto the abscissa axis (X-axis) the cross point of the two tangents. So it is a visual estimate. However we estimate that the error range is of ± 10 ºC in the worst case, but that depends on every curve, its quality signal or the slope. This analysis is used to infer the ferromagnetic mineralogy and in practical terms, these facies are all dominated by low-Ti titanomagnetite so adding this information is not particularly useful.

3.2.2. NRM directional stability and archaeomagnetic dating

- **Page 8, 1st paragraph (section 3.2.2):** *"All samples show…"* **Ref.2: are they from samples or specimens?** It is specimens. We have checked it along the manuscript.

- **Page 8, 2nd paragraph (section 3.2.2):** *"The ChRM direction in the carbonaceous sample was defined between 250 ºC and 450 ºC, reflecting a partial thermo-remanent magnetization (p-TRM) likely caused by moderate heating that this facies underwent"* **Ref.2: This sample is demagnetized by about 450 degrees reflecting moderate heating that this facies underwent**
Please, see answer to this question in answers to Ref. 1 (page 4, this document). It is specifically explained in reference to Reviewer 2.

- **Page 8, last paragraph:** *"Following the quality selection criteria established by Carrancho et al. (2013), ..."* **Ref.2: please summarize the selection criteria here shortly**
They are now included in the main text (3rd paragraph, section 3.2.2)

- **Page 9, end 1st paragraph (section 3.2.2):** *"As is discussed further in the case study 3 (section 3.3), all these features are indicative of some type of post-depositional reworking".* **Ref.2:.or heating to low temperatures?**
That is not likely because *in situ* ashes from this burning event show very high intensities, univectorial NRM demagnetization diagrams or high values of Q_n ratio. All of them features related with their *in situ* and well-heated nature. If the samples with "anomalous" magnetic behaviour (e.g., anomalous directions or multicomponent demagnetization diagrams, etc) come from the bioturbated area, post-depositional reworking is most likely the cause of such results.

- **Page 9, end of 2nd paragraph:** (about the archaeomagnetic dating of case study 1) *"The last one is within the bounds of possibility but is out of the radiocarbon date range (1510 - 1410 yr BC) by more than three centuries.* **Ref.2:.but this age has the largest probability according to fig. 4. Can you explain this discrepancy?**
It is true that this age range has the largest probability from the statistical point of view. However, it does not seem to be archaeologically consistent and is out of the radiocarbon date range (1510 - 1410 yr BC) by more than three centuries. This was pointed out but a brief comment is now included. Archaeomagnetism is a relative dating method and irrespective of the possible ages obtained, they must be coherent with the archaeological context to be reliable.

- **Page 9, last paragraph of section 3.2.2:** *"Beyond that, the important fact is that it is already possible to date with archaeomagnetism burnt archaeological features from Western Europe…"* **Ref.2: Please reform, not so clear to me.**
Ok, this paragraph has been modified to improve its understanding.

4. Case study 2: estimating heating temperatures

4.1 Background

- **Page 10, end of 2nd paragraph section 4.1: Ref.2:.Here you could also cite Rada Torres et el. (2011)**
Ok, a brief comment about this reference is now included.

4.2 Results and discussion

- **Page 11, 1st paragraph section 4.2:** *"...from El Mirador, Portalón and El Mirón Cave (Spain)."* **Ref.2:.please add reference to Fig. 1 after adding location**
Map of Fig. 1 now includes location of sites. The reference to Fig. 1 is added in the text here.

- **Page 11, 2nd paragraph section 4.2:** *"Finally, a high temperature component…"*. The acronym "HT" (high temperature) is added after its first time cited. Thus we avoid repetitive text hereinafter.

- **Page 11, 2nd paragraph section 4.2:** *"After removing a low temperature component probably of viscous origin (< 150 – 200 ºC),…"* **Ref.2: I see maximum temperature of the viscous component of 125 degrees**
  Looking carefully, max T_{UB} of the secondary low-temperature (viscous) component for some diagrams reaches 200 ºC (e.g., Fig. 6c or d). It is observable looking the demagnetization vectors for each diagram combining both the horizontal and the vertical projection. For example, in Fig. 6d the max T_{UB} of this viscous component is not 125 ºC, but clearly 200 ºC (see solid dots of NRM demagnetization diagram; the horizontal plane). Underestimating the max T_{UB} of the viscous component implies errors determining the ChRM direction.

- **Page 11, end of 2nd paragraph section 4.2: Ref.2:** *(replace the previous sentence for this one):* **This is at about 400-450 degrees where the intermediate magnetization component switches the direction ...** Ok, it has been changed (end of 2nd paragraph, section 4.2).

- **Page 11, 3rd paragraph section 4.2:** *"The fact that the intermediate magnetization component lies along the Earth´s magnetic field direction is the basic principle of the technique in these materials"* **Ref.2:.What are D and I of the present geomagnetic field at this location?**
  Declination and inclination for the three sites studied are shown below. They were calculated for the 2015 September 28th, with the WMM2015 model. However, we would like to give an explanation to this reviewer´s comment. These materials are Holocene so is obvious that, if they are *in situ*, they all should show normal polarity as is the case. It has no sense to perform any comparison of the pTRM directions obtained with the present geomagnetic field at the studied sites because of the secular variation (SV), since they do not necessary have to coincide. Precisely because of the SV, some directional variation with respect to the present field is expected for mid latitudes as the Iberian Peninsula (e.g., Gómez-Paccard et al. 2006): ± 20 º in declination and between about 45º to 70º in inclination. So, indicating the present field direction for each site will not give any useful information to the reader and will introduce confusion. Please, see next answer.

  The present geomagnetic field at <u>every</u> location is (Fig. 6 includes examples from 3 sites, not only one):
  -El Mirón Cave: -1° 4' 7" (W) / 58º 27´ 19´´
  -Mirador Cave (Sierra de Atapuerca): -1° 1' 53" (W) / 57° 26' 50"
  -Portalón Cave (Sierra de Atapuerca): -1° 2' 4" (W) / 57° 26' 49"

  Following this reasoning, why not to calculate the field direction for year 2000 or 1950 or 1900? It is a way of saying that this information is not useful to the reader.

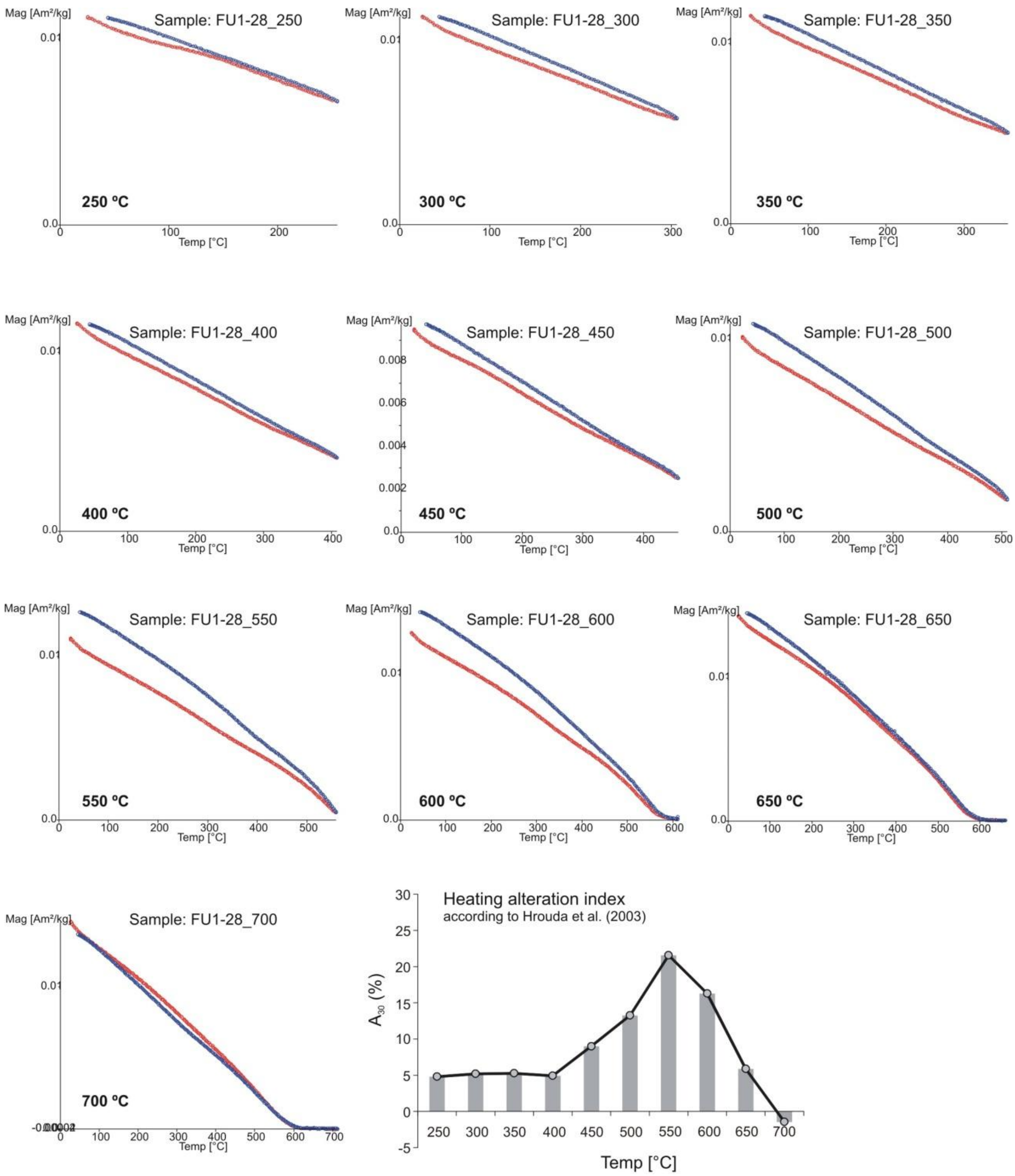
  Please add D and I of the pTRM in Fig 5.
  It is now included in the new figure 6. The important point is that the pTRM directions are northward as we argue in the text and is now shown in Fig. 6. This information is really helpful to the reader.

- **Page 12, end 2nd paragraph (section 4.2):** *"Nonetheless, some results suggest a TRM origin of the magnetization…"*. **Ref.2: which results? please specify!**
  We referred to the Q_n ratio explained in the next sentence and also to the J-T curves explained in the next paragraph. Following also suggestions of Ref. 1, the sentence has been modified.

- **Page 12, end 2nd paragraph (section 4.2): Ref. 2: Figure reference is wrong, should be 6 to keep the order. Please change the subsequent figure numbers.**
  Sorry, but the reference to that figure was correct. We referred to sample N11-21. As a new figure 2 has been included, this is now figure 6f.

- **Page 12, end of last paragraph:** *"This alteration can be quantitatively estimated…"* **Ref.2: Please put one sentence here, which explains how it is done.** Ok, a brief explanation is now included.

- **Page 12, end of last paragraph:** *"This alteration can be quantitatively estimated and starts at 450 – 500 ºC, reaching a maximum at 550 ºC (Fig. 6i)"* **Ref.2: How do you know that is is not at more than 550 degrees? You do not have partial thermomagnetic curves up to 700 each 50 degree steps. Why is A30(%) for 700 degrees missing in the figure? PLease add it in Fig. 6i.**
  We don´t know empirically because the maximum heating temperature applied in this experiment was 550 ºC, as it is said a few lines before in the main text. However, from 600 ºC to 700 ºC the alteration index progressively will reduce because magnetite neoformation is no possible. These temperatures are over the Curie temperature of magnetite (Tc ~ 580 ºC), so the sample loose its ferromagnetism. Unfortunately, this sample cannot be analyzed again because our Balance is currently not working due to a breakdown. However, to demonstrate our argument, we show below results from other carbonaceous sample from El Mirador Cave (sample FU1-28; see figure below) on which this experiment was performed from 250 ºC to 700 ºC. Please, note how the maximum alteration occurs between 400 and 550 ºC (exactly the same as the example shown in Fig. 7) and from 550 ºC to 700 ºC the alteration index is reduced for the reason given above. This example cannot be incorporated into the main text because we don´t have specifically a TH demagnetization diagram of the NRM of this sample and the idea is to compare the "pTRM method" with this partial thermomagnetic curve experiments on carbonaceous samples from the same burning event. Anyway, this result confirms that the range of temperatures at which carbonaceous facies were heated is comprised between 400 – 550 ºC. See graph below.



- **Page 13, 1st lines 1st paragraph:** *"As far as the ashes are concerned, these most likely reached temperatures over 600 – 700 ºC…".* **Ref.2: Please reference here, Figure not shown, or explain from which experiment you got this results.**
  The sentence has been rewritten following indications of Ref. 2. The references to the studies where this information come from were already in the text as well as a description of their behaviour.

- **Page 13, middle of 1st paragraph:** *"…from a series of actualistic fire experiments."* **Ref.2: I do not understand... actual?**
  Actualistic is correct. "Actualistic study": a detailed observation of the actual use of archaeological artifacts, ecofacts, and features, used to produce general analogies for archaeological interpretation

5. Case study 3: Assessment of post-depositional processes

5.1 Background

- **Page 14, 1st paragraph (section 5.1):** *"…samples for TL, OSL and ESR dating…"*. **Ref.2: please explain abbreviations.**
  Ok, they are now expanded.

- **Ref. 2: Please move also this part to chapter 2 (about the previous 3.3.2 section: Sampling and laboratory analyses**).
  It has been moved and described in 2.2.3 subsection (sampling case study 3).

5.2. Results and discussion.

- **Page 15, 1st paragraph section 5.2: Ref.2: Fig. 7: please add location of P3-16 in figure.**
  Ok, it has been added. It is new figure 8.

- **Page 15, 1st paragraph section 5.2:** *"…NRM demagnetization plots from the central-left part of the burning event …"*. **Ref.2: burrow?.**
  The sentence has been rewritten to be better understood.

- **Page 15, 1st paragraph section 5.2:** *"…displaying high values of the Qn ratio…"*. **Ref.2: in the range of xxx.**
  It is specifically said on page 16 (2nd line, 5th paragraph of section 5.2), when taking about the Q_n ratio. It is also visible in Fig. 10.

- **Page 15, 2nd paragraph section 5.2:** *According to thermomagnetic curves it is low-Ti Titanomagnetite with Curie temperatures of around 580 ºC (Fig. 8a-c) and possibly also maghaemite given the inflection at intermediate temperatures of Fig. 8b"*. **Ref. 2: Fig. 8a seems to have a Tc at about 600 degrees. PLease clarify..**
  Yes, for Fig. 9a the Tc is more 600 ºC than 580 ºC. It is better explained in the text now and Curie temperatures indicated in Fig. 9(a-c)

- **Page 15, end of 2nd paragraph section 5.2: "…***possibly also maghaemite given the inflection at intermediate temperatures of Fig. 8b"*. **Ref. 2: the inflection might also be due to change of grid structure.** Ok, it has been included.

- **Page 15, 3rd paragraph section 5.2:: "…***(ii) with the intensity of the burning (ash thickness)…"*
  Ref. 2: a lot of ash might be produced by a lot of fuel, but does not mean that burning took long.
  Yes, that´s true. It is now better indicated in the main text.

- **Page 16, end of 2nd paragraph:** *"It has been claimed the importance of combining these analyses with macroscopic field observations (Carrancho et al. 2012)."* **Ref. 2: This sentence is not clear to be, please reform.**
  The sentence has been modified to make it clearer.

- **Page 16, 3rd paragraph: Ref. 2: What about the other rock magnetic experiments: IRM, backfield, hystereses.... do they show differences between disturbed and undisturbed parts? Please mention here too.**
  A paragraph has been included with an appropriate explanation. No significant differences were observed between the *in situ* and the reworked ashes. A new figure 11 was included.

References:

The following references have been added:

Calvo-Rathert et al. (2012)
Carrancho (2010)
Dunlop (2002)
Grommé et al. (1969)
Kirschvink (1980)
Vergès et al. (this issue).

Figures:

- **Figure 1:** Site locations of all sites were added in the map
- **Figure 2:** A new Figure 2 was created showing representative IRM curves from Ci1 event.
- **Figure 3:** The corresponding T_{CS} for each curve were added in the figure (Ref. 2).
- **Figure 5:** The last line of the legend was eliminated (Ref. 1).
- **Figure 6:** Declination and Inclination of the pTRM component was indicated for each panel (Ref. 2)
- **Figure 8:** Location of specimen P3-16 (carbonaceous) was inserted in the photo (Ref. 2).
- **Figure 9:** The corresponding Tcs for each curve was added in the figures (Ref. 2).
- **Figure 10:** "(S.I.)" was not eliminated as Ref. 2 suggested. It refers to "Système Internationale" and is necessary to indicate it to differentiate from the "cgs" system (centimetre, gram, second).
- **Figure 11:** A new figure 11 was included with a Day plot and two representative hysteresis loops of an *in situ* and a reworked ash, respectively. (Ref. 2).

Caption figures:

They were revised following reviewers´ suggestions.