

Exploring the paleosecular variation in Iberia before 1000 BCE: new archaeomagnetic directions from *fumiers*' sequences

Ángela Herrejón Lagunilla^{a,*}, Ángel Carrancho Alonso^b, Juan José Villalaín Santamaría^a, Francisco Javier Pavón Carrasco^{c,d}, Philippe Lanos^{e,f}, Philippe Dufresne^{e,f}, Javier Fernández Eraso^g, Cristina Vega^h, Eduardo Carmona^{i,j}

^a Dpto. de Física, Universidad de Burgos, Escuela Politécnica Superior (Campus Vena), Avda. Cantabria s/n., Burgos, 09006, Spain

^b Área de Prehistoria. Dpto. de Historia, Geografía y Comunicación, Edificio I+D+I, Universidad de Burgos, Pza. Misael Bañuelos s/n, Burgos, 09001, Spain

^c Dpto. de Física de la Tierra y Astrofísica, Facultad de CC. Físicas, Universidad Complutense de Madrid, Pza. de las Ciencias, 1, Madrid, 28040, Spain

^d Instituto de Geociencias, Consejo Superior de Investigaciones Científicas-Universidad Complutense de Madrid, C/ Doctor Severo Ochoa, 7, Madrid, 28040, Spain

^e Archéosciences Bordeaux, UMR 6034, CNRS & Université Bordeaux-Montaigne, Domaine universitaire, Maison de l'archéologie, 8 esplanade des Antilles, Pessac Cedex, Bordeaux, 33607, France

^f Géosciences-Rennes, Université Rennes, Campus Scientifique de Beaulieu, CS 74205, Rennes Cedex, Rennes, 35042, France

^g Euskal Herriko Unibertsitatea, Vitoria-Gasteiz, Spain

^h Servicio Territorial de Cultura y Turismo de Segovia, Junta de Castilla y León, Segovia, Spain

ⁱ Servicio Territorial de Cultura y Turismo de Valladolid, Junta de Castilla y León, Valladolid, Spain

^j Área de Arqueología. Dpto. de Historia, Geografía y Comunicación, Facultad de Humanidades y Comunicación, Universidad de Burgos, Paseo de Comendadores, s/n, Burgos, 09001, Spain

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ABSTRACT

The recurrent updating of archaeo- and paleomagnetic databases has allowed the extension of knowledge about paleosecular variation (PSV) in Iberia. However, there is a low number of directional data for the region before ~1000 BCE. Thus, PSV reconstructions for this period could be biased by data from other regions for older periods. In this work, we present the study of several combustion episodes from three different *fumier* sequences from Northern Iberia: Abrigo de La Castañera (Cantabria), El Estillín (Burgos), and San Cristóbal (Alava). As a result, 15 new archaeomagnetic directions have been obtained. Most of them contribute to fill the total absence of data in the region ca. 2500-4000 BCE. Two tentative PSV Curves (PSVCs) between ca. 6000 yrs BCE and 1000 yrs BCE are presented, using different modelling techniques. A quality filtering of the mean directions ($\alpha_{95} \leq 10^\circ$) was carried out to perform the PSVCs. The PSVCs show some differences respect the available reconstructions. These advances in knowledge of PSV are key to improve the archaeomagnetic dating.

1. Introduction

The Earth's magnetic field (EMF) can be largely described by a geocentric dipole model. Nevertheless, there are also non-dipolar contributions. Among the phenomena with non-dipolar origin is the so-called paleosecular variation (PSV, e.g. Roberts and Turner, 2013, and references therein). One of the major challenges in archaeomagnetic research is to reconstruct these variations of the EMF over time with well-dated and quality records. Burned archaeological materials such as ovens, kilns or hearths are particularly suitable because they are

generally well preserved, heated at high temperatures and their age is usually well constrained. Reconstructing the patterns of PSV is useful to better understand the behaviour of the EMF at a regional scale. At the same time, the improvement and extension over time of the regional PSV patterns itself is useful for archaeomagnetic dating.

Inhomogeneous distribution of archaeomagnetic/paleomagnetic data in time and space influences the reconstructions of the Earth's magnetic field in the past (Brown et al., 2021). Therefore, having a database that covers as many periods and spaces as possible would be ideal for the reconstruction of the fluctuations of the EMF during the last

* Corresponding author.

E-mail addresses: aherrejon@ubu.es, angelaherrejonlagunilla@gmail.com (Á. Herrejón Lagunilla), acarrancho@ubu.es (Á. Carrancho Alonso), villa@ubu.es (J.J. Villalaín Santamaría), fjpavon@ucm.es (F.J. Pavón Carrasco), philippe.lanos@univ-rennes1.fr (P. Lanos), philippe.dufresne@univ-rennes1.fr (P. Dufresne), cvegamaeso@gmail.com (C. Vega), ecarmona@ubu.es (E. Carmona).

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millennia. Thus, the addition of new directional and/or intensity data to fill the current spatio-temporal gaps in archaeo-/paleomagnetic databases is an important task of interest for both geomagnetism and archaeology.

Since the first paleosecular variation curve (PSVC) for Iberia was published (Gómez-Paccard et al., 2006), several updates have been carried out (Molina-Cardín et al., 2018; Osete et al., 2020). However, none of these PSVCs go further back than 1500 BCE due to the scarcity of directional data before ~1000 BCE in the region. The European PSVC for the Neolithic (Carrancho et al., 2013) and recent global and regional reconstructions like SHA.DIF.4k (Pavón-Carrasco et al., 2021), SHAWQ-IronAge (Osete et al., 2020) or ArchKalmag14k (Schanner et al., 2022) can give a broad idea of the PSV behavior in Iberia prior to 1500 BCE. Nevertheless, specific regional features could be smoothed or biased by the greater amount of data from other areas and especially because of data gaps in some chronological intervals such as the 3rd-4th millennium BCE.

Fumier sequences are good candidates for that aim (Carrancho et al., 2013; Herrejón-Lagunilla et al., 2022; Kapper et al., 2014a, 2014b). These deposits appear in caves or rock-shelters and they are the outcome of livestock activities since the Neolithic (Angelucci et al., 2009). In these contexts, vegetal residues and animal dung were periodically burnt to reduce the volume of waste generated and to deworm the space. As a result, these sequences show an alternation of burn and unburnt layers. The combustion episodes (ash-carbonaceous/rubefaction couplets) in *fumiers*' sequences exhibit characteristics that make them good candidates for obtaining directional data: (1) they have been subjected to high temperatures (even >700 °C); (2) the chronological adscription of *fumier*'s sequences and their remarkable antiquity for traditional archaeomagnetic studies (the oldest date back to the Neolithic; Angelucci et al., 2009), (3) they are generally well-dated radiometrically, (4) their ubiquitous presence throughout the Mediterranean region (e.g.: Angelucci et al., 2009) and (5) their suitability for directional archaeomagnetic analyses (Carrancho et al., 2013, 2024; Herrejón Lagunilla et al., 2022; Kapper et al., 2014b). Nevertheless,

archaeomagnetic studies of combustion events in *fumiers*' sequences also present certain challenges. Sampling can be complex because these materials are not lithified and can be quite loose. Furthermore, it is often necessary to access them through stratigraphic profiles using devices specifically designed for soft materials (Herrejón Lagunilla et al., 2022; Carrancho et al., 2013). Additionally, their unconsolidated nature -combined with the specific taphonomic conditions of sheepfold caves-affects their preservation, meaning that the success rates of archaeomagnetic analyses may be lower than for other types of materials traditionally studied. Despite all this, recent studies have shown that combustion episodes of these sequences may be good recorders of the direction of the EMF (Carrancho et al., 2012, 2013, 2024; Herrejón Lagunilla et al., 2022; Kapper et al., 2014b).

Several burnt levels from this type of deposits are studied here to improve the knowledge of the PSV in Iberia before 1000 BCE. We present 15 new directions from combustion episodes sampled at three Iberian *fumiers*' sequences, whose ages range from 5th millennium BCE to 3rd millennium BCE. The main goal is to contribute to fill the gap of the Iberian archaeomagnetic database between 1000 BCE and 6000 BCE and to reconstruct in further detail better the PSV behavior in this region as it has geomagnetic and archaeomagnetic implications. With this aim, two tentative PSV Curves (PSVCs) between ca. 6000 yrs BCE and 1000 yrs BCE are presented, using different modelling techniques.

2. Materials and methods

15 combustion episodes from 3 different archaeological sites from Northern Iberia have been studied: 1 from Abrigo de La Castañera (Cantabria; Spain), 8 from San Cristóbal (Álava, Basque Country; Spain) and 6 from El Estillín (Burgos, Castilla y León; Spain) (Fig. 1). The chronology of the studied structures ranges from the 3rd millennium BCE to the 5th millennium BCE (Table 1). More detailed information about the sites and the studied combustion episodes is included in Appendix A.

In order to obtain directional data, a total of 252 oriented specimens

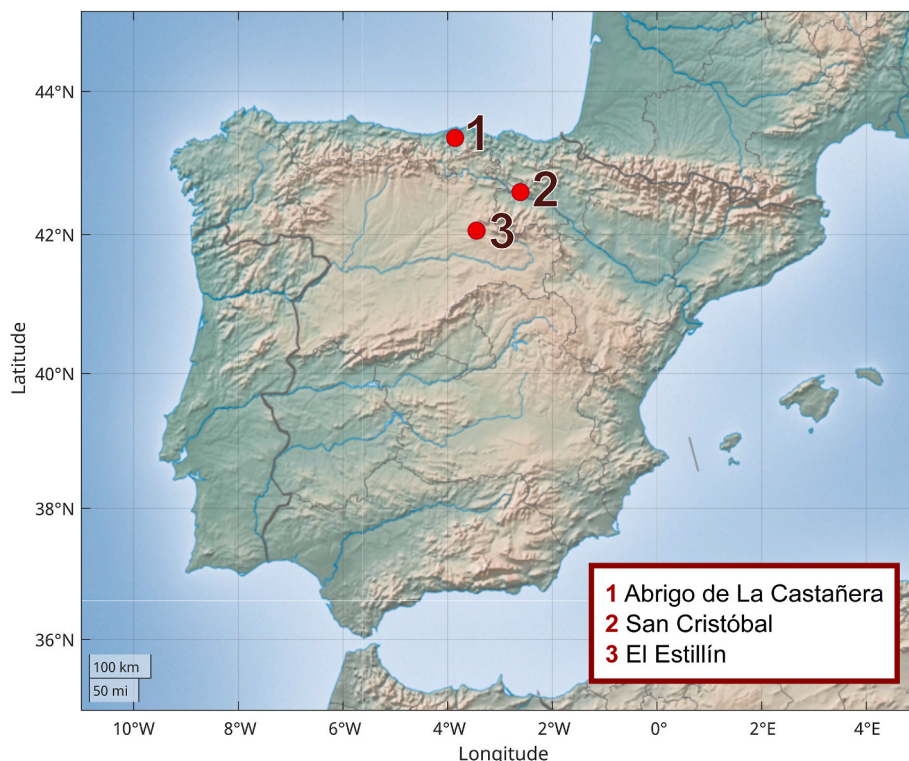


Fig. 1. Map of Iberia with the location of the studied sites.

Table 1

List of studied combustion episodes, along with their respective dates and mean archaeomagnetic directions. N = number of specimens considered to calculate the mean direction; N' = total number of demagnetized specimens per combustion episode; α_{95} = semiangle of the 95% confidence cone for the mean; k = precision parameter (Fisher, 1953).

ABRIGO DE LA CASTAÑERA (Villaescusa, Cantabria, Spain; Lat.: 43.3556° N; Long.: 3.8572° W)									
Combustion episode	Maximum age (years cal. BCE)	Minimum age (years cal. BCE)	Mean age (years cal. BCE)	N	N'	Dec. (°)	Inc. (°)	α_{95}	k
CA1	2882	2586	2734	9	19	331.0	58.1	13.7	15.1
SAN CRISTÓBAL (Laguadía, Álava, Spain; Lat.: 42.5991° N; Long.: 2.6097° W)									
Combustion episode	Maximum age (years cal. BCE)	Minimum age (years cal. BCE)	Mean age (years cal. BCE)	N	N'	Dec. (°)	Inc. (°)	α_{95}	k
SC1	4342	4171	4256.5	5	12	339.5	44.2	15.2	26.4
SC2	4308	4048	4178	9	16	330.7	41.4	9.8	28.4
SC3	3349	3017	3183	8	14	342.8	38.6	9.1	37.9
SC4	3349	3017	3183	10	12	336.5	46.9	7.5	42.0
SC5	3349	3017	3183	12	14	341.7	44.9	3.1	199.5
SC6	3010	2696	2853	10	14	346.3	40.2	5.8	71.4
SC7	2886	2627	2756.5	11	14	348.0	39.0	9.5	24.3
SC8	2837	2464	2650.5	12	14	349.0	34.8	4.8	84.2
EL ESTILLÍN (Hortigüela, Burgos, Spain; Lat.: 42.0562° N; Long.: 3.4478° W)									
Combustion episode	Maximum age (years cal. BCE)	Minimum age (years cal. BCE)	Mean age (years cal. BCE)	N	N'	Dec. (°)	Inc. (°)	α_{95}	k
CE6	4653	3528	4090.5	5	17	357.6	40.4	20.7	14.6
CE7	4653	3528	4090.5	13	20	3.6	42.0	13.1	11.0
CE8	4653	3528	4090.5	15	17	353.3	39.3	11.6	11.8
CE9	4653	3528	4090.5	15	19	359.9	45.4	4.8	63.8
CE10	4653	3528	4090.5	11	28	7.4	56.5	16.4	8.7
CE11	4653	4452	4552.5	13	22	10.6	51.2	5.4	59.0

(19 from Abrigo de La Castañera, 110 from San Cristóbal and 123 from El Estillín) were collected with the aid of a non-magnetic cylindrical piston specifically for non-consolidated materials (Carrancho et al., 2013; Herrejón Lagunilla et al., 2022). Mainly ash facies (which essentially consist of fuel residues) were sampled, but also some subjacent rubefactions and/or carbonaceous facies (the thermally-altered substrate on which the burning took place; Polo-Díaz et al., 2016) [Appendix B]. Identification of facies, their thickness, dimensions and lateral continuity was done macroscopically. These facies are usually a few cm thick, but occasionally they are millimetric. The classification used here (ashes, carbonaceous facies and rubefaction) refers to the facies that seems to be the predominant one in each specimen, although in some cases there are inclusions of other facies or other materials such as small clasts.

The oriented specimens were encapsulated in cylindrical plastic and quartz boxes (~3.6 cm³). In some cases, a mixture of sodium silicate and water was applied to consolidate the samples. Exceptionally, some samples from Abrigo de La Castañera were saved in handmade plaster cubes (~10 cm³) with a cylindrical hole inside (~3.6 cm³) to insert the sample. These cubes were previously demagnetized to a peak field of 60–80 mT to remove any possible magnetic noise from the plaster. Specimens in plaster cubes and some specimens in quartz capsules were sealed with plaster to prevent sample's disintegration or moving. Plastic capsules were sealed with custom plastic lids.

Specimens in plastic boxes were intended for alternating field (AF) demagnetization of the natural remanent magnetization (NRM) up to 90–105 mT. Specimens in quartz capsules and plaster boxes were meant for thermal demagnetization (TH) up to 580–660 °C. 42 oriented specimens were thermally demagnetized (7 from Abrigo de La Castañera; 32 from San Cristóbal, 3 from El Estillín) and 210 by alternating fields (12 from Abrigo de La Castañera, 78 from San Cristóbal, 120 from El Estillín).

Given that well-preserved ashes often exhibit a single component (e. g. Carrancho et al., 2013) due to the high temperatures reached during burning (easily >600–700 °C; e.g.: Canti and Brochier, 2017; Gur-Arieh and Shahack-Gross, 2020), AF demagnetization has been preferred for this facies. Despite this, thermal demagnetization has also been performed on some ash specimens comparable to others demagnetized by AF. In the case of subjacent carbonaceous facies (which typically reaches lower temperatures and it is likely that a pTRM was recorded), thermal

demagnetization has been the preferred method. Nevertheless, AF demagnetization has been performed on some specimens comparable to those that were thermally demagnetized. The specimens that primarily contained rubefaction were demagnetized by AF.

NRM was measured with a 2G 755 Superconducting Rock Magnetometer. AF demagnetization was carried out with an AF unit coupled to the magnetometer. TH demagnetization was developed with ASC Scientific TD48-SC and TD48-DC thermal demagnetizers. Paleomagnetic analyses were interpreted with the Remasoft 3.0 software (Chadima and Hroudá, 2006), which considers Fisher's statistics (Fisher, 1953). Initial magnetic susceptibility was measured with an AGICO's Kappabridge KLY-4S. Due to the non-lithified nature and complex sampling of the materials studied here, paleointensity analyses could not be performed.

Bulk samples (non-oriented) from representative facies [Appendix B] were collected to develop rock magnetic analyses: isothermal remanent magnetization (IRM) acquisition and backfield curves (up to ~1 T), hysteresis loops (± 1 T) and thermomagnetic curves (induced magnetization vs. temperature; applied field ≈ 38 mT) on air up to 700 °C. These experiments were carried out with a Magnetic Measurements' Variable Field Translation Balance. RockMag Analyzer software (Leonhardt, 2006) was used to interpret the rock magnetic results.

All the experiments (sample preparation, demagnetization procedures, and rock magnetic measurements) were performed at the Paleomagnetic Laboratory of the University of Burgos (Spain).

3. Results

NRM values range between 5.4×10^{-6} and 5.7×10^{-4} Am²kg⁻¹ in ash's specimens, between 5.3×10^{-6} and 4.4×10^{-4} Am²kg⁻¹ in carbonaceous facies and between 1.4×10^{-4} and 3.0×10^{-4} Am²kg⁻¹ in rubefaction (Fig. 2). In the case of magnetic susceptibility, it oscillates between 9.2×10^{-8} and 3.7×10^{-6} m³kg⁻¹ in ashes, between 2.6×10^{-7} and 6.3×10^{-6} m³kg⁻¹ in carbonaceous facies, and between 8.6×10^{-7} and 3.3×10^{-6} m³kg⁻¹ in rubefaction (Fig. 2). Relationship between NRM and magnetic susceptibility by means of Koenigsberger ratio (Koenigsberger, 1938; Stacey, 1967; $Q_n = \text{NRM}/\chi H$, where NRM = natural remanent magnetization, χ = susceptibility and H = local Earth's magnetic field; for our calculations, H = 40 A/m) has been shown as a useful tool to identify samples carrying stable thermoremanences (TRM) or partial thermoremanences (pTRM) in previous

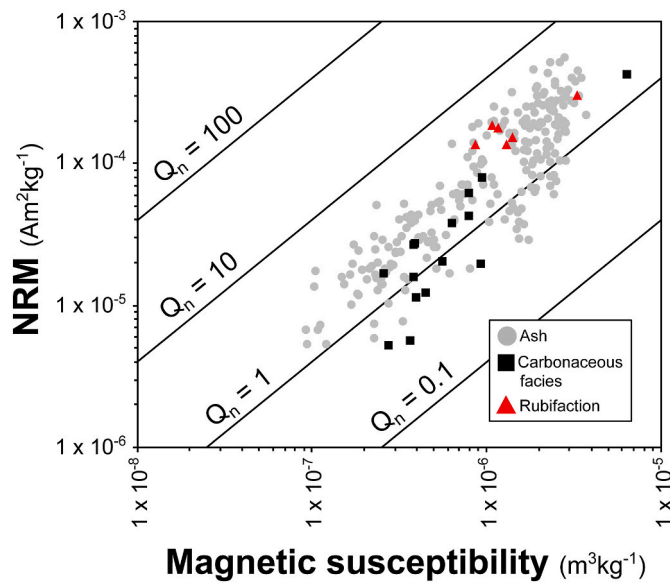


Fig. 2. Koenigsberger ratio plot (Koenigsberger, 1938; Stacey, 1967). Isolines of $Q_n = 0.1, 1, 10$ and 100 are also shown. $H = 40$ A/m has been considered for the calculations.

studies on burned archaeological materials (e.g. Carrancho et al., 2012, 2013; Ertepinar et al., 2016; Kapper et al., 2014b). In the present study, Koenigsberger ratio value is greater than 1 in most specimens and facies, ranging from 0.4 to 6.3 in ashes, from 0.4 to 2.2 in carbonaceous facies and from 2.3 to 4.3 in rubefaction (Fig. 2).

IRM acquisition curves points to the predominance of low coercivity minerals, showing saturation at 100 mT (Fig. 3a; mean SIRM in ashes = 7.9×10^{-3} Am²kg⁻¹; mean SIRM in carbonaceous facies = 9.8×10^{-3} Am²kg⁻¹). According to the thermomagnetic curves, slightly oxidized magnetite or partially maghemitized magnetite (e.g. Almeida et al., 2015) is the main ferromagnetic mineral detected in the ashes (with Curie temperatures around 600–620 °C; Fig. 4a–d). In general terms, the curves are highly reversible (coincidence between heating and cooling cycles). In some cases, an inflexion around 300 °C is observed in both heat and cooling cycles (Fig. 4a and b and 4d). This behaviour has been observed in previous studies on similar materials (Carrancho et al., 2013; Herrejón Lagunilla et al., 2022). Inversion of magnetite to haematite can cause a drop at these temperatures during the heating (this may occur at temperatures ranging between 250 °C and ≥ 750 °C; Dunlop and Özdemir, 1997). But it would imply a reduction of

magnetization during cooling that is not clearly observed, although some samples exhibit a slight reduction (e.g.: Fig. 4b). Another possible cause of this behaviour is the presence of pyrrhotite not altered by the heating (Torres-López et al., 2014; Villalán et al., 2014). The inflexion could also be caused by the presence of a spinel phase (magnetite or maghemite) with substituent cations (Ti, Al o Mg) (e.g.: Carrancho et al., 2009). Apart from this, some samples exhibit a peak of increase of magnetization around 180–200 °C in the heating cycles (absent in the cooling cycle) (Fig. 4c and d). The thermomagnetic curves in these samples are highly reversible, with the only exception of the mentioned peak. Occasionally, the inflexion at 300 °C also appears in these samples (Fig. 4d). Magnetite is the main ferromagnetic mineral detected in the curves of the carbonaceous facies (with Curie temperatures around ~ 550 –580 °C; Fig. 4e and f). This facies exhibits irreversible curves in all cases, showing an increase of the magnetization during the cooling. It is interpreted as neoformation of magnetite. The peak around 180–200 °C observed in some ashes is also detected in some carbonaceous facies (e.g.: Fig. 4f).

Saturation magnetization (M_S), saturation remanence (M_{RS}), coercivity field (B_C) and coercivity of remanence (B_{CR}) values have been obtained from corrected (paramagnetic/diamagnetic fraction) hysteresis and back field experiments and used to calculate the hysteresis ratios (M_{RS}/M_S and B_{CR}/B_C) [Appendix C]. Hysteresis ratios are plotted in the Day plot (Day et al., 1977; Dunlop, 2002) (Fig. 3b) and do not reveal significative differences among samples and/or facies. Only three ash samples from El Estillón (coming from CE6, CE7 and CE10) exhibits slightly higher values of B_{CR}/B_C ratio. Anyhow, all the samples are included in the pseudosingle domain (PSD) area or mixture single domain (SD) and multidomain (MD).

The Characteristic Remanent Magnetization (ChRM) of ashes [comp. A in Fig. 5a and b] was isolated between 200–250 and 500–625 °C (TH demagnetization) and between 15–35 mT and 70–105 mT (AF demagnetization). In carbonaceous facies, it was isolated between 180–200 and 360–475 °C [comp. A1 in Fig. 5c], being interpreted as a partial thermoremanent magnetization (p-TRM). Any component above maximum unblocking temperatures of the ChRM in carbonaceous facies is interpreted as acquired before the last burning. In the case of rubefactions, ChRM was isolated between 20 and 30 and 100 mT [comp. A in Fig. 5d]. In all cases, steps below 15–30 mT (AF)/150–200 °C (TH) were excluded from the calculation of the mean directions to avoid possible viscous influence.

Considering previous studies on similar materials (Carrancho et al., 2013; Herrejón Lagunilla et al., 2022; Kapper et al., 2014a, 2014b), specimens with Q_n ratio < 1.0 and specimens showing unstable NRM behaviour, overlaps and/or multiple components that hinder the proper identification and isolation of the component related to the firing were

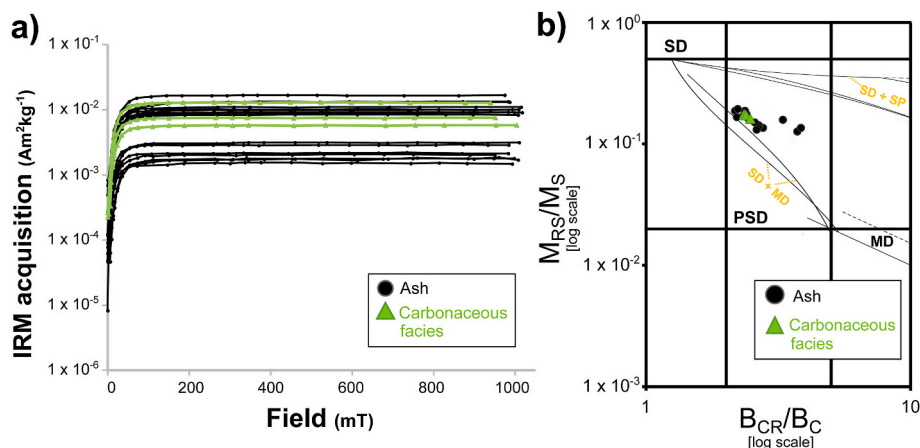


Fig. 3. Summary of some magnetic properties results: a) IRM acquisition curves; b) Day et al. (1977) plot, showing the theoretical curves of mixture areas (single domain + multidomain and single domain + superparamagnetic) according to Dunlop (2002).

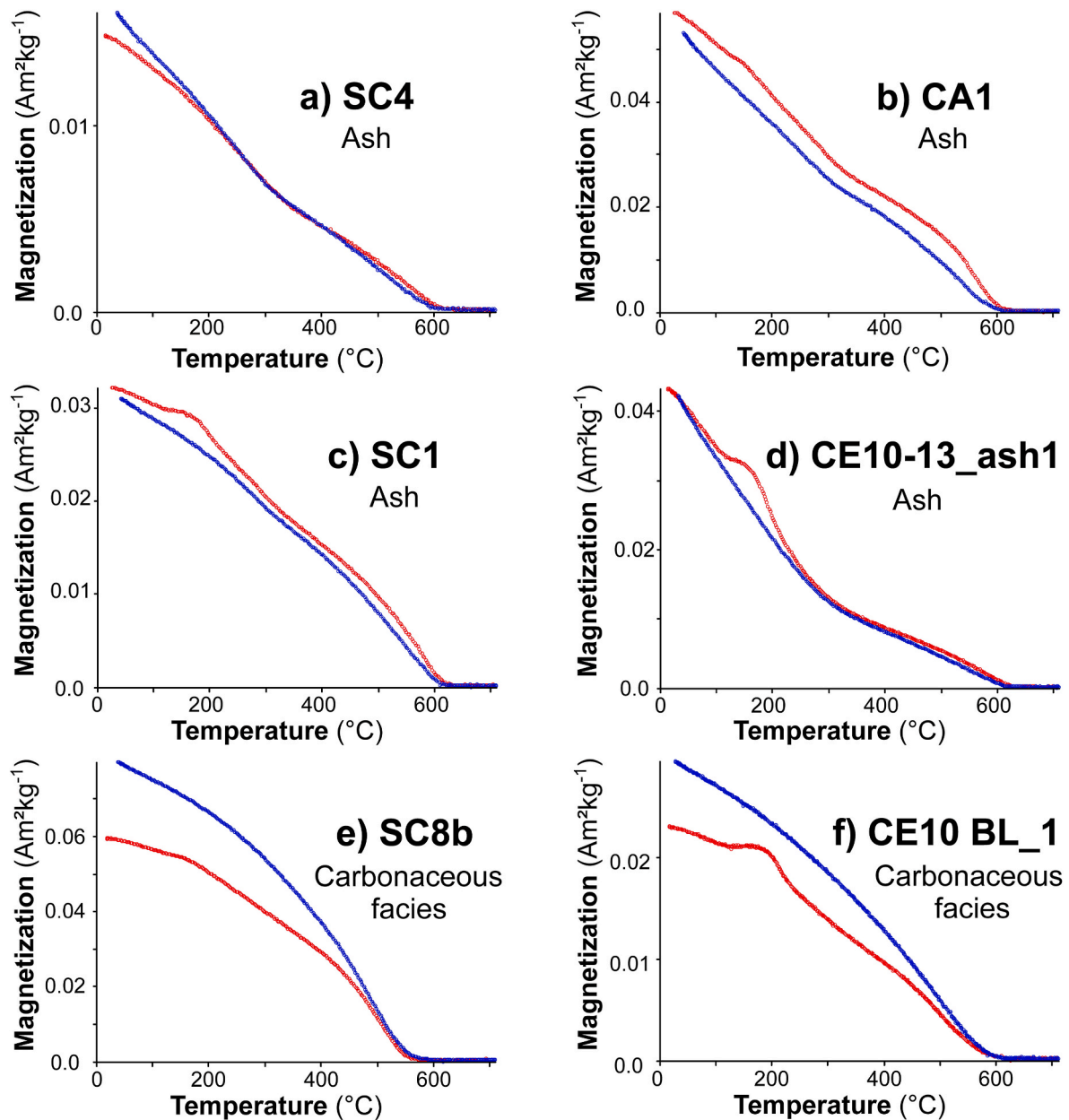


Fig. 4. Representative examples of thermomagnetic curves (induced magnetization vs. temperature) of (a-d) ash and (e-f) carbonaceous facies [dia-/paramagnetic correction was applied using RockMag Analyzer (Leonhardt, 2006)].

ruled out (e.g. Fig. 5e and f). After applying the previous criteria, mean archaeomagnetic directions were calculated and those specimens deviated from the mean direction more than $3 \cdot \alpha_{95}^\circ$ were disregarded for the calculation of the final mean direction (similar criteria were used, e.g., in Kapper et al., 2014a, 2014b).

As a result, 15 archaeomagnetic directions have been obtained. Their equal area projections are shown in Fig. 6. A summary of the main statistical parameters is presented in Table 1.

4. Discussion

4.1. Directional data quality and preservation conditions

Our results exhibit evident variability in the quality of the mean directions. The low quality of the statistical parameters of CA1 from Abrigo de La Castañera ($k = 15.1$; $\alpha_{95} = 13.7^\circ$; $N/N' = 9/19$; Fig. 6a) could be interpreted in terms of concentration of ferromagnetic minerals

($s.l.$), thermal impact and/or preservation. Susceptibility values (a parameter related to the concentration of ferromagnetic minerals, $s.l.$) fall mainly in the middle or middle-low range of the samples studied here, showing a mean value = $1.2 \times 10^{-6} \text{ m}^3\text{kg}^{-1}$ and a median = $8.4 \times 10^{-7} \text{ m}^3\text{kg}^{-1}$ (cf. Fig. 2). Therefore, it does not seem that a significantly lower concentration of ferromagnetic minerals ($s.l.$) is the key variable to explain the low quality of the directional record from La Castañera. Low temperatures experienced by the materials during combustion may also critically influence the quality of the directional data. However, although the carbonaceous facies may have undergone a relatively low thermal impact, ashes are known to have recorded high temperatures, easily $> 600 - 700^\circ\text{C}$ (e.g.: Canti and Brochier, 2017; Gur-Arieh and Shahack-Gross, 2020). Thus, low thermal impact does not appear to be the main cause of the observed behavior (at least not the only one). All of this leads us to suggest that internal mechanical disturbances (within the combustion episode) may have been the main cause of the poor quality of the directional data at La Castañera. This is

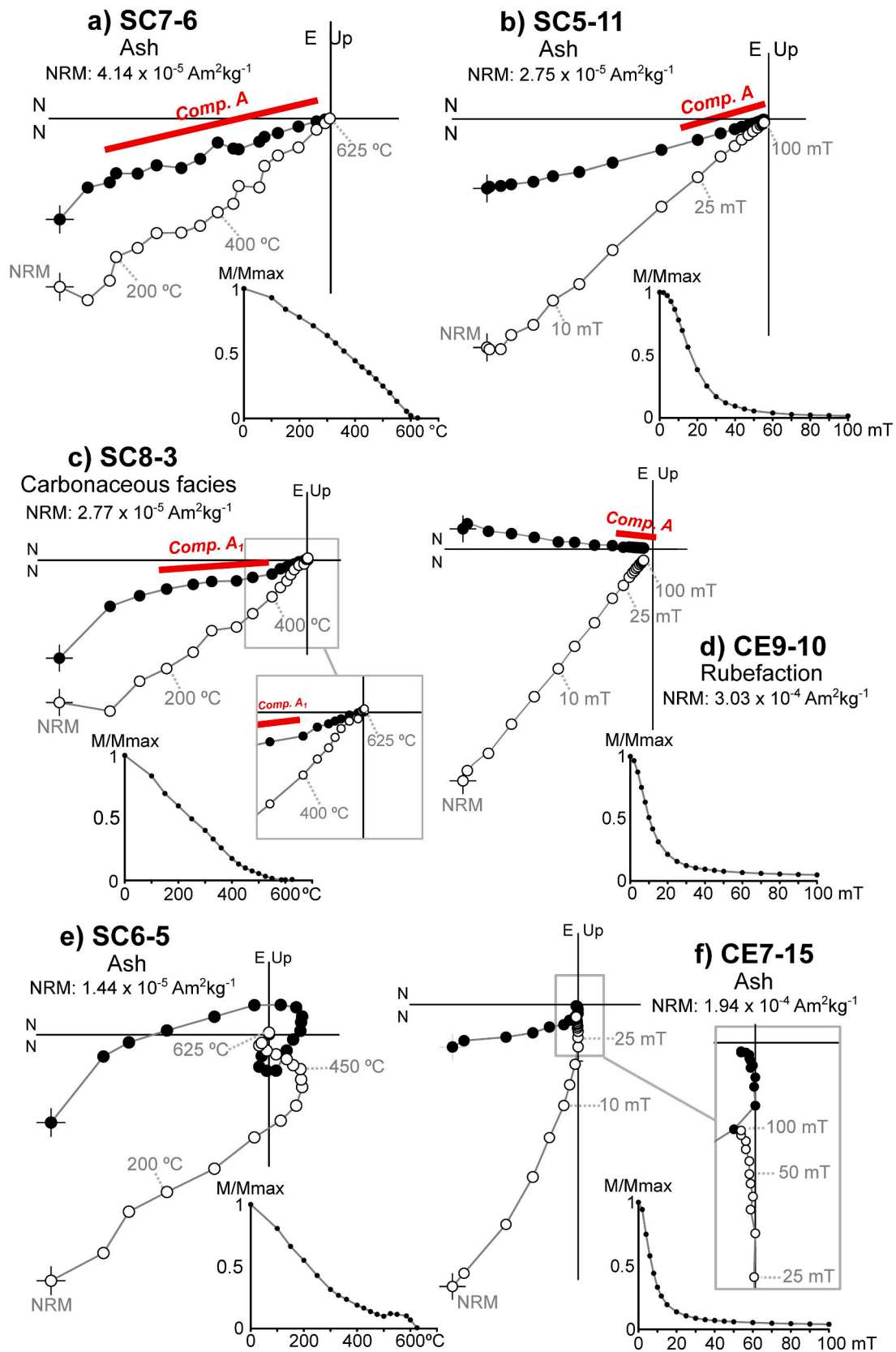


Fig. 5. Representative examples of orthogonal NRM demagnetization diagrams: (a-b) ash, (c) carbonaceous facies, (d) rubefaction, (e-f) rejected specimens. Examples on the left correspond to thermal demagnetization, and those in the right correspond to AF demagnetization. Specimen code, facies, initial intensity (NRM), main demagnetization steps and normalized demagnetization spectra are also shown. [Solid/open circles in orthogonal plots: projection of vector endpoint onto the horizontal/vertical plane, respectively].

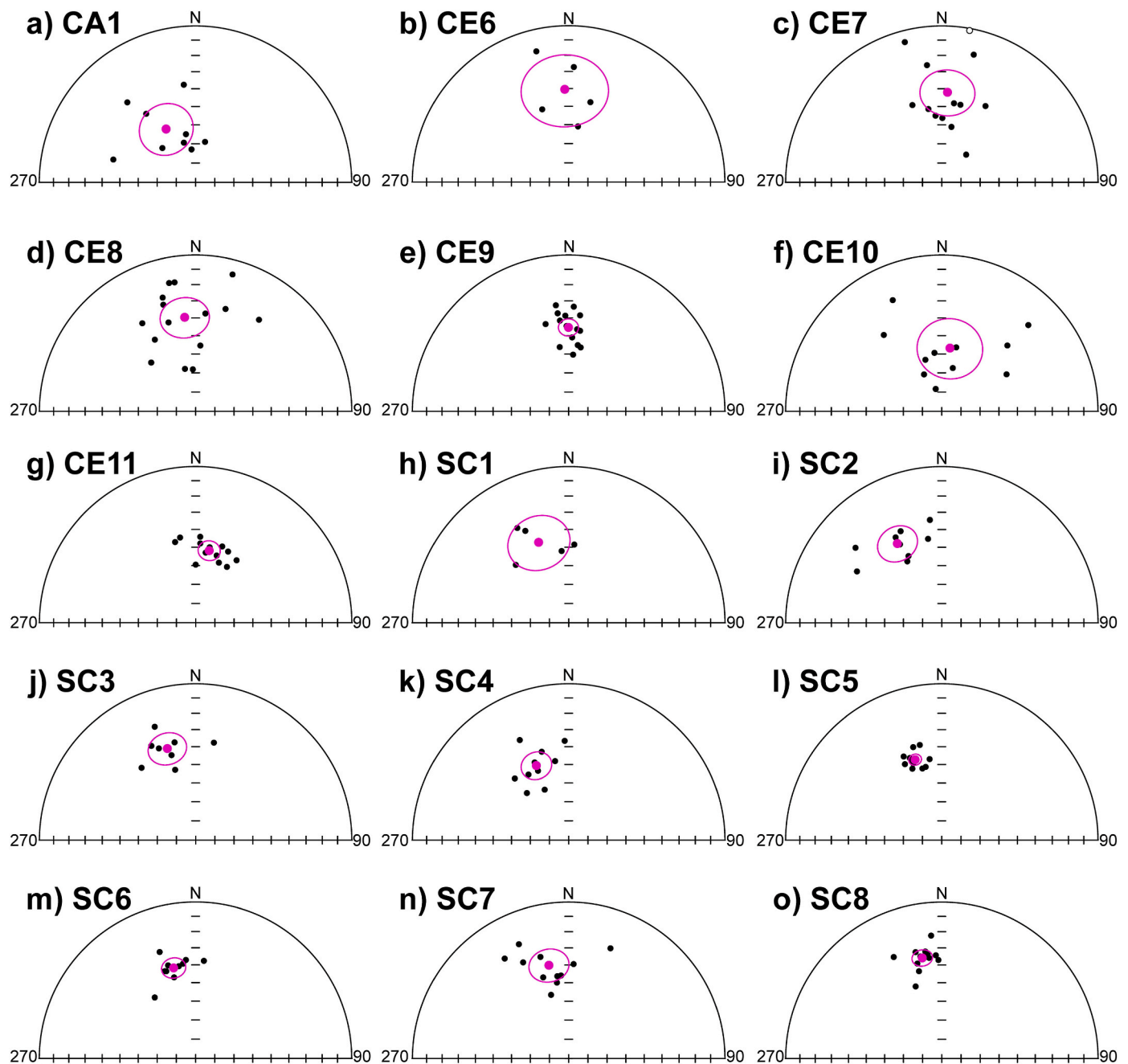


Fig. 6. Equal area projections of the mean archaeomagnetic directions obtained from the studied combustion episodes. Solid/open circles = positive/negative inclination. CA = La Castañera; CE = El Estillín; SC = San Cristóbal.

particularly interesting from an archaeological perspective, since macroscopic appearance of the episode was not *a priori* altered, exhibiting a layer of ashes on the top and carbonaceous layer beneath. Previous studies in *fumiers* sequences have also interpreted the disturbances of the magnetic signal in terms of preservation of the combustion episodes (e.g. Carrancho et al., 2012; Herrejón-Lagunilla et al., 2022).

Some combustion episodes from El Estillín Cave also present questionable quality data. The rate of accepted specimens from CE6 (Fig. 6b and Table 1) is low ($N/N' = 5/17$; 29.4%) and directional data are considerably scattered ($k = 14.6$; $\alpha_{95} = 20.7$). In the case of CE7 (Fig. 6c), CE8 (Fig. 6d) and CE10 (Fig. 6f), the rate of accepted specimens is higher (65% in CE7, 88.2% in CE8 and 39.3% in CE10). Nevertheless, their precision parameter (k) values are even lower than that from CE6 (Table 1). In addition, their α_{95} values are large (ranging

from 11.6° to 16.4°). Taking into account that this parameter is dependent on the number of specimens and that >10 specimens were considered to calculate the mean directions of these three episodes, it is interpreted that their preservation is not of high quality. On the other hand, the quality of CE9 (Fig. 6e) and CE11 (Fig. 6g) mean directions is better, with lower values of α_{95} and higher k values (Table 1). Although preservation at macroscopic level appeared to be good in all cases, it can be observed that there is variability in the quality of the directional data. Magnetic susceptibility values are very similar among the combustion episodes from El Estillín (ranging from 6.3×10^{-7} to $3.6 \times 10^{-6} \text{ m}^3\text{kg}^{-1}$; mean = $2.0 \times 10^{-6} \text{ m}^3\text{kg}^{-1}$; median = $1.9 \times 10^{-6} \text{ m}^3\text{kg}^{-1}$). Thermo-magnetic curves point to slightly oxidized magnetite or partially maghemitized magnetite as the main carrier of the remanent magnetization in the ashes. In the carbonaceous facies, magnetite is interpreted as the main carrier of the magnetization. Nevertheless, only three

oriented specimens from carbonaceous facies were demagnetized at El Estillón (all of them corresponding to CE10), so mineralogical differences between ash and carbonaceous facies does not seem to be the main cause of variability in the quality of directional data. Within the ashes, the only noticeable difference is the greater or lesser prominence of the inflection around 300 °C, which is clearer in an ash sample from CE10 (Fig. 4d) and to a lesser extent in another ash sample from CE7. Except for those two samples, the rest of the ashes' curves from El Estillón are very similar (including another sample of ash from CE10). The values of magnetization reached are very close in all the ashes' curves. All of this leads us to suggest that differences in the ferromagnetic (s.l.) mineralogy are not the main cause of the variability in the quality of the directional data in El Estillón (although it cannot be completely ruled out that there is some heterogeneity between and within combustion episodes). Another possible explanation for the variability in the quality of archaeomagnetic directions may lie in the differential preservation of the combustion events. As noted in the case of La Castañera, this is an interesting hypothesis from an archaeological standpoint, as it would point to mechanical alterations within the features that are not immediately detectable in the field.

San Cristobal's mean directions have relatively good statistical quality ($\alpha_{95} < 10^\circ$ in all cases except SC1; $k > 50$ in 3 episodes; Table 1).

There is one final point worth mentioning regarding the quality of the directional record. Among the specimens excluded from the calculations of the mean directions, a type of anomalous behavior characterized by a strongly curved demagnetization curve (Fig. 5e) has been observed. Such behaviour has been explained in other studies as an effect of gyroremanences caused by the presence of iron sulphides as greigite if AF demagnetizations (e.g. Snowball, 1997). While it is true that the presence of iron sulphides cannot be completely ruled out and has been suggested in the few or not burned facies of stabling sediments (Carrancho et al., 2024), our rock-magnetic results indicate that the main magnetic carrier is magnetite and/or partially oxidized magnetite in the burned facies, which are of archaeomagnetic interest. An ash sample carrying a TRM typically exhibits a linear, stable diagram of demagnetization. The behaviour illustrated in Fig. 5e is occasional, and any alteration process (even on a small scale) may explain this anomalous record. In any case, this has been excluded from the calculation of the ChRM direction.

The success rates of archaeomagnetic analyses on *fumiers'* sequences may be lower than those on other types of archaeological materials (e.g., kilns). Recently, an experimental recreation of *fumiers* conducted annually for more than 4 years has demonstrated that, under appropriate preservation conditions, these burned facies are good recorders of the Earth's magnetic field direction (Carrancho et al., 2024). Our findings and those of other analogous studies also indicate it (e.g., Carrancho et al., 2013; Kapper et al., 2014b). Their unconsolidated nature makes sampling and analysis particularly complex. Nevertheless, these materials are independently well-dated, exposed in stratigraphically continuous cave sequences, significantly old (dating back to the Neolithic period), and widely distributed across mediterranean Europe. Despite their limitations and under quality selection criteria like those outlined here, they can be valid recorders of the Earth's magnetic field direction in the past.

4.2. The evolution of PSV in Iberia before 1000 BCE

The new data reported in this study (with ages ranging between 4550 BCE and 2650 BCE approximately), along with others already available in archaeomagnetic databases (Appendix D), have been used to generate two PSVCs using different calculation methods (more details below; Fig. 7 and Appendix E-G), in order to explore the PSV behaviour in Iberia before 1000 BCE. With the help of GEOMAGIA50 v3.4 (Brown et al., 2015, 2021; <https://geomagia.gfz-potsdam.de/>), a database with the available archaeomagnetic directional data for Iberia, France and Morocco between 1000 BCE and 6000 BCE was generated [Appendix D]

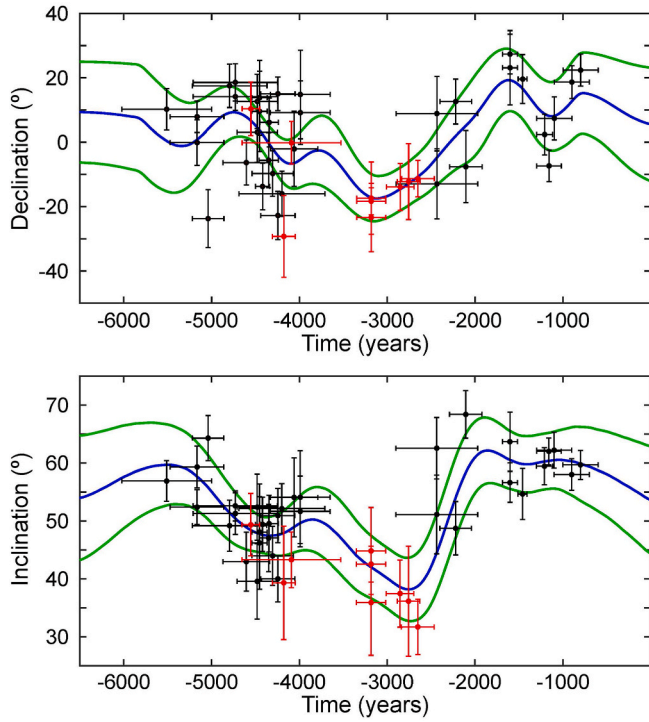
in order to assess the evolution of PSV in the region. The temporal limits for the database have been chosen to compare the new data with earlier and later directional trends.

Not all the collected data can be considered as their quality is rather variable. Directions with poor statistical parameters could bias ancient field reconstruction. Several selection criteria for the archaeomagnetic directions have been established in previous studies focused on PSV reconstruction in Iberia. A useful parameter to assess the quality of the data is the α_{95} . In the recent study of Molina-Cardín et al. (2018) covering the last 3 millennia, they only accepted directions with $\alpha_{95} \leq 5.0^\circ$. It is worth mentioning that there is a considerable amount of data in the area for this period. In the first version of the Iberian PSV curve, Gómez-Paccard et al. (2006) did not restrict the data according to their α_{95} . Nevertheless, they performed a test considering only data with $\alpha_{95} \leq 3.5^\circ$ and an age error ≤ 75 years. The results were not much different from those using the unconstrained data, in part because the low percentage of directions with $\alpha_{95} > 5^\circ$ (only 10 from a total of 134 directions). In our case, α_{95} criteria is less restrictive considering the scarcity of data for the studied period and the unlithified nature and age of the studied materials (not standard in archaeomagnetism). Anyway, only directions with $\alpha_{95} \leq 10^\circ$ have been accepted to assess the PSV trends. Kapper et al. (2014b) worked on similar materials (in terms of type and age) to those studied here and established a limit of $\alpha_{95} \leq 15^\circ$ to accept directions. From 43 directions accepted to generate the database for the present study, 19 show $\alpha_{95} \geq 5.0^\circ$. Only 7 of them exhibit $\alpha_{95} \geq 7.0^\circ$. Nevertheless, additional PSVCs were also generated using only data with $\alpha_{95} \leq 7^\circ$ (Appendix H-I) on a trial basis. They showed no substantial differences from those generated considering $\alpha_{95} \leq 10^\circ$. For all these reasons, we considered $\alpha_{95} \leq 10^\circ$ an acceptable threshold in this context.

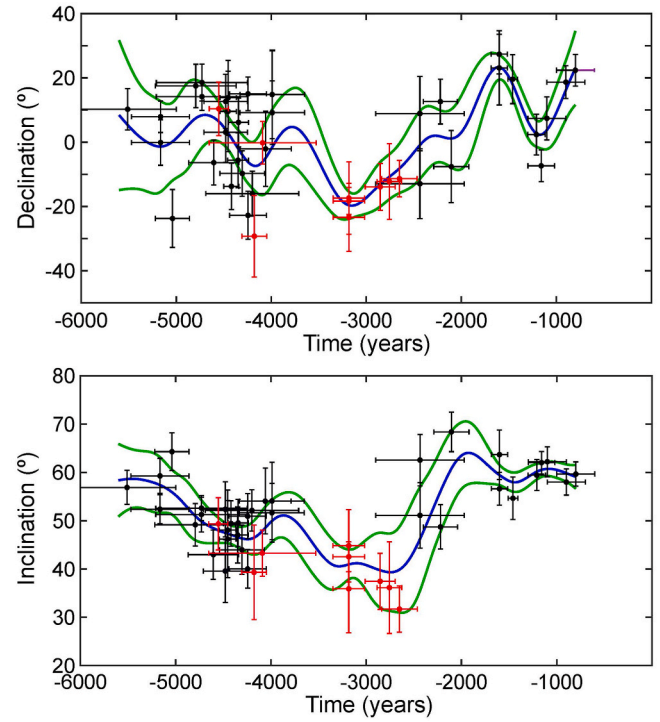
Another important variable when reconstructing the SV in the past is the quality of the dating associated to the materials. Molina-Cardín et al. (2018) and Osete et al. (2020) restricted the accepted data to those with an error in dating of ≤ 250 years relative to the mean age (an accumulated error range of ≤ 500 years). In the study of Gómez-Paccard et al. (2006), they did not find significant differences when restricting their database to directions associated with age errors of 75 years or less. However, this is to be expected since the studied materials exhibited considerably accurate ages. In the present study, no restriction of time error has been applied due to two main reasons: (1) the scarcity of data for the period and (2) the fact that error in dating is usually greater as you go further back in time. In spite of this, only 14 data yielded age errors of ≥ 500 years (± 250 years relative to the mean age). Indeed, these temporal uncertainties are not uncommon with radiometric techniques such as ^{14}C or TL for these chronologies. Additional PSVCs considering only data with age error ≤ 500 yrs have been performed (Appendix H-I). The main differences are observed in the period between -4200 and -3000 approximately and at the oldest limit of the PSVCs. In both cases, the strict filter means that no data remain for those periods. Therefore, the observed differences appear to be primarily related to the presence or absence of data, rather than to age uncertainty.

Another important factor to take into account is the considered spatial extent for the reconstruction. In the first PSV directional curve for Iberia (Gómez-Paccard et al., 2006), two datasets with different spatial coverage were used: one including sites within a 600 km radius from Madrid and another one with sites within a 900 km radius from Madrid. The narrowest area may be more representative to understand the specific PSV pattern in the region, since the 900 km dataset included some data from both France and Morocco. However, the use of this larger area implies the availability of a greater amount of data, which should improve the accuracy of the calculation. Anyway, the curves obtained with both sets were quite similar. Molina-Cardín et al. (2018) and Osete et al. (2020) also considered an area with a radius of 900 km from Madrid in their studies about the PSV in Iberia. In this work, taking into account the scarcity of data in the period under study and the criteria

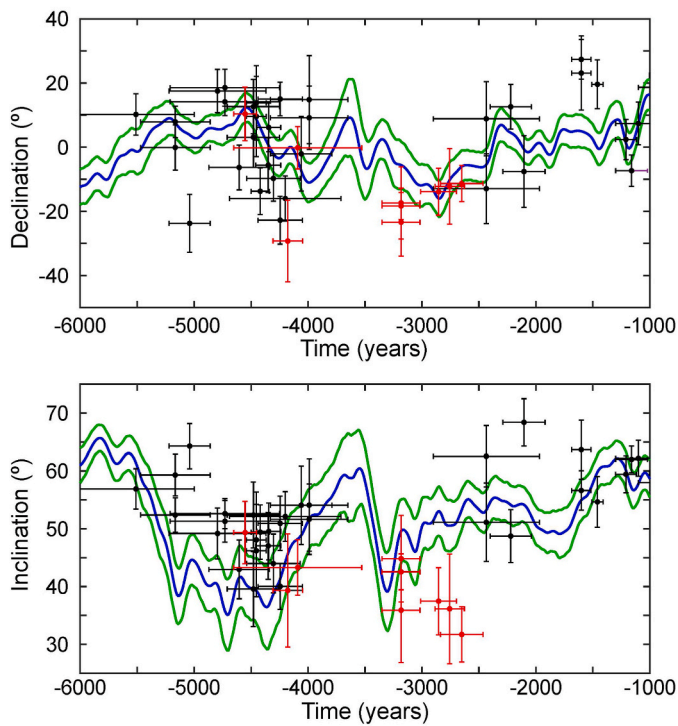
a) Bayesian method



b) Bootstrap method



c) SHA.DIF.14k (Pavón-Carrasco et al. 2014)



d) ArchKalmag14k (Schanner et al. 2022)

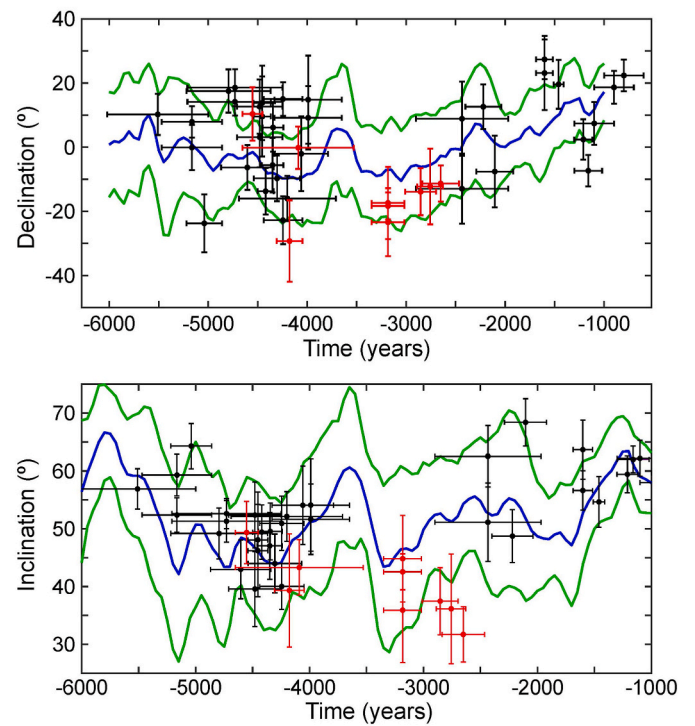


Fig. 7. New paleosecular variation curves (declination and inclination) developed using (a) a Bayesian approach and (b) Bootstrap techniques, along with the predictions of (c) SHA.DIF.14k (Pavón-Carrasco et al., 2014) and (d) ArchKalmag14k (Schanner et al., 2022). Blue and green lines represent the mean values of the PSVCs and their corresponding error bars [(a) 95% confidence level, based on the highest posterior density (HPD) region; (b-d) 2σ]. The new curves and predictions of the reconstructions are located at Madrid coordinates (Lat.: 40.4 N; Long.: 3.7 W). Red points = new directions presented here; black points = previous directional data. Each data point shows the error in declination/inclination and age uncertainty. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

followed in the previous studies, we consider a 900 km radius from Madrid too. For that reason, some directional data from France were also included for the calculations.

Two new PSV curves (PSVCs) were obtained using two different methods of calculation (Fig. 7a and b; Appendix E-G). Firstly, we applied a Bayesian approach using the tool ChronoCurve, integrated within ChronoModel v3.3 (Fig. 7a; Appendix E). More details about the method and the software are given in Lanos (2004), Schnepf et al. (2009, 2015), Hervé and Lanos (2018), Vibet et al. (2015, 2016), Lanos and Dufresne (2019, 2024), Noukpoape et al. (2025). Directional data was relocated to Madrid coordinates (40.4° N, 3.7° W) in order to generate the curve. When available, stratigraphical relationships were considered to create the model. Declination and inclination were considered together, maintaining the intensity as a constant. 300.000 MCMC (Monte Carlo Markov Chains) iterations [5 chains x 60.000 iterations] were performed to produce the curve. Secondly, another method based on penalized cubic splines fixed at 50-year intervals and a bootstrap technique following Thébaud and Gallet (2010) was used to generate another PSVC (Fig. 7b; Appendix F-G). In this case, all directional data were also relocated to Madrid coordinates. Stratigraphic constraints were also included when available in the PSVC construction. Declination and inclination were considered together. In absence of intensity data, elements of the magnetic vector were divided by the first element (see details in Molina-Cardín et al., 2018). The final PSVC was generated by combining 5000 different curves obtained by means of random variation of the magnetic data considering their α_{95} and ages with their respective errors.

It should be noted that uncertainty before 5000 BCE is significant in the new curves (Fig. 7a and b) due to the lack of data in this extreme of the curve. Apart from this, when the new curves are compared with the predictions of two global paleomagnetic reconstructions SHA.DIF.14k (Pavón-Carrasco et al., 2014) and ArchKalmag14k (Schanner et al., 2022) (both reconstructions cover the last 14,000 years and are based exclusively on data from materials carrying thermoremanent magnetizations), it is observed that the new curves are less detailed (Fig. 7a and b vs. Fig. 7c and d). This is due to the low density of data for Iberia during this period. Despite this issue, the new curves are useful for approximating the behavior of the PSV in Iberia.

Regarding general trends, there are similarities and differences between the models and the new curves. A certain eastern trend is observed in declination between ~5000 yrs BCE and ~4750 yrs BCE (Fig. 7a and b). In SHA.DIF.14k, this trend seems to continue up to ~4500 yrs BCE (Fig. 7c). However, in the case of ArchKalmag14k, it is not so obvious (Fig. 7d). After that, the declination moves towards the west in the new curves, reaching a minimum around 4200-4000 yrs BCE (Fig. 7a and b). This general trend is also observed in the SHA.DIF.14k reconstruction and to a lesser extent in the ArchKalmag14k reconstruction. The inclination reaches minimum values between ~5000 and ~4000 yrs BCE for both SHA.DIF.14k and ArchKalmag14k reconstructions (Fig. 7c and d). This parameter also decreases in the new PSVCs but it does not reach their lowest mean values (Fig. 7a and b). In the new curves, the inclination is around 45-50° (mean values), while it is even less than 40° for certain moments between 4750 and 4000 yrs BCE in the SHA.DIF.14k reconstruction (Fig. 7c).

An eastward trend is observed approximately in all cases between 4200-4000 and 3750-3600 yrs BCE. It coincides with a clear increase in the inclination in SHA.DIF.14k and ArchKalmag14k reconstructions (Fig. 7c and d). This is less evident in the new curves and appears shortly before (Fig. 7a and b).

Between ca. 3750-3600 and ca. 3200-2800 yrs BCE, the declination moves towards the West again. A rapid decrease in inclination is observed in both SHA.DIF.14k and ArchKalmag14k reconstructions, reaching a minimum around 3300 yrs BCE (Fig. 7c and d). In the new curves, there is an inclination decrease too, but the trend extends up to ~2750 yrs BCE (Fig. 7a and b). It reaches the lowest mean values of inclination in these two records, with mean values even lower than

40.0°. So far, it should be noted that the only data from Iberia between 3500 and 2500 yrs BCE come from this study. It would be useful to obtain more data for this period to assess more thoroughly the potential impact of the data scarcity and their uncertainties on this trend.

After that and up to 1000 yrs BCE, the reconstructions show a mainly eastern declination (Fig. 7c and d). There are small oscillations but do not imply drastic changes in the main trend. However, the curves show an important difference. Between 3150 and 2850 yrs BCE and 1500 yrs BCE there is indeed an eastern trend (Fig. 7a and b). However, declination then clearly moves to the West, up to ~1250 yrs BCE. Later, it moves to the East again. It is not so evident in the models. Inclination increases in the new curves between ~2750 yrs BCE and ~2000 yrs BCE, reaching a maximum. After that, the inclination decreases slightly up to 1500 yrs BCE, before remaining relatively stable. A similar general trend can be observed in SHA.DIF.14k and ArchKalmag14k (Fig. 7c and d).

These new PSVCs should be interpreted with caution, as small-scale PSV features may be masked by uncertainties of the directional data and their respective age control. Nevertheless, it is a first approach to reconstruct the PSV in Iberia for the last 4-5 millennia BCE with new TRM data.

5. Conclusions

The archaeomagnetic study of various combustion episodes in three fumi sequences in the Iberian Peninsula has yielded 15 new data between ~4650 and ~2460 BCE. This contributes to fill the great scarcity of data for these chronologies in Iberia. Two PSV curves (using two different modelling methods) for Iberia between 1000 BCE and 6000 BCE were developed compiling the new data and directions from previous studies, giving a broad idea of PSV behaviour in the region. Although the new curves still have intervals with low data density, they represent the first regional approach to PSV in such ancient times in this area.

It should be also noted that this work provides new data for chronologies for which there was no previous archaeomagnetic data, such as ca. 3500 – 2500 yrs BCE. In addition to modelling the PSV in the region, these curves are of geochronological interest to date the last use of archaeological combustion structures. The potential of combustion episodes from fumi sequences is reaffirmed as reliable geomagnetic field recorders to extend the PSV records in the Mediterranean Europe to the mid-Holocene, which contributes to an improvement in archaeomagnetic dating.

CRediT authorship contribution statement

Ángela Herrejón Lagunilla: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ángel Carrancho Alonso:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Juan José Villalaín Santamaría:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Francisco Javier Pavón Carrasco:** Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization. **Philippe Lanos:** Writing – review & editing, Software, Methodology, Formal analysis. **Philippe Dufresne:** Software, Methodology, Formal analysis. **Javier Fernández Eraso:** Writing – review & editing, Resources. **Cristina Vega:** Writing – review & editing, Resources. **Eduardo Carmona:** Writing – review & editing, Resources.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quageo.2026.101769>.

Data availability

The dataset of this work is available at the Institutional Repository of the University of Burgos (RIUBU): <https://doi.org/10.71486/z3a2-9d28>

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