Archaeometry **52**, 5 (2010) 882–898 doi: 10.1111/j.1475-4754.2010.00533.x

CHARACTERIZING THE SEDIMENTARY HISTORY OF CAVE DEPOSITS, USING ARCHAEOMAGNETISM AND ROCK MAGNETISM, ATAPUERCA (NORTHERN SPAIN)*

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We use a combination of rock magnetism (anisotropy of magnetic susceptibility, AMS) and magnetic polarity to characterize cave deposits and as a proxy for sedimentary fabric. In three localities at the Atapuerca archaeological site (Galeria, Gran Dolina and Sala de los Cíclopes), magnetic foliation (K_{max}/K_{int}) is always greater than lineation (K_{int}/K_{min}), consistent with a primary, depositional, sedimentary fabric. Our results, although preliminary, reveal a higher degree of anisotropy in autochtonous deposits compared to allochthonous deposits, possibly indicative of a higher hydrodynamic regime in the former. At two localities the magnetic lineation (K_{max}) defines a cluster, which is thought to be antipodal to the palaeocurrent direction. Hence we are able to retrieve palaeoflow directions in deposits that otherwise lack any other sedimentary structure. We conclude that AMS is a powerful tool for determining the hydrodynamic character of depositional environments in cave sediments at the Atapuerca archaeological site. A better understanding of the depositional environment and how sedimentation occurred allows reconstruction of the karst evolution and ultimately a better definition of human interaction with the environment.

KEYWORDS: ATAPUERCA, EURASIA, PLEISTOCENE, ROCK MAGNETISM, MAGNETIC REVERSALS, SEDIMENTARY FABRIC

INTRODUCTION

Although archaeomagnetism classically involves the study of remanent magnetization in recent materials such as pottery and baked hearths from archaeological sites, it embraces several palaeomagnetic methods that can be applied to address archaeological problems. In this study, we combine both magnetic polarity information and rock magnetism (anisotropy of magnetic susceptibility, AMS) to characterize cave deposits at the Pleistocene archaeological site of Atapuerca.

Caves and rockshelters are traditional habitation sites for prehistoric humans and they play a very important role in providing data on the environmental conditions in which humans lived. Cave terrigenous deposits are unique among other geological depositional environments in that: (a) sediment accumulation rates are typically high; (b) sediments form under a very specific range of physico-chemical conditions—that is, moisture and temperature; and (c) deposits are typically

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protected from severe weathering and erosion. Deciphering specific conditions of sedimentary processes in caves is often an intricate task. For example, distinguishing hydrodynamic from gravity-driven deposits, a rather usual situation in cave studies, is typically hampered by the lack of field or textural evidence in the sediments (e.g., Goldberg and Macphail 2006; Goldberg and Sherwood 2006). Here we present an approach to determine sediment fabric that is also a proxy for depositional environment, based on the anisotropy of magnetic susceptibility (AMS). A better understanding of the depositional environment—that is, under what conditions sedimentation occurs, and what the hydrodynamic regime is—allows reconstruction of the karst evolution and hence a better understanding on how humans interacted with the environment. Furthermore, recent literature on geoarchaeology—and specifically on cave environments—emphasizes the importance of considering the interconnectivity between human activity and the environment in which the human population interacted (e.g., Goldberg and Sherwood 2006). We specifically apply the AMS technique to cave deposits at the archaeological site of Atapuerca, Spain, which contains a rich record of hominids from Lower to Upper Pleistocene age (see Bermúdez de Castro *et al.* 1997; Arsuaga *et al.* 1999; Carbonell *et al.* 1999; Aguirre and Carbonell 2001 and references therein).

Anisotropy of magnetic susceptibility (AMS)—principles

The low-field magnetic susceptibility of a rock is given by the total contribution of its bulk mineralogy, including paramagnetic (e.g., phyllosilicates and iron-bearing feldspars), diamagnetic (e.g., quartz and calcite) and ferromagnetic (*sensu lato*) (e.g., magnetite, maghemite, goethite and hematite) mineral phases. An intrinsic property of most rock-forming minerals is that their magnetic susceptibility is anisotropic (Nye 1957) and thus $K_{ij} = M_i/H_j$. For example, mica grains show a close relationship between the crystallographic *c*-axis and the minimum susceptibility direction (Richter *et al.* 1993). The crystallographic preferred orientation of mica grains, therefore, is directly related to magnetic fabrics if the susceptibility is dominated by this mineral phase, as in most silts and fine sands.

The AMS in rocks depends mostly on crystallographic preferred orientation, compositional layering, distribution and size of microfractures, and the shape fabric of grains, which may interact in complex ways. AMS defines a symmetric, second-rank tensor that has six independent matrix elements. When the coordinate system is referred to the eigenvectors, these trace an ellipsoid that is termed the magnitude ellipsoid (Nye 1957), whose semi-axes are the three principal susceptibilities (the maximum, intermediate and minimum susceptibility orthogonal axes, or K_{max}, K_{int} and K_{min}). AMS has been a popular tool in petrofabrics since Ising (1942) and Graham (1954) first proposed its application in geology, and it has been used successfully since then to investigate the spatial and geometric configuration of the rock components for qualitative estimation of fabric development (see reviews by Hrouda 1982; McDonald and Ellwood 1987; Borradaile 1988; Tarling and Hrouda 1993). The AMS tensor provides information on the preferred grain orientation (fabrics) in rocks, and consequently its applications have embraced many disciplines in the earth sciences, including sedimentary depositional environments (e.g., Kent and Lowrie 1975; Ellwood *et al.* 1979; Kodama and Sun 1990; Kissel *et al.* 1997; Joseph *et al.* 1998; Park *et al.* 2000; Hus 2003; Parés *et al.* 2007).

In both terrigenous sedimentary rocks and laboratory experiments (e.g., Rees and Woodall 1975; summary in Tarling and Hrouda 1993), it has been observed that AMS reflects the depositional plane of sediments (see the review in Tarling and Hrouda 1993). Thus, the magnetic foliation (i.e., the plane containing the K_{max} and K_{int} axes) is parallel to the bedding plane, and the

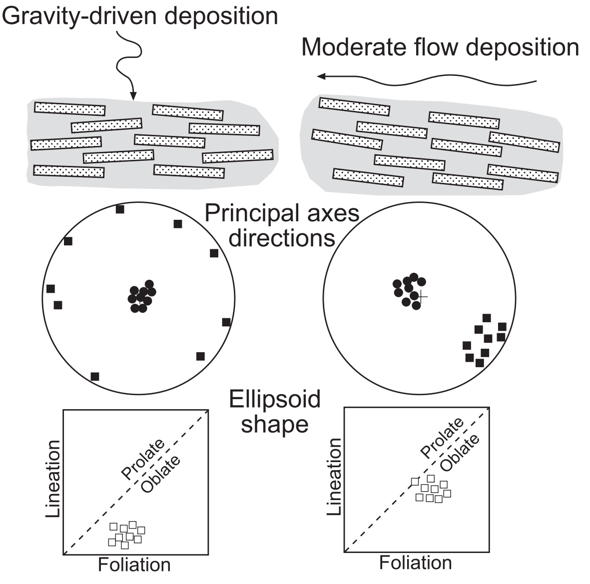

Figure 1 *The principle of the AMS method. Dots (squares) represent principal minimum (maximum) axes of susceptibility. In gravity-driven (e.g., quiet water) conditions, the minimum axes are perpendicular to the depositional plane and the fabric is characterized by an oblate magnetic ellipsoid. Under weak and moderate currents particles are imbricated, resulting in off-vertical minimum axes directions and a cluster of maximum axes, the orientation of which is antiparallel to the palaeoflow direction. Flinn-type (Flinn 1962) diagrams show the expected shape of the AMS ellipsoids for each depositional mode. Foliation is defined as* K_{max}/K_{min} *and Lineation as* K_{int}/K_{min}.

magnetic lineation (the cluster of K_{max} axes) is antiparallel or normal to the palaeocurrent direction, depending on the hydrodynamic regime (moderate or high velocity, respectively; see Fig. 1).

Several parameters have been used to describe the axial magnitude relationships of the susceptibility ellipsoid (see also Tarling and Hrouda 1993; Tauxe 1993). The simplest expressions are the axial ratios L (K_{max}/K_{int}) (Balsley and Buddington 1960), F (K_{int}/K_{min}) (Stacey *et al*. 1960) and P (K_{max}/K_{min}) (Nagata 1961). Other authors use the parameters P' $\{P' = \exp [2(a_1^2 + a_2^2 + a_3^2)]^{1/2}\}$ (Jelínek 1981), where $a_1 = \ln(K_{max}/K_b)$ and so on, and $K_b = (K_{max} + k_{int} + K_{min})/3$ (Nagata 1961) to express the fabric intensity as a measure of eccentricity, and T ($T = 2(\ln K_{int} - \ln K_{min})/[\ln K_{max} - \ln K_{min}] - 1$) (Jelínek 1981) to define the degree to which the ellipsoid is oblate or prolate.

METHODS

Oriented hand samples were collected in the field using two different methods. Clay and silt deposits that were sufficiently soft were sampled by hammering a brass tube with a reinforced stainless steel tip. With this method, standard 1 inch (2.54 cm) cores were obtained and oriented *in situ*. Otherwise small cubes (8 cm^3) were cut from oriented blocks using a small hand saw. Because of their friability, block samples were impregnated in the field with a 1:1 sodium silicate solution before magnetic analysis. All magnetic measurements were carried out in the palaeomagnetism laboratory at the University of Michigan. AMS measurements were carried out in a Kappabridge KLY-2.03 susceptibility bridge (Geofyzika Brno), and applying the 15 directional susceptibilities scheme of Jelínek (1978). The bridge operates at a frequency of 920 Hz (the sensitivity of the coil is ~5×10^{-7} SI). AMS data analysis was performed by linear perturbation analysis (LPA; Tauxe 1998), with statistical bootstrapping of anisotropy data in order to obtain the confidence ellipses. First, the matrix elements and residual errors for each individual sample are calculated using 15 measurements. Then, the bootstrap statistics for the matrix elements are calculated. Instead of plotting the 95% confidence ellipses to visualize the orientation distributions, which also all require unnecessary parametric assumptions (Tauxe 1998), we display the bootstrap eigenvectors on a stereonet as a smear of points around the eigenparameters. Confidence regions for the bootstrapped distributions can be drawn as a contour line enclosing 95% of the bootstrapped eigenvectors.

Natural remanent magnetization (NRM) and its progressive demagnetization of the samples were measured with a three-axis 2G SQUID magnetometer housed in a field-free room. The noise level of the magnetometer is ~7 $\mu A\ m^{-1}$, well below the magnetization intensity of the measured samples. Specimens were stepwise demagnetized in a ASC Thermal Demagnetizer. Characteristic remanent magnetization component directions were calculated for all specimens using principal component analysis (Kirschvink 1980), guided by visual inspection of orthogonal demagnetization plots (Zijderveld 1967). Mean directions and associated statistical parameters were estimated using Fisher's (1953) method.

THE GEOLOGICAL SETTING

The Sierra de Atapuerca is located in north central Spain, at the northeastern margin of the Iberian plateau, and within the Duero Basin (Fig. 2). This mountain range contains a rich variety of karstic cavities and fissures of a phreatic–vadose origin within Cretaceous limestones. Several caves of this karst system contain archaeological and palaeontological remains that have been the focus of numerous studies since the 1980s (see Aguirre *et al*. 1990; Arsuaga *et al*. 1997; Carbonell *et al*. 2008 and references therein). Detailed descriptions of the geological and karst development of the archaeological site can be found in Pérez-González *et al*. (1995), Zazo *et al*. (1983) and Martín *et al*. (1981). An old early 1900s railway trench revealed numerous fissures and caves in Cretaceous limestones of the slopes of the Sierra de Atapuerca. Many of the cave infilling sediments were found to be very rich in palaeontological remains (Torres 1976; Aguirre *et al*. 1990 and references therein). The railway sites include Gran Dolina, where the new species *Homo antecessor*, of early Pleistocene age, was discovered (Fig. 2) (Carbonell *et al*. 1995; Parés and Pérez-González 1995, 1999; Bermúdez de Castro *et al*. 1997; Cuenca-Bescós *et al*. 1999; Falguères *et al*. 1999), Galeria (Pérez-González *et al*. 2001) and Sima del Elefante (Carbonell *et al*. 1999; Cuenca *et al*. 2004; Parés *et al*. 2006). In addition, the Cueva Mayor system contains a number of archaeological sites, including the Sima de los Huesos, Portalón and Galeria del Silex (Fig. 2). Overall, the railway sites and the Cueva Mayor constitute what is known as the Sierra de Atapuerca archaeological site. The archaeological site was added to UNESCO's World Heritage List in 2000 and has become a key Eurasian palaeo-anthropological and palaeontological locality.

Sampled sites

For this study, we collected samples from Cueva Mayor (Sala de los Cíclopes), Galería and Gran Dolina (Fig. 2). Details on stratigraphy, lithostratigraphy and chronology for those sites can be found in Arsuaga *et al*. (1997), Rosas *et al*. (2001, 2004), Carbonell *et al*. (1999) and Pérez-González *et al*. (1995, 2001), Parés and Pérez-González (1999) and Falguères *et al*. (1999), and only the main features of the sampled sections that are relevant for this study are discussed here. In

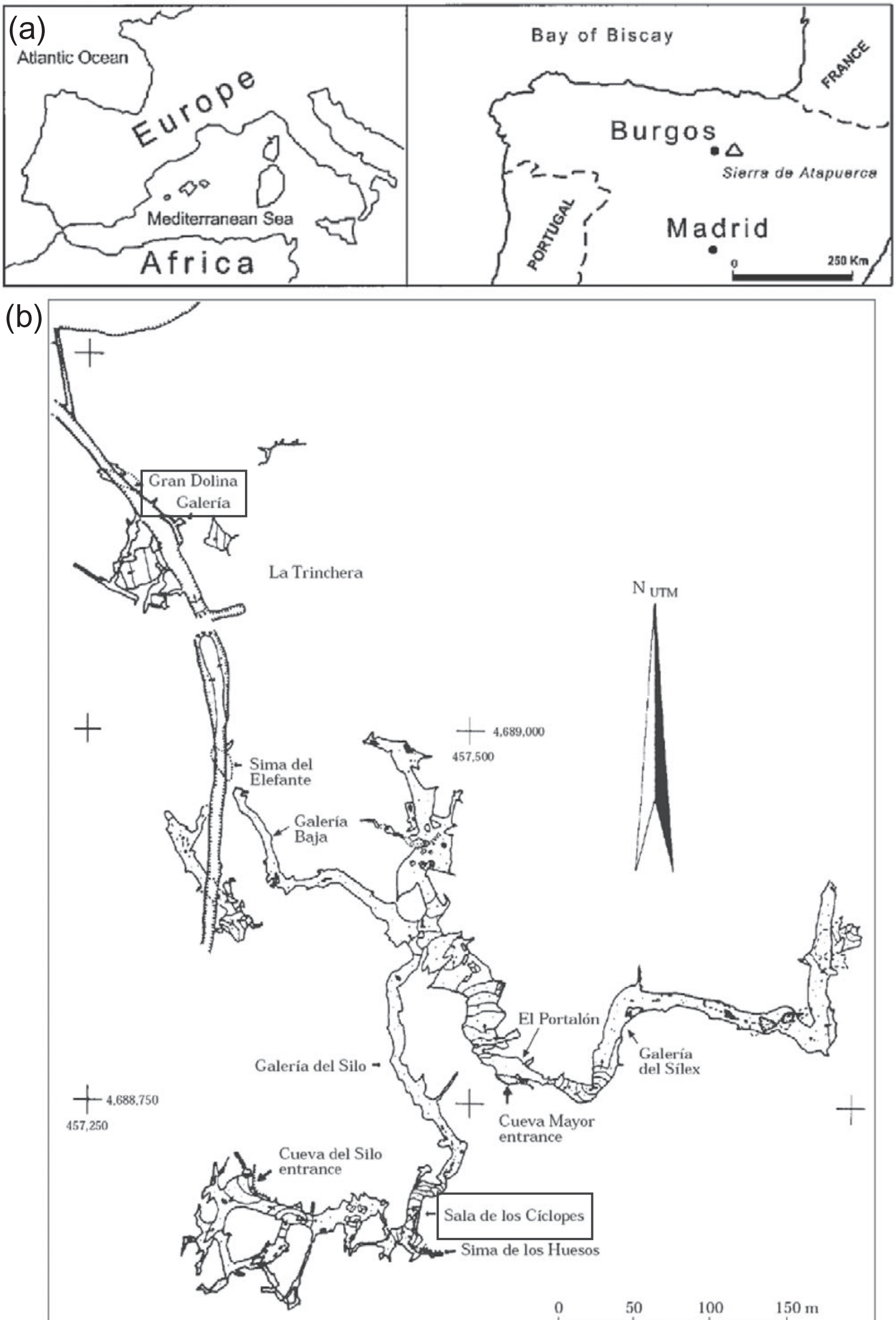

Figure 2 *(a) The location of the Atapuerca archaeological site. (b) A plan of the Sierra de Atapuerca karst system (from Arsuaga* et al. *1997).*

Table 1 *A summary of the anisotropy of magnetic susceptibility of sites used in this study: τ, eigenvalues; σ, standard deviation; Dec/Inc, the declination and inclination of the eigenvectors*

Site	*Eigenvector 1*				*Eigenvector 2*				*Eigenvector 3*			
	τ	*σ*	*Dec*	*Inc*	*τ*	*σ*	*Dec*	*Inc*	*τ*	*σ*	*Dec*	*Inc*
Galeria, Unit I	0.33540	0.00033	1.7	1.6	0.33501	0.00030	271.7	1.3	0.32959	0.00053	143.3	88.0
Galeria, Unit III	0.33474	0.00028	255.1	2.1	0.33440	0.00028	345.2	2.0	0.33086	0.00048	118.7	87.1
Gran Dolina	0.34486	0.00239	299.6	8.3	0.33991	0.000203	30.9	8.8	0.31524	0.00430	166.9	77.8
S. Cíclopes	0.33631	0.00042	265.0	10.9	0.33507	0.00032	173.5	7.8	0.32862	0.00057	48.6	76.6

the Sala de los Cíclopes, we sampled a ~1.30 m thick unit of brown laminated sandy silts. This sedimentary unit is attached on the rock wall, in the southwestern area of the cavity, and is the remnant of a much more extensive deposit that has been for the most part washed out in an erosive phase during the karst history (Ortega *et al*. 2005). On top of the silt there is a ~3 m thick red breccia deposit, including limestone clasts. A conspicuous contact separates the breccia from the underlying brown silt and will be discussed later. In Galeria, we sampled Units GI (upper part) and GIII (Pérez-González *et al*. 1999), which are mostly silty fine-grained sands. A detailed study by Pérez-González *et al*. (1995) reveals that the unit is composed mostly of quartz (92%) and that illite is the dominant clay mineral. Pérez-González *et al*. (1999) interpreted Unit GI as an autochthonous deposit—that is, sediments that originated at various locations inside the cave system (Goldberg and Sherwood 2006). Unit GI spans the Lower/Middle Pleistocene boundary, whereas Unit GIII has an age between 180 and 300 ka (Bischoff *et al*. 1997, 2003; Falguères *et al*. 2001). In the Gran Dolina section, we focused on silty fine-grained sediments from Unit TD1, of Lower Pleistocene age, that correspond to the autochthonous facies (Pérez-González *et al*. 1999). This unit consists of 1.5 m of clay, with very little sand (<2–3%) and parallel laminar bedding.

RESULTS

The following analysis and interpretation of the sedimentary fabric is mostly based on the orientation distribution of the principal axes of magnetic susceptibility, as revealed by the AMS measurements (Table 1). The feature common to all sites is that the principal AMS K_{max} axes lie within the depositional plane, which is subhorizontal in Galería and Gran dolina, and dips ~15° in Cíclopes. Such an axis distribution is consistent with a sedimentary, depositional fabric, with the expected AMS distributions and shapes. In all of the studied sites, the shape of the magnetic ellipsoid is oblate, as shown in the Flinn-type diagrams (Flinn 1962) (Fig. 3), with an average foliation (F) of ~1.03. The principal minimum AMS axes (K_{min}) are near-vertical—that is, normal to the magnetic foliation in all localities. These features define a magnetic sedimentary fabric, where mostly phyllosilicates rest within the basal plane parallel to the depositional surface, and hence the crystallographic *c*-axes are subvertical and determine the orientation of the K_{min} axes of the magnetic ellipsoids of the sediments. In the absence of a palaeocurrent, the K_{max} axes are distributed within the depositional plane; otherwise, a cluster would parallel the flow direction.

In Galeria, we sampled two different units (GI and GIII), which, from the lithostratigraphic point of view, seem to reflect deposits of different origin (autochthonous and allochthonous, respectively; Pérez-González *et al*. 1999). The AMS data show that Unit GI has a slightly higher AMS than Unit GIII (1.017 and 1.011, respectively). Furthermore, even though the magnetic

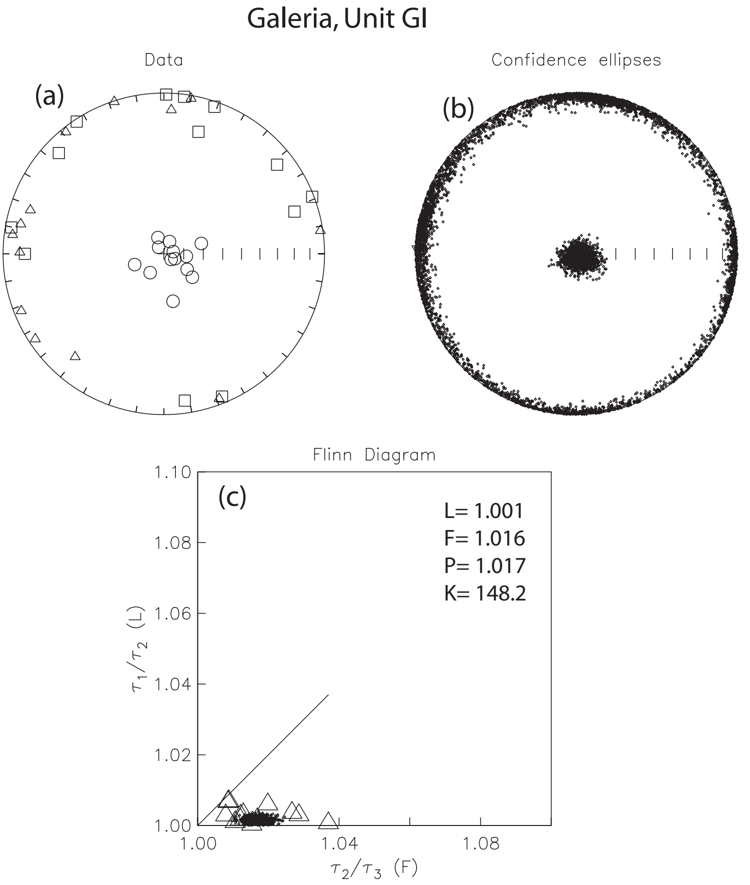

Figure 3 *AMS results for sites at Atapuerca. (a) The lower-hemisphere projection of the directions of the principal maximum (squares), intermediate (triangles) and minimum (circles) axes of susceptibility. (b) Bootstrapped eigenvectors from para-data sets of the data in (a). (c) The shape parameter from the data set on a Flinn-type diagram: data from individual samples are shown as triangles; dots are average values for bootstrapped para-data sets.*

lineation is very low in both cases ($L = 1.001$), the K_{max} axes in Unit GI are north-dipping, whereas in Unit GIII they show a larger scatter within the depositional plane, as defined by the girdle of K_{max} and K_{int} axes. These features are suggestive of a relatively higher hydrodynamic regime during the deposition of the Unit GI sediments and quiet depositional conditions in Unit GIII.

In the nearby Gran Dolina section, the principal axes distribution is slightly different. Whereas the K_{min} axes are subvertical and normal to the depositional plane, both K_{max} and K_{int} form two separate clusters, to the north-west and north-east, respectively. Sediments at Gran Dolina have, on average, a higher magnetic foliation and lineation than those from Galeria, suggesting a higher energy depositional regime. The mean value of the anisotropy degree P is 1.093, consistent with such a depositional environment. Also, the high value of magnetic lineation and degree of clustering of K_{max} axes suggests a dominant palaeocurrent with a WNW–ESE trend; and given the dominance of WNW-dipping K_{max} axes, the current flow was probably towards the ~ESE.

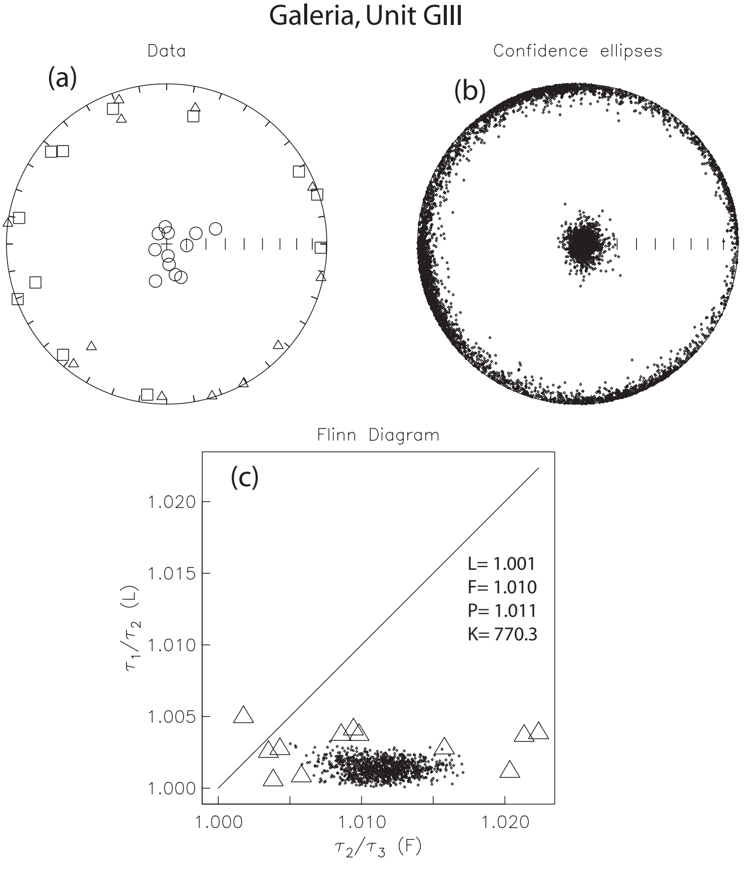

Figure 3—*Continued*

We sampled at one locality in Cueva Mayor, namely the Sala de los Cíclopes. This cavity is of great interest because it may help us to understand the karst evolution and development of the contiguous Sima de los Huesos, which contains a rich and important assemblage of hominids possibly 600 ka old (Arsuaga *et al*. 1999; Parés *et al*. 2000; Bischoff *et al*. 2003, 2006). The AMS results from the silts at Sala de los Cíclopes resemble those from the previously described sites (Fig. 3). The K_{min} axes are slightly off-vertical, steeply dipping to the east, and are normal to a well-developed magnetic foliation ($F = 1.019$). These results are consistent with the parallel lamination observed at that locality, which dips ~20° westwards (Fig. 4). Whether such lamination corresponds to inclined foreset laminae or, rather, is an original horizontal lamination that has been tilted is not evident from the field observations. The abrupt contact between the red breccia unit on top of the brown silt unit suggests a rather pronounced change in sedimentation pattern. In order to better understand the abrupt contact and the origin of the parallel lamination in the Sala de los Cíclopes silt, we obtained palaeomagnetic data from the sediments. Silts are very stable upon stepwise, progressive thermal demagnetization (Fig. 5). A low-temperature component (LT) is removed at about 300°C. Above that temperature, the characteristic remanent magnetization (ChRM) is defined, until spurious magnetization above ~500°C prevents further temperature increments (Fig. 5 (a)). Such behaviour during thermal demagnetization has previ-

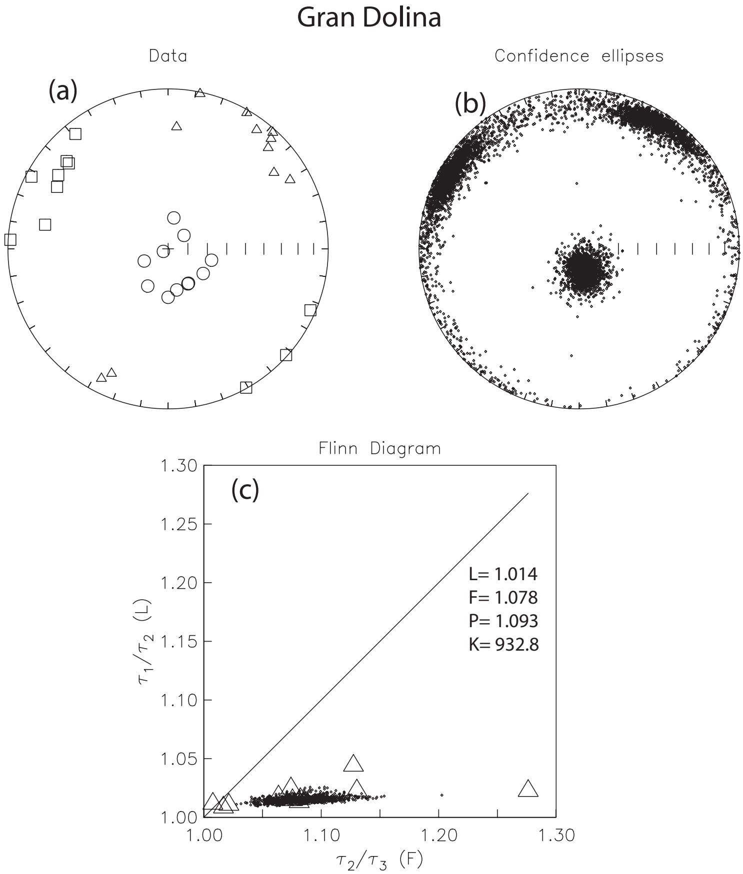

Figure 3—*Continued*

ously been observed in this type of cave sediment and is attributed to the growth of magnetite due to heating (see, e.g., Parés and Pérez-González 1999; Parés *et al*. 2000, 2006). Even so, the orientation of the high-temperature (HT) component can be calculated unambiguously using principal component analysis (Fig. 5 (b)). In all samples, the HT component is south- and up-directed (i.e., reverse polarity), whereas the LT component is almost antipodal (i.e., normal polarity). The LT magnetization component can be interpreted as a viscous overprint acquired during Brunhes Chron (<780 ka), whereas the HT magnetization component corresponds to the primary magnetization of the samples, which we interpret as being of Matuyama age (>0.78 Ma).

We now can combine the information obtained from the palaeomagnetism of the silt unit with that from the sediment fabrics. The HT mean inclination (–27.7) is very low for a Quaternary deposit (the expected inclination at the locality is ~60°). A flattening inclination error in sedimentary rocks is a phenomenon that has been known for a number of years (e.g., King 1955; Tauxe and Kent 1984), but it is unlikely to produce an error of more than 20°. We suspect that the shallow inclination observed at Sala de los Cíclopes is most likely due to a physical tilting of the deposit. We have therefore used the observed lamination in the field (20° to the west), which is

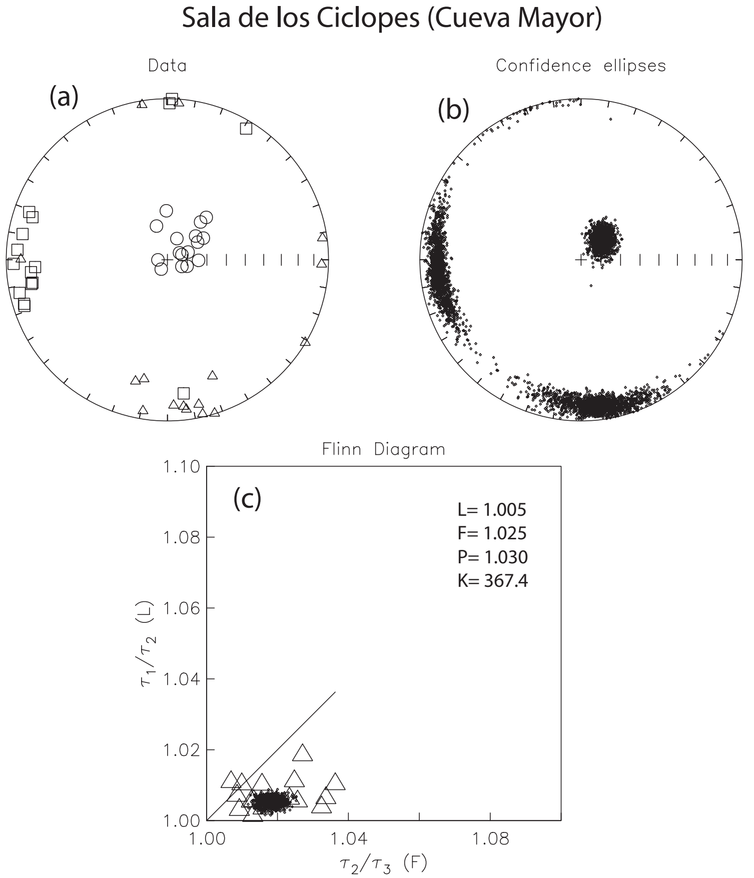

Figure 3—*Continued*

also revealed by the AMS, to 'correct' the palaeomagnetic direction. 'Untilting' is accomplished by restoring the palaeomagnetic direction about the local strike axis by the dip of the lamination. After untilting—that is, after rotating the depositional surface back to horizontal—the observed mean inclination (–43.8° ± 8.7°) is much closer to the expected inclination value. The discrepancy between the corrected and expected inclination can now easily be attributed to the flattening inclination error in the sediments (Tauxe and Kent 1984). Similarly, the viscous component, or LT, also shows better agreement with the present-day field after untilting. We therefore conclude that the lamination observed in the silt unit at Sala de los Cíclopes was originally horizontal when the primary magnetization (ChRM) was acquired. After an unknown period of time, but subsequent to the Matuyama–Brunhes reversal, the silts were partially overprinted by a viscous normal polarity. An episode of tilting postdates the acquisition of both magnetization components, LT and HT, and it produces the dip of the lamination of the deposit to the west. Even though we do not have additional data supporting or refuting such a hypothesis, it seems reasonable that a rigid-block rotation of the sediments occurred at some time in the Middle Pleistocene to produce the observed magnetic inclination. Hence, the palaeomagnetic data of the Sala de los Cíclopes deposits suggest that the magnetic foliation does not represent a deposition slope but, rather, that

Figure 4 *A detail of the Sala de los Cíclopes deposit sampled for AMS and palaeomagnetism (note the pencil for scale). The long-dashed lines show the unconformable contact between the sampled brown sandy silt unit and the overlying red breccia. The short-dashed lines highlight the parallel lamination within the lower unit. See the text for discussion.*

the depositional plane was originally horizontal and was subsequently tilted in the Middle or Upper Pleistocene.

DISCUSSION

Overall, the AMS properties of all three sites at Atapuerca, including Gran Dolina, Galería and Sala de los Cíclopes, suggest that sediments were deposited under very low to moderate flow conditions. The sediment fabric is generally strongly foliated, a characteristic of quiet depositional environments (see, e.g., Tarling and Hrouda 1993). The maximum and intermediate susceptibility directions are parallel to the basal plane of the particles and the direction of maximum magnetic susceptibility (K_{max}) of the sediment tends to lie close to the depositional plane, producing an oblate 'normal' AMS fabric (Rees and Woodall 1975). Whereas in both of the localities Galeria (Units GI and GIII) and Gran Dolina we observe oblate magnetic ellipsoids

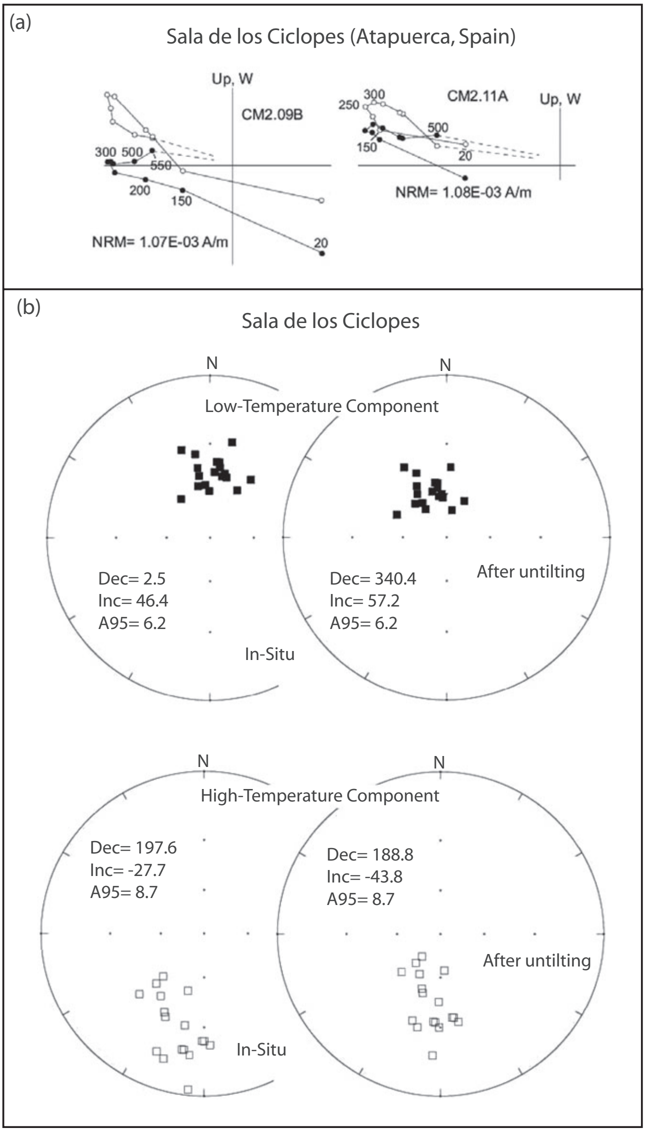

Figure 5 *Palaeomagnetic data for the Sala de los Cíclopes silt samples. (a) The results of progressive thermal demagnetization displayed by vector end-point diagrams (Zijderveld 1967) of representative samples. Each data point represents the NRM end-vector for individual demagnetization steps projected on to the horizontal (solid symbols) and vertical (open symbols) plane. Numbers adjacent to the magnetization directions indicate the demagnetization temperatures in degrees Celsius. The initial value of NRM is also shown. (b) Equal-area, lower-hemisphere stereographic projections of the characteristic remanent magnetization (ChRM) directions for the studied unit. Each symbol on the stereographic projections corresponds to an individual sample. Solid (open) symbols are projections on to the lower (upper) hemisphere and thus correspond to samples with normal (reverse) polarity. Mean directions for both LT and HT components are shown (Dec, declination; Inc, inclination; A95, associated 95% confidence circles).*

with near-vertical K_{min} axes, in Gran Dolina and Sala de los Cíclopes, the K_{min} axes are slightly off-vertical. Such a distribution of K_{min} axes occurs under moderate currents, resulting in particle imbrication and the concomitant clustering of K_{max} axes antiparallel to the palaeoflow direction (see, e.g., Tarling and Hrouda 1993; Liu *et al*. 2001).

As far as the degree of anisotropy is concerned, we notice that it is typically higher in the autochthonous deposits (Unit GI in Galeria, Gran Dolina and Sala de los Cíclopes). The only site where we studied allochthonous sediments corresponds to Unit GIII in Galeria, which has yielded an anisotropy degree (P') of 1.011. Whereas the anisotropy degree is not an absolute measure for current strength *per se*, it provides a quantitative way of determining the relative current strength (Ellwood and Ledbetter 1977, 1979; Ellwood *et al*. 1979; Ledbetter and Ellwood 1980; Joseph *et al*. 1998, 2004; Liu *et al*. 2001; Hassold *et al*. 2006; Parés *et al*. 2007). In this sense, our preliminary results indicate a higher hydrodynamic regime in autochtonous deposits in cave sediments.

The results from the Sala de los Cíclopes silts reveal the potential of using magnetic fabrics combined with palaeomagnetism in sediments as a proxy for geological evolution of cave sediments. Our results suggest that the lamination in the silt unit was in fact originally horizontal, as indicated by the palaeomagnetic direction. Upon restoration—that is, rotating the lamination plane to the horizontal—the palaeomagnetic inclination is in better agreement with the expected value. The AMS K_{max} axes cluster around an easterly direction, suggesting palaeoflow to the west. Such a palaeoflow direction should not be misconstrued as being the dominant palaeoflow direction within the cavity: a thorough study of numerous points within the cavity is necessary in order to infer the general pattern of water circulation and sediment deposition.

An important implication of our result is that the brown silt unit at Sala de los Cíclopes was tilted at some time in the Middle/Upper Pleistocene. Sediments that were tilted from their original horizontality have been previously observed in caves and rockshelters. For example, slumpling is thought to have produced tilted sediments in Kebara Cave, Israel (Laville and Goldberg 1989; Bar-Yosef *et al*. 1996; Goldberg and Macphail 2006). At the Sterkfontein cave site, South Africa, undermining and collapse led to sediment disturbance including tilting of the deposits (see Partridge *et al*. 2003). In Atapuerca, and specifically in Cueva Mayor, where the cave that contains the Sala de los Cíclopes is found, there is evidence for faulted and displaced flowstone slabs (Ortega *et al*. 2005), revealing episodes of deformation during the Middle/Upper Pleistocene. Our work in progress will furnish more data conducive to determining the extent and origin of such a deformation event.

CONCLUSIONS

The analysis of AMS in combination with magnetic polarity stratigraphy applied to Pleistocene cave sediments at the archaeological site of Atapuerca site provides features of the depositional environment that are otherwise unrecognizable by standard field procedures:

(1) The low-field, bulk magnetic susceptibility is from low to moderate, allowing the use of AMS to determine the sedimentary fabric of both autochthonous and allochthonous depositional units. Our observations are consistent with the presence of a mix of magnetite (see Parés and Pérez-González 1995; Parés *et al*. 2000) and phyllosilicates, a common byproduct of karstification.

(2) Phyllosilicates, in addition to magnetite, are most probably the main magnetic carriers contributing to the anisotropy. Previous studies show indeed that illite, smectite and kaolinite are common phyllosilicates in Galeria deposits (Pérez-González *et al*. 1999).

(3) The AMS can be interpreted in terms of preferred grain orientation of clay minerals, which means that AMS is a powerful tool to test the dominance of hydrodynamic versus gravity torques in determining the sedimentary fabric in detrital cave sediments.
(4) In all studied cases, the magnetic foliation (as defined by the plane containing the K_{max} and K_{int} axes) is higher than the magnetic lineation and mimics the depositional plane. In addition, the K_{max} axes occasionally produce clusters that can be interpreted in terms of palaeoflow direction during deposition. The sedimentary fabrics and palaeoflow directions that we have obtained should be simply taken as local readings of the hydrodynamic system and cannot be considered as representative of the overall sedimentary context of the studied cavities. Ongoing research will allow us to determine the variation in time and space of the palaeoflow directions through the Atapuerca cave system. A more comprehensive understanding of these cave sediments, taken as an integral part of the archaeological record, will ultimately help in obtaining unequal constraints on interpretation of human activities.

ACKNOWLEDGEMENTS

The authors thank two anonymous reviewers for thoughtful and very helpful comments. The fieldwork in Atapuerca is supported by the Junta de Castilla y León and the Fundación Atapuerca. This research was partially funded by MEC Grant DGI CGL2006-13532-C03-01. We would like to thank the Grupo Espeleológico Edelweiss (Burgos)—in particular, its president, Miguel A. Martín—for logistical support during sampling and for valuable discussions.

REFERENCES

Aguirre, E., and Carbonell, E., 2001, Early human expansions into Eurasia: the Atapuerca evidence, *Quaternary International*, **75**, 11–18.

Aguirre, E., Arsuaga, J. L., Bermúdez de Castro, J. M., Carbonell, E., Díez, M., Enamorado, J., Fernández-Jalvo, Y., Gil, E., Gracia, A., Martín-Nájera, A., Martínez, I., Morales, J., Ortega, A. I., Rosas, A., Sánchez, A., Sánchez, B., Sesé, C., Soto, E., and Torres, T. J., 1990, The Atapuerca sites and the Ibeas hominids, *Human Evolution*, **5**, 55–73.

Arsuaga, J. L., Martínez, I., Gracia, A., Carretero, J. M., Lorenzo, C., García, N., and Ortega, A. I., 1997, Sima de los Huesos (Sierra de Atapuerca). The site, *Journal of Human Evolution*, **33**, 109–27.

Arsuaga, J. L., Lorenzo, C., Carretero, J. M., Gracia, A., Martínez, I., García, N., Bermúdez de Castro, J. M., and Carbonell, E., 1999, A complete human pelvis from the Middle Pleistocene of Spain, *Nature*, **399**, 255–8.

Balsley, J. R., and Buddington, A. F., 1960, Magnetic susceptibility anisotropy and fabric of some Adirondack granites and orthogneisses, *American Journal of Science*, **258A**, 6–20.

Bar-Yosef, O., Arnold, M., Mercier, N., Belfer-Cohen, A., Goldberg, P., Housely, R., Laville, H., Meignen, L., Vogel, J. C., and Vandermeersch, B., 1996, The dating of the Upper Paleolithic layers in Kebara Cave, Mt. Carmel, *Journal of Archaeological Science*, **23**, 297–306.

Bermúdez de Castro, J. M., Arsuaga, J. U., Carbonell, E., Rosas, A., Martínez, I., and Mosquera, M., 1997, A hominid from the Lower Pleistocene of Atapuerca. Spain: possible ancestor to Neanderthals and modern humans, *Science*, **276**, 1392–5.

Bischoff, J. L., Shamp, D. D., Aramburu, A., Carbonell, E., and Bermúdez de Castro, J. M., 2003, The Sima de los Huesos hominids date to beyond U/Th equilibrium (>350 kyr) and perhaps to 400–500 kyr: new radiometric dates, *Journal of Archaeological Science*, **30**, 275–80.

Bischoff, J. L., Fitzpatrick, J. A., Leon, L., Arsuaga, J. L., Falguères, C., Bahain, J. J., and Bullen, T., 1997, Geology and preliminary dating of the hominid-bearing sedimentary fill of the Sima de los Huesos Chamber, Cueva Mayor of the Sierra de Atapuerca, Burgos, Spain, *Journal of Human Evolution*, **33**, 129–54.

Bischoff, J. L., Williams, R. W., Rosenbauer, R. J., Aramburu, A., Arsuaga, J. L., Garcia, N., and Cuebca-Bescós, G., 2006, High-resolution U-series dates from the Sima de los Huesos hominids yields 600 kyrs: implications for the evolution of the early Neanderthal lineage, *Journal of Archaeological Science*, **34**, 763–70.

Borradaile, G. J., 1988, Magnetic susceptibility, petrofabrics and strain, *Tectonophysics*, **156**, 1–20.

Carbonell, E., Bermúdez de Castro, J. M., Arsuaga, J. L., Diez, J. C., Rosas, A., Cuenca-Bescós, G., Sala, R., Mosquera, M., and Rodriguez, X. P., 1995, Lower Pleistocene hominids and artifacts from Atapuerca-TD6 (Spain), *Science*, **269**, 826–9.

Carbonell, E., Esteban, M., Nájera, A. M., Mosquera, M., Rodríguez, X. P., Ollé, A., Sala, R., Vergès, J. M., Bermúdez de Castro, J. M., and Ortega, A. I., 1999, The Pleistocene site of Gran Dolina, Sierra de Atapuerca, Spain: a history of the archaeological investigations, *Journal of Human Evolution*, **37**, 313–24.

Carbonell, E., Bermúdez de Castro, J. M., Parés, J. M., Pérez-González, A., Cuenca-Bescós, G., Ollé, A., Mosquera, M., Huguet, R., van der Made, J., Rosas, A., Sala, R., Vallverdú, J., García, N., Granger, D. E., Martinón-Torres, M., Rodríguez, X. P., Stock, G. M., Vergès, J. M., Allué, E., Burjachs, F., Cáceres, I., Canals, A., Benito, A., Díez, C., Lozano, M., Mateos, A., Navazo, M., Rodríguez, J., Rosell, J., and Arsuaga, J. L., 2008, The first hominin of Europe, *Nature*, **452**, 465–9.

Cuenca-Bescós, G., Laplana, C., and Canudo, J. I., 1999, Biochronological implications of the Arvicolidae (Rodentia, Mammalia) from the Lower Pleistocene hominid-bearing level of Trinchera Dolina 6 (TD6, Atapuerca, Spain), *Journal of Human Evolution*, **37**, 353–73.

Cuenca-Bescós, G., Rofes-Chávez, J., and García-Pimienta, J. C., 2004, Paleoclima y paisaje en el Pleistoceno inferior de Atapuerca: los insectívoros (Mammalia) de los niveles inferiores de Trinchera Elefante (Burgos, España), *GeoTemas*, **6**(5), 85–8.

Ellwood, B. B., and Ledbetter, M. T., 1977, Antarctic Bottom Water fluctuations in the Vema Channel: effects of velocity changes on particle alignment and size, *Earth and Planetary Science Letters*, **35**, 189–98.

Ellwood, B. B., and Ledbetter, M. T., 1979, Paleocurrent indicators in deep-sea sediment, *Science*, **203**, 1335–7.

Ellwood, B. B., Ledbetter, M. T., and Johnson, D. A., 1979. Sedimentary fabric tool to delineate a high velocity zone within a deep Western Indian Ocean bottom current, *Marine Geology*, **33**, 51–5.

Falguères, C., Bahain, J. J., Yokoyama, J., Arsuaga, J. L., Bermúdez de Castro, J. M., Carbonell, E., Bischoff, J. L., and Dolo, J. M., 1999, Earliest humans in Europe: the age of TD6 Gran Dolina, Atapuerca, Spain, *Journal of Human Evolution*, **37**, 343–52.

Falguères, C., Bahain, J. J., Yokoyama, J., Bischoff, J. L., Arsuaga, J. L., Bermúdez de Castro, J. M., Carbonell, E., Bischoff, J. L., and Dolo, J. M., 2001, Datation par RPE et U–Th des sites pléistocènes d'Atapuerca: Sima de los Huesos, Trinchera Dolina et Trinchera Galería. Bilan géochronologique, *L'Anthropologie*, **105**, 71–81.

Fisher, R. A., 1953, Dispersion on a sphere, *Proceedings of the Royal Society of London, Series A*, **217**, 295–305.

Flinn, D., 1962, On folding during three dimensional progressive deformation, *Journal of the Geological Society*, **118**, 385–428.

Goldberg, P., and Macphail, R. I., 2006, *Practical and theoretical geoarchaeology*. Blackwell, Oxford.

Goldberg, P., and Sherwood, S. C., 2006, Deciphering human prehistory through the geoarchaeological study of cave sediments, *Evolutionary Anthropology*, **15**, 20–36.

Graham, J. W., 1954, Magnetic susceptibility anisotropy, an unexploited petrofabric element, *Geological Society of America Bulletin*, **65**, 1257–8.

Hassold, N. J. C., Rea, D. K., van der Pluijm, B. A., Parés, J. M., Gleason, J. D., and Ravelo, A. C., 2006, Late Miocene to Pleistocene paleoceanographic records from the Feni and Gardar Drifts: Pliocene reduction in abyssal flow, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **236**, 290–301.

Hrouda, F., 1982, Magnetic anisotropy of rocks and its application in geology and geophysics, *Geophysical Surveys*, **5**, 37–82.

Hus, J., 2003, The magnetic fabric of some loess/palaeosol deposits, *Physics and Chemistry of the Earth*, **28**, 689–99.

Ising, G., 1942, On the magnetic properties of varved clay, *Arkiv för Matematik, Astronomi och Fysik*, **29a**, 1–37.

Jelínek, V., 1978, Statistical processing of anisotropy of magnetic susceptibility measured on groups of specimens, *Studia Geophysica et Geodetica*, **22**, 50–62.

Jelínek, V., 1981, Characterization of the magnetic fabrics of rocks, *Tectonophysics*, **79**, T63–7.

Joseph, L. H., Rea, D. K., and van der Pluijm, B. A., 1998, Use of grain size and magnetic fabric analyses to distinguish among depositional environments, *Paleoceanography*, **13**, 491–501.

Joseph, L. H., Rea, D. K., and van der Pluijm, B. A., 2004, History of the Deep Western Boundary Current, southwest Pacific (ODP Site 1124), *Marine Geology*, **205**, 185–206.

Kent, D. V., and Lowrie, W., 1975, On the magnetic susceptibility anisotropy of deep-sea sediment, *Earth and Planetary Science Letters*, **28**, 1–12.

King, R. F., 1955, The remanent magnetism of artificially deposited sediments, *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, **7**, 115–34.

Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of paleomagnetic data, *Geophysical Journal of the Royal Astronomical Society*, **62**, 699–718.

Kissel, C., Laj, C., Lehman, B., Labyrie, L., and Bout-Roumazeilles, V., 1997, Changes in the strength of the Iceland–Scotland Overflow Water in the last 200,000 years: evidence from magnetic anisotropy analysis of core SU90-33, *Earth and Planetary Science Letters*, **152**, 25–36.

Kodama, K. P., and Sun, W. W., 1990, SEM and magnetic fabric study of a compacting sediment, *Geophysical Research Letters*, **17**, 795–8.

Laville, H., and Goldberg, P., 1989, The collapse of the Mousterian regime and the beginnings of the Upper Palaeolithic in Kebara Cave, Mount Carmel, in *Investigations in South Levantine prehistory* (eds. O. Bar-Yosef and B. Vandermeersch), 75–95, British Archaeological Reports, International Series 497, Archaeopress, Oxford.

Ledbetter, M. T., and Ellwood, B. B., 1980, Spatial and temporal changes in bottom-water velocity and direction from analysis of particle size and alignment in deep-sea sediment, *Marine Geology*, **38**, 245–61.

Liu, B., Saito, Y., Yamazaki, T., Abdeldayem, A., Oda, H., Hori, K., and Zhao, Q., 2001, Paleocurrent analysis for the Late Pleistocene–Holocene incised-valley fill of the Yangtze delta, China by using anisotropy of magnetic susceptibility data, *Marine Geology*, **176**, 175–89.

Martín, M. A., Domingo, S., and Antón, T., 1981, Estudio de las cavidades de la zona BU-IV-A (Sierra de Atapuerca), *KAITE (Estudios de Espelología Burgalesa)*, 41–75, Grupo Espeleológico Edelweiss, Burgos, Spain.

McDonald, W. D., and Ellwood, B. B., 1987, Anisotropy of magnetic susceptibility: sedimentological, igneous and structural–tectonic applications, *Reviews of Geophysics*, **25**, 905–9.

Nagata, T., 1961, *Rock magnetism*, Maruzen, Tokyo.

Nye, J. F., 1957, *The physical properties of crystals*, Clarendon Press, Oxford.

Ortega, A. I., Pérez-González, A., Martín, M. A., Carretero, J. M., and Arsuaga, J. L., 2005, El sistema Cueva Mayor – Cueva del Silo: un estudio morfogenético del endokarst de la Sierra de Atapuerca (Burgos, España), in *Geoarqueología y patrimonio en la Península Ibérica y el entorno Mediterráneo* (eds. M. Santonja, A. Pérez-González and M. J. Machado), 161–79, ADEMA, Soria.

Parés, J. M., and Pérez-González, A., 1995, Paleomagnetic age for hominid fossils at Atapuerca archaeological site, Spain, *Science*, **269**, 830–2.

Parés, J. M., and Pérez-González, A., 1999, Magnetochronology and stratigraphy at Gran Dolina section, Atapuerca (Burgos, Spain), *Journal of Human Evolution*, **37**, 325–42.

Parés, J. M., Arsuaga, J. L., Pérez-González, A., and Weil, A., 2000, On the age of the hominid fossils at the Sima de los Huesos, Sierra de Atapuerca: paleomagnetic evidence, *American Journal of Physical Anthropology*, **111**, 451–61.

Parés, J. M., Hassold, N. J. C., Rea, D. K., and van der Pluijm, B. A., 2007, Paleocurrent directions from paleomagnetic reorientation of magnetic fabrics in deep-sea sediments at the Antarctic Peninsula Pacific margin (OPD Sites 1095, 1101), *Marine Geology*, **242**, 261–9.

Parés, J. M., Pérez-González, A., Rosas, A., Benito, A., Bermúdez de Castro, J. M., Carbonell, E., and Huget, R., 2006, Matuyama-age lithic tools in the 'Sima del Elefante' Site, Atapuerca (N Spain), *Journal of Human Evolution*, **50**, 163–9.

Park, C. K., Doh, S. J., Suk, D. W., and Kim, K. H., 2000, Sedimentary fabric on deepsea sediments from KODOS area in the eastern Pacific, *Marine Geology*, **171**, 115–26.

Partridge, T. C., Granger, D. E., Café, M. W., and Clarke, R. J., 2003. Lower Pliocene hominid remains from Sterkfontein, *Science*, **300**, 607–12.

Pérez-González, A., Parés, J. M., Gallardo, J., Aleixandre, T., Ortega, I., and Pinilla, A., 1999, Geologia y estratigrafia del relleno de Galeria de la Sierra de Atapuerca (Burgos), in *Atapuerca: ocupaciones humanas y paleoecologia del yacimiento de Galeria* (eds. E. Carbonell, A. Rosas and J. C. Diez Fernández), 31–42, Junta de Castilla y León, Consejeria de Educación y Cultura, Valladolid.

Pérez-González, A., Aleixandre, T., Pinilla, A., Gallardo, J., Benayas, J., Martínez, M. J., and Ortega, A. I., 1995, An approach to the Galeria stratigraphy in the Sierra de Atapuerca trench (Burgos), in *Human evolution in Europe and the Atapuerca evidence* (eds. J. M. Bermúdez de Castro, J. L. Arsuaga and E. Carbonell), 99–122, Junta de Castilla y León, Consejería de Cultura y Turismo, Valladolid, Spain.

Pérez-González, A., Parés, J. M., Carbonell, E., Aleixandre, T., Ortega, A. I., Benito, A., and Merino, M. A. M., 2001, Géologie de la Sierra de Atapuerca et stratigraphie des remplissages karstiques de Galería et Dolina (Burgos, Espagne), *L'Anthropologie*, **105**, 27–43.

Rees, A. I., and Woodall, W. A., 1975, The magnetic fabric of some laboratory deposited sediments, *Earth and Planetary Science Letters*, **25**, 121–30.

Richter, C., van der Pluijm, B., and Housen, B., 1993, The quantification of crystallographic preferred orientation using magnetic anisotropy, *Journal of Structural Geology*, **15**, 113–16.

Rosas, A., Pérez-González, A., Carbonell, E., van der Made, J., Sánchez, A., Laplana, C., Cuenca-Bescós, G., Parés, J. M., and Huget, R., 2001, Le gisement pléistocene de la 'Sima del Elefante' (Sierra de Atapuerca, Espagne), *L'Anthropologie*, **105**, 301–12.

Rosas, A., Pérez-González, A., Carbonell, E., Vallverdú, J., van der Made, J., Allué, E., Garcia, N., Martínez-Pérez, R., Rodríguez, J., Sala, R., Saladie, P., Simón, G., Martínez-Maza, C., Bastir, M., Sánchez, A., and Parés, J. M., 2004, Initial approach to the site formation and paleoecology of the Sima del Elefante: a Pleistocene karst locality at Atapuerca Hill, *Zona Arqueológica*, **4**, 134–55.

Stacey, F. D., Joplin, G., and Lindsay, J., 1960, Magnetic anisotropy and fabric of some foliated rocks from SE Australia, *Geophysica Pura e Applicata*, **47**, 30–40.

Tarling, D. H., and Hrouda, F., 1993, *The magnetic anisotropy of rocks*, Chapman and Hall, London.

Tauxe, L., 1993, Sedimentary records of relative paleointensity of the geomagnetic field: theory and practice, *Reviews of Geophysics*, **31**, 319–54.

Tauxe, L., 1998, *Paleomagnetic principles and practice*, Kluwer Academic, Dordrecht.

Tauxe, L., and Kent, D. V., 1984, Properties of a detrital remanence carried by hematite from study of modern river deposits and laboratory redeposition experiments, *Geophysical Journal of the Royal Astronomical Society*, **77**, 543–61.

Torres, T. J., 1976, El karst de la Sierra de Atapuerca, *Cuadernos de Arqueología de Deusto*, **1**, 13–15.

Zazo, C., Goy, J. L., and Hoyos, M., 1983, Estudio geomorfológico de los alrededores de la Sierra de Atapuerca (Burgos), *Estudios Geologicos*, **39**, 179–85.

Zijderveld, J. D. A., 1967, AC demagnetization of rocks: analysis of results, in *Methods in paleomagnetism* (eds. D. W. Collinson, S. K. Runcorn and K. M. Creer), 254–86, Elsevier, New York.