

Paleomagnetic study of the Messejana Plasencia dyke (Portugal and Spain): A lower Jurassic paleopole for the Iberian plate

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Abstract

The only Iberian lower Jurassic paleomagnetic pole come from the “Central Atlantic Magmatic Province”-related Messejana Plasencia dyke, but the age and origin of its remanence have been a matter of discussion. With the aim of solving this uncertainty, and to go further into a better understanding of its emplacement and other possible tectonic features, a systematic paleomagnetic investigation of 40 sites (625 specimens) distributed all along the 530 km of the Messejana Plasencia dyke has been carried out. Rock magnetic experiments indicate PSD low Ti-titanomagnetite and magnetite as the minerals carrying the NRM. The samples were mostly thermally demagnetized. Most sites exhibit a characteristic remanent component of normal polarity with the exception of two sites, where samples with reversed polarities have been observed. The paleomagnetic pole derived from a total of 35 valid sites is representative of the whole structure of the dyke, and statistically well defined, with values of $PLa=70.4^{\circ}N$, $PLo=237.6^{\circ}E$, $K=47.9$ and $A_{95}=3.5^{\circ}$. Paleomagnetic data indicates that: (i) there is no evidence of a Cretaceous remagnetization in the dyke, as it was suggested; (ii) most of the dyke had a brief emplacement time; furthermore, two dyke intrusion events separated in time from it by at least 10,000 y have been detected; (iii) the high grouping of the VGPs directions suggests no important tectonic perturbations of the whole structure of the dyke since its intrusion time; (iv) the pole derived from this study is a good quality lower Jurassic paleopole for the Iberian plate; and (v) the Messejana Plasencia dyke paleopole for the Iberian plate is also in agreement with quality-selected European and North American lower Jurassic paleopoles and the magnetic anomalies data sets that are available for rotate them to Iberia.

Keywords: Paleomagnetism; CAMP; Dyke; Iberia; Jurassic

1. Introduction

The Messejana Plasencia dolerite dyke constitutes the northeasternmost expression of the vast, more than 10 million km², Central Atlantic Magmatic Province

(CAMP) that is present in four continents: southwestern Europe, northwestern Africa, eastern North America and northeaster South America (e.g. [Marzoli et al., 1999](#)). It corresponds to the main representation of the CAMP in Europe and is comparable to other great dykes – Caraquet and Shelburne in Canada, Fom Zguid in Morocco – characteristic of the northern Province.

The dyke forms a SW–NE, slightly-curved alignment of dolerite intrusions along a prominent topographic

lineament, more than 500 km in length, that obliquely crosses the South Portuguese, Ossa Morena and Central Iberian zones of the Variscan Iberian Massif (Fig. 1). The length of the dyke must be even greater since its northern extreme disappears under the Neogene cover of the Duero Basin and the southern branch could continue under the Atlantic Ocean, to the south of the Portuguese coast.

The first published ages of the dyke were dispersed. A time of intrusion between 186 ± 6 Ma and 148 ± 8 Ma was obtained from K–Ar whole rock methods (Schermerhorn et al., 1978), whilst an interval between 209 ± 6 Ma and 137 ± 4 Ma was reported from mineral concentrates, generally plagioclase (Schott et al., 1981). These authors considered that the dispersion in age reflected the actual time interval of the intrusion. No conclusive $^{40}\text{Ar}/^{39}\text{Ar}$ results were obtained by Sebai et al. (1991). However, more recently published $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric ages of 203 ± 2 Ma (Dunn et al., 1998) and 202.8 ± 2.0 Ma (Rapaille et al., 2003) point to a brief period of intrusion, in accordance with the other regions of the Central Atlantic Magmatic Province.

Previous paleomagnetic studies were carried out on the dyke by Schott et al. (1981) and Perrin et al. (1991). Schott et al. (1981) studied 12 sites along the dyke that were systematically alternating field (AF) demagnetized, and occasionally chemically demagnetized. Perrin et al. (1991) carried out a paleointensity study in 6 sites from the central part of the dyke. Both studies found exclusively normal polarities with a relatively high scatter in directions that was interpreted by these authors

as being due to a relatively long intrusion time and to the paleosecular variation of the geomagnetic field. The authors concluded that the dyke had multiple intrusion events. The pole derived from the study of Schott et al. (1981) is the only paleomagnetic pole of early Jurassic age for the Iberian plate.

There are two consistent upper Jurassic (Oxfordian) paleomagnetic poles for Iberia, both derived from magnetostratigraphic studies (Steiner et al., 1985; Juárez et al., 1994, 1995). Juárez et al. (1994, 1995, 1996, 1998) carried out a systematic magnetostratigraphic and paleomagnetic study on 13 sites from the Iberian Ranges. In addition to a small primary component these authors observed a strong overprint interpreted as acquired in Cretaceous times (Juárez et al., 1998). Strong remagnetizations of normal polarity have also been observed in Jurassic sediments from the Lisbon area (western part of central Iberia, Galdeano et al., 1989), the southern Iberian Ranges (central Iberia, Moreau et al., 1992) and the Betics (southern Iberia, Villalaín et al., 1994, 1996). The similarity in direction of this Cretaceous remagnetized component with the Messejana Plasencia dyke direction calculated by Schott et al. (1981), along with the absence of samples with reversed polarities, were the main arguments given by Juárez et al. (1996) to doubt the primary origin of the magnetization of the dyke and to postulate the existence of an important event that remagnetized most Jurassic rocks at the Iberian plate.

Finally, an interesting geometrical feature of the Messejana Plasencia dyke is the change in its trend (Fig.

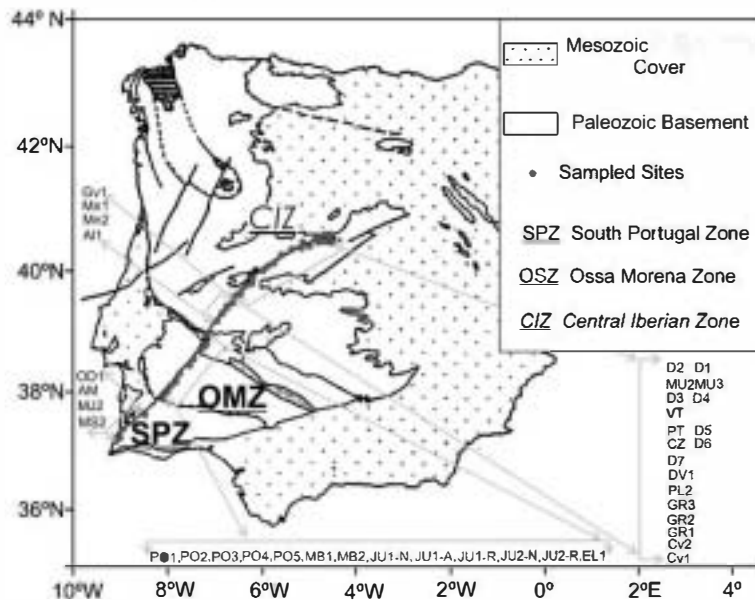


Fig. 1. Simplified geological map of the Iberian Peninsula showing the locations of the studied sites of the Messejana Plasencia dyke.

1). There is a tectonic model trying to interpret the angular deviation present in the northern part of the Messejana Plasencia dyke located in the Spanish Central System. The Spanish Central System constitutes an important morphostructural intraplate feature of Iberia that resulted from a concentration of crustal strain derived from stresses applied on the boundaries of the Betics and Pyrenees. This compressive regime was caused by the convergence of the African and European plates and subsequent accretion of Iberia to both Europe and Africa, from the Eocene up to the Tortonian. Vegas et al. (1990) proposed a tectonic model of the Spanish Central System in which deformation of this zone was produced by a mid-late Mesozoic shear zone, which absorbed part of the Iberia–Eurasia relative motion (Fig. 2). The subsequent N–S Africa–Eurasia convergence was partly accommodated within this intraplate zone weakness. The deformation within this E–W shear zone was partially compensated by means of blocks rotations and forced uplifting of the upper crust. Within this context, directions from the northern branch of the Messejana Plasencia dyke should be clockwise rotated with respect to paleomagnetic directions obtained from the southern branch.

The objectives of this new study of the Messejana Plasencia dyke are: (i) to resolve the uncertain origin of the magnetization of the dyke, ii) to obtain a new lower Jurassic paleomagnetic pole for the Iberian Peninsula (in the case of no remagnetization), (iii) to investigate if the dyke was intruded in a brief period of time or had a multiphase emplacement, (iv) to check if the angular deviation present in the northern part of the Messejana Plasencia fault and dyke is related to block rotations. In order to achieve these objectives we have carried out a new rock magnetic and a paleomagnetic study along the whole extension of the dyke.

2. Geological setting and sampling

Historically the dyke was first mapped along 170 km in southern Portugal (Torre de Assunção, 1949) and then its prolongation was described along the rest of its length in Spain (Del Valle Lersundi, 1959; García de Figuerola, 1963, 1965; García de Figuerola and Carnicero, 1973). Since the early descriptions, the occurrences of the dyke have been ascribed to a fault line younger than the Variscan folding (Feio, 1951). The fault has been also recognized as left-handed strike-slip with an offset ranging from 3 to 1.5 km (Zbyszewski and Freire de Andrade, 1957; Quesada García, 1960; Carvalhosa, 1965; Schermerhorn et al., 1978; Rincón et al., 2000).

The age of the fault that served as channel for the intrusion is a matter of debate. First descriptions refer it to a *post-Hercynian* fault formation with middle to late Pliocene reactivation (Feio, 1951; Carvalhosa, 1965; Parga, 1969). Later, Schermerhorn et al. (1978), by comparison with other dolerite dykes around the Atlantic, suggested a middle Triassic origin for the fault in connection with the early rifting of the Atlantic.

The age of the fairly small left-lateral motion of the fault possess also some problems. It could be slightly younger than, or coeval with, the dolerite intrusion because the dyke occurrences follow several typical strike-slip features – sigmoidal, *en échelon* relays; borders of small pull-apart basins; extensional and contractional bends and steps. The small lateral component of the fault could be related to the motion along an incipient intracontinental shear zone developed between Africa and Eurasia in the early stages of the Atlantic rifting (Vegas, 2000). On the other hand, the left lateral motion could also be related to a recent, mostly Tertiary and Quaternary, reactivation of the fault,

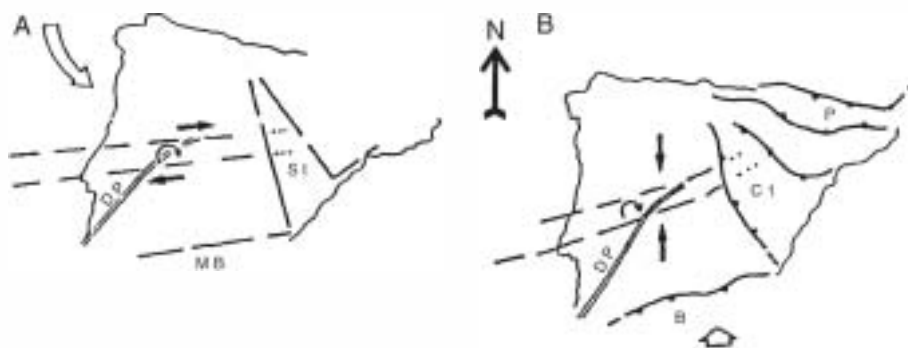


Fig. 2. Deformed zone related to the Spanish Central System proposed by Vegas et al. (1990). A) Late Cretaceous single shear zone and clockwise rotation of crustal blocks. B) Middle–late Miocene pure shear within the lower crust causing reactivation of rotations, uplift and reverse high angle faults at the boundaries. B=Betics; CI=Iberian Chain; DP=Plasencia Dyke; MB=Betic Margin; P=Pyrenees; SI=Iberian Trough (modified from Vegas et al., 1990).

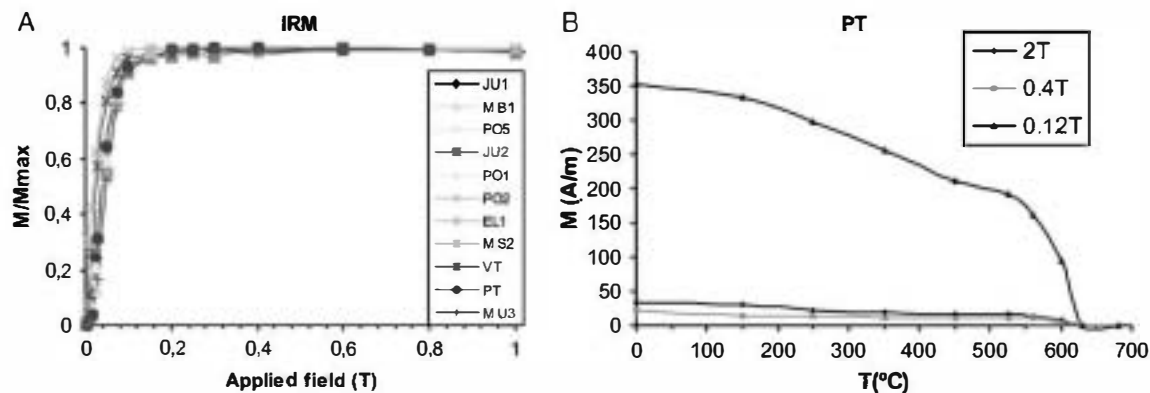


Fig. 3. A) IRM acquisition curves of samples from the dyke. B) Representative behaviour of the thermal demagnetization of a three-component IRM of a sample of the dyke (Lowrie, 1990).

considering the age of sediments included in several, small pull-apart-like basins (Capote et al., 1996; De Vicente, 2004). But surprisingly, this great tectonic lineament takes an insignificant portion of the Tertiary deformation of Iberia.

There are also different denominations of the dyke. We will refer it as Messejana Plasencia dyke combining the most current denominations for the Portuguese and Spanish segments.

The Spanish portion of the Dyke has been extensively studied, mainly from a petrological point of view, by García de Figuerola (1963, 1965), García de Figuerola and Camicero (1973) and García de Figuerola et al. (1974). Its Portuguese part was examined by Torre de Assunção (1949, 1951a,b). Thermal histories of two host granitic rocks derived from AFT (apatite fission tracks) ages (De Bruijne, 2001) constrain the depth of intrusion of the Dyke.

The host rocks traversed the PAZ (partial annealing zone) at the time of intrusion of the Dyke (200 Ma), thereafter a depth of 2–3 km can be assumed for the rocks investigated.

A total of 40 sites spanning the whole of the 530 km Messejana Plasencia dyke have been studied (Fig. 1). Samples were cored (2.54 cm in diameter) with a portable gasoline-powered drill and oriented using an inclinometer and magnetic compass. Cores were cut in the laboratory into standard specimens (2.2 cm length) for paleomagnetic measurements. Core chips and end pieces were used in some of the rock magnetic experiments.

In order to perform a contact test, the contact with the host rock was intensively investigated. Unfortunately, very often the contact did not outcrop, and when it outcropped, both the host rock and the dyke exhibited a high degree of alteration, probably related with the activity of the fault.

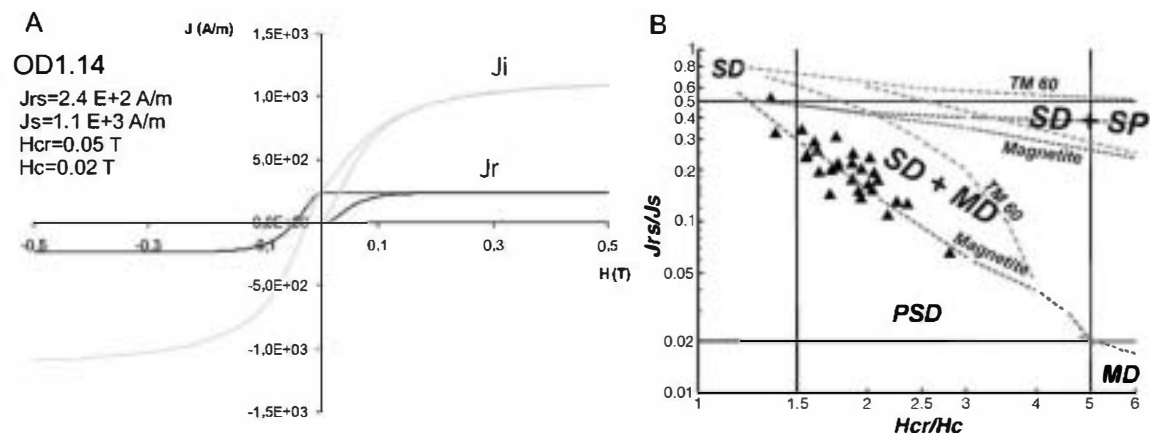


Fig. 4. A) Hysteresis curves: remanent (J_r) and induced (J_i) magnetizations of a typical sample. B) Plots of the hysteresis parameters J_{rs}/J_s vs. H_{cr}/H_c of some dyke's samples (Day et al., 1977), and theoretical curves for combinations of single domain (SD), multidomain (MD) and superparamagnetic (SP) grains for magnetite and 60% Ti-titanomagnetite (TM60), Dunlop (2002a).

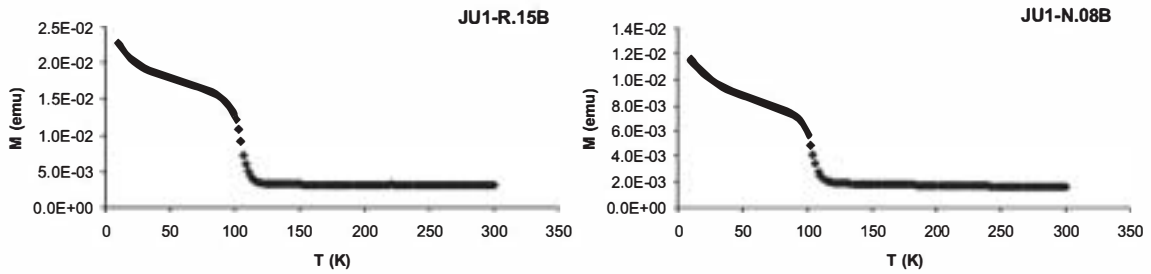


Fig. 5. Two examples of saturation remanence acquired at 4 K monitored during zero field heating to room temperature. JU1-R.15b corresponds to a sample which exhibited a reversed polarity and JU1-N.8b to a normal polarity.

In few localities near Juromenha (JU1 and JU2, Fig. 1) internal contacts within the main dyke were observed, which were interpreted as the intrusion of a later phase. The existence of secondary intrusions was also observed by Schermerhorn et al. (1978) in the Aljustrel area, to the south of Juromenha. In this area, we sampled 2 small secondary dykes (JU1-R and JU2-R) in addition to the main one (JU1-N and JU2-N). Due to the small dimensions of these secondary dykes, at JU2-R only 2 samples could be collected.

3. Laboratory procedures

The Natural Remanent Magnetization (NRM) and its response to stepwise thermal (Th) or alternating field (AF) demagnetization were measured using JR5-A and Molspin magnetometers in the Paleomagnetic laboratory of the Complutense University in Madrid (UCM). Demagnetization was achieved using TSD-1 and GSD-5 Schonsted demagnetizers. The initial

susceptibility and its variation upon thermal treatment were measured on a Kappabridge (KLY-3) instrument.

Representative samples were subjected to stepwise acquisition of uniaxial isothermal remanent magnetization (IRM) up to 1.5 T with a pulse magnetizer (ASC Scientific IM-10-30), with at least 16 acquisition steps.

TH demagnetization of 3-axis IRMs (Lowrie, 1990) was performed on representative specimens. The 3 orthogonal fields were 2 T, 0.4 T and 0.12 T.

Hysteresis parameters were obtained for representative samples with a coercivity spectrometer developed by the Kazan University (Burov et al., 1986). The coercivity meter measures the induced and remanent magnetization in 5E-4 T steps up to a maximum value of 0.5 T. A sample is placed near the edge of a rotating wheel which transports the sample from the coils used to generate the applied field (the sample magnetization is measured at the same time) to a separate sensor which measures the sample remanence. For each applied field,

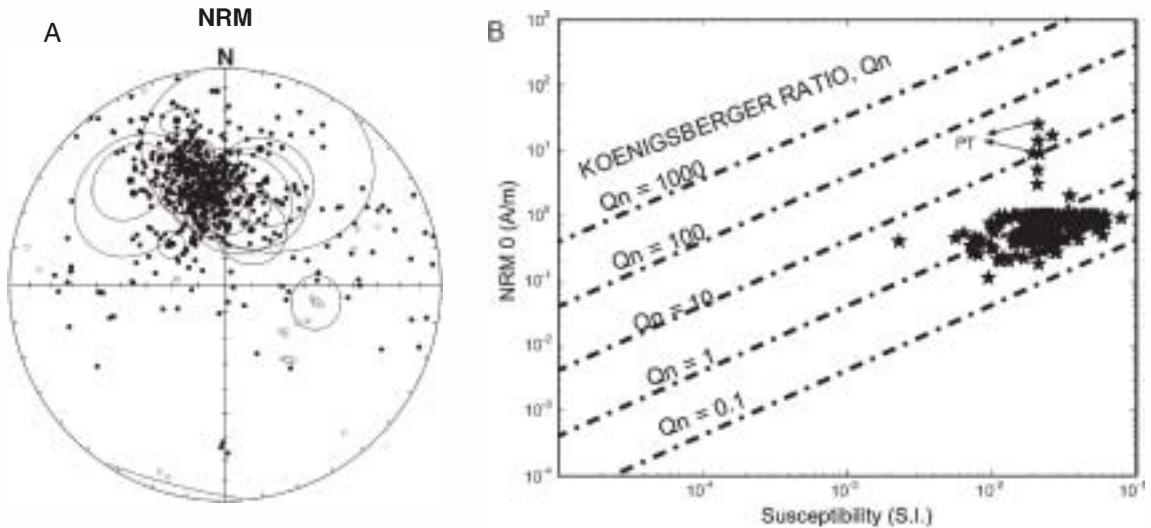
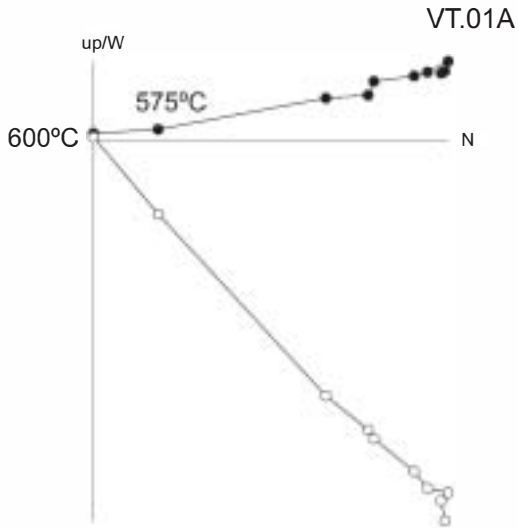
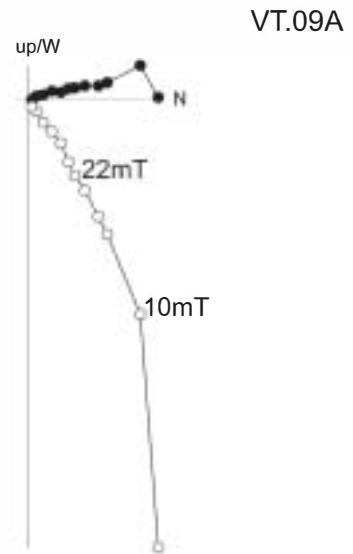
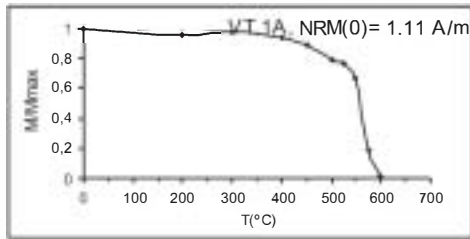


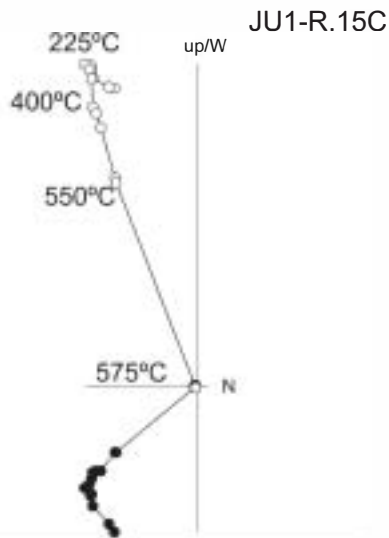
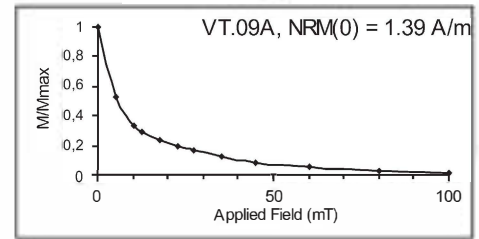
Fig. 6. A) Equal area projection of the NRM of the sampled sites, filled (open) symbols mean lower (upper) hemisphere. Mean directions and 95% confidence circle are also represented for each site. B) Initial NRM vs. initial susceptibility, Koenigsberger ratio Q_n .



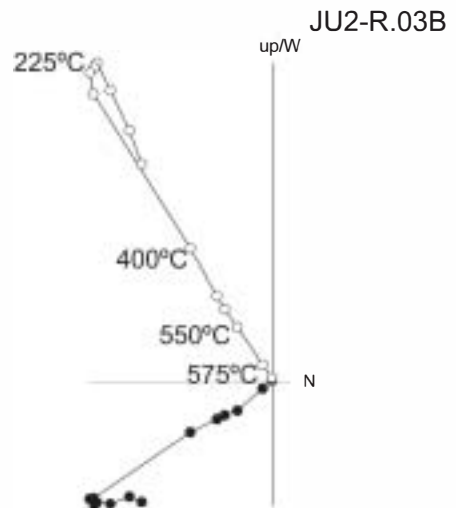
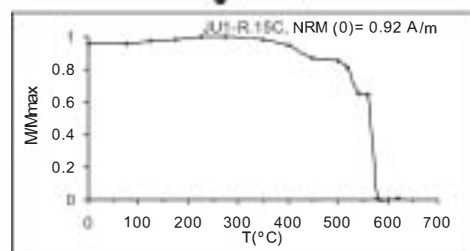
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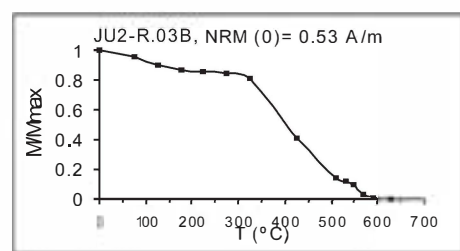
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D



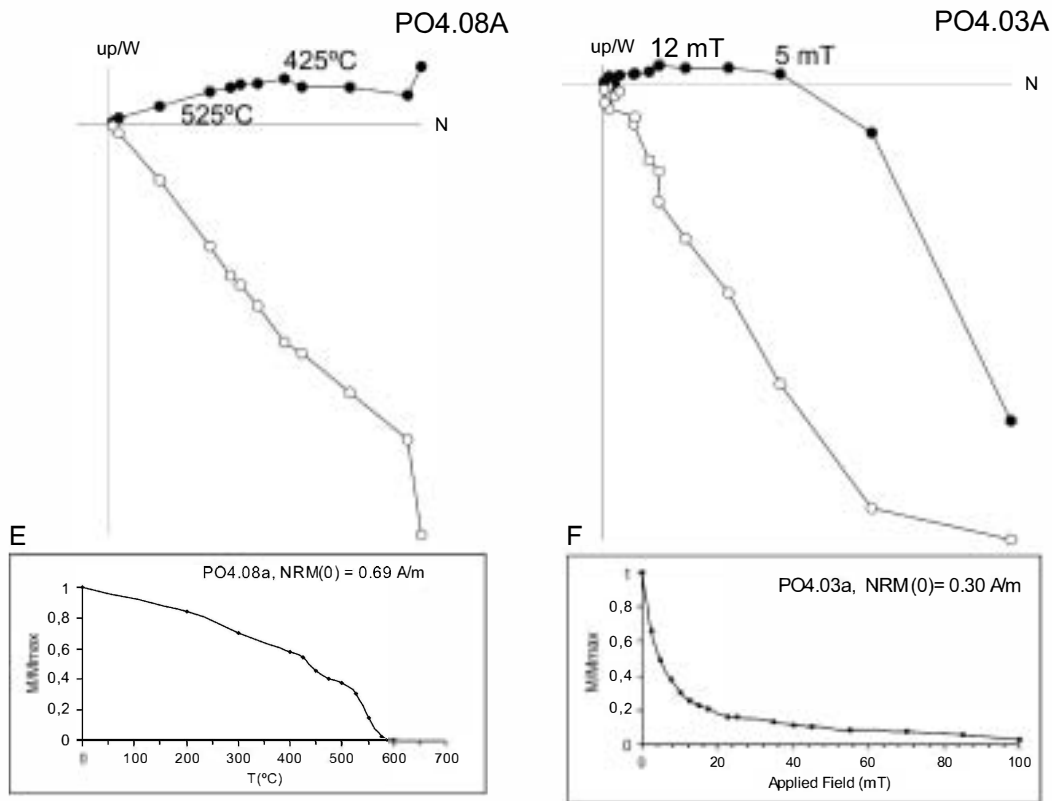


Fig. 7. Orthogonal vector plots and normalized magnetization during NRM demagnetization: A, B) Th and AF demagnetization of two typical specimens of group 1 of normal polarity; C, D) Th demagnetization of two typical samples of group 1 of reversed polarity; E, F) Th and AF demagnetization of two typical samples of group 2.

two data are measured — induced and remanent magnetization. The applied field is cycled from 0 to +0.5 T then back to -0.5 T.

Low temperature IRM experiments were performed. Samples were cooled to 4 K and subjected to 5 T field. The remanent magnetization was monitored during zero field heating to room temperature in a MPMS-XL squid magnetometer (Quantum Design) in the CAI (X Ray diffractions) of the UCM.

4. Rock magnetic results

4.1. IRM acquisition curves and thermal demagnetization of 3D-IRM

All studied samples display a similar behaviour during the gradual acquisition of IRM and subsequent Th demagnetization of three orthogonal IRM components. Saturation is reached below 0.3 T, indicating low coercivity minerals as the carrier of the magnetization (Fig. 3A). The 0.12 T coercivity fraction is completely demagnetized at 600 °C (Fig. 3B), indicating that the low coercivity mineral is

magnetite and/or low Ti-titanomagnetite. The 0.4 T and 2 T fractions made little or no contribution in the acquisition curves.

4.2. Hysteresis properties

The ascending and descending branches of the hysteresis curves were indistinguishable at fields greater than 0.3 T, indicating saturation of the ferromagnetic grains. Little or no paramagnetic or diamagnetic contribution could be seen at high fields. Fig. 4A shows the induced (J_i) and remanent (J_r) magnetization versus the applied field of a typical sample.

Saturation magnetization (J_s), saturation remanence (J_{rs}), coercive force (H_c) and coercivity of remanence (H_{cr}) were determined. Coercivity (H_{cr}/H_c) and remanence (J_{rs}/J_s) ratios were plotted in a Day diagram (Day et al., 1977), Fig. 4B. Also plotted are the theoretical curves for combinations of singledomain (SD), multidomain (MD) and superparamagnetic (SP) grains for magnetite and 60% Ti-titanomagnetite (TM60) (Dunlop, 2002a). The data fall in the upper left part of the pseudo-single-domain region (PSD)

region of Day plot, closely following the trend for SD-MD magnetite. The hysteresis properties are interpreted as being due to a mixture of SD and MD magnetite.

4.3. Low temperature experiments

Samples were cooled to 4 K and subjected to 5 T field. The remanent magnetization was measured stepwise during zero field heating from 4 K till room temperature. The Verwey transition (Verwey and Haayman, 1941) is expressed through the large drop in remanence around 110 K, corroborating the presence of magnetite, Fig. 5.

In summary, rock magnetic experiments show that main magnetic minerals carrying the NRM of the Messejana Plasencia dyke are a mixture of SD and MD grains of nearly pure magnetite.

5. Paleomagnetic results

5.1. NRM demagnetization

Natural Remanent Magnetization (NRM) intensity ranged from 17 A/m to 0.1 A/m. NRM directions of the 40 investigated sites were, in general, well grouped (Fig.

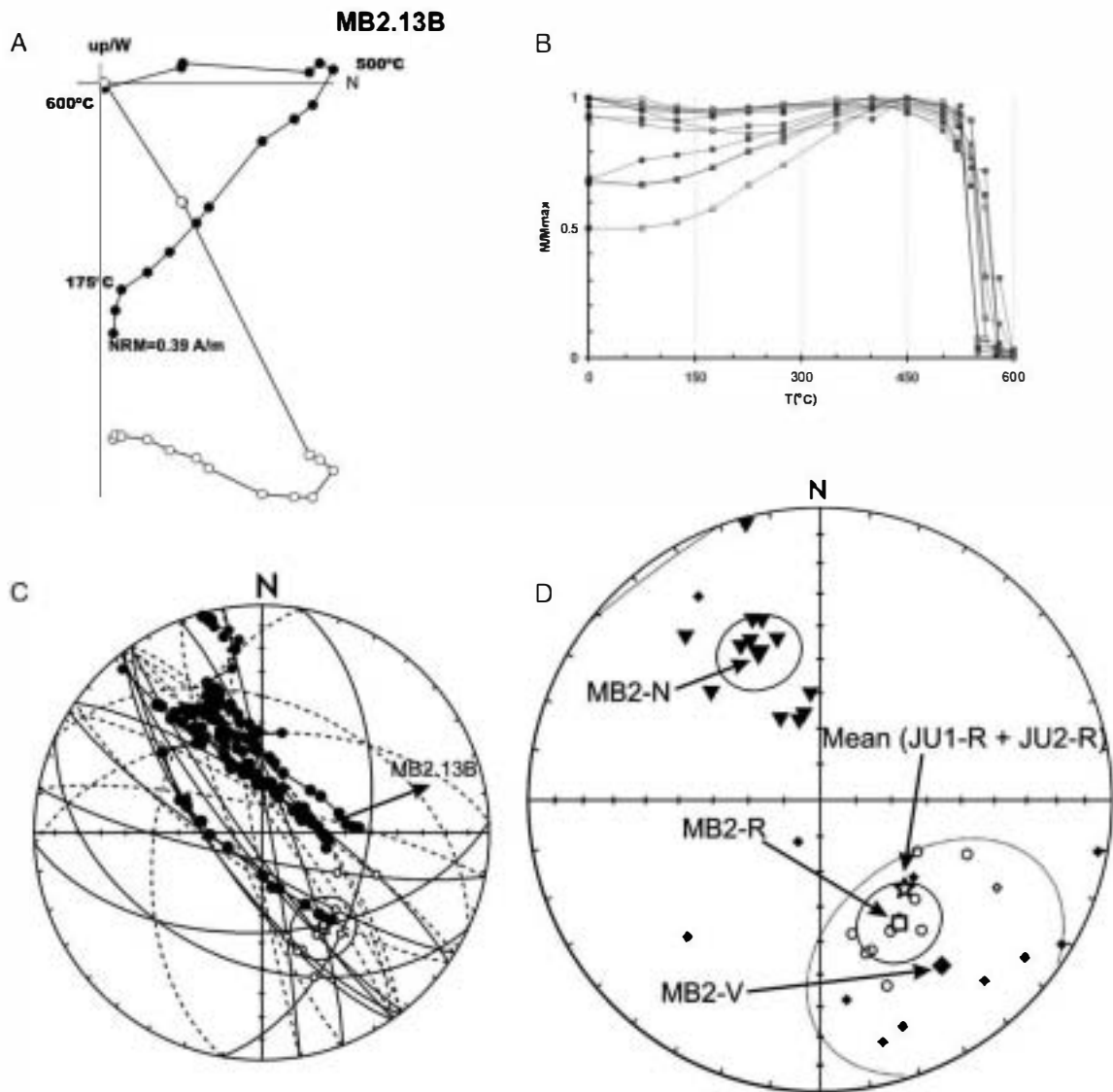


Fig. 8. A, B) Orthogonal vector plot of a typical sample of group 3 and normalized magnetization of all the specimens during NRM thermal demagnetization; C) Great circles for all the specimens during thermal demagnetization processes; D) Equal area projection of the three magnetic components of the specimens of MB2 (MB2-N, MB2-R and MB2-V), mean values with the α_{95} statistical parameters and mean value of the paleomagnetic reversed direction of sites JU1-R and JU2-R.

6A), with the exception of 3 sites that presented large α_{95} values of $>20^\circ$. Most sites exhibited normal polarities except two (JU1-R and JU2-R) where reversed polarities were observed. In addition, site MB2, exhibited two magnetic components of normal and reversed polarities.

At JU1 and JU2 site two different outcrops were sampled: JU1-N and JU2-N correspond to the main intrusion event and gave normal polarity; JU1-R and JU2-R represent small dykes intruding into the main dyke. These narrow dykes exhibited reversed polarities.

This indicates, at least, two different intrusion episodes.

Initial values of NRM intensities versus susceptibilities are plotted in Fig. 6B, together with the Koenigsberger ratios (Q_n) (Stacey, 1967). The values obtained are consistent with a TRM origin for the NRM. At one site, PT (located in the Tornavacas pass at an altitude of 1450 m) the values are more scattered: The high Q_n ratios and the dispersed NRM directions suggest the presence of IRMs acquired by lightning strikes (Dunlop et al., 1984).

Table 1
Site locations; paleomagnetic directions; VGPs and statistical parameters

Sites	SLat	SLong	<i>n</i>	Dec	Inc	<i>k</i>	α_{95}	PLa	PLo	Palat	Δm	Δp
*MJ2	37.2	-8.9	10	357.6	52.6	32.2	8.6	-	-	-	-	-
MS2	37.2	-8.9	11	342.0	43.1	167.4	3.5	70.5	227.9	25.1	4.3	2.7
AM	37.4	-8.9	15	2.0	45.6	42.9	5.9	79.2	161.5	27.0	7.5	4.8
OD1	37.6	-8.6	11	346.6	42.1	189.0	3.3	72.5	215.9	24.3	4.1	2.5
**PO1	38.2	-7.8	11	329.4	28.4	200.8	3.2	52.0	345.3	15.1	3.5	1.9
PO2	38.3	-7.7	5	332.6	57.1	227.8	5.1	68.5	269.3	37.7	7.4	5.4
PO3	38.3	-7.7	11	334.1	47.4	253.6	2.9	66.4	245.6	28.5	3.8	2.4
PO4	38.3	-7.7	11	333.5	51.3	122.6	4.1	67.5	254.0	32.0	5.6	3.8
PO5	38.3	-7.7	11	332.9	42.1	105.7	4.5	63.1	238.9	24.3	5.5	3.4
MB1	38.7	-7.3	7	342.9	54.7	263.4	3.7	75.9	253.7	35.2	5.2	3.7
MB2-N	38.7	-7.3	12	337.6	44.3	16.2	11.1	67.3	235.3	26.0	13.9	8.8
*MB2-R	38.7	-7.3	12	147.2	-48.8	17.5	11.5	-	-	-	-	-
JU1-N	38.7	-7.3	8	348.5	48.2	77.8	6.3	76.6	221.2	29.2	8.2	5.4
JU1-R	38.7	-7.3	11	133.3	-61.2	681.1	1.8	54.8	283.8	42.3	2.8	2.1
JU2-N	38.7	-7.3	4	346.5	47.9	187.0	6.7	75.2	225.7	29.0	8.7	5.7
JU2-R	38.7	-7.3	2	139.4	-49.3	-	-	55.7	260.8	30.2	-	-
EL1	38.8	-7.2	12	342.0	45.5	58.3	5.7	70.9	230.0	27.0	7.2	4.6
**AL1	39.3	-6.8	8	279.5	70.5	22.4	12.0	36.2	308.2	54.7	20.8	18.0
MN2	39.5	-6.8	10	335.4	38.2	18.2	11.6	62.3	229.8	21.5	13.7	8.1
MN1	39.5	-6.8	8	343.0	25.7	73.3	6.5	60.0	207.9	13.5	7.0	3.8
GV1	39.7	-6.6	12	339.9	44.3	264.3	2.7	68.4	230.3	26.0	3.4	2.1
CV1	39.7	-6.5	11	339.2	34.0	362.1	2.4	62.3	219.9	18.6	2.7	1.6
CV2	39.7	-6.5	5	331.1	29.9	11.6	23.4	55.4	228.5	16.0	25.9	14.4
GR1	39.8	-6.3	11	345.4	52.1	95.0	4.7	76.3	237.1	32.7	6.4	4.4
GR2	39.8	-6.3	7	355.4	54.7	114.3	5.7	84.2	213.7	35.2	8.1	5.7
GR3	39.8	-6.3	8	343.9	58.4	54.9	7.5	77.6	265.7	39.1	11.1	8.2
DV1	39.9	-6.2	12	349.3	53.1	28.4	8.3	79.4	231.0	33.7	11.5	8.0
PL2	40.1	-6.1	8	318.1	70.0	302.7	3.2	58.8	304.5	53.9	5.5	4.7
D7	40.1	-6.1	8	345.3	49.1	96.7	5.7	74.3	228.4	30.0	7.5	5.0
CZ	40.1	-5.8	11	343.8	41.7	632.7	1.8	68.9	219.3	24.0	2.2	1.3
PT	40.2	-5.7	10	329.2	53.6	78.9	5.5	64.9	260.2	34.1	7.7	5.3
D5-6	40.4	-5.3	11	346.4	45.0	124.4	4.1	75.2	218.0	26.6	5.2	3.3
VT	40.4	-5.3	10	352.7	52.8	62.7	6.1	80.9	216.7	33.4	8.4	5.8
D3	40.6	-4.6	3	344.3	56.0	179.5	9.2	77.1	252.2	36.5	13.2	9.5
D4	40.6	-4.6	6	330.4	42.9	89.5	7.1	60.8	242.1	24.9	8.8	5.4
MU2	40.6	-4.6	4	342.2	44.5	338.8	5.0	69.4	226.5	26.2	6.3	4.0
MU3	40.6	-4.6	12	341.1	30.2	429.0	2.1	60.6	214.8	16.2	2.3	1.3
D1	40.7	-4.5	5	333.5	38.6	285.7	4.5	60.7	233.3	21.8	5.3	3.2
D2	40.7	-4.5	3	339.6	35.7	137.6	10.5	62.8	221.3	19.8	12.2	7.1

SLat. and SLong. Site location in latitude and longitude; *n*. Number of specimens; Dec. and Inc. Declination and Inclination; *k* and α_{95} . Statistical parameters (Fisher, 1953); PLo. and PLa. Pole longitude and latitude; Palat. Paleolatitude; Δm , Δp . Semiaxes of the 95% level confidence ellipse for the VGPs; *Rejected directions: see explanation in text; **Rejected VGPs: see explanation in text.

Two or three pilot samples per site were thermally (Th) and alternating field (AF) demagnetized. The following steps were used for the thermal demagnetization of the pilot samples: steps of 50 °C from room temperature up to 475 °C and then steps of 25 °C up to 600–625 °C. Susceptibility was monitored after each heating to control possible thermally induced mineralogical changes. For pilot AF studies, steps of 2.5 mT (up to 20 mT), 5 mT (between 20 and 45 mT) and then 55 mT, 70 mT, 85 mT and 100 mT were used.

The magnetic behaviour of pilot samples indicated that thermal demagnetization is more effective than AF in isolating the Characteristic Remanent Magnetization (ChRM). Therefore thermal demagnetization was systematically used with the remaining specimens with at least 10 temperature steps up to a maximum of 600 °C. According to the magnetic behaviour during demagnetization, sites were divided into 4 groups:

- **Group 1, 19 sites** (*AM, OD1, PO1, PO2, PO5, JU1-N, JU1-R, JU2-N, JU2-R, GV1, CV1, CV2, D2, D5, D6, CZ, VT, MU2* and *MU3*). Specimens showed one stable magnetic component, after removal of a small viscous direction component. This magnetic component is isolated between 200–300 °C and 600 °C (maximum unblocking temperature) or between 10 mT and 100 mT (the maximum available field). This component exhibited normal polarity in 17 sites (Fig. 7a, b) but in two sites (JU1-R and JU2-R) showed reversed polarity (Fig. 7c, d).
- **Group 2, 18 sites** (*MJ2, MS2, PO3, PO4, MB1, EL1, AL1, MN2, MN1, GR1, GR2, GR3, DV1, PL2, PT, D1, D3* and *D4*). Most specimens exhibited one stable magnetic component, but some (three to five specimens per site) exhibited two: (a) The low temperature/low coercivity magnetic component was isolated between 100–200 °C and 400–450 °C or between 5–10 mT and 12–15 mT. This component presented, either, (i) the actual geomagnetic field direction (Fig. 7e) and is interpreted as a recently acquired secondary component; (ii) no common direction between different specimens of the same site (Fig. 7e, f). In this case the component is considered as a secondary one due to chemical alteration, hydrothermalism and/or IRMs acquired by lightning strikes (case of PT where specimens gave Qn ratios up of 10). (b) The high temperature component was isolated between 400–450 °C and 580–600 °C (maximum unblocking temperature) and was considered as the ChRM of the samples. This component exhibited normal polarity directions.

- **Group 3, site MB2**. Specimens exhibited three magnetic components (Fig. 8a): (a) A scattered viscous component (MB2-V: $n=12$, Dec=143.6, Inc=30.4, $k=2.6$, $\alpha_{95}=34.1$) was observed between room temperature up to 150 °C. Direction of this component was calculated by Principal Component Analysis (PCA, Kirschvink, 1980) and it is plotted in Fig. 8d (diamonds). (b) A medium temperature magnetic component was observed between 100–200 °C and 400–450 °C. This component exhibited a reversed polarity and was overlapped by the viscous component and by the high temperature component as well. Because of the overlapping, the mean direction of this component was calculated using the remagnetization circles method (Halls, 1976). The great circles considered were formed by the viscous (scattered) and the medium temperature magnetic components. In Fig. 8c great circles for all the specimens during thermal demagnetization processes are plotted, as well as the obtained mean direction (MB2-R). (c) A high temperature component was isolated between 400–450 °C and 580–600 °C (maximum unblocking temperature) and was considered the ChRM of the samples. This component exhibited normal polarity directions (MB2-N in Fig. 8d). The reversed component direction (MB2-R, Table 1) is statistically indistinguishable of the mean reversed direction of JU1-R and JU2-R (star, Fig. 8d) and is interpreted as a thermal or

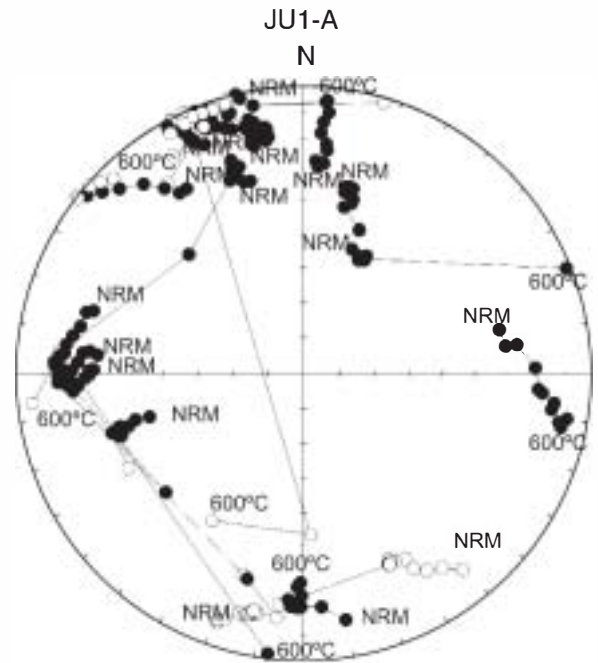


Fig. 9. Equal area of thermal demagnetization projections (site JU1-A).

Table 2
Mean Pole value, Fisherian test, ChRM directions, reversal test results and statistical parameters

VGPs (sites)	N	PLa	PLo	K	A_{95}	Fish (PLa/PLo)	
VGPs (all sites)	37	70.9	244.3	26.7	4.7	No/No	
VGP (excluding AL1 and PO1)	35	70.4	237.6	47.9	3.5	Yes/yes	
ChRM directions (excluding AL1 and PO1)	N	Dec	Inc	k	α_{95}	Rsum	Reversal test parameters
Normal (N)	33	341.0	46.3	57.9	3.3	32.447	$\gamma_0=17.72 < \gamma_c=36.89$; R_0
Reversed (R)	2	136.8	-55.3	-	-	1.988	
Total ($N+R$)	35	339.9	46.9	52.1	3.4	34.346	

N . Number of sites; PLa. Pole latitude; PLo. Pole longitude; Fish. Fisherian distribution in latitude and longitude; Dec. Declination; Inc. Inclination; K , A_{95} , k , α_{95} , and Rsum. Statistical parameters (Fisher, 1953); γ_0 , γ_c . Reversal test parameters (McFadden and McElhinny, 1990).

thermochemical overprint acquired during a reactivation of the dyke in a reversed geomagnetic field period. Site MB2 is in the proximity of Juromenha (JU1-R and JU2-R sites). Therefore, we interpreted that in this area the dyke had, at least, two intrusive events: (i) the main one occurred in a normal polarity geomagnetic period and (ii) the second intrusion emplaced in a reversed polarity geomagnetic time interval.

- **Group 4, site JU1-A.** Because of the presence of reversed polarities in JU1-R (small secondary dyke) and normal polarities in JU1-N (main dyke), a second field work was done. The aim of this sampling was to collect some rock specimens (JU1-A) at the contact of the main dyke with the small one.

Anomalous single directions or overlapped multi-components behaviour have been observed (Fig. 9). This site exhibited a very complex behaviour, probably due to thermal/thermo-chemical alterations produced in the main dyke due to the secondary intrusion of JU1-R. In Fig. 9 is plotted the equal area demagnetization projections of JU1-A. Because of this complex magnetic behaviour, this site was rejected for next calculations.

5.2. Paleomagnetic directions

Characteristic remanent magnetization (ChRM) directions were computed by least squares fitting (Kirschvink, 1980) of the orthogonal demagnetization

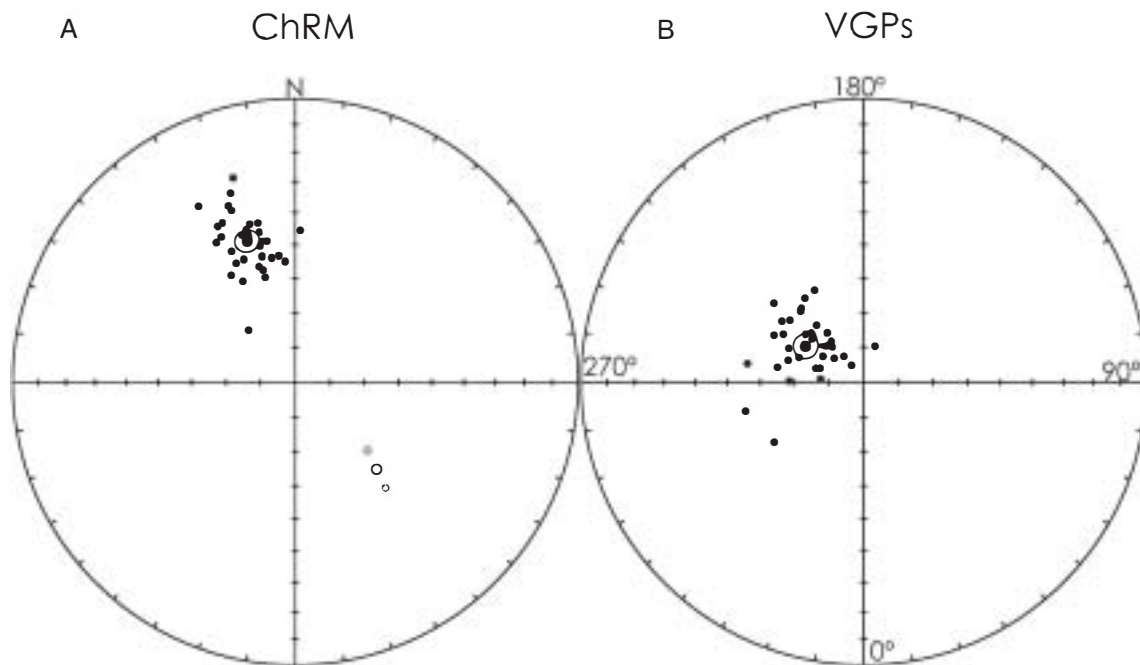


Fig. 10. Equal area projection of: (A) ChRM directions of the selected Messejana Plasencia sites, in filled symbols (normal polarities) open symbols (reversed polarities) and mean values with the α_{95} statistical parameters; and (B) VGPs directions of the selected Messejana Plasencia sites, mean value and the $A_{95\%}$ statistical parameter. See values in Table 2.

plots. ChRM directions are well grouped in all investigated sites (see Table 1). We combined the sites D5 and D6 because of their proximity in the field and the low number of cores that were drilled (D5–6).

Cores from site MJ2 were drilled close to the border of the dyke outcrop in Murração (the southernmost site studied) and seem to present meteoric alterations when compared with the fresh samples from the central part of the dyke at the same site (called MS2 in order to distinguish it from the samples of the border). The ChRM mean direction of MJ2 is closed to the actual geomagnetic field, in contrast with the ChRM direction of MS2 (Table 1). We interpreted that samples located closest to the border presented an important weathering and their ChRM is dominated by a secondary component that was probably acquired recently by chemical processes. This site was rejected for the computation of the VGPs.

For each accepted site we calculated the VGPs (Table 1) and checked if the population of the 37 VGPs belonged to a Fisherian distribution (Table 2). The Fisherian test was negative when considering all sites, but positive excluding two sites, P01 y AL1. There is field evidence indicating that AL1 has been affected by Tertiary and Quaternary deformation (Capote et al., 1996). P01 is close to the border of the Mendro Chain, which is related to the so-called “Vidigueira fault”, an inverse fault that crosses the dyke (Cabral and Ribeiro, 1988). These field evidences explains the negative Fisherian test result. On these bases, these two sites have been rejected.

The ChRM directions of the sites that belong to a Fisherian distribution pass the reversal test of McFadden and McElhinny (1990) with a positive indeterminate result (R_0), see Table 2 and Fig. 10a. This result implies that we cannot refute the possibility of a common mean direction between the normal and reversed polarities.

ChRM and VGPs directions of the selected sites are shown in Fig. 10a, b. The mean value of the 35 remaining VGPs gives the definitive paleopole for the Messejana Plasencia dyke with values of: $N=35$, $PLa=70.4(^{\circ}N)$, $PLo=237.6(^{\circ}E)$, $K=47.9$ and $A_{95\%}=3.5^{\circ}$.

6. Discussion

6.1. On the primary/secondary origin of the ChRM

The Messejana Plasencia paleopole derived from this study has been compared (see Fig. 11) with: those obtained by Schott et al. (1981), Perrin et al. (1991), the Cretaceous remagnetization ($N=11$, $PLo=224.8$, $PLa=$

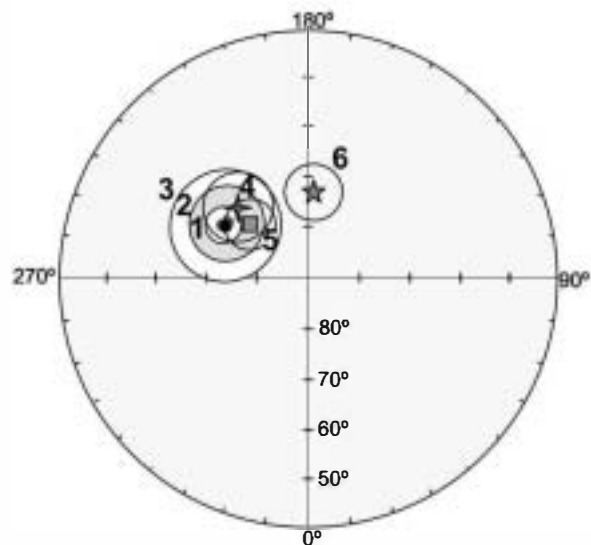


Fig. 11. Equal area projection of the paleopoles: (1) this study; (2) Schott et al. (1981); (3) Perrin et al. (1991); (4) the Cretaceous remagnetization of Juárez et al. (1998); (5) the mean Albian–Aptian paleopole of Iberia (Galdeano et al., 1989; Moreau et al., 1992, 1997); (6) the mean upper Cretaceous pole of Iberia (Van der Voo and Zijlerveld, 1971; Van der Voo, 1969; Storetvedt et al., 1987, 1990) and the $\alpha_{95\%}$ statistical parameters.

71.1, $k=98.0$, $A_{95\%}=6.8$) of Juárez et al. (1998), the mean Albian–Aptian paleopole of Iberia ($N=3$, $PLo=227.4$, $PLa=74.5$, $k=615.0$, $A_{95\%}=5.0$; Galdeano et al., 1989; Moreau et al., 1992, 1997) and the mean upper Cretaceous paleopole of Iberia ($N=5$, $PLo=176.3$, $PLa=73.2$, $k=190.1$, $A_{95\%}=5.6$; Van der Voo, 1969; Van der Voo and Zijlerveld, 1971; Storetvedt et al., 1987, 1990).

The paleopole of the Messejana Plasencia dyke is indistinguishable from those obtained by Schott et al. (1981) and Perrin et al. (1991). It is also indistinguishable from the Cretaceous remagnetization of Juárez et al. (1998) and from the mean Albian–Aptian pole, but distinguishable from the mean upper Cretaceous pole of Iberia.

If we assume a secondary origin for the ChRM, the age of the normal remagnetization should be Albian–Aptian (according with the paleomagnetic poles) and the reversed magnetic components should be primary and acquired within the short reversed polarity chron M0 or M1 (considering the magnetic polarity time scale of Gradstein et al., 1994). Therefore, after the widespread event that could remagnetize the whole Iberia, a new reactivation of the dyke could took place coeval with the intrusion of the narrow secondary dykes and the partial remagnetization of the site MB2.

Magnetic properties of the remagnetized components observed in the Iberian Ranges, Pyrenees and Betics are

common (Villalaín et al., 1994; Juárez et al., 1998; Dinarés-Turell and García-Senz, 2000): It is carried by magnetite of low unblocking temperature (450 °C). This behaviour has not been observed in the Dyke. In addition, magnetic properties of samples with normal (hypothetically remagnetized) and reversed polarities (primary origin) are very similar: Verwey transition well defined for both normal and reversed specimens; same unblocking temperatures and similar hysteresis parameters (Figs. 4, 5, 7).

The arguments given by Juárez et al. (1996), suggesting the remagnetization of the Messejana Plasencia dyke, were: (i) the absence of reversed polarities and (ii) the similitude of the Cretaceous and the Messejana Plasencia paleomagnetic directions.

The presence of reversed polarities in the two secondary dykes presented here allows us to reject the first of the arguments given by Juárez et al. (1996). In addition, the similitude in the magnetic properties of the normal and the reversed components point out to a common magnetization origin.

In relation with the second argument: If we transfer the African synthetic polar wander path of Besse and Courtillot (2002) to Iberia there is a loop in the curve in the Jurassic–Cretaceous segment. The expected middle Cretaceous and lower Jurassic poles are overlapped. Therefore the second argument given by Juárez et al. (1996) can be also been rejected. In our opinion it is more likely to consider that the dyke preserves its original magnetization than it is remagnetized. In the following discussion we will assume this hypothesis.

6.2. The multiphase character of the dyke

The existence of both polarities implies that the dyke had at least two intrusion events, separated in time by, at least, 10,000 y. In lower Jurassic times the maximum period of a normal chron is about 1 Ma (Gradstein et al., 1994) and the reversal rate is very high. Within this context, and taking into account that most of the sites exhibited normal polarities, we consider that the main dyke intruded in a single and brief (less than 1 Ma) important event. Later, a second event, of very short magnitude and extension, took place characterized by narrow dykes with reversed magnetisation. This scenario seems more consistent with paleomagnetic data than multiphase intrusions (in which normal and reversed polarities would have the same probability). This is in agreement with other studies concluding that flood basalts appear to have been geologically instantaneous over much of the CAMP (McHone, 1996; Olsen et al., 1996; Olsen, 1997; Hames et al., 2000; Olsen et al., 2003). In addition, published paleomagnetic data from the CAMP are consistent with this study: the vast majority of the CAMP rocks exhibited normal polarity, but few reversal episodes were also observed (Knight et al., 2004).

6.3. Block rotation in the Spanish Central System deformation

In order to test the tectonic model Vegas et al. (1990), we compared the paleodeclinations of sites located in the northern branch of the dyke (that must be affected by

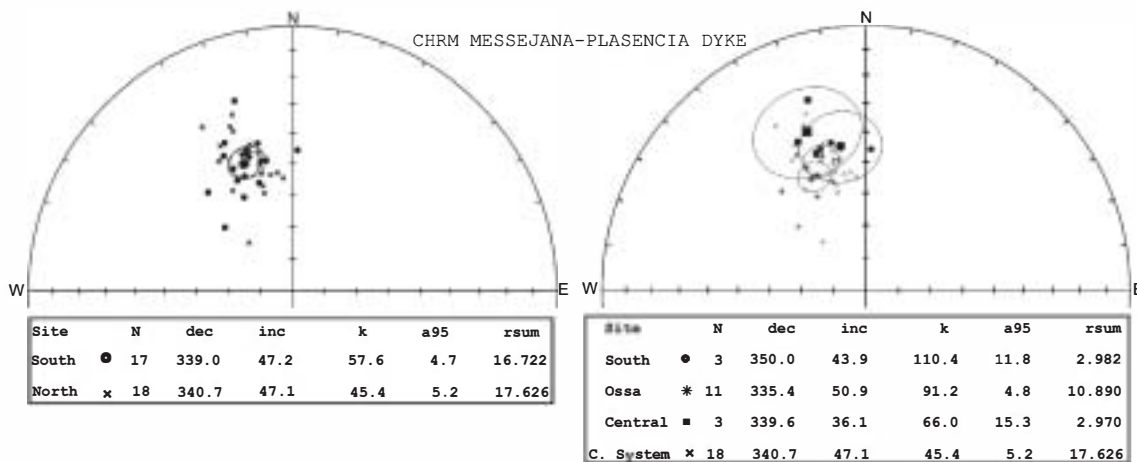


Fig. 12. Equal area projection of the ChRM directions of sites grouped in (a) the northern sites belong to the central Spanish System (dots) versus the 17 southern sites (crosses); and (b) sites grouped depending on the zones of Fig. 1: South Portuguese zone (dots), Ossa Morena zone (stars) and Central zone of the Variscan Iberian Massif: subdivided into Central Iberian zone (squares) and Spanish Central System zone (crosses).

block rotations) with the paleodeclinations of sites located outside of the Spanish Central System. ChRM directions of the Messejana Plasencia sites were divided into two groups: (i) the 18 sites of the dyke located in the Spanish Central System (from CV1 to D2) and (ii) the 17 southern sites (from MS2 to GV1) (Fig. 12a). Comparing the ChRM directions of these two groups, we observe that there is no statistical difference between the respective means of each group. Trying to observe if the ChRM directions of the sites of the dyke are in some way affected by the different structural zones that cuts the dyke (Fig. 1), we also divided the population of ChRM directions of the Messejana Plasencia sites into four groups (Fig. 12b): (i) the 3 sites located in the Southern Portuguese zone (sites MS2, AM, OD), (ii) the 11 sites located in the Ossa Morena zone

(sites PO2 to EL1); and the sites located in the Central Iberian zone that were subdivided into (iii) 3 sites located in the Central Iberian zone that is not affected by the Spanish Central System deformation (sites AL2, MN2, MN1) and finally (iv) the 18 sites of the dyke located in the Spanish Central System deformation (from CV1 to D2). There are no statistical differences in between the means ChRM directions of these groups, so there is no paleomagnetic evidence of block rotations affecting the dyke. Therefore the model proposed by Vegas et al. (1990) is not supported by the paleomagnetic data.

We derive from this comparison that the ChRM dyke directions are not affected by tectonics perturbations since its intrusion to the present day and this implies that the whole structure of the dyke remains in situ since lower Jurassic times.

Table 3
Selected paleomagnetic poles of lower Jurassic ages for Europe and North America from Besse and Courtillot (2002), and paleopoles rotated to Iberia

Place and rock name (North America)	Age	Dage	PLa	PLO	am	ap	SLat	SLong	PLa rotated to Iberia	PLO rotated to Iberia	Reference
North Carolina, northwest dykes	180	30	52.6	60.7	4.9	9.8	36	-79.8	76.4	147.6	Smith (1987)
North Carolina, north-south dykes	180	30	69.6	47.1	5.5	9.2	36	-79.8	84.4	285.5	Smith (1987)
Vermont (New Hampshire), White mountain volcanics	180	20	85.5	124.5	4.5	6	44	-71	64.6	277.7	Opatky and Wensink (1966)
New Brunswick (Canada), Caraquet dyke	191	5	74.1	114	7.6	11.4	46.8	-66	65.5	250.3	Seguin et al. (1981)
Nova Scotia (Canada), north mountain basalt	191	10	73	104	4.5	6.5	44.9	-65.4	68.2	246.4	Carnichael and Palmer (1968)
South Carolina Piedmont, diabase dykes	194	8	66.1	96.1	4.9	9.3	34.3	-81.5	69.5	226.1	Dooley and Smith (1982)
Combined Pennsylvania diabase	195	10	62	104.5	1.5	1.5	40.2	-76.3	64.5	220.3	Beck (1972)
Connecticut valley volcanics	198	15	65.5	87.5	7.2	12.6	41.5	-72.7	72.7	221.4	De Boer (1968)
Newark group	200	20	63	108	3	4	40.5	-75	63.6	224.2	Opatky (1961)
Newark supergroup volcanics	201	14	68	88.6	3.9	3.9	42	-73	72.8	229.9	Prevot and McWilliams (1989)
Pennsylvania, Culpeper Basin intrusive and baked sediments	201	14	65.5	73.1	3.7	3.7	39	-77.5	78.6	217.4	Kodama et al. (1994)
New Jersey, Newark Basin Hettangian red beds	206	5	5.5	94.5	5.4	5.4	40.5	-74.3	65.0	200.9	Witte and Kent (1990)
New Jersey, Passaic Formation, Preakness basalts	208	3	62.2	115.1	10.5	10.5	40.5	-75	60.4	226.4	Van Fossen et al. (1986)
Place and Rock Name (Europe)	Age	Dage	PLa	PLO	am	ap	SLat	SLong	PLa rotated to Iberia	PLO rotated to Iberia	Reference
Sweden, Scanian basalts	181	13	69	102	10	11	55.5	14	71.6	255.8	Bylund and Halvorsen (1993)
France Thouars and Airvault Toarcian stratotypes	183	9	70.1	102.6	5.1	5.1	48	-0.2	70.8	258.4	Galbrun and Daly (1987)
Yorkshire, U.K, Liassic sediments	192	6	76.9	134.7	2.5	2.5	54.6	-0.8	60.1	266.2	Hijab and Tarling (1982)
Bretagne, France, Kerfome dykes	198	20	61.3	78.8	10.2	10.2	48.3	-4.5	83.8	259.1	Sichler and Perrin (1993)

Age. Mean age of magnetization, in Ma; Dage. Maximum age of magnetization minus minimum age; PLa. and PLO. Pole latitude and longitude; am. and ap. Semiaxes of the 95% level confidence ellipse for the VGP; SLat. and SLong. Site latitude and longitude.

Table 4
Euler poles for rotation and finite angles used for this study

Euler pole	Age (Ma)	ELat (°N)	ELong (°E)	Rotation (deg)	Reference
Iberia respect to N. America	175	65.7	-12.8	-66.3	Srivastava and Verhoef (1992)
Europe respect to N. America	175	71.6	156.7	-25.3	Torsvik et al. (2001)

6.4. Comparison with lower Jurassic paleopoles of the North American and European plates

The Messejana Plasencia paleopole is the only lower Jurassic paleopole for the Iberian Peninsula, so it is very important to be sure about its quality in order to develop the Apparent Polar Wander Path (APWP) for Iberia. Considering the reliability criteria of Van der Voo (1993), the pole obtained in this study passes 5 of the 7 criteria. The Messejana Plasencia paleopole derived from this study has been compared with the (rotated to the Iberian plate) selection of Jurassic paleopoles from the North American and European plates (see Table 3) made by Besse and Courtillot (2002). The good quality Jurassic paleopoles from

Table 5
Mean values of the selected paleomagnetic poles rotated to Iberia of Table 3 together with the paleopole of this study

Mean values paleopoles	<i>N</i>	PLa	PLo	<i>K</i>	<i>A</i> _{95%}
Europe rotated to Iberia	4	71.6	260.9	68.3	11.2
North America rotated to Iberia	13	71.8	229.2	47.6	6.1
This study	35	70.4	237.6	47.9	3.5

N. Number of paleopoles or sites (in the case of this study); PLa. Pole latitude; PLo. Pole longitude; *K* and *A*_{95%}. Statistical parameters (Fisher, 1953).

North America and Europe have been rotated to Iberia using the Euler poles for rotation and finite angles listed in Table 4. As there are no direct Euler poles to rotate Europe in to Iberia, the European paleopoles were first rotated to North America and subsequently to Iberia.

In Fig. 13 the North American and European Jurassic paleopoles rotated to Iberia are plotted, along with their mean values with the respective *A*_{95%} statistical parameter, plus the Messejana Plasencia paleopole derived from the present study (Table 5). All poles are statistically indistinguishable. It means that the Euler Poles for rotation and finite angles used

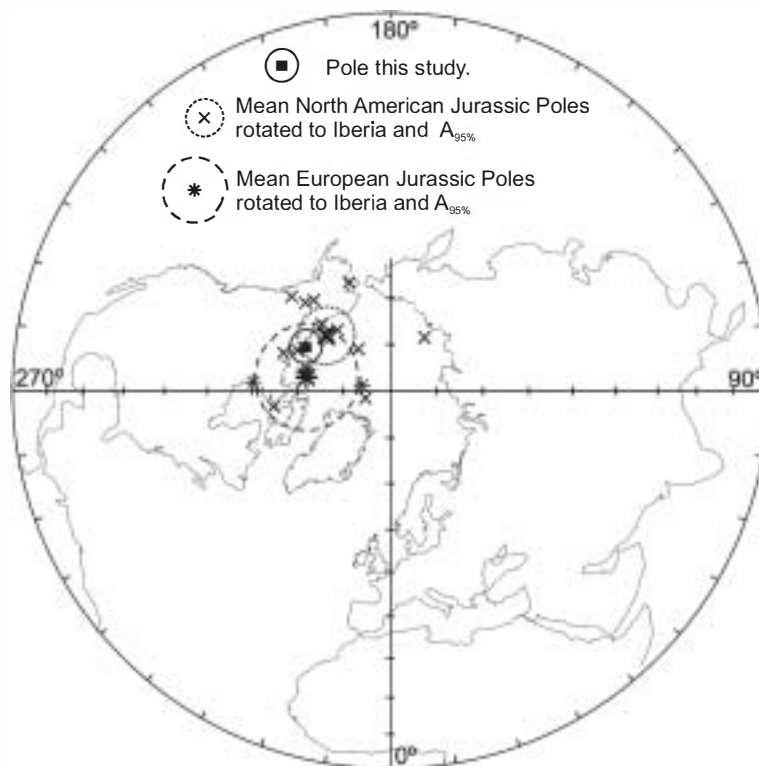


Fig. 13. Equal area projection of the selected North American and European Jurassic paleopoles rotated to Iberia, their mean values with the *A*_{95%} statistical parameters, and the Messejana Plasencia paleopole.

for this comparison are consistent with paleomagnetic data.

7. Conclusions

In conclusion, our paleomagnetic study of the Messejana Plasencia dyke showed that magnetite and/or low Ti-titanomagnetite are the minerals carrying the magnetization. The ChRM directions of the studied sites are mostly of normal polarity, with the exception of two sites in the Juroemha zone (Portuguese part) where reversed polarities ChRM directions are observed. The two polarities average ChRM directions are indistinguishable.

Considering the magnetic properties of the normal and reversed directions, the available Cretaceous poles for Iberia and the African poles, we concluded that the magnetization of the dykes is of primary origin.

The intrusion of the dyke appears to have been geologically instantaneous. But, the dyke had at least two intrusion events, separated in time by at least 10,000 y. The main intrusion took place during a period of normal polarity of the geomagnetic field. The second event was of less magnitude, restricted to a small region (Juroemha area, Portugal) and took place during a reversed polarity period of the field. The intrusion of the Messejana Plasencia dyke presents similar characteristics to the observed in much of the Central Atlantic Magmatic Province.

There is no important tectonic activity in the dyke affecting the paleomagnetic directions and structure of the dyke. The existence of a rotational deformation within the Spanish Central System is not evidenced by paleomagnetic data.

The Paleomagnetic Pole derived from the average of the VGPs is well defined, with values of: $N=35$, $PLa=70.4^{\circ}N$, $PLo=237.6^{\circ}E$, $K=47.9$ and $A_5=3.5^{\circ}$ and it is a good quality lower Jurassic paleopole for the Iberian plate.

The paleomagnetic pole from the Messejana Plasencia dyke is in agreement with the selection of Jurassic paleopoles from North America and Europe made by Besse and Courtillot (2002) when rotated to Iberia with the available Euler poles of Srivastava and Verhoef (1992) and Torsvik et al. (2001). This evidences the internal consistency between these paleomagnetic and magnetic anomalies data sets.

Acknowledgements

The authors appreciate very much the help of so many people involved in this project: Vicente Carlos

Ruiz-Martínez, Gregg McIntosh and Miriam Gomez, Miguel Miranda and Paulo Fonseca during field-work; Juanjo Villalain, Victor Villasante, Mónica Maceira for their work in some of the studied sites. We are grateful to Vicente Carlos Ruiz-Martínez for enriching discussion during revision of this paper. Criticism and suggestions of the reviewers, R. Van der Voo and B. Henry, help us to improve this paper. This work has been supported by the Dirección General de Investigación Científica y Tecnológica DGICYT (projects BTE2002-00854 and GCL2005-00211/BTE).

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