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Evidence of widespread Cretaceous remagnetisation in the Iberian Range and its relation with the rotation of Iberia

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Abstract

A palaeomagnetic investigation has been carried out at 13 sites of Jurassic age in the Iberian Range (northern Spain). Two components of remanent magnetisation have been found at each site. A primary high-temperature component shows an average counterclockwise rotation with respect to the north of 33 ± 2º clockwise about a vertical axis corresponding to the absolute rotation of the Iberian plate since the Jurassic. A secondary low-temperature component shows a systematic declination difference of 16 ± 4º with respect to the primary component. This indicates that a rotation of Iberia must have occurred between the two acquisition times. Comparison of the magnetisation directions with previous palaeomagnetic data and with sea-floor spreading data, constrains the age of the remagnetisation between 95 and 125 Ma. The remagnetisation may be associated with the extensional phases in the Iberian Basin in the Early Cretaceous (Barremian–early Albian) or Late Cretaceous (Cenomanian). A principal characteristic of the remagnetisation is its widespread character in the Iberian Range.

Keywords: remagnetization; Jurassic; Cretaceous; Iberian Peninsula; rotation

1. Introduction

The occurrence of remagnetisation in rocks has been known for many years. However, several palaeomagnetic investigations carried out during and since the 1980s have shown that remagnetisation is actually a much more common and widespread phenomenon than previously supposed. Since the earliest reports of the occurrence of ancient remagnetisations [1], many independent studies have documented the existence of remagnetisations ranging from local episodes to very widespread events (see [2] for a historical review). Remagnetisations play a very important role in palaeomagnetism. They may be related to important events in the geological history of a rock (e.g., tectonic episodes, fluid migrations, thermal events, etc.). They can also be the reason for misinterpretation of palaeomagnetic results [3]. It is, therefore, important to understand fully the occurrence and the causes of remagnetisation phenomena.

Several remagnetisation events have been observed in palaeomagnetic studies carried out at different locations in the Iberian Peninsula; their origins,

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ages and causes have been interpreted differently [4–10]. The anticlockwise rotation of the Iberian Plate relative to the Eurasian Plate, which took place during the Cretaceous, makes the study of remagnetisations in Mesozoic rocks from the Iberian Peninsula particularly interesting. The plate rotation, quantitatively described for the first time on the basis of palaeomagnetic results [11,12], and corroborated by several studies on magnetic anomaly lineations and plate tectonic reconstruction [13–20], was a major feature of Iberian tectonic history in the Cretaceous. During the rotation, magnetic minerals may have been created or modified in older rocks, thus giving rise to one or more remagnetisation phases. Palaeomagnetic studies in different areas of the Iberian Peninsula have indicated the existence of Cretaceous remagnetisations [4–6,8,9]. However, few palaeomagnetic studies have been carried out to investigate them. Consequently, the extent, timing and causes of these magnetic episodes still need to be defined.

In addition, the amount and timing of the rotation of the Iberian Plate are not yet fully established. Studies of oceanic magnetic anomalies suggest that most of the opening in the Bay of Biscay took place by seafloor spreading during the Cretaceous and continued until the Eocene [13,15,16,18]. However, these studies do not provide a unique answer for the exact timing or magnitude of rotation. Palaeomagnetic studies play an important role in the description of this motion, because they constitute an independent source of information. Unfortunately, palaeomagnetic studies of this event are few [e.g. [5,12,21–23]] and do not give a reliable apparent polar wander path for Iberia.

A palaeomagnetic interpretation of the rotation of the Iberian plate must fulfil two essential conditions. First, it must be based on studies carried out in areas that remained tectonically stable within Iberia, i.e. the so-called “Stable Iberia”. This may be defined as the group of regions within the Iberian plate that have not suffered any local or regional rotation about a vertical axis, so that their palaeomagnetic direction only reflects the rotation of the Iberian plate with respect to Eurasia. Secondly, the rocks must carry primary (or well-dated secondary) Mesozoic magnetisations.

The Iberian Range constitutes a favourable area for this type of evaluation. It has been shown to contain large areas that are representative of stable Iberia [8,9,24]. In addition, the limestones in this mountain range carry primary Jurassic magnetisations [8,25].

The present study has two goals. It serves to constrain better the remagnetisation feature that has been reported previously in rocks from the Iberian Range [6,8,9], and the results help to define the areas of the Iberian Range that belong to stable Iberia. Accordingly, we have carried out a detailed palaeomagnetic investigation of 13 Jurassic outcrops covering a wide area in the Iberian Range (Fig. 1). The results presented here also include data from a magnetostratigraphic study that was carried out at six of these sites [8,25].

2. Geological setting and sampling

The Iberian Range, located in northeastern Spain, constitutes an intraplate mountain range that shows a deformation intermediate between true alpine and platform structures [26]. It can be subdivided geographically into two main mountain alignments or “branches”: the Aragonian Branch in the north and the Castillian Branch in the south (Fig. 1). The mountain range originated by tectonic inversion of a rifted zone formed during Mesozoic extension [27–29]. Mesozoic basin evolution in Iberia was related to three main stages of lithospheric stretching, each followed by thermal subsidence [30]. The rifting history was followed by a Tertiary (Paleogene) inversion, which is responsible for the main structures of the chain. The first extensional phase, marked by a rapid tectonic subsidence, occurred in Triassic to Early Jurassic times. A second phase, of Oxfordian to earliest Albian age, is characterised by uplift followed by moderate, laterally varying subsidence. The third main phase corresponds to a Cenomanian–early Senonian acceleration of tectonic subsidence. Subsequently, convergent movements of Eurasia with respect to Africa from the Late Cretaceous onward [17] resulted in folding and shortening of the Iberian Basin and formation of the Iberian Range. A low-grade, Late Cretaceous metamorphism, which affected the northern part of the Iberian Basin [31–33], is probably related to the second extensional phase. Dating of this metamorphism indicates an Albian–Cenomanian age (99.5±2.2 Ma)

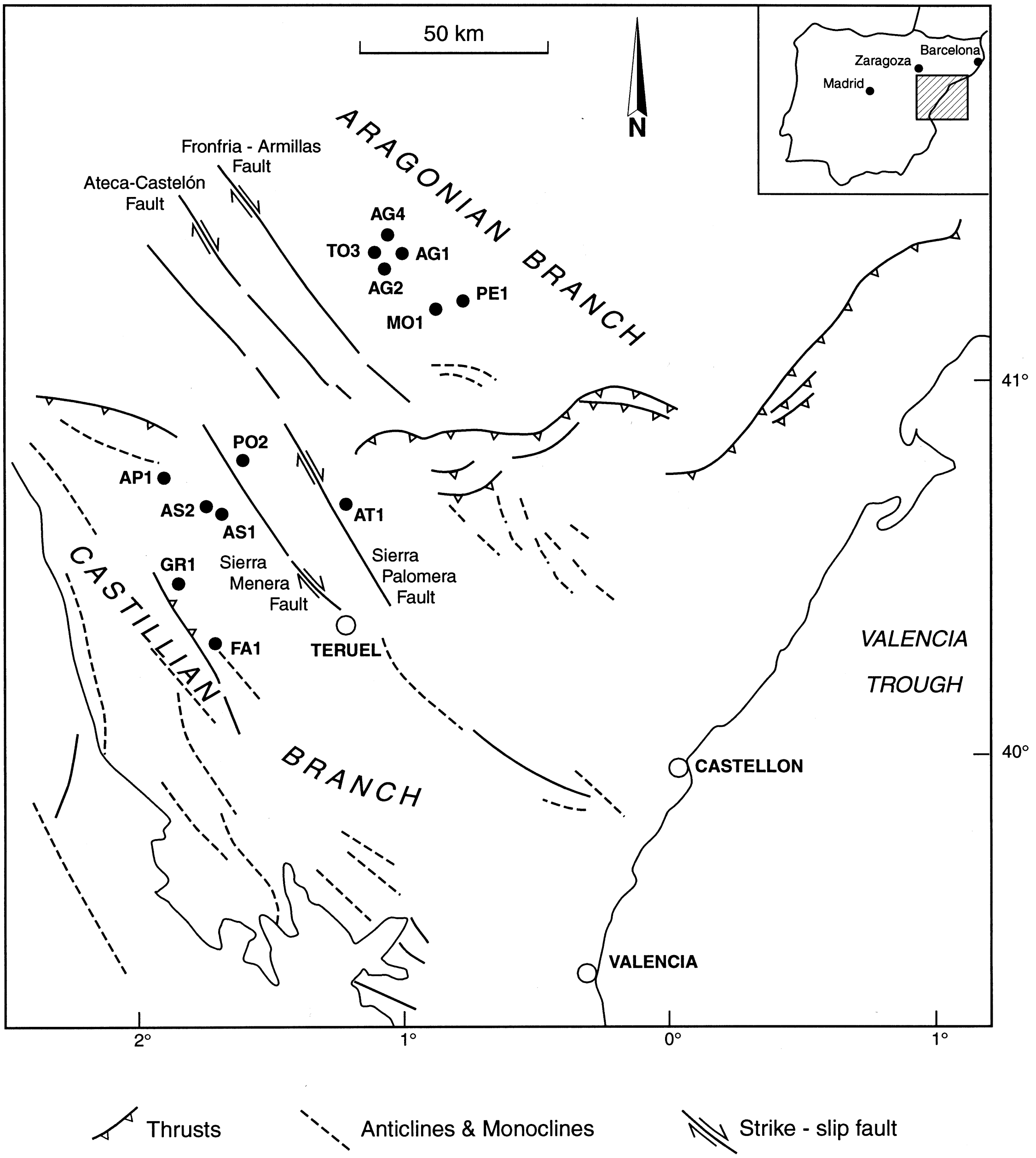

Fig. 1. Geological sketch map showing the location of the sampling sites. Some sites have been grouped and considered as a single unit (named "region" in the text) for the treatment of the data (region TO: sites AG1, AG2, AG4 and TO3; region MO: sites MO1 and PE1; region AS: AS1 and AS2).

[32]. The three extensional phases of the Iberian Basin correlate with rifting stages identified on the Betic, Lusitanian and Cantabrian margins of Iberia [27,28,30,34].

The 13 sites sampled in this study are situated in both branches of the Iberian Range. We have grouped the sites according to region (Fig. 1). Region TO includes sites TO3, AG1, AG2 and AG4; region MO

Table 1
Tectonic corrections applied in each of the sites

Region	Site	Strike	Dip
TO	AG1	67°	43°SE
	AG2	70°	45°SE
	AG4 [a]	283°	35°NE
	TO3	240°	84°NW
MO	MO1	73°	7°SE
	PE1	116°	16°SW
FA1	FA1	274°	10°NE
GR1	GR1	207°	15°NW
AS	AS1	168°	22°SW
	AS2	153°	19°SW
AP1	AP1	153	19°SW
AT1	AT1	327°	77°NW
PO2	PO2	319°	47°NE

[a] Averaged value when a single site involved more than one bedding attitude.

includes sites MO1 and PE1; region AS includes sites AS1 and AS2; in addition, there are five regions represented by only one site each: AT1, GR1, AP1, PO2 and FA1. Detailed palaeontological studies, based on ammonite zonation and carried out in all sites we have studied, yielded Middle and Late Jurassic ages [35–39]. Sites AS2 and AP1 have been dated as Middle Jurassic (Callovian) and the remaining sites correspond to the Oxfordian (Late Jurassic).

As a result of tectonic folding, the bedding attitudes at these sites have different dip- and strike-directions (Table 1). The sampled lithologies are shallow-water marine limestones. Most have a grey colour, although slight variations between sites and levels are observed. Some beige and even yellowish levels, as well as iron-oolitic beds, can be found in some of the sites.

3. Laboratory procedures

Detailed progressive thermal and alternating field (AF) demagnetisation experiments were carried on pilot samples. AF demagnetisation proved to be inefficient in the separation of the different components of the natural remanent magnetisation (NRM). On the basis of the pilot results, all remaining samples were demagnetised thermally by heating them stepwise from room temperature up to 600°C, in temperature increments ranging from 15° to 100°C. Bulk susceptibility was measured at room temperature after each heating step, in order to detect any mineralogical changes that could have occurred during heating. In addition, the acquisition and demagnetisation of isothermal remanent magnetisation (IRM) was studied in a representative selection of samples. Magnetisations were measured with 2G cryogenic magnetometers and susceptibility was measured with KLY2 Kappabridge susceptibility meters in the palaeomagnetic laboratories of Utrecht and Zürich.

4. Experimental results

4.1. IRM experiments and susceptibility measurements

Representative samples of each of the different lithologies and from each site were given IRM in progressively increasing magnetic fields up to 1 or 1.5 T. A total of 55 samples distributed among the sites were subjected to this IRM acquisition experiment. Thermal demagnetisation of a composite IRM consisting of three orthogonal components [40] was then carried out on these samples. The peak fields applied along the three orthogonal axes were, successively, 1 or 1.5, 0.4 and 0.12 T. The results show the presence of a variety of magnetic minerals in the different sites and lithologies.

The samples can be classified in three different groups (Fig. 2). A first group (group A) consists of samples that contain only low-coercivity minerals. These samples acquire saturation IRM at low fields, in general <200 mT. Only the low-field component of the composite IRM is significant. Thermal demagnetisation shows a continuous decay of intensity of this low-coercivity component. This suggests a wide and continuous grain size distribution, ranging from grains with unstable magnetisations that demagnetise at low heating temperatures — and thus are close to superparamagnetic size at room temperature — to grains with very stable magnetisations that are only demagnetised close to the magnetite Curie point (585°C). The presence of a near-superparamagnetic

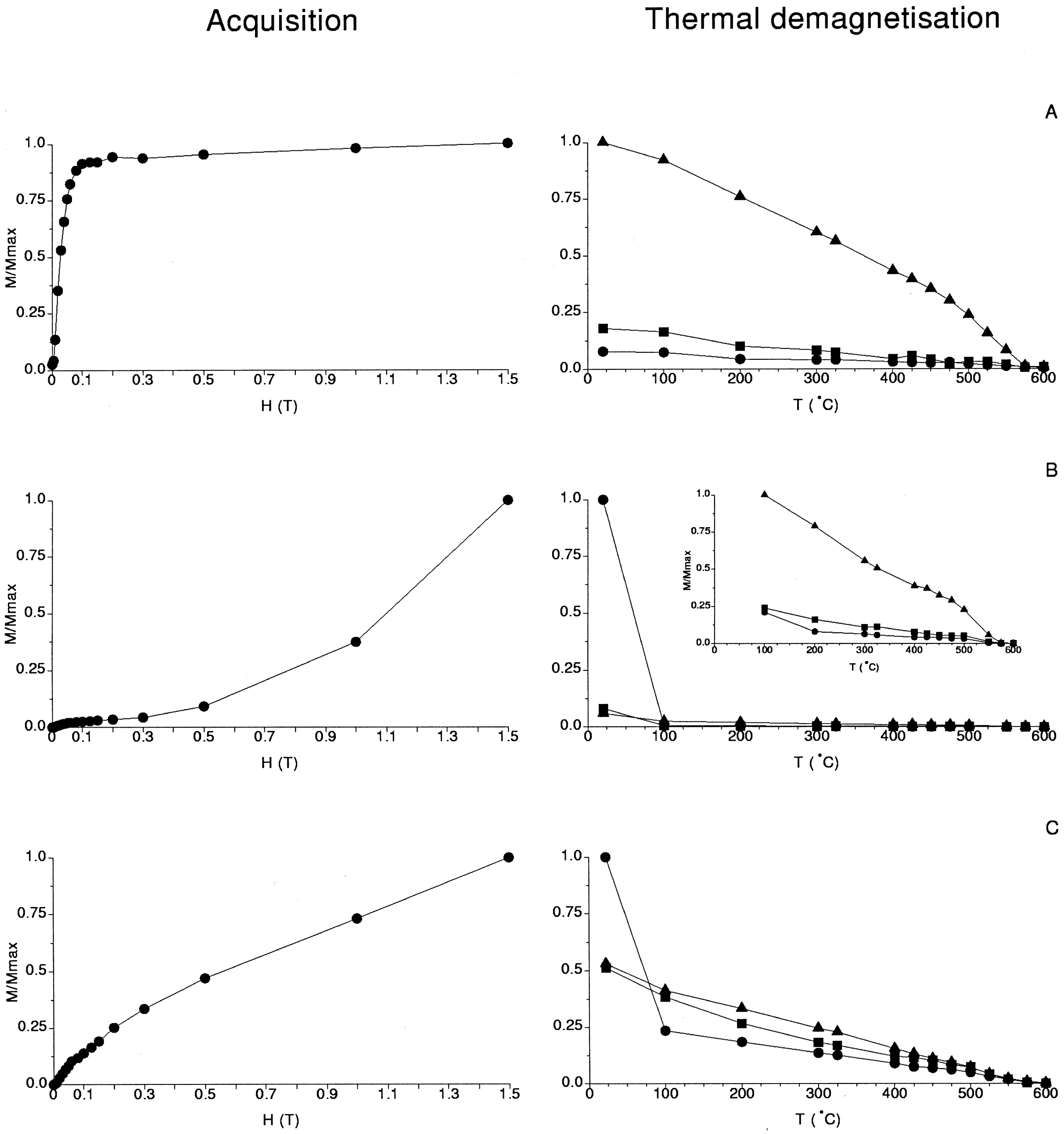

Fig. 2. IRM acquisition and subsequent thermal demagnetisation of three orthogonal IRM components for each of the three different behavioural groups A, B and C, as defined in the text.

component is also indicated by the observed decay of the NRM at room temperature when the samples are left in a zero-field environment. Most of the analysed samples belong to this first group.

A second group of samples (group B) show the presence of two different minerals: in addition to the magnetite observed in group A, there is a high-coercivity component with a very low unblocking temperature (100°C). The high-coercivity, low unblocking temperature mineral is inferred to be goethite. This group includes the samples from the iron oolite beds and from the yellow-coloured levels that are present in some of the sites.

Finally, a third group of samples (group C) exhibit three coercivity phases. As in sample groups A and B, there is a low-coercivity phase that demagnetises at high temperature. In addition there are substantial fractions with medium (0.12–0.4 T) and high (>0.4 T) coercivity, which also unblock at high temperature, but below 600°C. There is also evidence of the mineral characterised by high coercivity and low unblocking temperature that was observed in group B samples. The samples from region MO (sites MO1 and PE1) belong to this group.

We infer that samples of group A carry only magnetite as the ferromagnetic mineral, and that samples of group B carry both magnetite and goethite. However, the results obtained for group C are more complex. These samples also contain magnetite and goethite; the mineral with high coercivity (>0.4 T) and high unblocking temperature (>500°C) is interpreted to be hematite.

Magnetic susceptibility was monitored at room temperature after every heating step (Fig. 3). In samples of group A, which do not contain goethite, a strong increase in susceptibility is observed after heating above 350°C. It is probably due to the creation of new magnetite during the heating process as a result of chemical changes in existing minerals, as has been observed in other marine limestones [41]. Part of the newly formed magnetite shows superparamagnetic behaviour at room temperature, which gives rise to the growth of a viscous remanent magnetisation (VRM). This VRM component is stronger than the stable NRM that remains after heating to high temperatures (above 500°C). In order to isolate the direction of the high-temperature magnetisation it was necessary to allow the viscous component to relax in each measurement. The samples containing goethite (groups B and C) show an initial decrease in susceptibility above 300°C, where goethite breaks down to hematite. This is followed by an increase above 500°C, accompanying the creation of a new magnetite phase.

4.2. Demagnetisation of the NRM

The initial NRM intensity is very similar in each of the sections. Callovian sites generally show lower intensities than Oxfordian sites. The average values

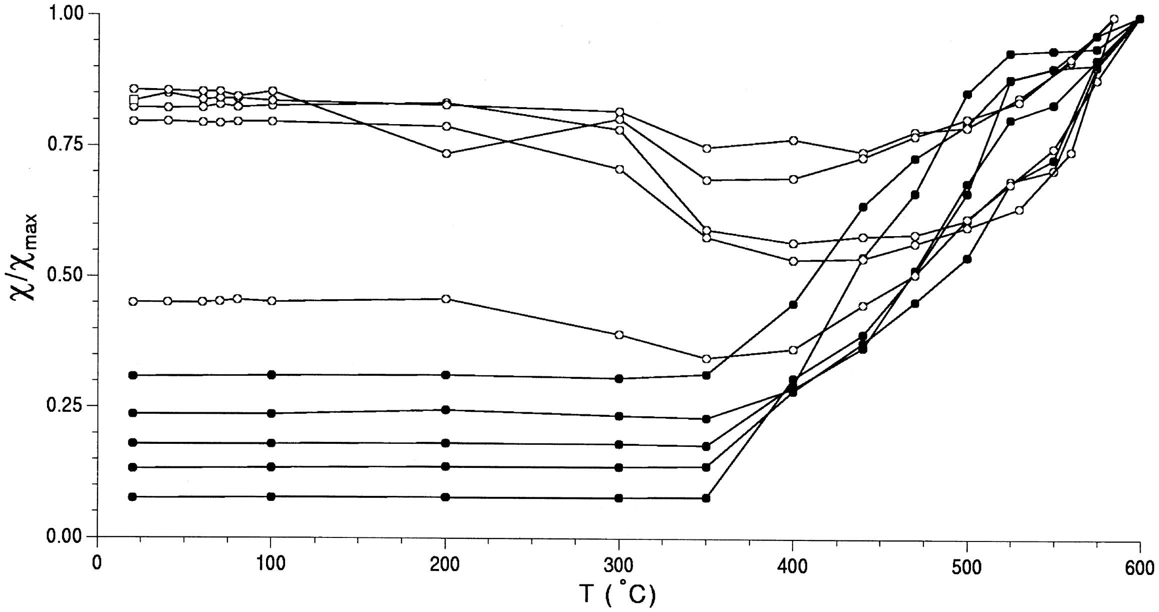

Fig. 3. Susceptibility behaviour during thermal demagnetisation. Open and closed symbols indicate samples with and without goethite, respectively.

of the initial NRM are 1 mA/m and 2.5 mA/m in the Callovian and Oxfordian samples, respectively. The samples that contain goethite show a higher initial NRM intensity (up to 5 mA/m in some cases), which decreases to the above-mentioned values after heating to temperatures above the unblocking temperature of the goethite (∼100ºC). We have concentrated our investigation on the higher temperature components.

In contrast to the results of the IRM experiments, all sites show similar behaviour during thermal demagnetisation of the NRM (Fig. 4). Two different components of the magnetisation can be distinguished in all samples. A low-temperature component has a maximum unblocking temperature between 350º and 450ºC; it always shows normal polarity of the magnetisation and carries approximately 80% of the initial NRM intensity. After removing this component, a high-temperature component carrying a small percentage (∼10%) of the initial NRM magnetisation is isolated. This component shows both normal and reversed polarities of magnetisation. Its unblocking temperature lies between 540º and 580ºC. Following the nomenclature used in previous studies in the Iberian Range limestones [8,9], we refer to the low- and high-temperature components as the S- and P-components, respectively.

The palaeomagnetic direction of the P-component in 6 of the 8 regions (TO, MO, FA1, AP1, AS and GR1; Fig. 5, Table 2) corresponds to the expected Jurassic direction for stable Iberia [21]. It shows an anticlockwise rotation of 33 ± 2º with respect to the north, which corresponds to the known rotation of the Iberian Plate [21]. The S-component is systematically rotated clockwise with respect to the P-component in all sites. In regions PO2 and AT1 both components of magnetisation are rotated clockwise by approximately 50º with respect to the other regions (Fig. 5, Table 2). However, the angle between the P- and S-components in these two regions is the same as in the other six regions. We regard the P- and S-components at PO2 and AT1 as representing the same magnetisation phases as in the other regions. Their clockwise rotation of 50º relative to the other regions has been attributed to local tectonic rotation about a vertical axis of the area in which they are situated [9]. Sites MO and AS show slightly higher inclinations of the S-component than those of the P-component, perhaps indicating another small rotational component between P and S, however these differences are comprised within the errors of the total average values, so we will not consider them in our analysis. Mean declinations and inclinations for the Iberian Range (Table 2)

Table 2
Palaeomagnetic directions (Dec and Inc) and statistical parameters (K and α_{95}) of the P- and S-components of magnetisation for all regions, and the mean direction for the Iberian Range

Region	N	n	P-component				S-component				
			Dec	Inc	K	α_{95}	Dec	Inc	K	α_{95}	ΔD
TO	4	268	324.1	40.6	9.9	2.9	340.9	44.9	31.0	1.7	16.8
MO	2	83	329.1	48.4	12.3	4.6	343.2	56.1	48.0	2.4	14.1
FA1	1	11	325.3	37.3	18.8	10.8	348.8	37.3	35.3	8.2	23.5
GR1	1	15	327.7	44.0	32.4	7.7	345.2	44.8	126.3	3.4	17.5
AS	2	49	330.4	45.2	16.6	6.4	344.9	52.2	42.8	3.1	14.5
AP1	1	14	325.0	37.5	11.8	12.6	345.2	38.0	24.8	8.1	20.2
AT1	1	69	14.9	37.0	11.3	5.3	27.1	34.2	46.6	2.5	12.2
PO2	1	20	18.4	32.8	42.9	8.5	30.7	38.1	37.7	5.4	12.3
Ave (no rot)	11	440	326.8	42.2	281	4.0	344.9	45.2	98.0	6.8	
All	13	529									16.4

ΔD represents differences in declination between both components. The mean values of declination and inclination for the Iberian Range are calculated taking into account only the non-rotated regions (i.e. excluding PO2 and AT1) while the mean differential rotation ΔD corresponds to the average value from all regions. The P-component is averaged after inverting directions with reversed polarity. N: number of sites per region, n: number of samples per site

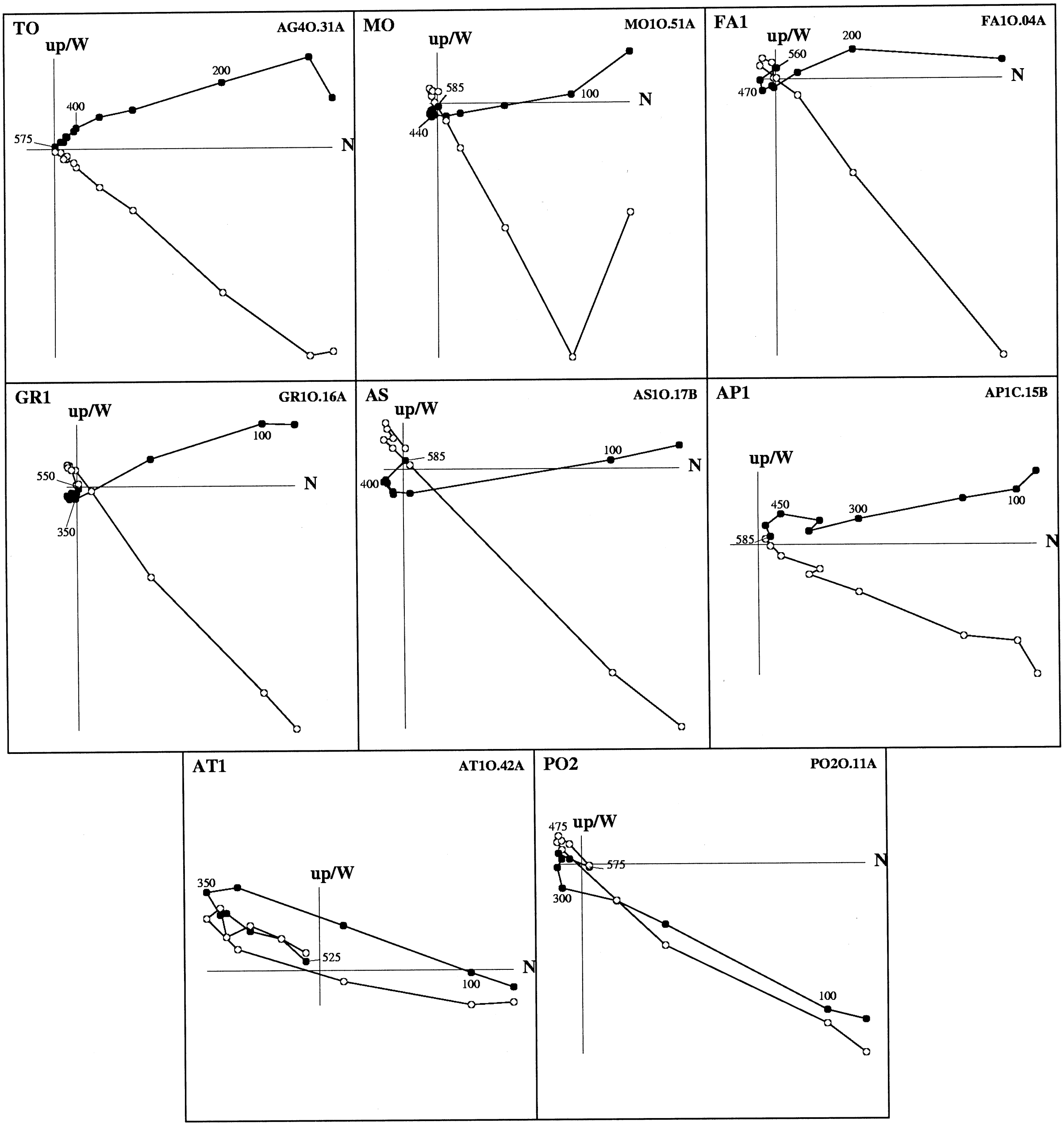

Fig. 4. Zijderveld plots for a typical sample from each region plotted after tectonic correction. The low-temperature (S-) component of the magnetisation always shows normal polarity. The high-temperature (P-) component shows both normal and reverse polarities in all sites; examples of both polarities are shown. Closed (open) symbols represent projection on a horizontal (vertical) plane. Numbers indicate heating temperature in °C.

have been calculated by averaging the directions at sites unaffected by local rotation. The observed deviation between the directions of P- and S-components has an average value $\Delta D = 16 \pm 4^{\circ}$ (Table 2).

In some samples from regions AP1 and PO2

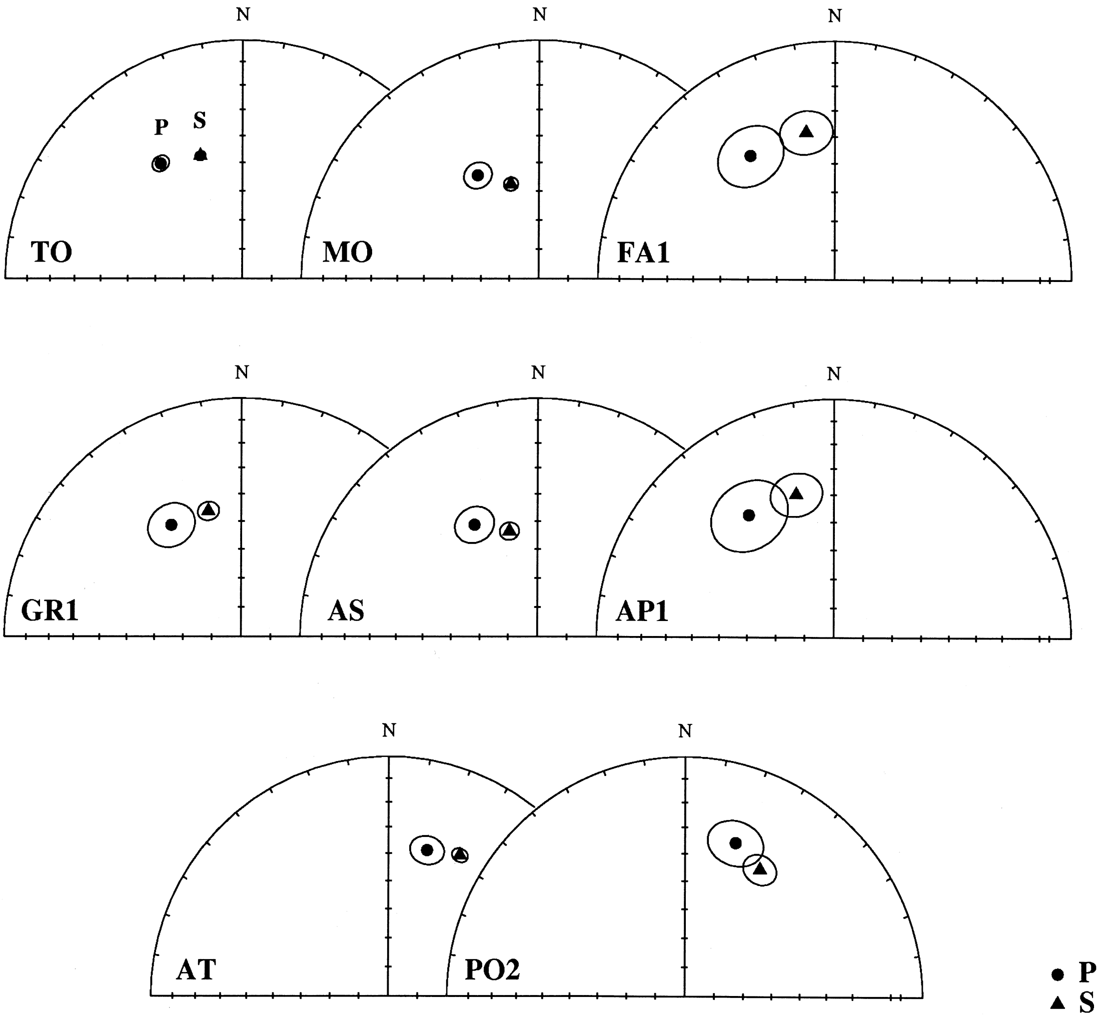

Fig. 5. Stereographic projection of average directions of both magnetisation components and their cones of confidence (α_{95}) for each of the regions. Circles represent the P-component (Jurassic), and triangles the S-component (Cretaceous). A clockwise rotation of ~50° of each component is evident at sites AT1 and PO2.

it was difficult to isolate a clean P-component of magnetisation, because of the growth of VRM after heating to high temperature. As a result, the P-component directions have a higher uncertainty and their distributions are characterised by a large scatter. The circle of confidence of the P-component at each of these two sites overlaps slightly with that of the S-component. However the mean directions of each component, as well as the angular difference between them, are coherent with the other regions. Moreover, a statistical test [42] shows that the directions of the P- and S-component at each site are significantly different: the values of γ_c are 7.1° and 14.7° in PO2 and AT1 respectively, these values are lower than the corresponding γ values (11.3 and 15.9, respectively). Consequently, we consider these data to be representative of the same magnetisation events as at the other sites.

A fold test performed on the samples from the TO region showed that both the P-component and the S-component were acquired before the folding episode in the Paleogene [8,43]. Moreover, the P-component in some of the regions (TO, MO and AT1) shows both normal and reversed polarities. A positive reversals test [8] suggests that the P-component is a primary magnetisation. Moreover, the polarity sequence has been used for a reconstruction of the geomagnetic polarity pattern for the middle and late Oxfordian [8,25]. The S-component is a secondary overprint acquired at some time between deposition of the sediments in the Jurassic and folding of the limestones in the Paleogene.

In accordance with the results of the IRM experiments we can assume that in most samples the P- and S-components are both carried by magnetite, although other minerals (such as hematite) may be involved. Presumably small grains with low unblocking temperatures are the carriers of the S-component, while larger grains with higher unblocking temperature carry the P-component. In samples from the MO region, which contain different coercivity fractions, NRM demagnetisation reveals the same P- and S-components of magnetisation as at sites with simpler magnetic mineralogies. The magnetisation components for this region are presumably also determined predominantly by differences in grain size of the magnetic fraction.

5. Discussion

The P- and S-components are present at each of the sites investigated in this study. The P-component is interpreted to be the primary Jurassic magnetisation at each site. The S-component constitutes a later secondary magnetisation that was acquired contemporaneously throughout the area of investigation in the Iberian Range. The directions of the two components in each of the regions in our study are shown in Fig. 5. The palaeomagnetic data allow us to interpret the timing and extent of the remagnetisation event.

5.1. Timing of the remagnetisation

The S-component of magnetisation was acquired during a period of normal geomagnetic field polarity before the Paleogene folding. Its rotated direction suggests that it was acquired during the Cretaceous rotation of the Iberian Plate. The average difference in declination of 16 ± 4° between the P- and S-components thus represents the amount of plate rotation that took place between the acquisition times of these components. The rotation of Iberia is documented on one hand by palaeomagnetic data and on the other hand by the interpretation of marine magnetic anomaly profiles in conjunction with the plate tectonic reconstruction of the Bay of Biscay.

The palaeomagnetic evidence for plate rotation is manifest as changes of magnetic declination at sites in the Iberian plate. Fig. 6 shows a compilation of the available palaeomagnetic data that define the declination path during the rotation of the Iberian plate. The number of studies is small and there is some disagreement between the results of the individual studies. Consequently, the declination path is rather poorly defined. However, the data indicate that the complete rotation took place between Late Jurassic and Late Cretaceous. The amount of the absolute rotation has been variously inferred from palaeomagnetic data to be between 32° [44] and 42° [4,5]. The data plotted in Fig. 6 form three groups. The mean declination of the oldest group is 322°, with a standard deviation (SD) of 4°; the youngest group has a mean declination of 360° (SD=4°); the difference between these means is 38° with an uncertainty of about 8°. By comparison, the results of our study give a total rotation of 33° with respect to the north. Paleomagnetic studies in Iberian rocks of Aptian age have also shown anticlockwise rotation, but by a smaller amount than the older rocks; their declinations are marked by data points 6, 7 and 8 in Fig. 6. A fast anticlockwise rotation of 22° during the Barremian, which lasted only 8 Ma, has been proposed to explain the intermediate declinations [23]. If the data in the corresponding studies represent primary magnetisations, they imply that the anticlockwise rotation of Iberia took place more rapidly than generally believed, or that it occurred in two phases.

From Plate kinematic analysis of the North Atlantic ocean, the opening of the Bay of Biscay started in the Early Cretaceous, when Iberia separated from Eurasia [15–18]. The separation took place at about the time of — or shortly after — reversed polarity chron M0 [15–20], which marks the beginning of the Cretaceous Normal Polarity Superchron (CNPS) [45,46] and has an early Aptian age (118 Ma [47]). Most of the opening took place before the time of normal polarity chron C33N (74–79 Ma; Campanian), with a smaller amount of rotation between the

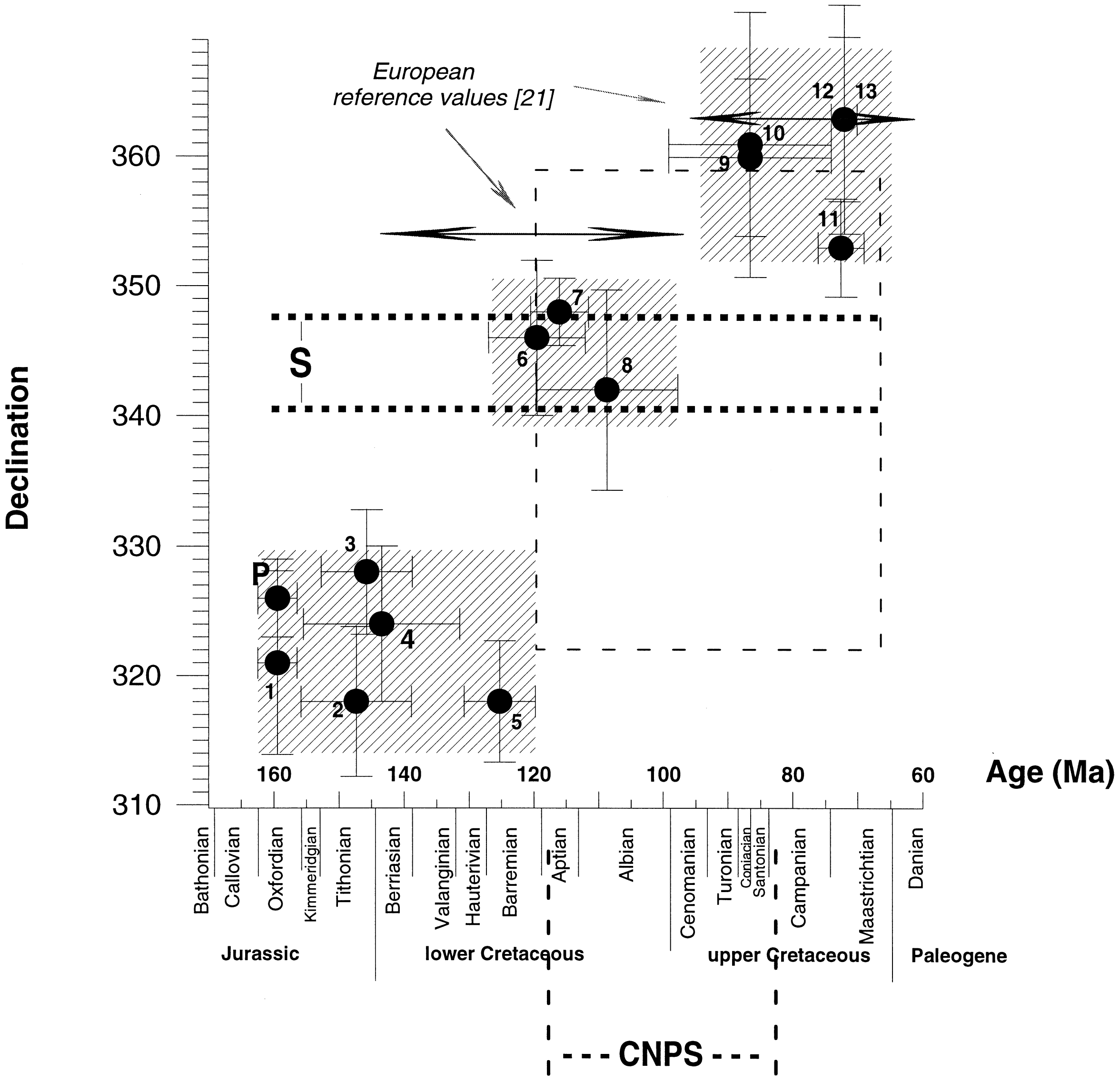

Fig. 6. Variation with geological age (based on the time scale of Ogg [47]) of palaeomagnetic declinations from the Iberian Peninsula (compiled by Van der Voo [21], enlarged by points 3, 4, 6 and 8). The palaeomagnetic data (solid dots) include error bars for declination and age and are calculated for a common reference point at Madrid (40ºN, 4ºW). Shaded areas represent confidence limits (±2SD) for the three groups of declinations discussed in the text. Sea-floor spreading data give the range for the amount and timing of rotation comprised within the fine-dashed rectangle. The declinations of the P- and S-components obtained in the present study are also indicated; the age of the S component is not known, but its declination is bounded by the thick dashed horizontal lines. European reference declination values [21] are also referred to the same common location at Madrid. Numbers beside the points identify the sources of the palaeomagnetic data: *1* = Steiner et al. [49], Iberian Range; *2* = Schott and Peres [4], North–Central Spain; *3* = Galbrun et al. [44], Algarve; *4* = Moreau et al. [23], Algarve, 5 = Galdeano et al. [5], Lisbon; *6* = Moreau et al. [6], Maestrazgo; *7* = Galdeano et al. [5], Lisbon; *8* = Moreau et al. [23], Algarve, *9* = Storetvedt et al. [50], Central Portugal; *10* = Van der Voo [12], Central Portugal; *11* = Van der Voo and Zijderveld [51], Lisbon; *12* = Van der Voo [12], South Portugal; *13* = Storetvedt [52], South Portugal.

Campanian and the Maastrichtian. The timing of the opening is thus constrained to be between 118 and 67 Ma. The amount of rotation that could have occurred before is very small as the motion is constrained by the M0 anomaly in the Central Atlantic, off Iberia and the Grand Banks of Newfoundland. The motion of Iberia since chron 34 is well constrained, partly by seafloor spreading anomalies in the bay of Biscay, but mainly by anomalies to the west of Iberia, north and south of Kings Through. If any later reversals are present, the spreading velocity was so small that no significant signal was observed [18]. According to this model the relative movement between the two plates continued until the time of chron C6CN (∼24 Ma, latest Oligocene). The additional motion across King's Through of about 4° is, however, too small to be resolved with palaeomagnetic data, but is clearly established from seafloor spreading anomalies. It is interesting to mention that the opening of the Bay of Biscay might also have a translation component. Nevertheless, the amounts of rotation interpreted by different authors from marine magnetic anomaly data are estimated variously to be 30° [13], 34° [19] and 37° [20], which are compatible with the total rotation estimated from palaeomagnetic data.

The palaeomagnetic data and the interpretations of marine magnetic anomaly profiles in the Bay of Biscay agree in confining the Cretaceous rotation of Iberia to an interval between the earliest Aptian and the Campanian–Maastrichtian, but the exact timing and evolution of the rotation are still uncertain. The palaeomagnetic data are scarce and consist of a few discrete points with rather large uncertainties in both age and palaeomagnetic declination, while the lack of detailed sea-floor spreading data results in disparate interpretations and different proposed models for the opening of the Bay of Biscay. Moreover, when including the European reference declination data [21] (Fig. 6), the interpretation of the marine magnetic anomalies in the Bay of Biscay becomes in contradiction with these paleomagnetic data. Taking into account the European reference values, the rotation of Iberia with respect to Europe can be constrained to the Cenomanian at the latest, the later (post-Cenomanian) rotation of Iberia having occurred attached to Europe.

Comparison of the direction of the S-component with the palaeomagnetic and sea-floor spreading data in Fig. 6 allows us to demarcate more precisely the timing of the remagnetisation. The intermediate value of the observed declination of the S-component between the pre-rotational and post-rotational limits indicates that the remagnetisation occurred during the Cretaceous rotation of Iberia. The normal polarity of the S-component makes a timing of acquisition during the CNPS likely. The S-component has the same declination range as palaeomagnetic data points 6, 7 and 8 (Fig. 6), which derive from studies in which the palaeomagnetic vectors were assigned a Barremian to Albian age. This would place the remagnetisation event in normal polarity chron M1N or early in the CNPS, that is to say, it would be comprised within a window range that goes from the Barremian to the Cenomanian.

Considering now the tectonic history of the Iberian Range, the second and third phases of extension of the Iberian Basin may have caused thermal events to which the remagnetisation can be linked. The second phase started in Oxfordian–Kimmeridgian times and terminated in the earliest Albian (around 112 Ma ago); the third phase started in the Late Cretaceous at around 95 Ma ago, corresponding to the uppermost part of the CNPS. A remagnetisation related to the thermal event accompanying the second phase is in agreement with the Barremian–Albian age deduced from palaeomagnetic data, but would constrain it until the early Albian because this tectonic phase did no last later than the earliest Albian [29]. On the other hand, acquisition of the S-component in conjunction with the third thermal event would give it a Cenomanian age (∼95 my). This younger age is compatible with the model of rotation proposed by the sea-floor spreading studies, but to be combined with the palaeomagnetic data needs to define the rotation of Iberia as a multiple phase event. That is to say that the total rotation took place partly before the Barremian and partly after the Cenomanian with no (or little) rotation during these two epochs.

5.2. Extent of the remagnetisation

The remagnetisation observed in the Iberian range can be compared with remagnetisations reported from elsewhere in the Iberian Peninsula. These are present in the Cantabrian arc, the southern Iberian

Range, and near Lisbon [4–6,48] among others. It is noteworthy that data points 6 and 7 in Fig. 6 correspond to investigations of Mesozoic sedimentary series of different ages [5,6]. These studies showed the existence of remagnetisations affecting the older sediments. Data points 6 and 7 correspond to the younger sediments of the series, which possess magnetisations that are interpreted as original (i.e., not remagnetised), and which have an Early Cretaceous age, between Barremian and early Albian. The remagnetisations that affect the older sediments from these series have been interpreted as Early Cretaceous events and could result from the same remagnetisation event that produced our S-component. This association agrees with the tectonic correlation between the Mesozoic Iberian and the Cantabrian and Lusitanian rifting systems [27,28,30,34]. This suggests that a widespread remagnetisation might have occurred in a large area in the Iberian Peninsula during the Early Cretaceous.

If our secondary S-component has a Cenomanian age, data points 6–8 should be reinterpreted as secondary directions, as found in older sediments from the same series (the widespread remagnetisation having occurred later in the Late Cretaceous) or the rotation of Iberia should be explained as multiple phase event where no rotation occurred between the Barremian and the Cenomanian.

5.3. Remagnetisation process

The fact that the secondary overprint is carried by two different minerals suggests that it is more probable that a thermoviscous process was involved in the acquisition of the remagnetisation. This is also corroborated by the occurrence of the mentioned thermal events in the Iberian basin at the time in which the remagnetisation was probably acquired. However, we consider that our data do not make this point clear enough and that a chemical origin of the remagnetisation, related for example to circulation of hot fluids, cannot be completely excluded.

6. Conclusions

A prominent remagnetisation has been documented in Jurassic (Oxfordian) limestones from the Iberian range. It has normal polarity and its palaeomagnetic direction is rotated anticlockwise by 15° with respect to the north. These characteristics indicate that it was acquired during a normal polarity interval of the Earth's magnetic field in the Cretaceous, and likely during the rotation of the Iberian Plate.

To obtain a closer estimate of the age of the remagnetisation, we have considered three different sources of data: palaeomagnetic, sea-floor-spreading and tectonic data. They do not give a unique acquisition time for the remagnetisation but place it in either the Early Cretaceous or Late Cretaceous. A Barremian to early Albian age is in accordance with other palaeomagnetic data (Fig. 6). This dating allows association of the remagnetisation with the second extensional phase of the tectonic history of the Iberian Basin. A Cenomanian age, associated with the third extensional phase of the tectonic evolution of the Iberian Basin, is compatible with interpretation of the sea-floor spreading data, but is not in agreement with interpretation of other palaeomagnetic data unless the rotation of Iberia took place in more than one phase.

On the other hand, our data may be linked with other remagnetisations reported from other locations in the Iberian Peninsula. This suggests that a widespread remagnetisation event might have affected a large area of the Iberian Peninsula during its rotation.

The average direction obtained for the primary component of magnetisation in the limestones from the Iberian Range indicates that an anticlockwise rotation of 33 ± 2° has taken place since their deposition in the Oxfordian. There is no evidence of a prior Mesozoic rotation of the Iberian Plate with respect to Eurasia [21], so this amount represents the total post-Palaeozoic rotation of Iberia. A rotation of 16 ± 4° with respect to the north took place before the acquisition of the remagnetisation, that is to say between the Oxfordian and the Barremian–early Albian, or the Cenomanian at the latest.

Finally, the clockwise rotation of approximately 50° of both the P- and S-components at sites AT1 and PO2 suggests that this area of the Iberian range has probably undergone a further local rotation about a vertical axis. Consequently, the area between the faults of Sierra Menera and Fonfria–Armillas

(Fig. 1) cannot be regarded as representative of stable Iberia.

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