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# Diachronous pervasive remagnetization in northern Iberian basins during Cretaceous rotation and extension

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#### ABSTRACT

Northern Iberia exposes a series of Mesozoic sedimentary basins, whose final formation history is tied to a rotation episode of Iberia during the Aptian, related to the opening of the Bay of Biscay. Many of these basins experienced widespread remagnetization, previously loosely tied to a 'Mid-Cretaceous thermal event'. Here we make use of the improved apparent polar wander path (APWP) of Iberia to narrowly constrain the age of their remagnetization to show that several basins experienced a regional diachronous remagnetization. We apply the small circle intersection (SCI) method to reconstruct the paleomagnetic field direction during remagnetization in the Organyà Basin in the Southern Pyrenees, Spain, where the age of remagnetization is stratigraphically well-dated to around the Barremian-Aptian boundary, and where the paleomagnetic direction during remagnetization has been well-established. The resulting direction of  $D/I = 316.8 \pm 5.7^{\circ}/54.8^{\circ} \pm 3.3^{\circ}$ (where the uncertainty in declination is approximated by  $\alpha_{95}/\cos I$  and the error in inclination by  $\alpha_{95}$ ) corresponds closely to a recently improved APWP of Iberia, providing support for the applicability of this method. Application of the SCI method allows us to show that the older portion of the remagnetized beds was already tilted by ~15–20° to the South during the remagnetization as a result of half-graben formation in the Organyà Basin. Moreover, the positive outcome of the SCI technique enables us to argue that previously published results from three other basins-the Cabuérniga and Cameros Basins and the Iberian Range-can be straightforwardly compared to the APWP. Hence, we show that the four pervasively remagnetized basins under consideration all acquired their remagnetization at different times. The remagnetization events were thus confined to these sedimentary basins on an individual 'per basin' scale-albeit occurring on a regional scale over a period of at least ~ 10–15 Myr. Therefore, we propose that the Cretaceous remagnetization events in northern Iberia are related to the extensional tectonic rifting. The pervasive remagnetization is most likely basin confined because there is no apparent overall regional or temporal trend among the basins. Reasonable explanations for remagnetization are those that can occur on the scale and within the context of individual sedimentary basins. These include the interplay of burial depth and an elevated geothermal gradient to reach the diagenetic temperatures required for magnetite-producing reactions. In the Iberian situation, there is no need to invoke more speculative regional Iberia-wide mechanisms.

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# 1. Introduction

Paleomagnetism is a frequently used, quantitative tool for (plate) tectonic studies. Pervasive remagnetization, common in many geological environments, evidently complicates the geological interpretation of the natural remanent magnetization (NRM) for the paleomagnetic studies. Remagnetized strata do not carry a primary NRM, i.e. an NRM of the same age as the rock unit, making those sample collections unsuited for classic paleogeographic or tectonic reconstructions. Remagnetization was considered a fairly rare phenomenon in the 1960s but became increasingly documented since the

early 1980s (McCabe et al., 1983), in particular in limestones and marls that make up large portions of orogenic belts and their forelands. At present, remagnetized rock units are common place in many orogens and paleomagnetic data sets are tested to identify possible remagnetization. Often such analyses are based on the application of field-tests, in particular (versions of) the fold test, and comparing paleomagnetic pole positions to the apparent polar wander path (APWP) of the respective tectonic unit.

The recognition of the causes, and possibly, correction for remagnetization to reconstruct the primary magnetization has been subject of many studies (e.g. Katz et al., 1998; Machel and Cavell, 1999; Elmore et al., 2006). One notorious problem with identification of the mechanisms behind remagnetization concerns the timing and regional extent of such events: a remagnetization event that is restricted to a sedimentary basin may require other explanations than

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remagnetization events that occur continent-wide. A region which has been inferred to be remagnetized regionally during the Cretaceous concerns the Iberian Peninsula (e.g. Galdeano et al., 1989; Moreau et al., 1992; Villalaín et al., 1994; Moreau et al., 1997; Juárez et al., 1998; Villalaín et al., 2003; Dinarès-Turell and García-Senz, 2000; Márton et al., 2004; Gong et al., 2008a; Soto et al., 2008; Casas et al., 2009). This remagnetization has been attributed to the 'Mid-Cretaceous thermal anomaly that prevailed during the extensional phase' (Juárez et al., 1998; Dinarès-Turell and García-Senz, 2000). This extensional phase refers to the opening of the Bay of Biscay, during a contemporaneous Aptian counter-clockwise rotation phase of Iberia. The Cretaceous remagnetization has regionally been documented from the Cabuérniga Basin to the Iberian Range (Fig. 1).

Remagnetization may occur well after sedimentation and the beds may have been tilted prior to remagnetization. Correction for bedding tilt thus does not necessarily yield the paleomagnetic direction during remagnetization. Proper reconstruction of this direction, which allows comparison to the APWP, however, may put important constraints on the timing of remagnetization, which in turn is essential in assessing its cause. The small circle intersection (SCI) method which is proposed by Shipunov (1997) and later perfected by Enkin et al. (2002), Enkin (2003), and Waldhör and Appel (2006), can be used to determine the paleomagnetic direction during remagnetization from a series of remagnetized sites. This method has recently been applied to remagnetized Mesozoic basins in the Iberian Peninsula (Soto et al., 2008; Casas et al., 2009). The SCI method uses the inherent variability in bedding strike of a folded tilted basin. Upon rotation around the bedding strike the NRM component directions of individual sites describe small circles. The only possible direction that fits all small circles is their common crossing point and by minimizing the sum of the angular distances to the small circles, the paleomagnetic direction during remagnetization can be calculated. A major advantage of the SCI method is that different limbs, thrusts or other structures may have been tilted to varying extents on the way to full 100% restoration to paleohorizontal.

The Organyà Basin in north-eastern Iberia contains a Berriasian-Barremian remagnetized and an Aptian-Cenomanian non-remagnetized, syn- and post-rift sedimentary sequence (García-Senz, 2002). From these syn-rift sedimentary sequences, Gong et al. (2008b) reconstructed and dated the Aptian rotation history of Iberia, further constrained by a review of Iberian paleomagnetic and marine magnetic anomaly data. From the stratigraphic relationships (Dinarès-Turell and García-Senz, 2000) already inferred that remagnetization occurred around the onset of the intensive rifting phase in the basin. Because the timing and the paleomagnetic direction of the remagnetization in the Organyà Basin are well constrained, this basin provides a unique opportunity to further investigate the validity of the SCI method in the reconstruction of synremagnetization paleomagnetic directions, using new and published data. The reconstructed direction of Organyà Basin, as well as published remagnetization directions, will then be compared to the recently improved Iberian APWP to determine their ages.

By analyzing the Cretaceous northern Iberian basins we thus investigate whether the remagnetization was a single event that has operated 'Iberia-wide' or whether it was active more regionally on a 'per basin' scale. Either option has its bearing on remagnetization scenarios, an item that we address at the end of this contribution.

# 2. Remagnetization mechanisms

The regular occurrence of remagnetization in anchimetamorphic and very low-grade metamorphic rocks has motivated research into its mechanism. Broadly speaking two main categories of mechanisms have been proposed. The first involves viscous resetting of existing magnetic minerals at the burial temperature for the burial duration, referred to as the thermoviscous remagnetization (TVRM) model (Kent, 1985). This mechanism may have some credibility for rocks that are at their most elevated burial temperature during a long single polarity chron, for example the reversed Kiaman Superchron during the Hercynian orogeny, and could occur on a regional scale. However, in many cases the prevailing burial temperatures are too low to make the TVRM model plausible and neoformation of magnetic minerals has been put forward as an alternative. This model is referred to as the chemical remanent magnetization (CRM) model (McCabe and Elmore, 1989). Fluids are presumed to have delivered the constituents for the newly formed magnetic minerals. Older scenarios involved vast amounts of 'orogenic fluids' that would have moved orogen-wide (e.g. Oliver, 1986; Morris and Robertson, 1993) More recent remagnetization studies take a more conservative approach and do not involve (large amounts of) external fluid (sometimes referred to as squee-gee fluid) (Katz et al., 1998; Machel and Cavell, 1999; Katz et al., 2000; Blumstein et al., 2004). These latter studies document that diagenetic reactions deliver iron, required to form magnetite, amongst others by reactions involving clay minerals obviating the need for external fluids. This scenario can also occur in a more confined regional scale. When dolomitization of the carbonates is occurring, evolved fluid is reported to have migrated in relation to remagnetization and oil generation (O'Brien et al., 2007). The role of pressure solution in remagnetization is equivocal (Evans et al., 2003; Elmore et al., 2006) but it requires compression and would be less likely in an extensional setting.

## 3. Organyà Basin: Geological setting and sampling

The Organyà Basin is located in the Bóixols thrust sheet in the southeast Pyrenees, Spain (Fig. 1). During the Cretaceous opening of the Bay of Biscay, the Iberian microplate rotated ~35° counterclockwise (CCW) with respect to Eurasia (Carey, 1958; Bullard et al., 1965; Van der Voo, 1967, 1969; Srivastava et al., 1990; Sibuet et al., 2004; Gong et al., 2008b, 2009). Based on both paleomagnetic data from Iberia and ocean floor magnetic anomaly data from the Bay of Biscay, the timing of the Iberian rotation is now well constrained to the Aptian (Gong et al., 2008b). During the Iberian rotation, several syn-rotational extensional basins including the Organyà Basin, formed along northern Iberia, which later inverted since ~80 Ma during the Pyrenean orogeny.

The Organyà Basin, a west–east trending inverted half-graben, is now exposed in the hanging wall of the Bòixols thrust (Dinarès-Turell and García-Senz, 2000). Its extensional history is characterized by Tithonian–Barremian proto to early syn-rift, Aptian syn-rift and post-Aptian post-rift covers. The bulk of the inversion occurred during the Santonian–Maastrichtian compression. The southern margin of the graben was inverted as the Bòixols thrust sheet (Bond and McClay, 1995). The original northern margin is known with less certainty since exposures coincide with a passive-roof backthrust, located in the contact with the Axial Zone antiformal stack (Dinarès-Turell and García-Senz, 2000). The compressive tectonics led to the development of folds in the basin, such as the present main structure, the approximately E–W trending Santa Fè syncline (Fig. 1).

The Organyà Basin comprises about 4.5 km of hemi-pelagic to pelagic Cretaceous sediments (Fig. 2). These are mainly limestones and marls. Their age is well constrained by biostratigraphy in stages and sub-stages (Becker, 1999; Bernaus et al., 1999, 2000; Bernaus, 2000, 2003). The lower sediments include Berriasian–Barremian platform carbonates with a lagoonal depositional environment (García-Senz, 2002). The limestones grade into Aptian–Albian marls and depositional conditions changed to coastal-marine with a high sedimentation rate (~27 cm/kyr). Before the post-rifting Cenomanian sediments were deposited, erosion occurred in the eastern end of the Organyà Basin, producing an upper Albian to lower Cenomanian and sometimes longer hiatus leading to an angular unconformity.

Previous studies (Dinarès-Turell and García-Senz, 2000; Gong et al., 2008a) show that the upper part of the stratigraphy in the Organyà Basin has a primary NRM. This is supported by positive fold



**Fig. 1.** Geological map of the Pyrenees modified after Vergés et al. (2002) and the Organyà Basin with the locations of the sampling sites; numbers refer to those reported in Table 1. At the bottom left in the top map, the Organyà Basin (OB), Cabuérniga Basin (CB), Iberian Range (IR), Cameros Basin (CM) are indicated by pale orange, pale green, pale purple, pale blue solid rectangles respectively. The map area of the geological map of the Pyrenees is indicated with the blue rectangle on the topographic map. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 2.** Stratigraphic column of the Organyà Basin with lithologies, formations, and broad stratigraphic locations of paleomagnetic sites (new sites in bold), correlated to the geological time scale (Ogg et al., 2004). The geomagnetic polarity time scale (GPTS) is also included: grey (white) is normal (reversed) polarity. Chron nomenclature follows CK92 (Cande and Kent, 1992). The Berriasian–lower Barremian limestones are remagnetized; the Aptian–Cenomanian sediments are non-remagnetized; the uppermost Barremian Prada C Formation is the transition between the remagnetized and non-remagnetized rocks (Dinarès-Turell and García-Senz, 2000; Gong et al., 2008b).

tests, normal polarities in the Cretaceous Normal Superchron, and rock magnetic results. The non-remagnetized formations include Cabó marls, Senyús marls, Font Bordonera marls, Lluçà marls, Coll d'Abella limestones and Santa Fè limestones (Fig. 2). However, the sediments from the lower part of the stratigraphy, from the Berriasian to Barremian, are remagnetized. These involve the Prada A, Prada B, Hostal Nou and Barranc de la Fontanella formations (Fig. 2). The Prada C formation represents the transition from remagnetized to non-remagnetized rocks. These remagnetized sediments all show normal polarity, whereas biostratigraphy would suggest that approximately half of the sites should have a reversed polarity (Dinarès-Turell and García-Senz, 2000; Gong et al., 2008a,b) (Fig. 2). The associated rock magnetic studies show that the magnetic mineral is mainly magnetite with minor hematite and goethite (Dinarès-Turell and García-Senz, 2000; Gong et al., 2008a).

For this study, twenty nine sites covering the entirely remagnetized as well as transitional series in the Organyà Basin were used (Table 1). Two new sites (OR13 and OR14; Fig. 1) from the eastern side of the basin were sampled in north-dipping beds in the strongest inverted and folded part of the basin (García-Senz, 2002; Gong et al., 2009). Sampling occurred with a portable gasoline-powered drill, and combined with 13 other sites (labelled OR#) from our previous studies (Gong et al., 2008a,

#### Table 1

The remanent magnetization parameters of the paleomagnetic sites in the Organyà Basin.

Site	Strike/ dip	Unit/formation	Age	In situ					Tectonic Corrected			
				N/n	D	Ι	к	$\alpha_{95}$	D	Ι	к	$\alpha_{95}$
OR49	111/57	Prada C	Barremian-Aptian	7/8	342.3	25.2	75.7	7.0	316.1	60.1	75.7	7.0
OR53	109/42	Prada C	Barremian-Aptian	6/9	350.4	30.1	67.3	8.2	318.0	61.7	67.3	8.2
OR54	89/46	Prada C	Barremian-Aptian	4/8	333.8	22.5	73.3	10.8	306.9	60.1	73.3	10.8
OR58	116/50	Prada C	Barremian-Aptian	7/8	4.5	24.6	52.4	8.4	330.0	66.3	52.4	8.4
OR72	105/65	Prada C	Barremian-Aptian	28/34	345.3	8.6	131.8	2.4	306.2	53.0	28.3	4.7
OR80	108/68	Prada C	Barremian-Aptian	30/31	347.1	9.6	325.5	1.5	305.8	57.9	325.5	1.5
OR81	105/66	Prada C	Barremian-Aptian	30/32	341.8	6.4	287.7	1.6	308.4	53.6	287.7	1.6
J21	120/67	Prada C	Barremian-Aptian	9/9	358.4	10.7	52.3	7.2	316.9	57.5	52.3	7.2
J22	104/62	Prada C	Barremian-Aptian	5/5	337.6	4.9	220.5	5.2	311.0	48.5	222.1	5.1
J23	100/60	Prada C	Barremian-Aptian	10/11	346.3	10.0	70.0	5.5	316.4	60.4	66.1	5.7
OR13	278/42	Prada B, A	Barremian	7/7	280.7	66.1	41.7	6.2	332.0	40.5	41.7	9.5
OR14	296/18	Prada B, A	Barremian	6/7	339.9	58.9	216.5	4.6	354.5	44.8	216.3	4.6
J24	104/55	Prada B, A	Barremian	6/6	343.9	28.0	108.4	6.5	290.8	63.6	108.7	6.5
J25	120/50	Prada B, A	Barremian	7/7	348.9	24.4	72.2	7.2	311.8	52.3	72.3	7.1
J26	114/58	Prada B, A	Barremian	7/7	346.3	22.4	358.2	3.2	300.4	55.3	359.3	3.2
J27	110/45	Prada B, A	Barremian	5/5	339.6	33.5	63.1	9.7	296.2	57.1	63.1	9.7
J28	110/50	Prada B, A	Barremian	5/5	349.2	30.2	253.1	4.8	301.7	63.1	251.7	4.8
OR21 + J31	116/51	Hostal Nou	Valanginian	20/20	341.3	31.5	87.3	3.5	278.8	54.4	70.1	3.9
OR68	110/60	Hostal Nou	Valanginian	70/80	343.1	24.0	96.3	1.7	290.8	57.1	97.7	1.7
J29	116/59	Hostal Nou	Valanginian	7/7	337.0	29.7	70.1	7.3	284.5	47.9	69.4	7.3
J30	116/51	Hostal Nou	Valanginian	5/8	345.0	33.7	304.6	3.2	290.5	57.5	305.0	3.2
OR1 + J34	106/46	Barranc de la Fontanella	Berriasian	12/12	340.1	34.5	59.4	5.7	298.3	55.5	63.7	5.5
OR2 + J32	97/55	Barranc de la Fontanella	Berriasian	10/10	336.5	33.5	174.9	3.7	280.2	55.7	179.3	3.6
OR3 + J33	97/56	Barranc de la Fontanella	Berriasian	12/12	337.6	15.0	72.9	5.1	307.0	53.4	66.2	5.4
OR63	91/57	Barranc de la Fontanella	Barremian	8/9	329.6	20.9	26.0	12.1	292.3	58.2	21.7	12.2

The OR sites are from our studies (the new sites in bold) (Gong et al., 2008a,b) and numbers as plotted in Fig. 1; the J sites are from Dinarès-Turell and García-Senz (2000). N/n, is the number of samples contributing to the mean/measured samples from each site. D and I, are declination and inclination in degrees.  $\kappa$  and  $\alpha_{95}$ , are the precision parameter and their cone of confidence (Fisher, 1953).

b). Furthermore, 14 of sites (labelled J#) from Dinarès-Turell and García-Senz (2000) were used (Table 1, Fig. 1).

#### 4. Paleomagnetic analysis and small circle intersection (SCI) results

# 4.1. Paleomagnetic analysis

Thermal demagnetization for sites OR13 and OR14 was processed in a laboratory-built furnace with small steps from room temperature up to 500 °C; the NRM was measured with a 2G Enterprises DC-SQUID magnetometer. Zijderveld diagrams (Zijderveld, 1967) and principal component analysis (Kirschvink, 1980) were used to determine the characteristic remanent magnetization (ChRM) directions. The NRM intensity of these limestone samples ranges between ~0.1 and ~1.1 mA/m. A low-temperature component (lower than 240 °C) with normal polarity before tilt correction was interpreted as the present-day geomagnetic field overprint and was not analyzed further. A univectorial high-

temperature component in both sites, from 240 °C to 380 °C, is considered to be the ChRM component (Fig. 3), at higher demagnetization temperatures magnetochemical changes preclude definition of a meaningful remanence direction. After tectonic correction, the ChRMs from both sites have a positive inclination and also a normal polarity, however, their declinations are distinctly different with a northerly direction for OR14 and north-westerly direction for OR13, respectively (Fig. 3, Table 1). Previous results from the same formation (Prada A, B), also revealed a single, normal polarity component with a similar demagnetization behaviour. Therefore, these two sites are also considered to be remagnetized and used together with the other remagnetized sites for further analysis.

# 4.2. Small circle intersection (SCI) results

The SCI method (Waldhör and Appel, 2006) assumes that a tilted remanence has been rotated around a horizontal axis parallel to the



**Fig. 3.** Demagnetization results of the new sites (OR13 and OR14) after bedding tilt correction (TC). (a, b). Representative orthogonal vector diagrams (Zijderveld, 1967) from OR13 and OR14. Closed (open) circles indicate the projection on the horizontal (vertical) plane. (c). Equal-area projections of the characteristic remanent magnetization (ChRM) distributions of sites OR13 and OR14 after bedding tilt correction. The open circles indicate their cone of confidence ( $\alpha_{95}$ ).

bedding strike. Following this presumption, if no differential vertical axis rotation has occurred between the sites of a folded sequence or area, the paleomagnetic directions can be restored by the intersection of the remanence small circles (Shipunov, 1997). This method can be applied not only to syn-folding, but also to pre-folding NRMs (Waldhör and Appel, 2006). The two new sites OR13 and OR14 we present in this paper come from north-dipping beds, allowing us to carry out a foldtest with best clustering of data at ~70% untilting using the foldtest of Tauxe and Watson (1994).

In this case, we can use the SCI method to restore the remagnetization direction. According to the geological record in the Organyà Basin, all sites in this study belong to the same overall fold structure. Thus, the local geological background fits the SCI criteria. In Fig. 4, we applied the SCI method to the transitional and remagnetized directions (29 sites) of the Organyà Basin. The bedding strikes range from 89° to 120° (except for two sites with northerly dips), and the remanence small circles are intersecting. Our restored paleomagnetic direction is  $D=316.8\pm5.7^\circ$ ,  $I=54.8^\circ\pm3.3$ , which is very close to the transitional direction (Prada C) in the Organyà Basin (Fig. 4).

# 5. Discussion

# 5.1. Bedding tilt of the Organyà Basin during remagnetization

Application of the SCI method to the remagnetized sites of the Organyà Basin shows that the best clustering of paleomagnetic directions almost coincides with the 100% tilt-corrected directions from the Prada C Formation. From this we can infer that the Prada C Formation was subhorizontal during remagnetization. However, the SCI results show that a full tilt correction of the remagnetized paleomagnetic directions obtained from older strata in the Organyà Basin gives an overcorrection to the south of approximately 10–20°, e.g. sites 49 and 58. From this we can infer that the older strata below Prada C were already mildly tilted to the south by approximately 10–20° when the remagnetization occurred. The same holds true for sites OR13 and OR14, suggesting a slight northward tilt in the north of the basin during remagnetization. It is plausible that this tilt relates to the early moderate



**Fig. 4.** Equal angle (Wulff net) projection of the small circles of the mean paleomagnetic directions in the Organyà Basin. Purple open dots (blue open stars) indicate the transitional (remagnetized) bedding tilt-corrected directions (see Table 1). The red dot ( $D=316.8^{\circ}$ ,  $l=54.8^{\circ}$ ,  $\alpha_{95}=3.3$ ) indicates the resulting paleomagnetic direction after applying the small circle intersection (SCI) method (Waldhör and Appel, 2006). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

extension history of the Organyà Basin in pre-Aptian time, which created a roll-over anticline due to motion along the normal fault which later became the Bòixols thrust. A comparable conclusion was recently reached for the bedding tilt during remagnetization in the Cabuérniga Basin by Soto et al. (2008).

#### 5.2. Timing of the Cretaceous remagnetization across Iberia

In the Organyà Basin, the paleomagnetic direction of the Prada C Formation (uppermost Barremian–lowermost Aptian) was reported as transitional between the remagnetized and non-remagnetized sequences. In the equal angle projection (Fig. 4), the transitional directions plot in a narrow range closer to the restored direction. The restored paleomagnetic field declination ( $D=316.8^{\circ}$ ) is virtually the same as the direction derived from the oceanic magnetic anomaly pattern at M0 (~317°) (Sibuet et al., 2004), which defined the beginning of the Iberian rotation at the base of the Aptian (Fig. 5). Meanwhile, the obtained inclination ( $I=54.8^{\circ}$ ) agrees as well with the APWPs of Iberia and Eurasia at the beginning of the Aptian (Besse and Courtillot, 2002; Gong et al., 2008b; Torsvik et al., 2008; Fig. 5).

The stratigraphy shows that the boundary between remagnetized and non-remagnetized rocks occurred at the beginning of intensive rifting at the Barremian/Aptian boundary (Fig. 2). Therefore, both the results from SCI method and geological evidence yield the same age for the timing of the remagnetization, which supports the approach of the SCI method. Thus, we can use the results from the SCI method applied to other Iberian basins by Soto et al. (2008) and Casas et al. (2009), where stratigraphic control at the age of the remagnetization is absent, to obtain the timing of their remagnetization by comparison of the restored remagnetized direction to the well defined Iberian APWP of Gong et al. (2008b).

Many paleomagnetic studies have reported on the widespread Iberian remagnetization during the Cretaceous (Galdeano et al., 1989; Moreau et al., 1992; Villalaín et al., 1994; Moreau et al., 1997; Juárez et al., 1998; Dinarès-Turell and García-Senz, 2000; Villalaín et al., 2003; Márton et al., 2004; Gong et al., 2008a; Soto et al., 2008; Casas et al., 2009). Based on the recent study from Gong et al. (2008b) which combined all the available paleomagnetic data sets in Iberia and oceanic magnetic anomaly data in the Bay of Biscay together, the APWP of Iberia was calculated: the pre-rotation direction is approximately 320/50° and the post-rotation direction is approximately  $360/50^{\circ}$  (Fig. 5). The Iberian rotation happened during the Aptian, ~35° CCW with respect to Eurasia (Gong et al., 2008b). Hence, for this study, we have a well defined APWP for Iberia. Meanwhile, recently the SCI method has been used to restore the paleomagnetic directions in the remagnetized sediments from the Cabuérniga Basin in the westernmost sector of the Basque-Cantabrian Basin (Soto et al., 2008) and Cameros Basin in the northwesternmost part of the Iberian Chain (Casas et al., 2009; Fig. 1). Both of these basins have a similar basin development history as the Organyà Basin. The preserved sediments in the Cabuérniga Basin were entirely remagnetized with a syn-tectonic secondary NRM: a SCI restored paleomagnetic direction of  $D = 335.4 \pm 5.2^{\circ}$ ,  $I = 49.1 \pm 3.4^{\circ}$  was obtained (Soto et al., 2008). Juárez et al. (1998) reported a Cretaceous remagnetization in two ranges of the inverted Mesozoic basins that presently form the Iberian Range. Here, two paleomagnetic components were resolved. A dual-polarity primary component from the Jurassic, giving a declination of  $326.8 \pm 5.3^\circ$ , comparable to the pre-rotation declination of Iberia (Gong et al., 2008b), and a remagnetized component with a direction  $D = 344.9 \pm 9.6^{\circ}$ ,  $I = 45.2 \pm 6.8^{\circ}$ . Indeed, Juárez et al. (1998) already concluded that part of the Iberian rotation had occurred between the acquisition of the primary and secondary component. The Cretaceous sediments in the Cameros Basin (Fig. 1) are also completely remagnetized (Villalaín et al., 2003). Application of the SCI method here gives a paleomagnetic direction of  $D = 359.0 \pm 6.7^{\circ}$ ,  $I = 51.5 \pm 4.2^{\circ}$  (Casas et al., 2009).



**Fig. 5.** The SCI based paleomagnetic directions (Organyà Basin, Cabuérniga Basin, Iberian Range and Cameros Basin) plot onto the APWP of Iberia of Gong et al. (2008b). The red stars indicate the mean directions after application of the SCI method: Organyà Basin ( $D = 316.8^\circ$ ,  $I = 54.8^\circ$ ,  $\alpha_{95} = 3.3^\circ$ ), Cabuérniga Basin ( $D = 335.4^\circ$ ,  $I = 49.1^\circ$ ,  $\alpha_{95} = 3.4^\circ$ ; Soto et al., 2008) and Cameros Basin ( $D = 359.0^\circ$ ,  $I = 51.5^\circ$ ,  $\alpha_{95} = 4.2^\circ$ ; Casas et al., 2009). The remagnetization direction for the Iberian Range ( $D = 344.9^\circ$ ,  $I = 45.2^\circ$ ,  $\alpha_{95} = 6.8^\circ$ ) did not require reconstruction through the SCI method, as it provided a positive foldtest (Juárez et al., 1998). Interpretational error boundaries of the ages of the remagnetization from the different locations are shown as different color shadings: pale orange (Organyà Basin), pale green (Cabuérniga Basin), pale purple (Iberian Range) and light blue (Cameros Basin). The Iberian rotation path (blue) is calculated: Tithonian–Barremian (pre-rotation:  $323.4^\circ/50.2^\circ \pm 9.7^\circ$ ); Albian–Campanian (post-rotation:  $357.5^\circ/47.1^\circ \pm 4.0^\circ$ ). The solid dots indicate the data used for APWP reconstruction by Gong et al. (2008b). Vertical error bars denote age uncertainty, horizontal error bars denote  $\Delta D (= \alpha_{95}/\cos(I))$  and  $\Delta I (= \alpha_{95})$ . The light yellow and orange shaded areas are the APWP for Eurosia from Besse and Courtillot (2002) and Torsvik et al. (2008), respectively. The purple asterisks give the declinations as derived from the sea-floor anomaly data from the Bay of Biscay (Srivastava et al., 2000; Sibuet et al., 2004) notably the M0 anomaly at the Barremian/Aptian boundary, and the A330 anomaly in the late Cretaceous. The geological time scale is from Ogg et al. (2004). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To explain the different remagnetization declinations reconstructed from these four basins in northern Iberia, two scenarios are possible: either these basins were all remagnetized at the same time, but rotated with respect to each other after the remagnetization event, or the remagnetization occurred at different moments during the rotation of Iberia.

The first explanation is not very likely. First of all, the paleomagnetic results from the Iberian Range (Juárez et al., 1998) give both the pre-rotation direction, and a remagnetized direction of 344.9°. The pre-Iberian rotation direction fits that of Iberia, i.e. no additional rotation is required to restore it. Therefore local (or regional) rotations with respect to Iberia after the remagnetization event are only remotely possible because the Jurassic pre-rotation direction would be affected as well by this postulated rotation, something which is not observed. If all remagnetizations were synchronous, the remagnetization declinations of the other basins should coincide with the overprint direction of the Iberian Range in the absence of later differential rotations amongst the basins. Now we turn to the Organyà Basin, which provides a remagnetized direction as well as non-remagnetized directions. The latter recorded the Iberian rotation during sedimentation (Gong et al., 2008a,b). The remagnetized direction in Organyà Basin virtually coincides with the oldest non-remagnetized direction. The remagnetizations in the Organyà Basin and the Iberian Range therefore cannot have been synchronous.

If the Cameros and Cabuérniga Basins were remagnetized together with either the Organyà Basin or the Iberian Range, they would have rotated after the remagnetization. The Cameros Basin would have rotated clockwise over ~35° or ~15°, respectively, and the Cabuérniga basin over ~15° counter-clockwise or ~15° clockwise, respectively. The remagnetization directions from these basins are based on a large number of sites spanning a considerable areal extent within these basins, which precludes intra-basinal rotation differences. Therefore, if rotated, these basins should have rotated as a whole with respect to Iberia. We consider this scenario less likely for reasons outlined below.

The Cameros Basin is bounded in the north by a >50 km long, roughly E–W trending thrust, which forms a décollement below the basin (Casas et al., 2009). Because there are no major sidewall ramps or intra-basinal strike-slip discontinuities reported, a ~35° or even only ~15° of clockwise rotation of this basin over the décollement would require a lateral displacement difference between the eastern and western part of the thrust of several tens of kilometers, which is an order of magnitude larger than the displacements reconstructed by Casas et al. (2009). Likewise, there is no structural argument in the internally just mildly deformed Cabuérniga Basin to suspect a lateral displacement difference of ~10 km along the Cabuérniga thrust bounding the basin to the north (Soto et al., 2008).

A synchronous remagnetization in all basins is therefore not very likely, if not impossible. The alternative, however, seems more appropriate: all remagnetized directions can be straightforwardly explained by separate, basin-restricted remagnetization events which have occurred during the rotation of Iberia (Fig. 5). Using the Iberian APWP of Gong et al. (2008b), the timing of these remagnetization events can be estimated. Our new data show that the lower part of the Organyà Basin stratigraphy was remagnetized at the onset of the Iberian rotation, i.e. around the Barremian–Aptian boundary. The remagnetized direction of the Cabuérniga Basin reported by Soto et al. (2008) suggests an early to middle Aptian age of remagnetization. The overprint direction reconstructed from the Iberian Range by Juárez et al. (1998) suggests a middle–late Albian remagnetization, and finally, the Cameros Basin must have been remagnetized after the Iberian rotation, i.e. post-Aptian, but before Pyrenean compression (Casas et al., 2009).

#### 5.3. Implications for remagnetization mechanism

The Cretaceous evolution of Iberia is related to the opening of the Bay of Biscay and North Atlantic Ocean, and Iberia was mainly in a lithospheric stretching regime. The Iberian remagnetization was thus loosely linked to an elevated geothermal regime due to the extensional tectonics (e.g. Juárez et al., 1998; Márton et al., 2004). Here we assemble available information basin by basin.

In the Organyà Basin, the remagnetization occurred exactly at the beginning of the intensive rifting. As a remagnetization mechanism, thermoviscous resetting was excluded because the burial temperature of ~150 °C is too low (Gong et al., 2008a). In the CRM model, burial essentially without external fluid is considered to be the most likely remagnetization mechanism in the elevated geothermal gradient regime during the syn-rift extension (Gong et al., 2008a).

In the Cabuérniga Basin, Soto et al. (2008) pointed out that the remagnetization is related to the basin extension when a high level of subsidence was reached because of thick syn-rift deposits (that have been eroded since). Further details were not provided. Because the remagnetization is syn-rotational, its duration (a few Myr only) is too

short for thermoviscous resetting being a viable option. Therefore, we consider a CRM most probably for this basin.

In the Iberian Range, Juárez et al. (1998) argue that the remagnetization could well have been caused by a thermoviscous process related to the thermal event(s). However, their data do not make this argument entirely clear and a chemical origin of the remagnetization cannot be excluded (as actually realized by authors). Juárez et al. (1998) favoured the TVRM model in the absence of a precise Cretaceous APWP for Iberia which left the whole Cretaceous Superchron available for remagnetization, with indeed sufficient time for TVRM acquisition. The age of their remagnetization is now much narrower constrained to the late Aptian being syn-rotational. Therefore, the originally suggested TVRM model is unlikely in this part of the Iberian Range and a CRM remagnetization model related to the thinner lithosphere during the rotation is a plausible alternative.

In the Cameros Basin, the remagnetization (Villalaín et al., 2003) is suggested between the Albian and Santonian, the ages of the extensional and compressional deformation stages. Villalaín et al. (2003) prefer to relate the remagnetization that resides in hematite to the Albian, early in the possible window. The syn-rift deposits (Kimmeridgian to Early Albian; fluvial and lacustrine sandstones, siltstones and shales, at least 4 km thick) in the Cameros Basin underwent low-grade thermal metamorphism; isotopic dating of illite vields an age around 100 Ma (between 86 and 108 Ma) for the peak conditions (Goldberg et al., 1988; Casquet et al., 1992) that post-dates the extensional phase. It is also younger than cleavage-related folding because of textural relationships of the metamorphic minerals (Mata et al., 2001). The maximum temperature was 350 °C in the deepest buried rocks (uniquely high for the Iberian Chain) that were at a low pressure of <2 kbar, Mata et al., 2001). The geothermal gradients are calculated to be 27-41 °C/km for the extensional stage and 70 °C/km during the thermal peak (Mata et al., 2001). Fluid inclusions in quartz veins point to a local, within basin scale, origin of the fluid (Mata et al., 2001). While the hematite is either formed or recrystallized during the metamorphism, it is unlikely that the remagnetization is thermoviscous because the available temperature-time period is too short to explain the maximum unblocking temperatures observed in the hematite. Indeed Villalaín et al. (2003) relate the remagnetization to subsidence-first mainly tectonic and later also thermal-in an elevated geothermal gradient regime in a stretched lithosphere. This situation is feasible since Iberia was moving eastward with respect to stable Europe as a consequence of the opening of the Atlantic Ocean.

The present study shows that although the remagnetization in the four basins occurred at different times, they are all somehow related to the rifting phase in their geological history, in line with other remagnetizations found in Iberian sedimentary basins formed under basinal rifting (Galdeano et al., 1989; Moreau et al., 1992, 1997; Márton et al., 2004). Under syn-rift and early post-rift conditions an elevated geothermal regime prevails. It is the interplay of the geothermal gradient and burial depth that determines when the diagenetic reactions set in that result in the remagnetization. In Iberia this has led to a mozaic of remagnetized basins without a clear regional trend. Because of their distinct timing a single Iberia-wide mechanism can now be excluded and mechanisms that operate on a basin scale are favoured. We envisage that the approach applied here can be utilized elsewhere to constrain the remagnetization timing and mechanism where remagnetization can be broadly related to rotation of (micro)plates.

# 6. Conclusions

To determine the timing of the regional Cretaceous remagnetizations in northern Iberia, we provide new data from the Organyà Basin, where both the age and the corresponding paleomagnetic direction of the remagnetization are well-established. To this end, we apply the small circle intersection (SCI) method, and restore a direction of  $D/I=316.8\pm5.2^{\circ}/54.8\pm3.3^{\circ}$  closely corresponding to a recently improved apparent polar wander path (APWP) of Iberia. We also compare previously published results from three other basins—the Cabuérniga and Cameros Basins and the Iberian Range—to the APWP of Iberia. We draw the following conclusions:

- Application of the SCI method allows us to show that most of the remagnetized beds of the Organyà Basin were already tilted by ~15-20° as a result of half-graben formation starting prior to remagnetization.
- 2. Each of the four remagnetized basins provides a different paleomagnetic direction during remagnetization and, therefore, each basin acquired its remagnetization at different moments. Comparison of these directions to the Iberian APWP shows that the remagnetizations occurred at the onset of, during, and at the end of, or after the Iberian rotation in Aptian to early Albian times.
- The remagnetization events were—albeit occurring on a regional scale over a period of at least ~10–15 Myr—confined to these individual sedimentary basins.
- 4. Although the remagnetization in all four locations occurred at the different times, they are all temporally related to the rifting phase in their geological history. The Cretaceous Iberian remagnetization events in northern Iberia are hence temporally related to the extensional tectonics.
- 5. Existing explanations for remagnetization that can occur on the scale and within the context of sedimentary basins, including elevated temperatures during diagenesis and circulating basin fluids may therefore be the most reasonable explanations. There is no need to infer more speculative Iberia-wide mechanisms.

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#### References

- Becker, E., 1999. Orbitoliniden-Biostratigraphie der Unterkreide (Hauterive-Barrême) in den spanischen Pyrenäen (Profil Organyà, Prov. Lérida). Revue de Paléobiologie 18, 359–489.
- Bernaus, J.M., 2000, L'Urgonien du Bassin d'Organyà (NE de l'Espagne): micropaléontologie, sédimentologie et stratigraphie séquentielle. Géologie Alpine; Memoir Hors Serie Laboratoire de géodynamique des chaînes alpines de l'Université Joseph Fourier, 138 p.
- Bernaus, J.M., 2003. Carbonate platform sequence stratigraphy in a rapidly subsiding area: the Late Barremian–Early Aptian of the Organya basin, Spanish Pyrenees. Sediment. Geol. 159, 177–201.
- Bernaus, J.M., Arnaud-Vanneau, A., Caus, E., 1999. La sedimentación "Urgoniense" en la cuenca de Organyà (NE España). Libro homenaje a José Ramírez del Pozo. De Geol. Y Geofis. Españoles del Petróleo 71–80 AGGEP.
- Bernaus, J.M., Caus, E., Arnaud-Vanneau, A., 2000. Aplicación de los análisis micropaleontológicos cuantitativos en estratigrafía secuencial: El Cretácico inferior de la cuenca de Organyà (Pirineos, España). Rev. Soc. Geol. Esp. 13, 55–63.
- Besse, J., Courtillot, V., 2002. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr. J. Geophys. Res. 107, 2300. doi:10.1029/ 200018000050.
- Blumstein, A.M., Elmore, R.D., Engel, M.H., Elliot, C., Basu, A., 2004. Paleomagnetic dating of burial diagenesis in Mississippian carbonates, Utah. J. Geophys. Res. 109, B04101. doi:10.1029/2003JB002698.
- Bond, R.M.G., McClay, K.R., 1995. Inversion of a Lower Cretaceous extensional basin, south central Pyrenees, Spain. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin Inversion: Geol. Soc. Spec. Publ., vol. 415–431, p. 88.
- Bullard, E., Everett, J., Gilbert Smith, A., 1965. A symposium on continental drift. Philos. Trans. R. Soc. Lond. Ser. A 258, 41–51.
- Cande, S.C., Kent, D.V., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and the Cenozoic. J.Geophys. Res. 100, 6093–6095.
- Carey, S.W., 1958. A tectonic approach to continental drift. In: Carey, S.W. (Ed.), Continental Drift. A Symposium, vol. 177–355. Hobart, Tasmania.
- Casas, A.M., Villalaín, J.J., Soto, R., Gil-Imaz, A., del Río, P., Fernàndez, G., 2009. Multidisciplinary approach to an extensional syncline model for the Mesozoic Cameros Basin (N Spain). Tectonophysics v. 407 (iss. 1–2), 3–20.

- Casquet, A., Galindo, C., González-Casado, J.M., Alonso, A., Mas, R., Rodas, M., García, E., Barrenechea, J.F., 1992. El metamorfismo en la cuenca de los Cameros. Geocronologíae implicaciones tectónicas. Geogaceta 11, 22–25.
- Dinarès-Turell, J., García-Senz, J., 2000. Remagnetization of Lower Cretaceous limestones from the southern Pyrenees and relation to the Iberian plate geodynamic evolution. J. Geophys. Res. 105, 19405–19418.
- Elmore, R.D., Dulin, S., Engel, M.H., Parnell, J., 2006. Remagnetization and fluid flow in the
- Old Red Sandstone along the Great Glen Fault, Scotland. J. Geochem. Explor. 89, 96–99. Enkin, R.J., 2003. The direction-correction tilt test: an all-purpose tilt/fold test for paleomagnetic studies. Earth Planet. Sci. Lett. 212, 151–166.
- Enkin, R.J., Mahoney, J.B., Baker, J., Kiessling, M., Haugerud, R.A., 2002. Syntectonic remagnetization in the southern Methow block: resolving large displacements in the southern Canadian Cordillera. Tectonics 21 ISI:000179018800001.
- Evans, M.A., Lewchuk, M.T., Elmore, R.D., 2003. Strain partitioning of deformation mechanisms in limestones: examining the relationship of strain and anisotropy of magnetic susceptibility (AMS). J. Struct. Geol. 25, 1525–1549.
- Fisher, R.A., 1953. Dispersion on a sphere. Proc. R. Soc. Lond. A217, 295-305.
- Galdeano, A., Moreau, M.G., Pozzi, J.P., Berthou, P.Y., Malod, J.A., 1989. New Paleomagnetic results from Cretaceous sediments near Lisbon (Portugal) and implications for the rotation of Iberia. Earth Planet. Sci. Lett. 92, 95–106.
- García-Senz, J., 2002, Cuencas extensivas del Cretacico Inferior en los Pireneos Centrales formacion y subsecuente inversion [PhD thesis]: Barcelona, University of Barcelona.
- Goldberg, J.M., Guiraud, M., Maluski, H., Séguret, M., 1988. Caractères pétrologiques etâge du métamorphisme en contexte distensif du bassin sur décrochement de Soria Crétacéinférieur, Nord Espagne). C. R. Acad. Sci., Paris 307, 521–527.
- Gong, Z., Dekkers, M.J., Dinarès-Turell, J., Mullender, T.A.T., 2008a. Remagnetization mechanism of Lower Cretaceous rocks from the Organyà Basin (Pyrenees, Spain). Stud. Geophis. Geod. 52, 187–210.
- Gong, Z., Langereis, C.G., Mullender, T.A.T., 2008b. The rotation of Iberia during the Aptian and the opening of the Bay of Biscay. Earth Planet. Sci. Lett. 273, 80–93.
- Gong, Z., van Hinsbergen, D.J.J., Vissers, R.L.M., Dekkers, M.J., 2009. Early Cretaceous synrotational extension in the Organyà basin–New constraints on the palinspastic position of Iberia during its rotation. Tectonophysics 473, 312–323.
- Juárez, M.T., Lowrie, W., Osete, M.L., Meléndez, G., 1998. Evidence of widespread Cretaceous remagnetisation in the Iberian Range and its relation with the rotation of Iberia. Earth Planet. Sci. Lett. 160, 729–743.
- Katz, B., Elmore, R.D., Cogoini, M., Ferry, S., 1998. Widespread chemical remagnetization: Orogenic fluids or burial diagenesis of clays? Geology 26, 603–606.
- Katz, B., Elmore, R.D., Cognoini, M., Engel, M.H., Ferry, S., 2000. Associations between burial diagenesis of smectite, chemical remagnetization, and magnetite authigenesis in the Vocontian trough, SE France. J. Geophys. Res. 105, 851–868.
- Kent, D., 1985. Thermoviscous remagnetization in some Appalachian limestones. Geophys. Res. Lett. 12, 805–808.
- Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophys. J. R. Astrol. Soc. 62, 699–718.
- Machel, H.G., Cavell, P.A., 1999. Low-flux, tectonically-induced squeegee fluid flow ("hot flash") into the Rocky Mountain Foreland Basin. Bull. Can. Pet. Geol. 47, 510–533.
- Márton, E., Abranches, M.C., Pais, J., 2004. Iberia in the Cretaceous: new paleomagnetic results from Portugal. J. Geodyn. 38, 209–221.
- Mata, M.P., Casas, A., Cil, A., Pocovi, P., 2001. Thermal history during Mesozoic extension and Tertiary uplift in the Cameros Basin, northern Spain. Basin Res. 13, 91–111.
- McCabe, C., Elmore, R.D., 1989. The occurrence and origin of Late Paleozoic remagnetization in the sedimentary rocks of North America. Rev. Geophys. 27, 471–494.
- McCabe, C., Van der Voo, R., Peacor, D.R., Scotese, C.R., Freeman, R., 1983. Diagenetic magnetite carries ancient yet secondary remanence in some Paleozoic sedimentary carbonates. Geology 11, 221–223.
- Moreau, M.G., Canerot, J., Malod, J.A., 1992. Paleomagnetic study of Mesozoic sediments from the Iberian Chain (Spain). Suggestions for Barremian remagnetization and implications for the rotation of Iberia. Bull. Soc. Geol. Fr. 163, 393–402.
- Moreau, M.G., Berthou, J.Y., Malod, J.-A., 1997. New paleomagnetic Mesozoic data from the Algarve (Portugal): fast rotation of Iberia between the Hauterivian and the Aptian. Earth Planet. Sci. Lett. 146, 689–701.
- Morris, A., Robertson, A.H.F., 1993. Miocene remagnetisation of carbonate platform and Antalya Complex units within the Isparta Angle, SW Turkey. Tectonophysics 220, 243–266.
- O'Brien, V.J., Moreland, K.M., Elmore, R.D., Engel, M.H., Evans, M.A., 2007. Origin of orogenic remagnetizations in Mississippian carbonates, Sawtooth Range, Montana. J. Geophys. Res. 112, B06103. doi:10.1029/2006JB004699.
- Ogg, J.G., Agterberg, F.P., Gradstein, F.M., 2004. The Cretaceous period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), A Geologic Time Scale 2004. InCambridge University Press, pp. 344–383.
- Oliver, J., 1986. Fluids expelled tectonically from orogenic belts: their role in hydrocarbon migration and other geologic phenomena. Geology 14, 99–102.
- Shipunov, S.V., 1997. Synfolding magnetizations: detection, testing and geological applications. Geophys. J. Int. 130, 405–410.
- Sibuet, J.C., Srivastava, S.P., Spakman, W., 2004. Pyrenean orogeny and plate kinematics. J. Geophys. Res. 109, B08104. doi:10.1029/2003JB002514.
- Soto, R., Villalaín, J.J., Casas-Sainz, A.M., 2008. Remagnetizations as a tool to analyze the tectonic history of inverted sedimentary basins: a case study from the Basque– Cantabrian basin (north Spain). Tectonics 27, TC1017. doi:10.1029/2007TC002208.
- Srivastava, S.P., Roest, W.R., Kovacs, L.C., Oakey, G., Levesque, S., Verhoef, J., Macnab, R., 1990. Motion of Iberia since the Late Jurassic: results from detailed aeromagnetic measurements in the Newfoundland Basin. Tectonophysics 184, 229–260.
- Srivastava, S.P., Sibuet, J.C., Cande, S., Roest, W.R., Reid, I.D., 2000. Magnetic evidence for slow seafloor spreading during the formation of the Newfoundland and Iberian margins. Earth Planet. Sci. Lett. 182, 61–76.

Tauxe, L., Watson, G.S., 1994. The fold test: an eigen analysis approach. Earth Planet. Sci. Lett. 122, 331–341.

- Torsvik, T.H., Müller, R.D., Van der Voo, R., Steinberger, B., Gaina, C., 2008. Global plate motion frames: toward a unified model. Rev. Geophys. 41, RG3004. doi:10.1029/ 2007RG000227.
- Van der Voo, R., 1967. The rotation of Spain: palaeomagnetic evidence from the Spanish Meseta. Palaeogeogr. Palaeoclimatol. Palaeoecol. 3, 393–416.
- Van der Voo, R., 1969. Paleomagnetic evidence for the rotation of the Iberian Peninsula. Tectonophysics 7, 5–56.
  Vergés, J., Fernàndez, M., Martínez, A., 2002. The Pyrenean orogen: pre-, syn-, and post-
- collisional evolution. J. Virtual Explorer 8, 57–76.
- Villalaín, J.J., Osete, M.L., Vegas, R., García-Duenas, V., Heller, F., 1994. Widespread Neogene remagnetization in Jurassic limestones of the Southern-Iberian palaeomargin (Western Betics, Gibraltar Arc). Phys. Earth Planet. Inter. 85, 15–33.
- Villalaín, J.J., Fernandez-Gonzalez, G., Casas, A.M., Gil-Imaz, A., 2003. Evidence of a Cretaceous remagnetization in the Cameros Basin (North Spain): implications for basin geometry. Tectonophysics 377, 101–117.
- Waldhör, M., Appel, E., 2006. Intersections of remanence small circles: new tools to improve data processing and interpretation in palaeomagnetism. Geophys. J. Int. 166, 33–45.
- Zijderveld, J.D.A., 1967. A.C. demagnetisation of rocks: analysis of results. In: Collinson, D.W., et al. (Ed.), Methods in Palaeomagnetism. InElsevier, Amsterdam, pp. 254–286.