Remagnetization of Lower Cretaceous limestones from the southern Pyrenees and relation to the Iberian plate geodynamic evolution

Jaume Dinarès-Turell[1]

Paleomagnetic Laboratory, Fort Hoofddijk, Utrecht, Netherlands

Jesús García-Senz

Departament de Geodinàmica i Geofísica, Universitat de Barcelona, Barcelona, Catalonia, Spain

Abstract. Paleomagnetic study (34 sites) of thick Cretaceous ~5000 m marine carbonate strata from the Organyà Basin (OB) in the southern Pyrenees reveals a uniformly normal polarity characteristic remanence with varying declination (*D*) (Berriasian-Barremian, $D = 295^{o}$; Aptian-Albian, $D = 348^{o}$, upper Cretaceous, $D = 354^{o}$) that resides in magnetite and predates Late Cretaceous/Tertiary folding. The lack of reverse polarity magnetizations in the Berriasian-Barremian series, together with their distinct hysteresis properties that are typical of remagnetized carbonates elsewhere, are taken as evidence for a secondary overprint in the lower part of the succession. A hypothesized age of remagnetization near the Barremian/Aptian boundary fits with a major tectosedimentary event in the basin that changed deposition from platform to basinal conditions and increased subsidence during the Aptian. The angular difference (~53^{o}) between declination from the remagnetized strata and the mean for Aptian-Albian strata indicates that a counterclockwise rotation occurred between the two acquisition times. Part of this rotation is interpreted to be local and due to slip variation along strike of a normal fault that bounded the basin and tilted the pre Aptian series. This Cretaceous extensive phase is framed in the rift evolution of the northern margin of the Iberian plate. The inferred remagnetization age within the OB falls within the range of previously inferred widespread Cretaceous remagnetization events affecting the Iberian plate. In the OB, remagnetization is speculated to have taken place through chemical (burial diagenetic) origin rather than simple thermoviscous resetting.

1. Introduction

It has always been critical in paleomagnetic research to accurately assign ages to the different magnetization components identified in progressive demagnetization. This aspect has acquired paramount importance since it has become clear in the last 20 years that many rocks can acquire geologically stable, secondary yet ancient, magnetizations that post-date the absolute or biostratigraphic age of the rock [e.g., *Kent*, 1979, 1985; *Scotese et al.*, 1982; *McCabe et al*., 1983]. A prominent example has been the recognition that sedimentary rocks over a large part of North America (and Europe) were remagnetized during the Pennsylvanian and Permian periods (the well-known late Paleozoic remagnetization “event” in the Appalachian orogen) (see *McCabe and Elmore* [1989] for a review).

Many paleomagnetic studies of different rock units from the Iberian Peninsula are suggestive of remagnetization processes, although the ages and inferred mechanisms appear to be different [*Schott,* 1985*; Schott and Peres*, 1987; *Galdeano et al.*, 1989; *Moreau et al*., 1992; *Villalaín et al*., 1994; *Juárez et al*., 1994, 1996, 1998; *Parés and Roca*, 1996]. Most studies report the existence of a Cretaceous remagnetization, dated either by the biostratigraphic age of the rocks studied [*Galdeano et al*., 1989; *Moreau et al*., 1992], or inferred by comparison with the Iberian apparent polar wander path (APWP) [*Juárez et al*., 1994, 1996, 1998]. The Cretaceous APWP for Iberia, however, is only poorly determined, and well-defined paleomagnetic data are required to quantify the Mesozoic counterclockwise rotation of the Iberian Peninsula, which is related to the opening of the North Atlantic and the Bay of Biscay. This major geodynamic feature is documented through paleomagnetic studies [e.g., *Van der Voo*, 1967, 1969] and oceanic magnetic anomalies [e.g., *Srivastava et al*., 1990]. It is essential, however, that paleomagnetic directions are obtained from tectonically stable areas of Iberia and that good magnetic age control is available (especially for secondary remanences). It is worth pointing out that data from contractional belts (i.e., thrusted units within the alpine orogens) might still be useful if relative vertical axis rotations of the different stratigraphic units from a given homogeneous tectonic block are documented. The relative angular variations of declination are independent of younger emplacement-related rotations and may be extrapolated/compared with data from the “stable” areas.

The present study reports on the paleomagnetic and rock-magnetic signature of a thick (~5000 m) Cretaceous series that crops out in the Bóixols thrust sheet from the southern Pyrenees. The study is a follow-up of an extensive magnetotectonic research project carried out in the south Pyrenean Upper Thrust Sheets that provided directional information for the Aptian-Albian (16 sites) and Upper Cretaceous (4 sites) series from the Bóixols unit [*Dinarès-Turell*, 1992; *Dinarès-Turell et al*., 1991]. The study has now been extended to the Berriasian-Barremian series (14 sites), and we have completed rock-magnetic investigations for the entire Cretaceous series in order to tackle the problems outlined above. We document both the existence of an Early Cretaceous remagnetization that affected part of the series, and subsequent counterclockwise rotation, which has implications for the Iberian Mesozoic geodynamic scenario.

[1]Now at Istituto Nazionale di Geofisica, Rome, Italy.

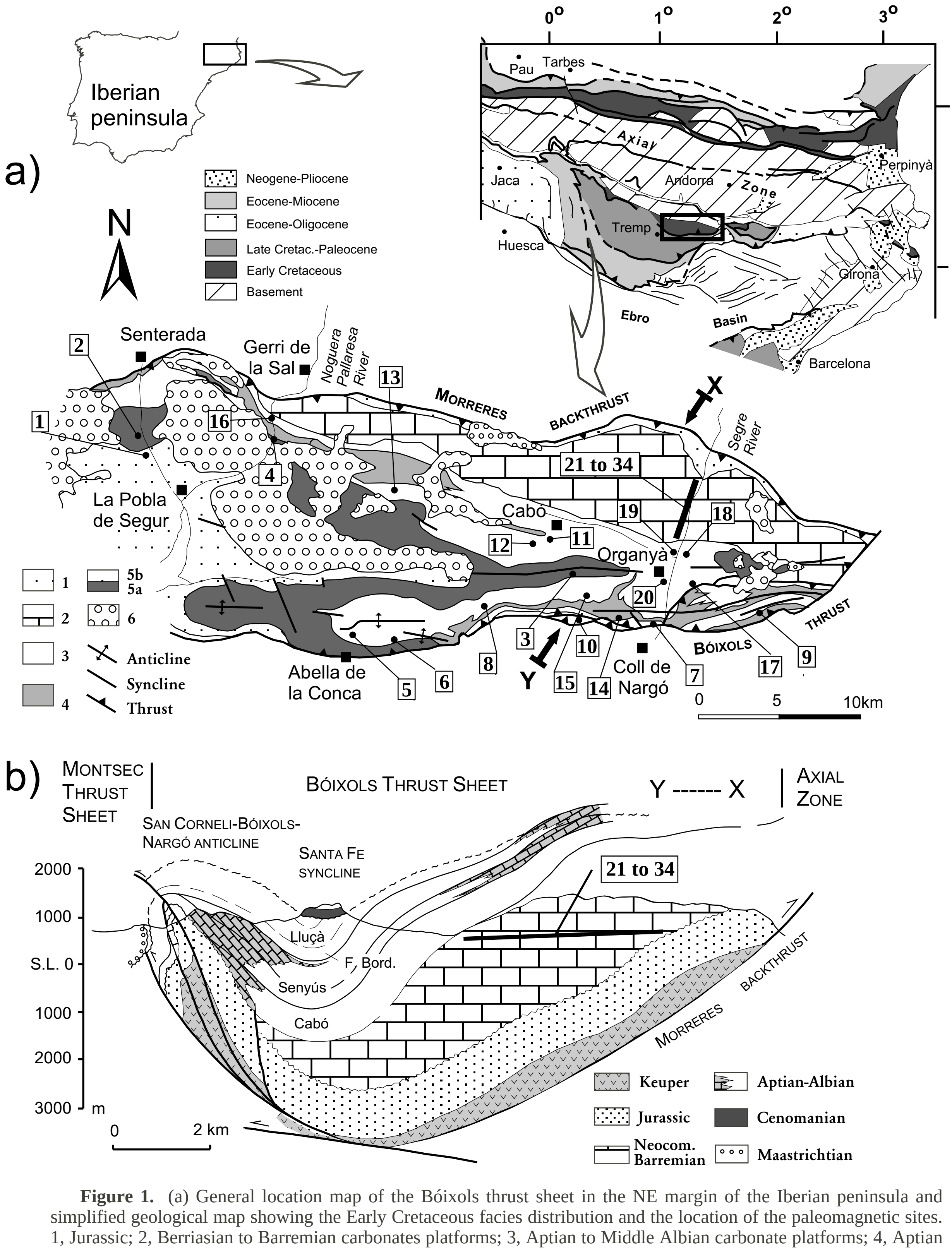

Figure 1. (a) General location map of the Bóixols thrust sheet in the NE margin of the Iberian peninsula and simplified geological map showing the Early Cretaceous facies distribution and the location of the paleomagnetic sites. 1, Jurassic; 2, Berriasian to Barremian carbonates platforms; 3, Aptian to Middle Albian carbonate platforms; 4, Aptian to Middle Albian slope and basinal marls; 5, Upper Cretaceous post-rift sequences (5a, stable platform deposits; 5b, Flysch deposits); 6, Upper Eocene to Oligocene conglomerates. (b) Cross section with location of the Berriasian-Barremian sites. The Aptian-Albian and Upper Cretaceous sites are located at the different limbs of the Sant Corneli-Bóixols-Nargó anticline and Santa Fè syncline along the strike of this cross section (modified from *García-Senz et al.* [1995]).

2. Geologic Setting

The Organyà Basin (OB) is a west-east trending graben over 80 km long and up to 15 km wide, filled with 4500 m of Lower Cretaceous sedimentary rocks. It forms part of a system of Mesozoic basins linked to the evolution of the North Atlantic margin. The OB was formed upon a substratum of Hercynian basement with a cover of Stefanian, Permian, Triassic and Jurassic sediments. During the Alpine orogeny, part of the sedimentary cover was detached and involved into the South Pyrenean Upper Thrust Sheets [*Muñoz*, 1991]. The southern margin of the graben is inverted in the frontal part of the Bóixols thrust sheet as a footwall short cut and related hangingwall folds [*Bond and McClay*, 1995]. The northern exposures coincide with a passive-roof backthrust located in the contact with the Axial zone antiformal stack (Figure 1). To the east the Bóixols thrust is cut by the Segre oblique thrust, which was active during the Early Oligocene as an out-of-sequence thrust [*Vergés*, 1993].

Chronostratigraphy for the Lower Cretaceous series is based on ammonites, planktonic and benthic (chiefly orbitolinids) foraminifera together with calpionellids and indicates an Early Tithonian-Late Berriasian age for the lower part of the section (N1a unit, Figure 2) up to the middle Albian for the Coll d'Abella limestones (Figure 2) [*Peybernès*, 1976; *Caus et al.*, 1990; *Martínez*, 1982; *Schwenke*, 1993; *Bernaus*, 1995; *García-Senz et al.*, 1995]. The chronostratigraphy of the Upper Cretaceous strata is based primarily on planktonic foraminifera [*Gómez-Garrido*, 1987] and ammonite biostratigraphy [*Martínez*, 1982]. The development and subsequent inversion of the Organyà Basin can be summarized in four phases.

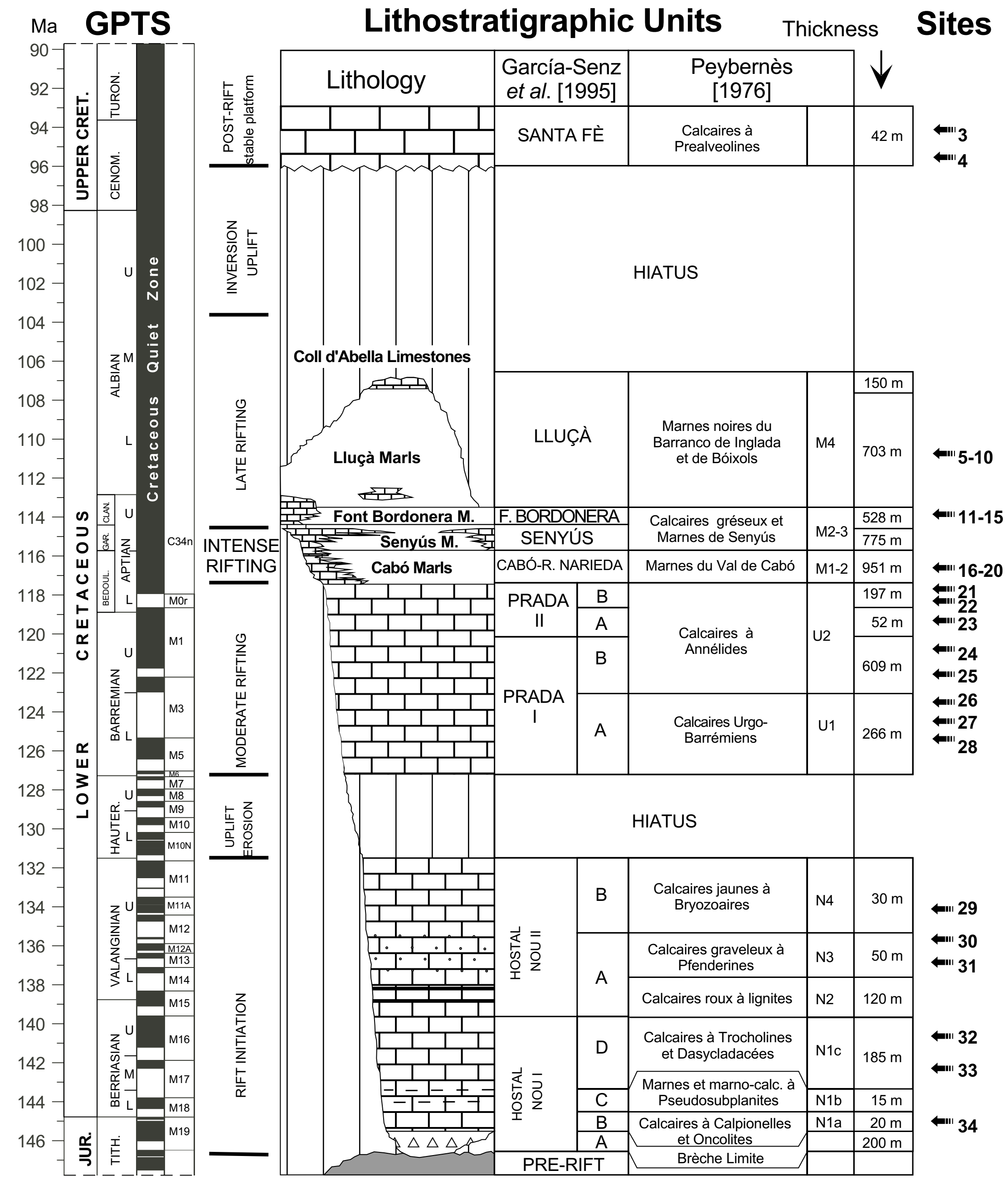

Figure 2. Stratigraphic scheme of the Organyà Basin showing the different tectonostratigraphic stages and location of the paleomagnetic sites (Table 1). geomagnetic polarity time scale (GPTS) is from *Ogg* [1995]. The uppermost sites 1 and 2 (not shown) are located in the Upper Cretaceous Anserola (Coniacian-Santonian) and Reguard (Cenomanian-Turonian) Formations, respectively, corresponding still to chron C34n.

2.1. Extensional Basin (Berriasian-Middle Albian)

The graben formed in the hangingwall of a major south bounding fault oriented E-W. In transversal section the basin margin was monoclinally flexed at the fault tip, as proved by the onlap and tilting toward the basin of the Aptian sequences. The displacement of the fault dies-out westward along strike, linking to an oblique NW-SE transfer zone located near La Pobla de Segur. Four distinct infilling phases are recorded.

2.1.1. Berriasian-Valanginian sequence. The onset of rifting is marked by a major unconformity close to the Tithonian-Berriasian boundary. The Jurassic platform became emergent and was deeply eroded in the footwalls of the basin-forming faults. Initial breccias shed from fault scarps are overlain by open marine carbonates and shales, with a shallowing-up evolution (Hostal Nou I sequence) (Figure 2). Valanginian deposition is characterized by condensed parasequences in restricted marine nvironments (Hostal Nou II sequence). This phase of "early extension" ended with an important unconformity extending from the Late Valanginian to the Hauterivian.

2.1.2. Barremian-lower Aptian sequence. The Barremian stratigraphy is overall characterized by shallow carbonates with a transgressive-regressive evolution (Prada I and Prada II sequences) (Figure 2).

2.1.3. Bedoulian-Gargasian sequence. A fundamental change in deposition occurred close to the Barremian/Aptian boundary. The area occupied by the Barremian platform became basinal in a facies sense, with accumulation of hemipelagic marls and black shales that indicate an increase in bathymetry (Cabó and Senyús Formations). This transgressive cycle is related to the acceleration in slip along the major southern boundary fault. After the tilting maxima the basin was progressively filled at sea level, with no signs of active faulting, ending the sequence with a widespread regression.

2.1.4. Clansayesian-Middle Albian sequence. Black shales and hemipelagic marls make up most of the succession (Font Bordonera and Lluçà Formations). The top of the sequence is eroded under the Cenomanian unconformity (Figure 2).

2.2. Cenomanian Inversion

Up to 3000 m of Lower Cretaceous strata were removed before the mid to Late Cenomanian as consequence of contraction oblique to the graben boundaries that gently folded the synrift package.

Table 1. Paleomagnetic Sites

Original Site	Site[a]	Grid Reference[b]	Unit/Formation	Age	Lithology[c]	Strike/Dip[d]
			Upper Cretaceous			
JDT43	1	4683.4/330.3	Anserola	Coniacian-Santonian	dark M	115/70
JDT44	2	4684.5/330.2	Reguard	Cenomanian-Turonian	dark L	112/44
JDT34	3	4674.4/355.8	Santa Fe	Cenomanian	light L	272/32
JDT42	4	4682.8/337.9	Santa Fe	Cenomanian	dark L	109/62
			Lower Cretaceous (Aptian-Albian)			
JDT24	5	4669.9/342.6	Lluçà	Aptian-Albian	dark M and ML	064/86
JDT27	6	4670.1/346.0	Lluçà	Aptian-Albian	dark M	069/36
JDT30	7	4671.2/361.1	Lluçà	Aptian-Albian	dark M and ML	045/127
JDT36	8	4672.2/350.8	Lluçà	Aptian-Albian	dark M	263/40
89J3	9	4671.1/364.3	Lluçà	Aptian-Albian	dark M	263/80
89J26	10	4671.2/358.0	Lluçà	Aptian-Albian	dark M	086/140
JDT38	11	4676.1/353.6	Font Bordonera	Aptian	dark M	103/44
JDT39	12	4675.8/353.6	Font Bordonera	Aptian	dark M	095/30
JDT40	13	4679.0/346.0	Font Bordonera	Aptian	dark M	111/35
89J1	14	4671.2/359.3	Font Bordonera	Aptian	dark M	123/123
89J2	15	4673.1/355.9	Font Bordonera	Aptian	dark M	258/28
JDT41	16	4683.7/338.2	Cabó	Aptian	dark M	133/37
89J4	17	4673.8/363.8	Cabó	Aptian	dark M	237/72
89J5	18	4676.0/364.8	Cabó	Aptian	dark M	134/38
89J7	19	4676.2/362.6	Cabó	Aptian	dark M	113/53
89J10	20	4673.8/362.0	Cabó	Aptian	dark M	201/17
			Lower Cretaceous (Neocomian-Barremian)			
97J12	21 (10)	4676.3/362.7	Prada II	Barremian-Aptian?	dark L	120/67
97J11	22 (10)	4676.5/362.8	Prada II	Barremian-Aptian?	dark M and L	104/62
89J8+97J10	23	4676.6/362.9	Prada II	Barremian-Aptian?	dark L	100/60
98J6	24	4676.7/363.3	Prada I	Barremian	dark L	104/55
98J5	25	4676.8/363.4	Prada I	Barremian	dark L	120/50
97J9	26	4677.0/363.5	Prada I	Barremian	dark L	114/58
97J8	27	4677.1/363.5	Prada I	Barremian	dark L	110/45
98J4	28	4677.5/363.4	Prada I	Barremian	dark L	110/50
97J7	29 (18)	4677.7/363.5	Hostal Nou II	Valanginian	dark L	116/59
89J9	30 (10)	4677.8/363.5	Hostal Nou II	Valanginian	dark L	116/51
97J6	31 (40)	4677.9/363.5	Hostal Nou II	Valanginian	dark M and L	113/60
97J2	32	4678.4/363.3	Hostal Nou I	Berriasian	dark L	109/53
97J1	33 (50)	4679.9/361.3	Hostal Nou I	Berriasian	dark L	102/53
98J1	34 (10)	4678.7/363.5	Hostal Nou I	Berriasian	dark L	119/42

[a] Site code as referred in this paper (stratigraphic thickness in meters is indicated in parentheses when site encompasses 10 m or more).
[b] Grid reference from the 1:50,000 scale Spanish topographic maps.
[c] L, limestone; M, marl; ML, marly limestone.
[d] Average bedding strike and dip angles in degrees (right-hand side convention). Dip angles >90° indicate overturned limbs.

2.3. Stable platform (Mid-Late Cenomanian-Early Santonian)

Following inversion, subaerial erosion reduced the Lower Cretaceous strata to a nearly smooth plain. Overlying the erosion surface, relatively uniform sedimentation prevailed from Cenomanian through Early Santonian time (Santa Fe, Reguard, and Anserola Formations).

2.4. Pyrenean Orogeny (Late Santonian-Maastrichtian)

Compressive tectonics led to basin inversion with the development of folds and shortcut thrusts. Detailed investigations of the syninversion deposits indicates that the Bóixols thrust, along with the Sant Corneli anticline and the Santa Fe syncline (Figure 1), grew during the Campanian and the Maastrichtian [*Simó*, 1986, *Bond and McClay*, 1995] and was later reactivated with lesser amount of displacement during the late Eocene and early Oligocene.

3. Sampling and Laboratory Procedures

A total of 34 sites spanning the Cretaceous series from the Bóixols thrust sheet has been studied (Table 1). In general, the rock types are dark gray colored limestones (mudstones to wackstones), marly limestones, and marls (Table 1). Massive platform limestones predominate in the pre-Aptian sequences and well-bedded hemipelagic marls and marly limestones constitute the main lithology for the Aptian-Albian sequences (see point 2). Samples were cored (2.54 cm in diameter) with a portable gasoline-powered drill. A site typically consists of 5 to 8 samples distributed along 5 to 10 m of stratigraphic section. In some sites, however, more than 10 m were covered (Table 1) and/or a major number of samples were taken. Cores were split in the laboratory into standard specimens (2.2 cm in length) for paleomagnetic measurements. The natural remanent magnetization (NRM) and its response to stepwise thermal or alternating field demagnetization were measured in a GM400 two-axis cryogenic magnetometer at the University of Oxford (Aptian-Albian and Upper Cretaceous sites), and in a 2G Enterprises cryogenic magnetometer at the University of Utrecht (Berriasian-Barremian sites). Characteristic remanent magnetizations (ChRM) were computed by least squares fitting [*Kirschvink*, 1980] on the orthogonal demagnetization plots [*Zijderveld*, 1967]. The initial susceptibility and its variations upon thermal cleaning were measured on a Kappabridge (KLY-2) instrument. Stepwise acquisition of a uniaxial isothermal remanent magnetization (IRM) up to 1.5 T in a pulse magnetizer and subsequent thermal demagnetization were performed. Hysteresis behavior was studied with an alternating gradient force magnetometer (AGFM, Micromag, Princeton Measurements Corporation) capable of resolving magnetic moments as low as about 2 x 10^{-8} emu (1 emu = 10^{-3} Am^2, SI). Small chips of sample (~30-50 mg) were mounted directly on the probe tip with the aid of vacuum grease for adhesion. Values of saturation magnetization (*Ms*), saturation remanence (*Mrs*) and coercive force (*Hc*) were determined from hysteresis loops. The coercivity of remanence (*Hcr*) was obtained from backfield demagnetization of *Mrs* in the AGFM. Most determinations of magnetic moment were repeatable to within 2%.

4. Results

4.1. IRM Experiments and Susceptibility

All studied Berriasian-Barremian samples display a similar behavior in acquisition of a 1.5 T IRM (Figure 3a). Saturation is normally reached below the maximum applied field while 80-

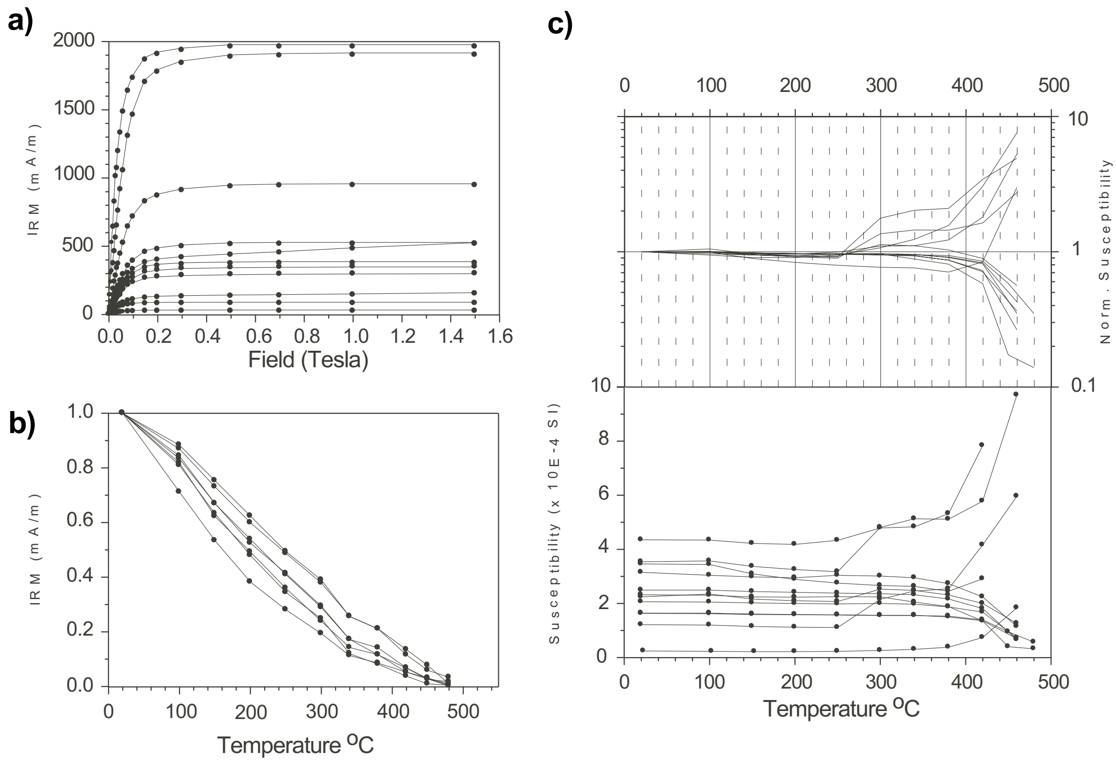

Figure 3. (a) IRM acquisition experiments and (b) thermal demagnetization of saturation IRM for samples from the Berriasian-Barremian sites. (c) Normalized and unnormalized low-field magnetic susceptibility variations in thermal demagnetization.

90% of the saturation isothermal remanent magnetization is attained below 0.2 T, indicating a low-coercivity mineral as the carrier of the magnetization. Only very occasionally samples did not saturate, and a progressive increase of IRM intensity above 0.2 T, indicating the minor contribution of a high-coercivity phase, is observed. The same behavior was observed for rocks from Aptian-Albian and Upper Cretaceous strata [*Dinarès-Turell*, 1992; *Dinarès-Turell et al.*, 1991]. Thermal demagnetization of the IRM (Figure 3b) shows maximum unblocking temperatures below 500^{o}C, which are compatible with some type of magnetite, and not necessarily Ti-rich magnetite (e.g., low unblocking CRM of relatively pure authigenic magnetite). A subtle change of slope at 340^{o}C could indicate the contribution of a magnetic iron sulfide (pyrrhotite?) to the IRM. Maximum unblocking temperatures of 450^{o}-480^{o}C are also observed upon thermal demagnetization of the NRM (see below) but no substantial decay is observed in the 300^{o}-340 ^{o}C interval. Hence it is believed that magnetite is the main remanence carrier in those rocks, although a minor contribution of iron sulfides cannot be ruled out.

Low-field magnetic susceptibility measured after every heating step for the Berriasian-Barremian rocks (Figure 3c) indicates two general behaviors. Most of the samples display a gradual decrease of susceptibility, which is most pronounced above 380^{o}C and coincides with the unblocking of remanence. The other set of samples is characterized by an important increase of susceptibility at about 400^{o}-450^{o}C that can start at lower temperatures. Samples from this second group are chiefly marly lithologies (sites 22 and 31). It is common to observe in marly lithologies an increase in susceptibility at around 400^{o}-450^{o}C, which is usually ascribed to the breakdown of clays and/or the accompanying pyrite and the formation of new magnetite [*van Velzen and Zijderveld*, 1982]. As a rule, the Aptian-Albian strata, which are dominated by marly lithologies, also display this typical increase of susceptibility at around 400^{o}-450^{o}C [*Dinarès-Turell*, 1992; *Dinarès-Turell et al.*, 1991].

4.2. Hysteresis

Hysteresis loops generated for the Berriasian-Barremian samples display “wasp-waisted” behaviors regardless of having paramagnetic or diamagnetic slopes (Figure 4). Wasp-waistedness is considered indicative of a bimodal distribution of grains with contrasting coercivity [*Jackson*, 1990; *Roberts et al.*, 1995; *Tauxe et al.*, 1996]. This leads to high *Hcr*/*Hc* ratios. For the case of a single mineralogy, the behavior must be explained by differences in grain size. In the Berriasian-Barremian sites under study, where only magnetite is expected as the dominant phase, the data are consequently better explained by a large population of superparamagnetic grains in association with the more stable single domain (SD) grains carrying the remanence. In contrast, samples from the Aptian-Albian and Upper Cretaceous strata do not display wasp-waisted hysteresis loops (Figure 4).

Coercivity (*Hcr*/*Hc*) and remanence (*Mrs*/*Ms*) ratios for the Berriasian-Hauterivian and oldest Barremian sites (sites 24 to 34, Table 1 and Figure 2) are high in comparison to those reported for a synthetic mixture of SD plus multidomain (MD) grains [*Parry*, 1982] but are consistent with results for remagnetized carbonate rocks (Figure 5a) [e.g., *Jackson*, 1990; *Channell and McCabe*, 1994]. On the other hand, the younger strata (sites 1 to 23, Table 1, and Figure 2) generally plot on the non remagnetized trend. Considering the hysteresis ratios as a “remagnetization fingerprint” [*McCabe and Channell*, 1994], the separation of the Cretaceous rocks studied into a Berriasian-Barremian remagnetized group and a younger unremagnetized

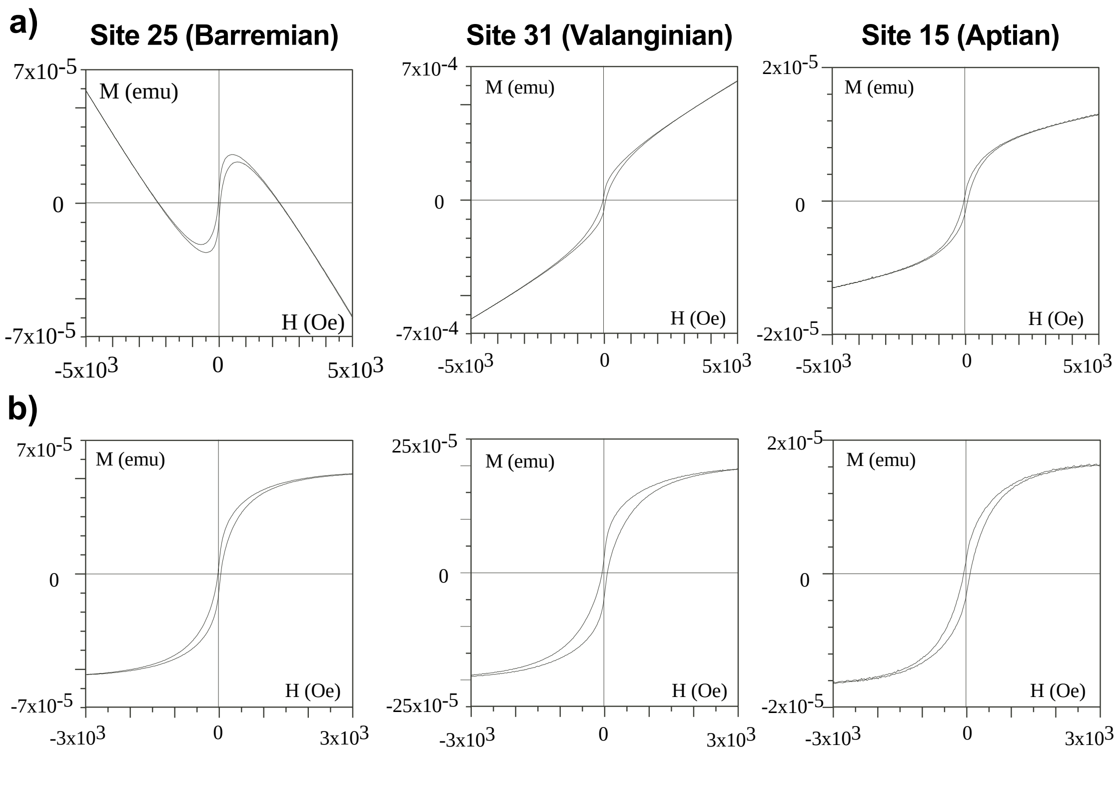

Figure 4. (a) Representative hysteresis loops for sites showing diamagnetic (site 25) and paramagnetic slopes (site 31 and 15). (b) The same data after slope correction (1 emu = 10^{-3} A m^2, SI).

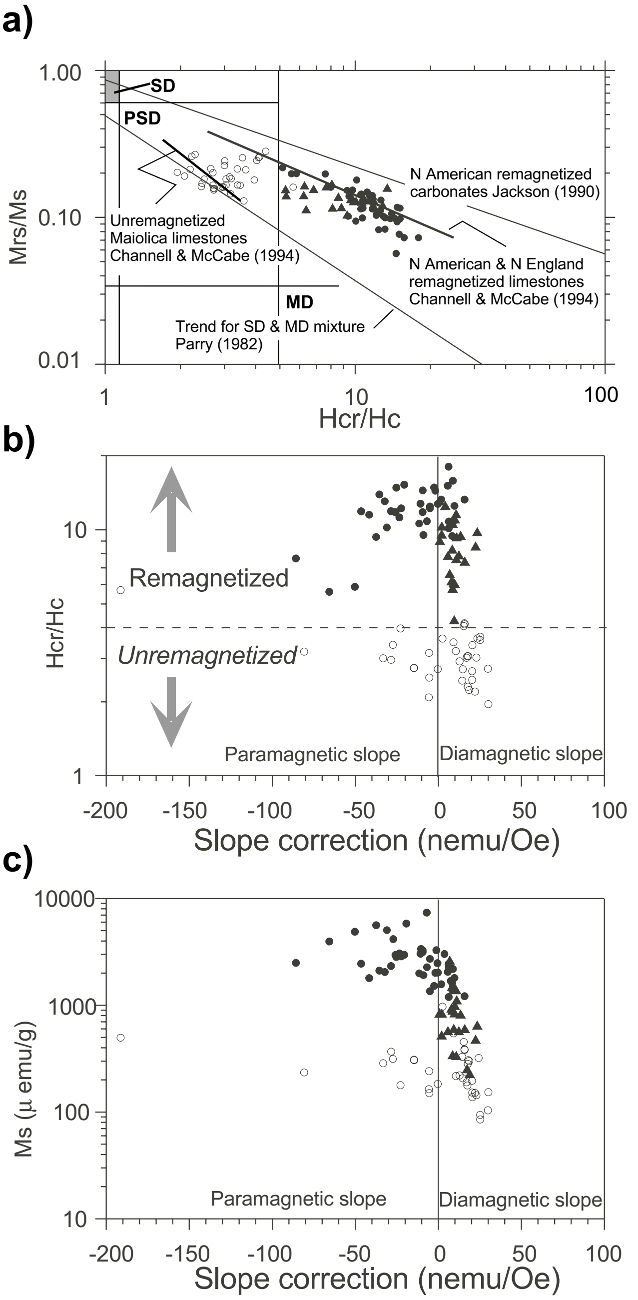

Figure 5. (a) Bilogarithmic plot of *Mrs*/*Ms* against *Hcr*/*Hc* showing different trends for known remagnetized and unremagnetized rocks and data from the Organyà Basin. The SD, PSD, and MD fields are indicated. (b) *Ms* plotted against slope correction. Positive and negative slope corrections correspond to diamagnetic and paramagnetic slopes, respectively. (c) *Hcr*/*H*c ratio against the slope correction. In all graphs, solid circles represent data from pre-Barremian sites (29-34); solid triangles represent data for the oldest Barremian sites (24-28); open circles represent data for the three uppermost Barremian sites (21-23) and younger rocks (sites 1-20).

group is obvious. The coercivity ratio *Hcr*/*Hc* = 4, which defines the higher boundary of the pseudosingle domain (PSD) threshold field (Figure 5a and 5b), roughly delimits the two groups. Few samples from the younger group plot above this limit and fit better to the remagnetized trend (Figure 5a), but excluding these few exceptions, samples from the Aptian-Albian and Upper Cretaceous strata normally have *Hc*r/*Hc*<4 and fit to the known unremagnetized trend. Samples from the Prada II sequence (sites 21 to 23; Table 1 and Figure 2), which can be assigned an Upper Barremian-Lower Aptian age, are included in the younger unremagnetized group. Saturation magnetization (*Ms*), which can be taken as a rough indication of concentration, spans 2 orders of magnitude (Figure 5c). *Ms* is highest for the oldest remagnetized Berriasian-Hauterivian sites (Hostal Nou I-II sequences, sites 29 to 34), intermediate for the remagnetized Barremian sites (Prada I sequence, sites 24 to 28), and lowest for the unremagnetized younger rocks (sites 1 to 23), although some overlap between the three groups exists (Figure 5c). The same variation pattern is observed for the NRM intensities, which range from 3 to 30 x 10^{-3} A/m for the Berriasian-Hauterivian sites, 3 to 60 x 10^{-4} A/m for the Barremian sites and 1 to 15 x 10^{-4} A/m for younger strata.

4.3. Demagnetization of the NRM

All Aptian-Albian and Upper Cretaceous strata (sites 1 to 20; Table 1 and Figure 6a) show similar behavior during NRM d e magnetization. Thermal and alternating field treatment yield similar directions but thermal demagnetization was preferably used. Two remanent magnetization components can be identified, in addition to a third component, which is removed below 100 ^{o} -150 ^{o} C and seems to be related to a drilling or storage viscous acquisition (i.e., is parallel to the specimen long axis). A low-temperature, low-coercivity component (*L*) with unblocking te m peratures of less than 300 ^{o} C or a coercivity of about 20-25 mT is then removed (Figure 6a). This component conforms to the pre s ent geomagnetic field direction and therefore is regarded as a secondary recent overprint. Finally, a high-temperature comp o nent (*H*) with unblocking temperatures distributed from about 250 ^{o} C to 450 ^{o} -500 ^{o} C is observed. The high-temperature comp o nents decay toward the origin in their orthogonal vector plots. Above those temperatures, growth of new magnetite is identified by an increase in susceptibility and erratic behavior in dema g netization. The paleomagnetic site mean directions of the *H* co m ponent for the Aptian-Albian sites (sites 5 to 20; Table 2 and Figure 6b) pass the fold test (Figure 6c), indicating that magnet i zation predates the Late Santonian-Maastrichtian folding. A r o bust fold test for the Upper Cretaceous sites (sites 1 to 3) is pr e cluded because too few sites are available. However, the statist i cal parameters are much better grouped after tectonic correction (i.e., the *k* parameter increases from an in-situ value of 3.8 to a tectonic corrected value of 77.1; Table 2). This suggests a pr e folding origin for the magnetization. Three Aptian-Albian sites (9, 16, and 17) and one Upper Cretaceous site (4) were excluded from the statistical computations. Site 9 was rejected although its site-mean direction agrees with the overall Aptian-Albian mean direction (Table 2) because it is located in a tectonic subunit bounded to the north by a backthrust (Figure 1). Site 17, which is located in the footwall and very close to the backthrust mentioned above (Figure 1), was excluded because the mean declination deviates significantly from the overall Aptian-Albian direction (Table 2). The inferred relative counterclockwise rotation at site 17 is interpreted as a local effect related to the backthrust (Figure 1). Finally, site 16 (located along the Noguera Pallaresa river (Figure 1) is excluded because it represents an outlying direction indicating a relative clockwise rotation when compared to the rest of the Aptian-Albian sites (Table 2). This rotation is confirmed by a neighboring site in Upper Cretaceous strata (site 4, Table 2) and likely reflects local deformation within the Bóixols thrust sheet. Hence the exclusion of the directional data from these two sites along the

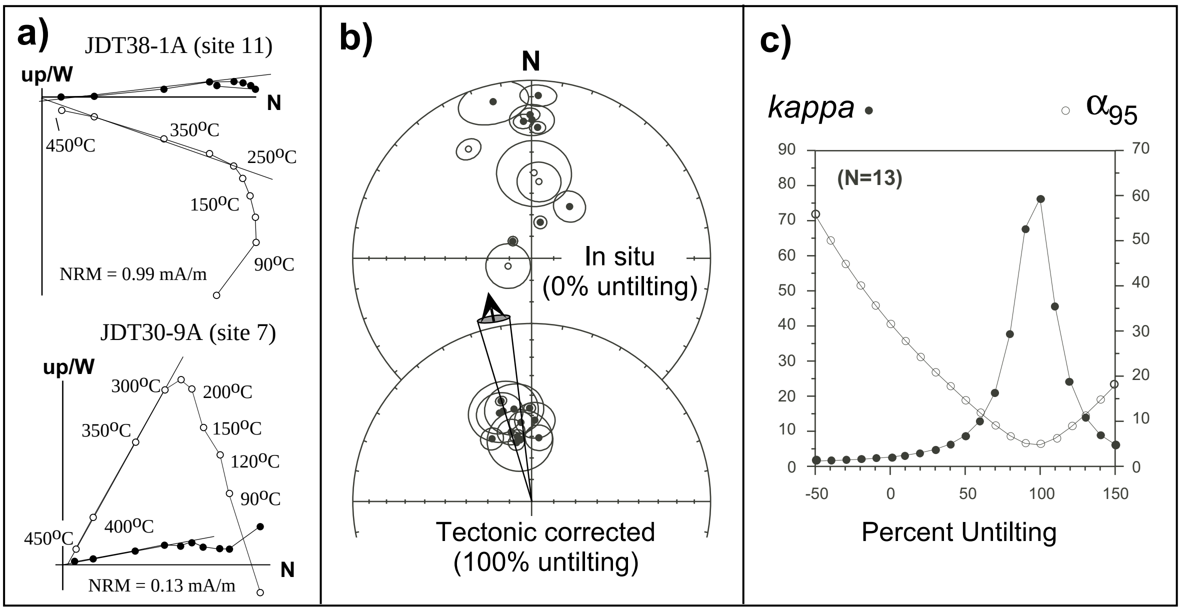

Figure 6. (a) In situ orthogonal plots of thermal demagnetization of representative Aptian-Albian sites. (b) Equal-area projection of the individual ChRM site mean directions for the Aptian-Albian (see Table 2). The 95% confidence cone for the grand site mean direction is represented. (c) Incremental fold test on the Aptian-Albian sites showing the variation in statistical parameters *k* and α_{95} with percent untilting.

Noguera-Pallaresa river is justifiable (Table 2).

NRM demagnetization for the Berriasian-Barremian sites (sites 21 to 34, Table 2) shows a constant behavior (Figure 7a), that is similar to that described for the Aptian-Albian and Upper Cretaceous sites (*L* and *H* components). In this case, however, NRM intensities are usually higher and the viscous component removed below 150 ^{o}C is somewhat more prominent. Due to the similar bedding attitude at the Berriasian-Barremian sites, no statistically significant fold test can be carried out. However, the inclination of the *H* component in geographic (in situ) coordinates is too shallow to represent any field direction of Cretaceous or younger age (Table 2 and Figure 7b). This suggests that this component was probably acquired prior to or during the Late Cretaceous-Tertiary folding in the region (see discussion). The younger Barremian sites (21-23) have more north directed declinations than the oldest sites and largely contribute to the dispersion of the declination in the Berriasian-Barremian set (Figure 7b). For this reason and the fact that the

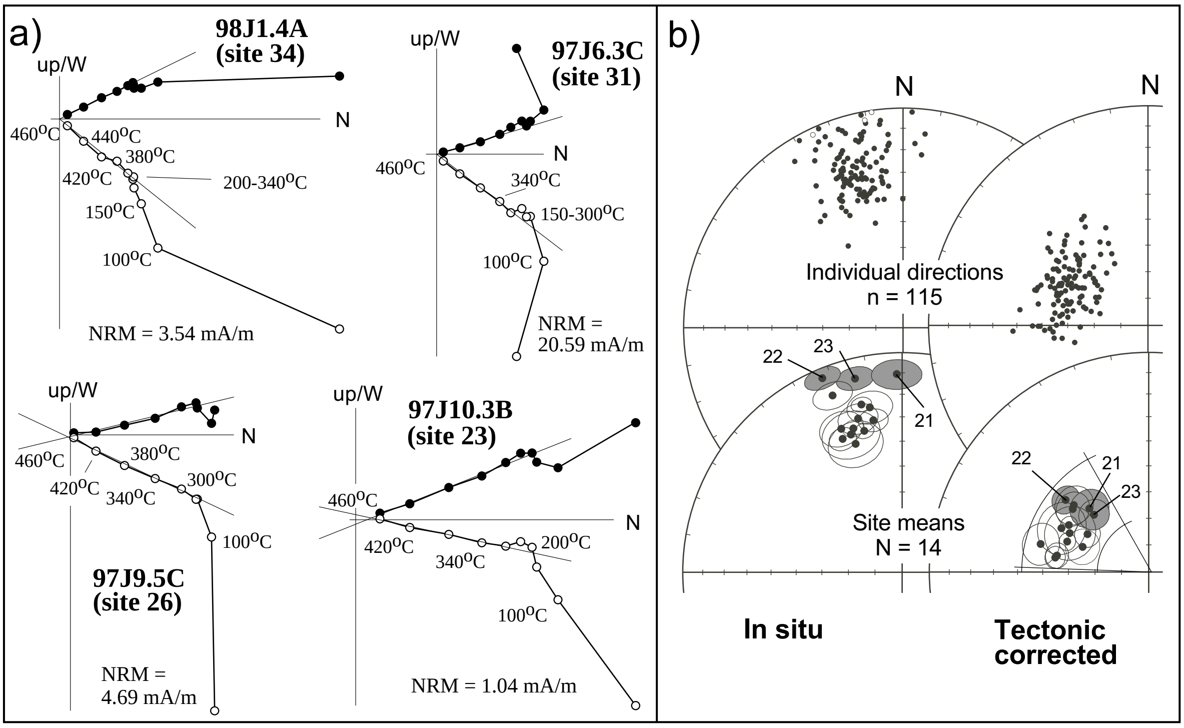

Figure 7. (a) In situ orthogonal plots of thermal demagnetization results for Berriasian-Barremian sites. (b) Equal-area projection of the individual ChRM and site-mean directions for the Berriasian-Barremian sites (see Table 2). The three youngest Barremian sites (21-23) are indicated (see text for explanation).

Table 2. Paleomagnetic Data and Statistical Parameters

		In Situ				Tectonic Corrected[a]			
Site	*N*/*n*	*D*	*I*	*k*	α_{95}	*D*	*I*	*k*	α_{95}
Upper Cretaceous									
1	7/10	10.9	-2.3	58.1	6.4	351.7	63.2	51.8	6.8
2	9/15	13.1	25.5	193.9	2.8	349.0	64.4	196.2	2.7
3	6/6	352.5	80.6	106.5	6.5	359.7	48.7	106.6	6.5
4[b]	6/6	13.2	-21.8	99.0	6.8	11.9	39.8	101.2	6.7
Mean (*N* = 3 sites)		10.4	33.8	3.8	74.8	354.4	58.9	77.1	14.1
Lower Cretaceous (Aptian-Albian)									
5	7/9	330.1	-30.0	103.2	5.1	327.8	55.8	103.2	5.1
6	5/5	346.3	10.4	38.4	12.5	349.3	46.0	38.3	12.5
7	10/10	5.5	-54.3	26.8	9.5	2.3	52.2	32.1	8.7
8	8/18	312.8	78.4	260.9	2.1	343.2	40.6	220.1	2.3
9[b]	6/7	177.9	54.2	38.0	9.9	348.5	45.8	72.8	7.1
10	5/8	251.7	-78.8	30.7	10.2	340.2	46.0	27.8	9.9
11	6/13	359.4	20.3	129.8	3.7	345.5	62.0	135.9	3.6
12	7/18	356.7	23.9	80.0	3.9	352.3	53.0	46.6	5.1
13	8/11	2.6	27.2	207.0	3.2	347.6	59.3	200.6	3.2
14	7/9	1.6	-50.2	11.3	16.0	349.3	61.2	13.6	14.5
15[b]	11/18	13.6	73.1	142.9	2.9	358.8	46.5	196.1	2.5
16[b]	8/14	20.6	19.1	233.0	2.6	7.3	52.0	390.0	2.0
17[b]	8/13	152.8	48.8	147.0	3.6	320.5	59.2	136.2	3.6
18	8/9	0.1	23.1	37.5.0	8.5	337.7	46.0	23.8	10.8
19	7/10	2.4	9.2	58.3	6.4	343.6	56.5	65.2	6.0
20	9/9	36.1	60.4	52.7	7.2	6.3	60.4	73.8	6.0
Mean (*N* = 13 sites)		356.3	11.4	2.7	31.7	347.7	53.1	74.4	4.8
Lower Cretaceous (Neocomian-Barremian)									
21	8/9	358.4	10.7	52.3	7.2	316.9	57.5	52.3	7.2
22	5/5	337.6	4.9	220.5	5.2	311.0	48.5	222.1	5.1
23	10/11	346.3	10.0	70.0	5.5	316.4	60.4	66.1	5.7
Mean (N = 3, 21-23)		347.4	8.6	56.4	16.6	314.4	55.5	155.8	9.9
24	6/6	343.9	28.0	108.4	6.5	290.8	63.6	108.7	6.5
25	7/7	348.9	24.4	72.2	7.2	311.8	52.3	72.3	7.1
26	7/7	346.3	22.4	358.2	3.2	300.4	55.3	359.3	3.2
27	5/5	339.6	33.5	63.1	9.7	296.2	57.1	63.1	9.7
28	5/5	349.2	30.2	253.1	4.8	301.7	63.1	251.7	4.8
29	7/7	337.0	29.7	70.1	7.3	284.5	47.9	69.4	7.3
30	5/8	345.0	33.7	304.6	3.2	290.5	57.5	305.0	3.2
31	16/20	341.3	31.5	87.3	3.5	278.8	54.4	70.1	3.9
32	8/8	335.9	33.9	146.7	4.6	280.2	55.0	154.5	4.6
33	10/10	338.5	14.5	64.9	6.0	309.7	52.9	60.6	6.3
34	7/7	340.0	37.8	42.9	9.3	296.7	53.3	42.8	9.3
Mean (N = 11, 24-34)		342.4	29.1	111.3	4.3	294.6	56.1	108.0	4.4

N/*n*, is the number of samples/specimens; *D*, *I* are declination and inclination in degrees; *k*, α_{95}, are the statistical parameters associated with the means.

[a] Simple untilting along the bedding strike (unbuckling) with the exception of site 5 that included unplunging followed by unbuckling.

[b] Sites excluded from calculations.

corresponding hysteresis properties are also different in those sites (i.e., they match the "unremagnetized" class as discussed above) the mean paleomagnetic direction for the Berriasian-Barremian sites has been separated in two groups (Table 2).

5. Discussion

The polarity of the *H* component for all sites in Aptian-Albian and Upper Cretaceous strata (sites 1 to 20) is normal. This is in agreement with the biostratigraphic age of the rocks (i.e., it corr e sponds to the normal chron C34n or Cretaceous Quite Zone, Figure 2). Moreover, the positive fold tests as well as hysteresis properties collectively argue in favor of a primary magnetization (i.e., acquired during or soon after deposition). The mean Aptian-Albian direction from the OB (Table 2 and Figure 6b) is statist i cally coincident with the expected Aptian reference direction for Iberia derived from strata near Lisbon [*Galdeano et al.*,1989] (*D*/*I* = 349.1°/51.8°, α_{95} = 7.0). Reference directions are calc u lated for a common location at Tremp (42.2°N/1°E, Figure 1). Seemingly, the Upper Cretaceous mean direction (Table 2) does not differ significantly from the Upper Cretaceous calculated reference direction obtained from the Lisbon basalts [*Van der Voo and Zijderveld*, 1971] (*D*/*I* = 354.9°/43.9°, α_{95} = 3.0). These observations have been previously used to support lack of vertical axis rotation during Alpine deformation and emplacement of the Bóixols thrust sheet [*Dinarès-Turell*, 1992; *Dinarès-Turell et al*., 1991].

Normal polarities for the *H* component were also observed for all our Berriasian-Barremian sites (sites 21 to 34). In this case, however, the inferred biostratigraphic age places them within an interval with numerous reversals (Berriasian-Barremian, Figure 2). Even considering that the Hauterivian is

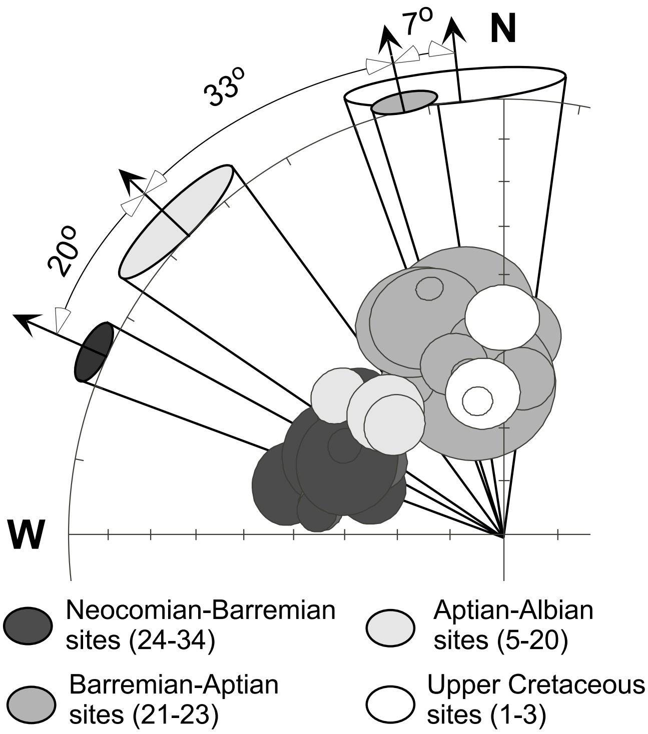

Figure 8. Stereographic projection after tectonic correction of the confidence ellipses of the individual site means from the Organyà Basin. The confidence cone for the four considered group mean directions and their relative angles are depicted (Table 2).

missing and that paleomagnetic sampling is not continuous, the absence of reverse polarity *H* magnetizations in those sites makes them suspicious of remagnetization. As an example, sites 30 and 31, which span 10 and 40 m, respectively, along the entire N3 Valanginian unit (sampling resolution of ~2 m) (Table 1 and Figure 2), do not show any reverse polarity magnetizations. As outlined above, the hysteresis properties for the Berriasian-Hauterivian and older Barremian sites (24-34) indeed indicate that those sites are r e magnetized. As mentioned above, strata at the three younger Barremian sites (Prada II sequence, sites 21-23), which might be Aptian in age given the biostratigraphic information, have hy s teresis properties that classify them as unremagnetized and ther e fore they have been considered separately. The aspects related to the paleomagnetic directional data from the Berriasian-Barremian sites are discussed below.

5.1 Timing and Mechanism for the Remagnetization

The secondary nature for the *H* component in the Berriasian-Hauterivian (sites 29-34) and older Barremian strata (sites 24-28) is realistic considering the lack of reverse polarity magnetizations and their rock magnetic properties as described above. However, assigning an accurate age to the secondary magnetization is difficult. A Tertiary, posttilting origin for the remagnetization has been already ruled out, given the uninterpretable remanence inclination values in geographic coordinates. Consequently, the age of the remagnetization is bracketed between the age of the youngest strata containing secondary magnetizations (upper Barremian) and the age of main folding in the region (Campanian-Maastrichtian) and hence likely represents a Cretaceous remagnetization considering that an Early Tertiary age related to tectonic deformation seems more unlikely (see below). The possibility of a synfolding age of the remagnetization cannot be examined because of the lack of sufficiently distinct bedding attitudes among the sites to adequately perform a fold test. Partial untilting from about 50% to 100% would bring the mean inclination to compatibility with expected Cretaceous (or younger) inclinations of about 50° to 55°. However, we prefer to exclude the possibility of a late Cretaceous-Tertiary synfolding origin for the remagnetization because this would require explaining the following observations: (1) both the Aptian-Albian (mostly marls) and Cenomanian-Santonian (limestones) sequences have escaped remagnetization and, more importantly, (2) the declination of the mean direction in the 50-100% untilting interval (327°-295°) is difficult to interpret in that a rather intricate pattern of both counterclockwise and clockwise rotation is required because the older (following the hypothesis of late Cretaceous-Tertiary age for the remagnetization) primary Aptian-Albian and Cenomanian-Santonian directions have more northerly declinations. This is a significant argument against a Tertiary age for the remagnetization process in the Bóixols thrust sheet either related to folding or to activity along a Tertiary regional fault structure. Tertiary age secondary magnetizations of reverse polarity residing in hematite from Mesozoic strata have been described in more external structures in the southern Pyrenees [*Dinarès-Turell and McClelland*, 1991; *Dinarès-Turell*, 1992, 1994]. They were related to weathering along aerial exposure associated to Tertiary thrust-sheet emplacement. The nature and different polarity of such secondary magnetizations seem to be unrelated to the observed secondary magnetization in the Organyà Basin.

Next we analyze the alternative possibility of remagnetization prior to Late Cretaceous folding and the potential mechanisms for such remagnetization. One possibility is that the remagnetization took place around the Barremian/Aptian boundary. This is based on the following observations: (1) the boundary between remagnetized and non remagnetized rocks, as defined by the hysteresis properties, occurs around the Barremian/Aptian boundary; (2) this boundary coincides with a significant change in declination toward more north directed directions in younger non remagnetized strata. If this interpretation is correct, the mean remanence declinations in the Organyà Basin define a rotational path from west directed declinations for the remagnetized Berriasian-Barremian sites to north directed declinations for younger strata with primary magnetizations (Table 2 and Fig. 8). The directional implications of this interpretation are discussed below.

One of two mechanisms, including chemical remagnetization related to one or more diagenetic events [e.g., *McCabe et al.*, 1983; *McCabe and Elmore*, 1989] and thermoviscous resetting [*Kent*, 1985], is usually invoked for remagnetized carbonate rocks. Generally, however, the ultimate process responsible for the remagnetization is often poorly understood and open to debate. Migration of fluids [e.g., *Ge and Garven*, 1992] expelled or derived from orogenic belts is regarded as a possible mechanism of remagnetization because the circumstantial spatial and temporal association with secondary magnetizations, although often no direct geochemical characterization of the fluid can be made. A burial diagenetic origin for a secondary magnetization has recently been described for some North American Pennsylvanian carbonate rocks [*Banerjee et al.*, 1997] and is supported by oxygen isotope ratios in their authigenic magnetites [*Ripperdan et al.*, 1998]. A widespread

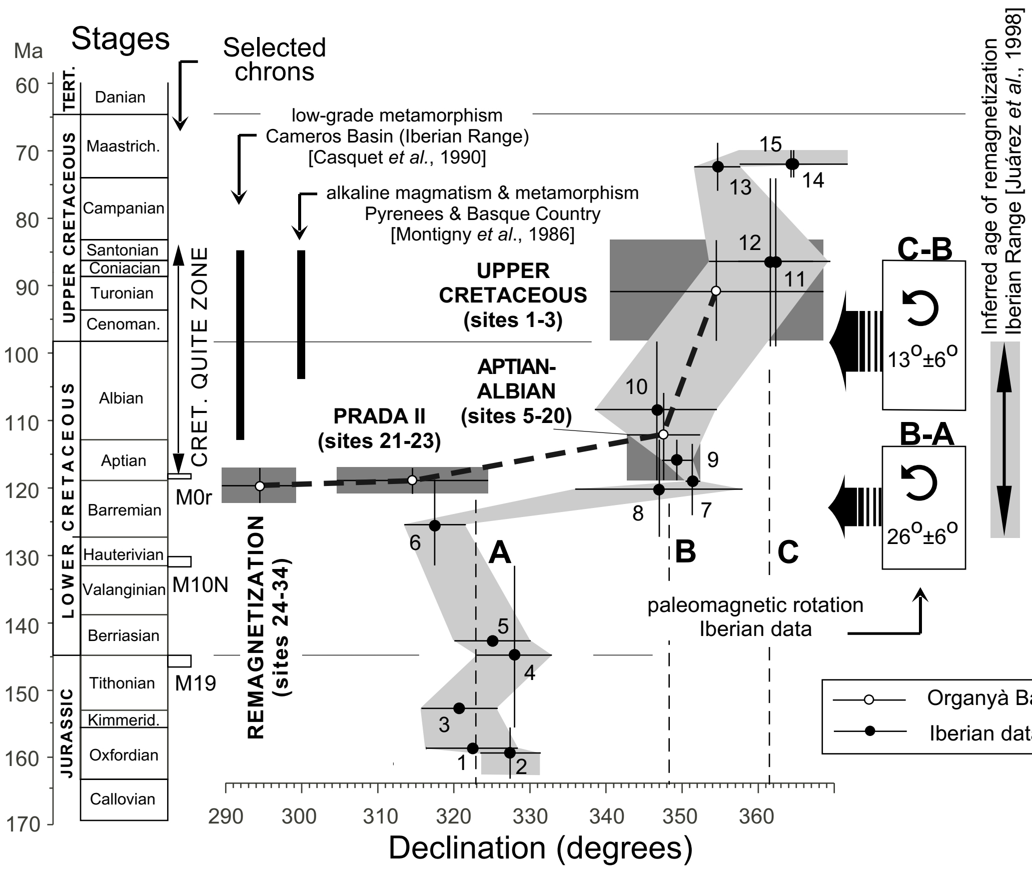

Figure 9. Plot of paleomagnetic declinations versus geologic time (timescale of Ogg [1995]) for results from Iberia and the Organyà Basin calculated for a common reference site at Tremp (42.2^{O}N, 1^{O}E). The α_{95} error envelope is drawn for the Iberian data, and three declination group means that define two rotational events are marked (A, B, and C). Numbers besides the points identify the sources of the data: 1, *Steiner et al.* [1985], Sierra de Aguilón (Iberian Range); 2, *Juárez et al.* [1998], Iberian Range; 3, *Schott and Peres* [1987], north central Spain; 4, *Galbrun et al.* [1990], Bias do Norte (Algarve): 5, *Moreau et al.* [1997], Algarve; 6, *Galdeano et al.* [1989], sediments near Lisbon; 7, *Vandenberg* [1980], Vega del Pas (northern Spain); 8, *Moreau et al.* [1992], Maestrat (Iberian Range); 9, *Galdeano et al.* [1989], sediments near Lisbon; 10, *Moreau et al.* [1997], Algarve; 11, *Storetvedt et al.* [1987], Sintra mafics only (central Portugal); 12, *Van der Voo* [1969], Sintra granit (central Portugal); 13, *Van der Voo and Zijderveld* [1971], Lisbon basalts; 14, *Van der Voo* [1969], Monchique syenite (southern Portugal); 15, *Storetvedt et al.* [1990], Monchique dikes (southern Portugal).

remagnetization of Mesozoic carbonates of the Vocontian trough, southeast France, has also been interpreted as a consequence of burial diagenesis during basin maturation [*Katz et al.*, 1998]. A transition from high to low NRM and anhysteretic remanent magnetization intensities was found to correlate with presence/absence of smectite, with both features occurring at different biostratigraphic positions along the basin [*Katz et al.*, 1998]. Moreover, strontium isotope data are not consistent with alteration by orogenic-type fluids, which reinforces the burial diagenetic remagnetization hypothesis for those rocks.

We have shown in the OB how saturation remanence (*Ms*) and NRM intensity both vary from high values in the oldest remagnetized strata to lower values in the younger non remagnetized strata. Unfortunately, the clay mineralogy and their burial diagenetic trends in the Cretaceous of the OB have not been studied to allow direct comparison with the paleomagnetic results. Also, data on the organic matter maturation throughout the basin are not available to independently test the burial diagenetic mechanism as the cause for the secondary authigenesis of magnetite. Nevertheless, this mechanism remains a testable hypothesis in the OB. Moreover, there is a good agreement between the postulated timing of this remagnetization and the subsidence history derived for the OB. The hypothesized age near the Barremian/Aptian boundary for the remagnetization event coincides with an increase of subsidence that changed the depositional trend to basinal conditions with a high sedimentation rate (Figure 2). The possibility of a thermoviscous resetting related to a thermal event remains more unlikely. This is basically because there is no apparent coincidence between the timing of remagnetization in the OB, as outlined in this study, and other known Mesozoic thermal events in the Pyrenean and Iberian realm, which have been dated by isotope age methods between the Albian and the Cenomanian [*Montigny et al.*, 1986; *Casquet et al.*, 1990; *Vergés and García-Senz*, 2000] (Fig. 9).

5.2. Implications for the Iberian Cretaceous Evolution

If the ChRM of the Berriasian-Barremian limestones truly represents a secondary magnetization acquired at about the Barremian/Aptian boundary time, then the implications of the paleomagnetic data from the OB can be further analyzed. As the respective Aptian-Albian and Late Cretaceous data from the OB match the corresponding reference directions for Iberia, we have no reason to invoke significant rotation related to thrust sheet emplacement. The angular difference between the Aptian-Albian mean direction and the direction of the Barremian/Aptian secondary magnetization is ~53^o, whereas the site mean direction for the oldest non remagnetized sites (21-23, Upper Barremian-Lower Aptian strata) is at an intermediate position (Figures 8 and 9). Given that the rotation of the Iberian peninsula estimated from paleomagnetic data amounts to less than 40^o [*Van der Voo*, 1967; *Galdeano et al*., 1989; *Van der Voo*, 1993], the internal relative rotation observed along the stratigraphic package of the OB must represent, at least partially, a Cretaceous age local rotation of the basin or of a larger “Pyrenean” domain. The rotation of the Iberian peninsula (Figure 9) can be partitioned as two phases considering all the available paleomagnetic data. A fast Barremian age counterclockwise rotation of ~26^o is likely, although data for this age and hence the rate of rotation is largely defined by a single study on sedimentary rocks near Lisbon [*Galdeano et al*., 1989] (point 6 in Figure 9). An additional counterclockwise rotation of ~13^o occurred between the Albian and the Maastrichtian. The data from the OB are consistent with a very fast counterclockwise rotation of pre-Albian age and a subsequent minor rotation. However, the exact age and magnitude do not coincide with the Iberian data set. In the OB the main rotational phase appears to have taken place between Late Barremian and the Early Aptian and is about 53^o. Furthermore, the hypothesized Barremian/Aptian age for the remagnetization in the OB is similar to the range of the inferred age for the secondary magnetization acquisition in Jurassic rocks from the Iberian Range deduced by comparison with the Iberian reference dataset [*Juárez et al*., 1998] (Figure 9). Yet, the total amount of Mesozoic rotation in the Iberian Range (~33 ^{o}), as defined by the primary Jurassic direction, is less than the inferred Cretaceous rotation in the OB. Therefore, and independently of whether the remagnetization events are coeval, the data from the OB indicates that this domain has likely behaved individually at least during its pre-Albian evolution. We believe that most of the counterclockwise rotation observed in the OB represents a Cretaceous local rotation. This is consistent with a westward slip decrease of the E-W normal fault that bounded the basin at the time (now frontal thrust as consequence of the Pyrenean inversion) as inferred by tectosedimentary evidences [*Vergés and García-Senz*, 2000].

6. Conclusions

A prefolding magnetization of normal polarity residing in magnetite (*H* component) has been recovered in all Lower and Upper Cretaceous strata from sites in the Organyà Basin at the Bóixols thrust sheet. Despite the similar behavior of samples from all parts of the section during NRM demagnetization, we believe that the *H* component does not date to the age of the rocks in oldest Berriasian-Barremian sites and hence represents a remagnetization. One argument supporting this is that all sites display normal polarity magnetization, although the biostratigraphic age of the rocks places them in an age interval with numerous reversals. Additionally, the hysteresis properties are consistent with previously recognized properties of other limestones that have been remagnetized. A primary nature of the *H* component is likely for younger sites in Aptian-Albian and Upper Cretaceous strata, based on both their polarity-biostratigraphic placement and their rock magnetic properties.

The paleomagnetic direction of the *H* component implies about 53^o counterclockwise relative rotation between the time of acquisition of the secondary magnetization in the Berriasian-Barremian sites and that in the Aptian-Albian sites, which have a primary magnetization. Assuming the hypothesis of remagnetization at about the Barremian/Aptian boundary (i.e., the magnetization of the Berriasian-Barremian sites has this age) the amount of rotation is well above the accepted maximum amount of Mesozoic rotation for Iberia (~35^o-40^o). Consequently, we invoke that at least part of the inferred rotation is local and probably linked to faulting along basin bounding structures. Furthermore, rocks were remagnetized during a stage preceding the subsidence maxima in the basin and the rotation itself. Burial diagenesis is regarded as a plausible mechanism of remagnetization. Independent studies on the clay mineralogy and organic matter evolution remain to be done in the OB. In any case, the use of hysteresis parameters as "remagnetization fingerprint" has shown to be a valuable analytical tool in carbonate rocks, and it is expected that its use in other Mesozoic carbonate rocks from Iberia will help to further establish the extent and ultimately the mechanisms of remagnetization when coupled with additional independent studies.

Acknowledgments. J. M. Bernaus is thanked for discussions on the local stratigraphy. J. D.-T. acknowledges an EU “Marie Curie” fellowship (ERB4001GT956999). M. L. Osete and R. D. Elmore provided constructive advice on an earlier version of the paper. We are indebted to journal reviewers M. Lewchuk and J. Geissman for their amendments that helped to clarify the paper.

References

Banerjee, S., R.D. Elmore, and M.H. Engel, Chemical remagnetization and burial diagenesis: Testing the hypothesis in the Pennsylvanian Belden Formation, Colorado, *J. Geophys. Res*., *102*, 24,825-24,842, 1997.

Bernaus, J.M., L’evolució dels foraminífers com avaluació de la plataforma carbonatada de l´Aptià de la conca d’Organyà (Lleida), Ms.C. thesis, 99 pp., Univ. Autònoma de Barcelona, Bellaterra, Spain, 1995.

Bond, R.M.G. and K.R. McClay, Inversion of a Lower Cretaceous extensional basin, south central Pyrenees, Spain, in *Basin Inversion* edited by J.G Buchanan,. and P.G. Buchanan, *Geol. Soc. Spec. Publ*., *88*, 415-431, 1995.

Casquet, C., C. Galindo, J.M. González-Casado, A. Alonso, R. Mas, M. Rodas, E. García, and J.F. Barrenechea, El metamorfismo en la Cuenca de Cameros: Geocronología e implicaciones tectónicas, *Geogaceta*, *11*, 22-25, 1990.

Caus, E., J.M. García-Senz, D. Rodés, and A. Simó, Stratigraphy of the Lower Cretaceous (Berriasian-Barremian) sediments in the Organyà Basin, Pyrenees, Spain, *Cretaceous Res.*, *11*, 313-320, 1990.

Channell, J.E.T., and C. McCabe, Comparison of magnetic hysteresis parameters of unremagnetized and remagnetized limestones, *J. Geophys. Res* ., *99* , 4613-4823, 1994.

Dinarès-Turell, J., Paleomagnetisme a les unitats sudpirinenques superiors: Implicacions estructurals, Ph.D. thesis, 461 pp., Univ. de Barcelona, Barcelona, February 1992.

Dinarès-Turell, J., Remagnetizations associated to diagenesis and their relationship with thrust sheet emplacement in the Southern Pyrenees, *Geogaceta* , *15*, 105-110, 1994.

Dinarès-Turell, J. and E. McClelland. A cautionary tale for palaeomagnetists: A spurious apparent single component remanence due to overlap of blocking temperature spectra of two components. *Geophys. Res. Lett.*, *18* , 1297-1300, 1991.

Dinarès-Turell, J., E. McClelland, and P. Santanach, Contrasting rotations within thrust sheets and kinematics of thrust-tectonics as derived from paleomagnetic data: An example from the southern Pyrenees, in *Thrust Tectonics*, edited by K.R. McClay, pp. 255-265, Champman and Hall, New-York, 1991.

Galbrun, B., P.Y. Berthou, C. Moussi, and J. Azéma, Magnétostratigraphie de la limite Jurassique–Crétacé en faciès de plateforme carbonatée: La coupe de Bias do Norte (Algarve Portugal), *Bull. Soc. Géol. Fr*., *8*, 133–144, 1990.

Galdeano, A., M.G. Moreau, J.P. Pozzi, P.Y. Berthou, and J.A. Malod, New paleomagnetic results from Cretaceous sediments near Lisboa (Portugal) and implications for the rotation of Iberia, *Earth Planet. Sci. Lett*., *92*, 95–106, 1989.

García-Senz, J.M., X. Berástegui, E. Caus, M. Losantos, and C. Puigdefábregas, El Cretácico inferior de la Cuenca de Organyà (lámina cabalgante de Bóixols), in *El Cretácico Inferior del Nordeste* *de Iberia, Guía de Campo del III Coloquio del Cretácico de España, Morella, 1991*, pp. 95-153, Univ. de Barcelona, Barcelona, 1995.

Ge, S., and G. Garven, Hydromechanical modelling of tectonically driven groundwater flow with application to the Arkoma Foreland Basin, *J. Geophys. Res.*, *97*, 9119-9144, 1992.

Gómez-Garrido A., Foraminíferos plantónicos del Cretácico superior surpirenaico, Ph.D. thesis, 184 pp., Univ. Autònoma de Barcelona, Bellaterra, Spain, 1987.

Jackson, M., Diagenetic sources of stable remanences in remagnetized Paleozoic cratonic carbonates: A rock magnetic study, *J. Geophys. Res.*, *95* , 2753-2761, 1990.

Juárez, M.T., M.L. Osete, G. Meléndez, C.G. Langereis, and J.D.A. Zijderveld, Oxfordian magnetostratigraphy of the Aguilón and Tosos sections (Iberian Range, Spain) and evidence of a pre-Oligocene ove r print, *Phys. Earth Planet. Inter*., *85* , 195–211, 1994.

Juárez, M.T., M.L. Osete, R. Vegas, C.G. Langereis, and G. Meléndez, Paleomagnetic study of Jurassic limestones from the Iberian Range (Spain): tectonic implications, in *Paleomagnetism and Tectonics of the Mediterranean Region,* edited by A. Morris and D.H. Tarling, pp. 83–90, Geol. Soc., London, 1996.

Juárez, M.T., W. Lowrie, M.L. Osete, and G. Meléndez, Evidence of widespread remagnetization in the Iberian Range and its relation with the rotation of Iberia, *Earth Planet. Sci. Lett*., 160, 729-743, 1998.

Katz, B., R.D. Elmore, M. Cogoini, and S. Ferry, Widespread chemical remagnetization: Orogenic fluids or burial diagenesis of clays?, *Geology*, *26* , 603-606, 1998.

Kent, D.V., Paleomagnetism of the Devonian Onondaga limestone revi s ited, *J. Geophys. Res*., *84* , 3576-3599, 1979.

Kent, D.V., Thermoviscous remagnetization in some Appalachian limestones, *Geophys. Res. Lett*., *12* , 805-808, 1985.

Kirschvink, J.L., The least squares lines and planes analysis of paleomagnetic data, *Geophys. J. R. Astron. Soc*., *62*, 699-718, 1980.

Martínez, R., Distribución de los ammonites del Cretácico Sudpirenaico. *Cuad. Geol. Ibérica*, 8, 1035-1047, 1982.

McCabe, C., and J.E.T. Channell, Late Paleozoic remagnetization in limestones of the Craven Basin (northern England) and the rock ma g netic fingerprint of remagnetized sedimentary carbonates, *J. Geophys. Res*., *99* , 4603-4612, 1994.

McCabe, C., and R.D. Elmore, The occurrence and origin of late Pale o zoic remagnetization of sedimentary rocks of North America, *Rev. Geophys*., *27* , 471–494, 1989.

McCabe, C., R. Van der Voo, D.R. Peacor, C.R. Scotese, and R. Freman, Diagenetic magnetite carries ancient yet secondary remanence in some Paleozoic sedimentary carbonates, *Geology*, *11* , 221-223, 1983.

Montigny, R., B. Azambre, M. Rossy, and R. Thuizat, K-Ar study of Cretaceous magmatism and methamorphism from the Pyrenees: Age and length of rotation of the Iberian peninsula, *Tectonophysics*, *129*, 257-274, 1986.

Moreau, M.G., J. Canerot, and J.A. Malod, Paleomagnetic study of Mes o zoic sediments from the Iberian Chain (Spain): Suggestions for Barremian remagnetization and implications for the rotation of Iberia, *Bull. Soc. Geol. Fr* ., *163* , 393–402, 1992.

Moreau, M.G., J.Y. Berthou, and J.A. Malod, New paleomagnetic Mes o zoic data from the Algarve (Portugal): Fast rotation of Iberia between the Hauterivian and the Aptian, *Earth Planet. Sci. Lett*., *146*, 689-701, 1997.

Muñoz, J.A., Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section, in *Thrust Tectonics* edited by K.R. McClay, pp. 235-247, Chapman and Hall, New York, 1991.

Ogg, J.G., Magnetic polarity time scale of the Phanerozoic, in *Global Earth Physics: A Handbook of Physical Constants* , *AGU Ref. Shelf, vol. 1* , edited by T.J. Ahrens, pp. 240–270, Washington D.C., 1995.

Parés J.M., and E. Roca, The significance of tectonic-related tertiary remagnetization along the margins of the Valencia trough, *J. Geodyn*., *22*, 207–227, 1996.

Parry, L.G., Magnetization of immobilized particle dispersions with two distinct particle sizes, *Phys. Earth Planet. Inter*., *28* , 230-241, 1982.

Peybernès, B., Le Jurassique et le Crétacé inférieur des Pyrénées franco-espagnoles entre la Garonne et la Méditerranée., thèse Doct. Sci. Nat., 459 pp., Univ. Toulouse, Toulouse, France, 1976.

Ripperdan, R.L., L.R. Riciputi, D.R. Cole, R.D. Elmore, S. Banerjee, and M.H. Engel, Oxygen isotope ratios in authigenic magnetites from the Belden Formation, Colorado. *J. Geophys. Res* , *103* , 21,015-21,023, 1998.

Roberts, A.P., Y.L. Cui, and K.L. Verosub, Wasp-waisted hysteresis loops: Mineral magnetic characteristics and discrimination of components in mixed magnetic systems, *J. Geophys. Res.*, 100, 17900-17924, 1995.

Schott, J.J., Paléomagnetisme des séries rouges du Permien, du Trias et du Crétacé inferieur dans les Chaïnes pyrénéo-cantabrique, et nord-ouest ibérique: Implications géodynamiques, thése Doct. Etat, 382 pp., Univ. Strasbourg I, Strasbourg, France, 1985.

Schott, J.J., and A. Peres, Paleomagnetism of the lower Cretaceous re d beds from northern Spain: evidence for a multistage acquisition of magnetization, *Tectonophysics* , 139, 239–253, 1987.

Schwenke, M., Geologische Kartierung des Westteils des Val Cabó (Provinz Lérida/mittlere Südpyrenäen/NE Spanien) unter besonderer Betrachtung der Sedimentationsentwicklung im Apt/Alb, diplomkartierung, 99 pp., Univ. Bremen, Bremen, Germany, 1993.

Scotese, C.R., R. Van der Voo, and C. McCabe, Paleomagnetism of the Upper Silurian and Lower Devonian carbonates of N.Y. State: Ev i dence for secondary magnetizations residing in magnetite, *Phys. Earth Planet. Inter*., *30* , 385-395, 1982.

Simó, A., Carbonate platform depositional sequences, Upper Cretaceous, \South Central Pyrenees (Spain), *Tectonophysics*, *129*, 205-231, 1986.

Srivastava, S.P., W.R. Roest, L.C. Kovacs, G. Oakey, S. Lévesque, J. Verhoef, and R. Macnab, Motion of Iberia since the Late Jurassic: R e sults from detailed aeromagnetic measurements in the Newfoundland Basin, *Tectonophysics* , *184* , 229-277, 1990.

Steiner, M.B., J.G. Ogg, G. Meléndez, and L. Sequeiros, Jurassic magn e tostratigraphy, 2, Middle–Late Oxfordian of Aguilón, Iberian Cordi l lera, northern Spain, *Earth Planet. Sci. Lett* ., *76* , 151–166, 1985.

Storetvedt, K.M., H. Mogstad, M.C. Abranches, J.G. Mitchell, and A. Serralheiro, Palaeomagnetism and isotopic data from Upper Cret a ceous igneous rocks of West Portugal: Geological correlation and plate tectonic aspects, *Geophys. J. R. Astron. Soc*., *88*, 241–263, 1987.

Storetvedt, K.M., J.G. Mitchell, M.C. Abranches, and S. Oftedahl, A new kinematic model for Iberia: Further palaeo-magnetic and isotopic age evidence, *Phys. Earth Planet. Inter*., *62*, 109–125, 1990.

Tauxe, L., T.A.T. Mullender, and T. Pick, Potbellies, wasp-waists, and superparamagnetism in magnetite hysteresis, *J. Geophys. Res*., *101*, 571-583, 1996.

Vandenberg, J., New paleomagnetic data from the Iberian Peninsula, *Geol. Mijnbouw*., *59*, 49–60, 1980.

Van der Voo, R., The rotation of Spain: paleomagnetic evidence from the Spanish Meseta, *Palaeogeogr. Palaeoclimatol. Palaeoecol*., *3*, 393–416, 1967.

Van der Voo, R., Paleomagnetic evidence for the rotation of the Iberian Peninsula, *Tectonophysics* , *7*, 5–56, 1969.

Van der Voo, R., *Paleomagnetism of the Atlantic*, *Tethys and Iapetus Oceans* , Cambridge Univ. Press, New York, 1993.

Van der Voo, R., and J.D.A. Zijderveld, Renewed paleomagnetic study of the Lisbon volcanics and implications for the rotation of Iberian Pe n insula, *J. Geophys. Res*., *76* , 3913–3921, 1971.

van Velzen, A.J., and J.D.A. Zijderveld, A method to study alterations of magnetic minerals during thermal demagnetization applied to a fine-grained marine marl (Trubi formation, Sicily). *Geophys. J. Int*., *110*, 79-90, 1982.

Vergés, J., Estudi geològic del vessant sud del Pirineu oriental i central: Evolucio cinemàtica en 3D, Ph.D. thesis, 203 pp., Univ. de Barcelona, Barc e lona, Spain, 1993.

Vergés, J., and J. García-Senz, Mesozoic evolution and Cenozoic inversion of the Pyrenean rift. in: *Peritethyan Rift Wrench Basins and Passive Margins*, edited by P.A. Ziegler, W. Cavazza, and A.H.F. Robertson, *Mem. Mus. Nat. d´Hist. Nat*., in press, 2000.

Villalaín, J.J., M.L. Osete, R. Vegas, V. García-Dueñas, and F. Heller, Widespread Neogene remagnetization in Jurassic limestones from the south-Iberian palaeomargin (western Betics Gibraltar Arc), *Phys. Earth Planet. Inter*., *85* , 15–33, 1994.

Zijderveld, J.D.A., AC demagnetization of rock: Analysis of results, in *Methods in Paleomagnetism*, edited by D.W. Collinson et al., pp. 254-286, Elsevier Sci., New York, 1967.

J. Dinarès-Turell, Istituto Nazionale di Geofisica, Via di Vigna Murata, 605, 00143 Rome, Italy.(dinares@ingrm.it)

J. García-Senz, Departament de Geodinàmica i Geofísica, Universitat de Barcelona, Martí i Franquès s/n, 08028, Barcelona, Catalonia, Spain.

(Received August 4, 1999; revised February 7, 2000; accepted April 10, 2000.)