Oblique structures are characterized by their lack of perpendicularity with respect to the regional transport direction. They can be primary, progressive or secondary based on the timing relationships between their formation and the development of their obliquity (Sussman & Weil 2004). The deformation mechanisms and kinematics of structures vary according to the type of obliquity. This has important implications in evaluating the characteristics of potential geological reservoirs or estimation of shortening, for example. Primary oblique structures form already oblique with respect to the regional tectonic transport direction during an initial deformation event, and their trends do not change during subsequent deformation. They can develop as a result of several causes such as lateral rheological and thickness changes of the pre-tectonic series, lateral variations of the detachment level (e.g. Cotton & Koyi 2000; Soto et al. 2002, 2003; Vidal-Royo et al. 2009) or along-strike variations of syntectonic sedimentation and erosion rates. Secondary oblique structures acquire their obliquity subsequently by means of vertical-axis rotations. In progressive curved structures, the strike of the structure changes progressively during deformation and rotation and thrusting occur simultaneously.

Numerous methods have been used to unravel vertical-axis rotations in fold and thrust belts (see Weil & Sussman 2004); palaeomagnetism (e.g. McCaig & McClelland 1992); changes in strain orientations (e.g. Mitra & Yonkee 1986;
Among those, the strongest method of unravelling the kinematics of curved orogens and/or oblique structures is the combination of palaeomagnetism and detailed structural analysis (Weil & Sussman 2004). The use of palaeomagnetism to quantify vertical-axis rotations is not always possible however, because of: (1) rocks with intensities of the natural remanent magnetization (NRM) below the instrumental noise (e.g. c. 10^{-12} Am^2) of current superconducting magnetometers; (2) rocks recording a magnetization acquired after the rotational movement of structures; (3) complex areas (e.g. superimposed folding, non-coaxial folding) without having a reliable control of their evolution in order to correctly restore palaeomagnetic data (see Pueyo 2010); and/or (4) in areas located at very high latitudes showing subvertical inclinations of the palaeomagnetic vector (see Baraldo et al. 2003).

Other factors include a lack of suitable rocks from which to obtain palaeomagnetic samples and/or the existence of unstable palaeomagnetic components and remagnetizations.

In the interior of the Iberian plate, despite Cenozoic deformation responding to the relative movements between Africa, Iberia and Europe with a general north–south and NW–SE orientation (e.g. Rosenbaum et al. 2002), the resulted contractional structures in the Iberian Chain do not present a homogeneous trending (Fig. 1a). This variety has been interpreted in different ways, for example multiphase evolutionary models (e.g. Liesa & Simón 2007) or the influence of the inversion of previous Variscan and/or Mesozoic faults with different orientation (e.g. Guimerà et al. 2004; De Vicente et al. 2009). One of the most interesting and attractive structural features of the SW deformation front of the Iberian Chain (NE Spain) is the occurrence of a series of approximately north–south to NNE–SSW and NNW–SSE-trending structures forming a subtle arc, oblique with respect to the general NW–SE trend of the Iberian Chain.
In this work, we use palaeomagnetic data to detect possible vertical-axis rotations to account for their obliquity together with two other datasets: (1) theoretical vertical-axis rotations calculated using shortening estimates from balanced cross-sections from Muñoz-Martín & De Vicente (1998), following the methodology proposed by Pueyo et al. (2004); and (2) basement-cover structural relationships in two areas located inside the Loranca Basin from subsurface and surface data.

**Geological setting**

**Structural features**

The Altomira Range and Loranca Basin constitute the SW termination of the Iberian Chain (i.e. the deformation front at this latitudinal portion; Fig. 1). The Iberian Chain is an intraplate range formed in a generalized north–south-aligned compressive context between the Palaeocene and the Early Miocene (e.g. Casas-Sainz & Faccenna 2001; De Vicente et al. 2004) due to the relative movements between Africa, Iberia and Europe with a general north–south and NW–SE orientation (e.g. Rosenbaum et al. 2002). It formed by the tectonic inversion of previous Permo-Triassic and Upper Jurassic–Cretaceous basins during the Alpine Orogeny (e.g. De Vicente et al. 2009). Structures belonging to the Altomira Range and Loranca Basin are oblique with respect to the general NW–SE trend of the Iberian Chain (Fig. 1). They are oriented north–south at its central portion, NNE–SSW at its northern sector and north–south to NNW–SSE at its southern sector, therefore tracing a subtle arc convex towards the west (Figs 1b & 2). Muñoz-Martín (1997) described several ‘transfer zones’ (sets of strike-slip and transtensional faults) that would accommodate these differences in the orientation between sectors along the Altomira Range and the Loranca Basin.

Deformation in the Altomira Range and Loranca Basin did not occur simultaneously both across- and along-strike. At its northern and central sector, the Altomira Range structures formed firstly during Eocene–Late Oligocene time (Gómez et al. 1996) with a westwards transport direction. Their formation individualized the Loranca Basin, an inward piggyback basin, also containing approximately north–south-aligned west-vergent thrust-related folds formed later during Late Oligocene–Early Miocene time (Diaz Molina et al. 1995), in an out-of-sequence thrusting with respect to Altomira’s structures (Gómez et al. 1996; Fig. 1). At the southern sector, by contrast, the Loranca structures formed firstly during the Late Eocene?–Oligocene, following an in-sequence thrusting that ended there with the formation of the Altomira structures (Muñoz-Martín 1997; Muñoz-Martín & De Vicente 1998). Although most Loranca structures do not crop out, they are identifiable in seismic profiles (Querol 1989; ITGE 1990). Both the Altomira and Loranca structures affect a Mesozoic–Cenozoic cover detached over a regional décollement level formed by Middle–Upper Triassic evaporites and clays (e.g. Gómez et al. 1996; Muñoz-Martín & De Vicente 1998; Fig. 1c).

The obliquity of the Altomira and Loranca thrusts and folds in relation to the NW–SE Iberian orientation and the north–south general compression in Iberia is controversial. It has been classically related to either: (1) their origin as oblique ramps of the Iberian Chain (Guimerà 1988); (2) the influence of the across-strike westwards thinning of the main detachment level, the Upper Triassic rocks (from 800 m thick to the east to less than 400 m thick at the western part of the studied area; Suárez-Alba 2007) and even its disappearance to the west of the Altomira Range (Van Wees & Stephenson 1995); (3) the influence of previous north–south-trending basement faults, which could have controlled both the Perno-Triassic and Upper Jurassic–Cretaceous rifts, their normal fault pattern and the orientation of posterior structures (Muñoz-Martín & De Vicente 1998); and (4) the superposition of transmitted major palaeostress fields coming from the Betic and Pyrenean active margins added to factors described in (2) and (3) (Muñoz 1997; Muñoz-Martín et al. 1998; Andeweg et al. 1999).

**Stratigraphy of the Altomira Range–Loranca Basin**

The stratigraphic sequence of the SW border of the Iberian Range can be divided into the following units (Muñoz-Martín 1997; Muñoz-Martín & De Vicente 1998): (1) the Palaeozoic and Lower Triassic rocks (Buntsandstein facies) that constitute the basement; (2) the Middle–Upper Triassic evaporites and clays (Muschelkalk and Keuper facies), acting as the regional detachment level; (3) 400-m-thick Jurassic dolomites with interbedded marls and c. 500 m thickness of Cretaceous rocks mainly including limestones, dolomites and marls; (4) the so-called Villalba de la Sierra Formation (Campanian–Lutetian), a transition formation between the Mesozoic marine rocks and the fully continental Cenozoic rocks including 200 m thickness of marls, limestones, sandstones, clays and gypsum (Muñoz-Martín 1997; Hernaiz et al. 1999a; Torres et al. 2006; and (5) Bartonian–Pliocene continental rocks, consisting of several levels of clay, sandstone, lacustrian limestones and evaporites grouped into seven different units (Hernaiz et al. 1999a, b; Gabaldón et al. 1999a, b, c, d); Palaeogene
The formation of their structures. Sible vertical-axis rotations which occurred during the Miocene pre- and syntectonic rocks of the Altomira Basin, close to the Altomira Range. Sampling was therefore constrained to the very limited non-dolomitic outcrops located at the Altomira Range and to a few suitable outcrops for palaeomagnetic sampling in the pre- and syntectonic deposits located at the westernmost part of the Loranca Basin (Fig. 2). Seven to twelve samples per site were drilled and oriented in situ with a magnetic compass coupled to a core-orienting device. Clays and fine-grained sandstones, which represent most of the sampled materials, were drilled with an electrical power drill cooled with water, whereas limestones were sampled with a gas power drill. All cores were sliced in standard palaeomagnetic specimens (cylinders 25 mm in diameter and 22 mm in height) to conduct the palaeomagnetic and rock-magnetic study. A total of 385 samples from our 45 sites were analysed in this study.

Palaeomagnetic analysis

Palaeomagnetic analyses were carried out in the Paleomagnetic Laboratory of Barcelona (CCTUB-ICTJA CSIC). These consisted of progressive thermal demagnetization of the natural remanent magnetization (NRM) up to 660°C with a maximum of 20 steps per specimen. Thermal demagnetizers MMTD-80 (Magnetic Measurements) and TSD-1 (Schonstedt) and a superconductor rock magnetometer SRM 755R (2G Enterprises) were used. Magnetic susceptibility was monitored after each demagnetization step using a KLY-2 (Agico) in order to control possible mineralogical changes during heating. Characteristic components were determined by linear regression techniques after visual inspection of the orthogonal demagnetization diagrams. The obtained directions were classified as either Class 1, 2 or 3. Class 1 directions show straight trajectories directed towards the origin and maximum angular deviations (MADs) of the linear regression lower than 10. Directions also well directed towards the origin but more scattered, or with MAD greater than 10, were classified as Class 1 directions. Finally, scattered directions not directed towards the origin were classified as Class 3 directions (see Table 1 for the complete set of directions). The site mean directions and dispersion parameters (k and α95) were calculated following Fisher’s statistics (Fisher 1953; Table 1).

Site mean directions were also classified into three groups: Class 1 sites were defined for α95 lower than 10; Class 2 sites for α95 between 10 and 20; and Class 3 sites with α95 higher than 20. Class 3 sites were not analysed further.

Magnetic mineralogy experiments were performed in representative samples to characterize the ferromagnetic particles of the different sampled lithologies. These experiments were: curves of progressive acquisition of isothermal remanent
magnetization (IRM) up to 1.2 T using a pulse magnetizer IM10-30 (ASC Scientific) and demagnetization curves of three-axes IRM (in fields of 1.2, 0.3 and 0.1 T) according to Lowrie (1990) using IM10-30 and a thermal demagnetizer TSD-1 (Shondstedt).

Fig. 2. Detailed map of the sampling sites in their geological context. Location of cross-sections II, IV, V and VI (from Muñoz-Martín & De Vicente 1998) selected for theoretical calculation of vertical-axis rotation. Red squares represent locations of Figures 7 and 8.
Table 1. Mean palaeomagnetic directions for class 1, 2 and 3 sites

| Site   | Unit    | Age  | No. specimens | Bedding attitude $S_0$ (dip direction/dip) | In situ | Bedding-corrected |
|--------|---------|------|---------------|--------------------------------------------|---------|-------------------|
|        |         |      | $N$           |                                            | $D$     | $I$   | $\alpha_{95}$ | $k$ | $D$ | $I$ | $\alpha_{95}$ | $k$ |
|        |         |      |               |                                            |         |       |               |     |       |     |               |     |
|        |         |      |               |                                            |         |       |               |     |       |     |               |     |
| Class 1 and 2 ($\alpha_{95} < 20^\circ$) |
| Northern Sector |
| SA14   | NU1     | Aq   | 7             | 090/10                                     | 192     | -40   | 14          | 19.6 | 199 | -37 | 14          | 19.6 |
| SA02*  | PNU     | Rup-Aq | 8          | 083/34                                     | 0.2     | 17.0  | 13.1        | 18.8 | 6.7  | 13.2 | 12.2        | 21.7 |
| AL11   | PU      | Bar-Rup | 6          | 095/49                                     | 342.8   | 36.4  | 17.4        | 15.8 | 22.7 | 37.2 | 17.4        | 15.8 |
| SA07   | PU      | Bar-Rup | 7          | 047/20                                     | 9       | 54.1  | 10.9        | 31.9 | 199.9| -36.8| 10.9        | 21.9 |
| SA11*  | PU      | Bar-Rup | 9          | 075/40                                     | 13      | 52    | 8           | 42.2 | 38   | 24   | 8           | 42.2 |
| AL01   | Cr      | Tur  | 4             | 233/23                                     | 8.3     | 54.3  | 7.5         | 149.6| 332.0| 66.0 | 7.5         | 149.6|
| Central Sector |
| AL07   | PNU     | Rup-Aq | 5          | 030/15                                     | 5.2     | 56.4  | 11.4        | 45.7 | 11.3 | 42.3 | 11.4        | 45.7 |
| AL13*  | PU      | Bar-Rup | 7          | 030/20                                     | 158.0   | -23.6 | 6.3         | 91.6 | 161.5| -14.6| 6.5         | 88.2 |
| Southern Sector |
| AL25   | PNU     | Rup-Aq | 4             | 250/30                                     | 17.5    | 29.8  | 18.2        | 26.4 | 356.9| 44.7 | 18.2        | 26.4 |
| AL26   | PU      | Bar-Rup | 8          | 250/30                                     | 353.1   | 27.3  | 9.7         | 33.3 | 336  | 30   | 8           | 49   |
| Class 3 ($\alpha_{95} > 20^\circ$) |
| Northern Sector |
| AL10   | PNU     | Rup-Aq | 4             | 085/39                                     | 356     | 38.6  | 34.7        | 8    | 21.8 | 27.6 | 34.7        | 8    |
| SA08   | PNU     | Rup-Aq | 6             | 106/25                                     | 13.4    | 37.5  | 35.7        | 4.5  | 31.6 | 33.9 | 35.7        | 4.5  |
| SA15   | PNU     | Rup-Aq | 5             | 000/00                                     | 8       | 39.4  | 52.7        | 3.1  | 7.8  | 39.4 | 52.7        | 3.1  |
| SA06   | PU      | Bar-Rup | 7          | 130/74                                      | 18.9    | -6.6  | 84.6        | 1.5  | 50.7 | -16.7| 84.6        | 1.5  |
|         | (overturned) |     |               |                                            |         |       |               |     |       |     |               |     |
| SA12   | PU      | Bar-Rup | 7          | 109/40–117/55                              | 7       | 26.8  | 48.9        | 2.5  | 38.5 | 26.4 | 51.6        | 2.3  |
| SA16   | PU      | Bar-Rup | 7          | 090/25                                     | 24.8    | 32.6  | 33.7        | 4.2  | 35.4 | 19.3 | 33.7        | 4.2  |
| SA19   | PU      | Bar-Rup | 10         | 115/40                                     | 335.2   | 17.6  | 25          | 4.7  | 354.5| 43.5 | 25          | 4.7  |
| Central Sector |
| AL08   | PNU     | Rup-Aq | 7             | 088/40                                     | 3       | 33    | 39.2        | 3.3  | 23.4 | 20.8 | 39.2        | 3.3  |
| AL06   | PU      | Bar-Rup | 7          | 124/14                                     | 358.7   | 20    | 29.4        | 5.2  | 4    | 27.2 | 29.4        | 5.2  |

NU1: First Neogene Unit (Aq: Aquitanian); PNU: Palaeogene–Neogene Unit (Rup-Aq: Rupelian–Aquitanian); PU: Palaeogene Unity (Bar-Rup: Bartonian–Rupelian); Cr: Cretaceous (Tur: Turonian). $D, I$: declination, incination; $\alpha_{95}, k$: statistical parameters (Fisher 1953). *Class 1 and 2 sites with anomalously shallow inclinations ($I < 25^\circ$) after bedding correction, discarded for further interpretation.
Results

The samples showed two magnetic behaviours corresponding to the two sampled lithologies (i.e. red clays/fine-grained sandstones and limestones). The characteristic remanent magnetization (ChRM) component ranged between 200–450 and 600 °C for red clays and fine sandstones and between 200–380 °C and 380–470 °C for limestones (Fig. 3). These maximum unblocking temperatures point to hematite as the main remanence carrier for the red clays and fine sandstones and to (titano-) magnetite for limestones. This is confirmed by the thermal demagnetization of the three-axes IRM.

All red clays and fine sandstones show a similar IRM acquisition behaviour (Fig. 4a, b, left); saturation is not reached in magnetic fields of 1.2 T. Thermal demagnetization of three-axes IRMs also shows the dominance of the high-coercivity phase with magnetization decaying smoothly from 0 to 675 °C (Fig. 4a, b, right). This indicates that the magnetic mineralogy of these samples is controlled by hematite. Regarding the limestones, most samples show IRM acquisition curves dominated by low-coercivity minerals saturated at fields of 300–400 mT, suggesting that (titano-)magnetite is the main carrier of the magnetization (Fig. 4c, d, left).

The thermal decay of the magnetization also shows the contribution of low- and medium-coercivity minerals decaying at between 200 °C and 350 °C, probably due to the presence of iron sulphides. However, the final decay of the magnetization occurs at c. 550 °C for the low-coercivity minerals, indicating the presence of magnetite (SA03, Fig. 4c, right). Site SA07 also shows a variable contribution of a higher-coercivity phase not saturated at 1.2 T (Fig. 4d). This high-coercivity phase decays between 100 and 200 °C during thermal demagnetization, suggesting the presence of goethite at this site (Fig. 4d).

After analysing the demagnetization diagrams of all samples, only samples with unambiguous ChRMs following the quality criteria mentioned in the last section and sites with low $\alpha_{95}$ angles ($<20^\circ$) were selected. From the 12 sites sampled on Cretaceous rocks, only site AL01 shows reliable ChRMs (see Table 1). However, this result has not been considered for further interpretation due to the impossibility of constraining the age of magnetization with data from only one site. Moreover, sites with anomalously shallow inclinations ($I<25^\circ$) after bedding correction (SA02, SA11 and AL13; Table 1) were not analysed further.

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**Fig. 3.** Demagnetization diagrams of representative samples from selected sites. Black (white) dots represent projection onto the horizontal (vertical) plane. TH: thermal demagnetization; ABC: after bedding correction.
It is worth noting that only 6 sites satisfied all these quality criteria (see Table 1), representing only 13% of the original sites in the dataset. In the studied area, rocks showing unsuccessful palaeomagnetic data, not analysed further because they do not satisfy the quality criteria probably due to unstable
and/or very low NRM intensities are: (1) all sampled Cretaceous marls and limestones, despite one sample (AL01) being performed on Turonian marls; (2) Campanian–Lutetian sandstones belonging to the Villalba de la Sierra Formation; and (3) sandstones and sandy clays sampled both on the Palaeogene (PU; Bartonian–Rupelian) and Palaeogene–Neogene units (PNU; Rupelian–Aquitanian), whereas clays and limestones of these units yielded successful lithologies.

Samples of both lithological groups show either normal or reverse polarity of the ChRM (Table 1; Fig. 5). Before bedding correction, site-mean directions are slightly scattered with a north direction and variable inclinations. After tectonic correction, their clustering does not improve significantly but the mean directions acquire similar inclinations (34–43°; Table 1; Fig. 5). We interpret the observed dispersion in declinations after tectonic correction of site-mean directions as being caused by differential vertical-axis rotation of individual sites with respect to the reference direction for the Eocene–Miocene interval for the geographic coordinates of the study area \( (D = 004^\circ, I = 48^\circ, \alpha_95 = 6^\circ) \). This reference direction was calculated from the Eocene, Oligocene and Miocene reference directions from Taberner et al. (1999), Barberà et al. (1996) and Larrasoaña et al. (2006), respectively, relocated to the geographic coordinates of the study area by the pole conversion method (Noël & Batt 1990). Sites AL07 and AL25 therefore show no vertical-axis rotation considering their error intervals and that of the reference direction; sites SA07, SA14 and AL11 (all of them located at the northern sector of the studied area) display an average clockwise rotation of \( 17^\circ \); and site AL26, located at the southern sector, displays an anticlockwise rotation of \( 21^\circ \) (Fig. 5c). A comparison of the strike deviations relative to declination deviations (strike test; see Eldredge et al. 1985) does not yield a conclusive result due to the scarcity of reliable data.

Theoretical vertical-axis rotations from shortening estimates

Most vertical-axis rotations deduced in compressional scenarios are related to the differential displacement of thrust sheets and/or lateral variations of tectonic shortening in fold and thrust belts (e.g. Bates 1989; McCaig & McClelland 1992; Allerton 1998; Wilkerson et al. 2002; Bayona et al. 2003; Sussman et al. 2004, 2012; Soto et al. 2006; Muñoz et al. 2013). This implies that simple map-view models of the rotational movement of thrust sheets can quantify shortening and how it varies along strike by means of trigonometric relations as proposed by Pueyo et al. (2004) and Oliva-Urcia & Pueyo (2007) (Fig. 6a). In a natural example with a high-resolution palaeomagnetic dataset of vertical-axis rotations, the theoretical shortening will coincide with the measured shortening from restored cross-sections only if it has been correctly estimated taking into account possible out-of-plane motions and internal deformation, which is often underestimated (Sussman et al. 2012).

In order to test this approach in the studied area and reinforce our palaeomagnetic results, a theoretical estimate of the amount of vertical-axis rotations was performed using four balanced cross-sections from Muñoz-Martín & De Vicente (1998), built perpendicular to the present-day orientation of the structures, with approximate WNW–ESE, west–east and WSW–ENE orientations (II-II′, IV-IV′, V-V′ and VI-VI′ sections, Fig. 6). From these cross-sections, we select only shortening values (ii, iv, v and vi in Fig. 6b) regarding the Altomira and Loranca structures, avoiding shortening from structures belonging to hinterland-wards Iberian structures (Sierra de Bascunñana Range, located to the east). According to Muñoz-Martín & De Vicente (1998), these shortening values are 7.2, 9.2, 14.3 and 14.3 km for the selected parts (ii, iv, v and vi, Fig. 6d) of cross-sections II, IV, V and VI, respectively. After applying the trigonometric technique by Oliva-Urcia & Pueyo (2007), the theoretical vertical-axis rotations obtained are 3.6° and 9.7° in a clockwise sense for sectors between cross-sections II and IV, V and VI, respectively (Fig. 6c). This would imply that the northern and central sectors of the Altomira–Loranca fold and thrust belt, as outlined in Figure 2, experienced clockwise vertical-axis rotations of 3.6° and 9.7°, respectively. However, the sector located between cross-sections V and VI (see Fig. 2) demonstrates an absence of vertical-axis rotations, as shortening considered from both cross-sections is the same (Fig. 6c).

Basement-cover structural relationships

The Altomira and Loranca fold and thrust belts display an Alpine contractual thin-skinned structure detached on the Middle–Upper Triassic evaporites and clays that affect the Jurassic–lower Palaeogene sediments (Muñoz-Martín 1997). Below the Mesozoic–Cenozoic cover, available seismic data show quite a flat basement (Palaeozoic and Lower Triassic rocks) top cut by high-angle Mesozoic faults (Muñoz-Martín & De Vicente 1998). Several authors have already postulated the influence of these previous basement faults on the nucleation of the posterior Tertiary structures (Muñoz-Martín 1997; Muñoz-Martín & De Vicente 1998; Biete et al. 2012).
Fig. 5. (a) Mean palaeomagnetic directions before (BBC) and after (ABC) bedding correction. The star represents the reference direction for the Eocene–Miocene interval for the geographical coordinates of the study area ($D = 004, I = 48, \alpha_{95} = 6$; see text). (b) Geological sketch of the studied area showing palaeomagnetic data considered for further kinematic interpretation. Arrows represent the site mean declination after bedding correction and cones represent the declination error of the mean directions ($\text{Dec err} = \alpha_{95}/\cos\text{Inc}$).
In this work, we study basement-cover structural relationships in order to deduce possible vertical-axis rotations, assuming the decoupling of deformation produced by the Middle–Upper Triassic décollement between the basement and cover units. This study was performed by means of

![Image of diagrams and text](image-url)

**Fig. 6.** (a) Trigonometric model for theoretical estimate of the vertical-axis rotations by means of gradient of shortening calculations. $G_s = (S_{c1} - S_{c2})/D = 2 \sin (\beta/2)$. Sketch modified from Oliva-Urcia & Pueyo (2007). (b) Location of balanced cross-sections by Muñoz-Martín & De Vicente (1998) (II-II', IV-IV', V-V', V-VI') in bold lines and parts of the sections considered in this work (ii, iv, v, vi) in dotted lines. (c) Application of the trigonometric technique by Oliva-Urcia & Pueyo (2007) to the Altomira–Loranca case. Estimated angles obtained through the comparison of shortenings of balanced cross-sections II v. IV ($\beta_1$), IV v. V ($\beta_2$) and V v. VI ($\beta_3$). (d) Cross-sections considered in this study, modified from Muñoz-Martín & De Vicente (1998).
the detailed analysis of surface and subsurface data of two selected areas located in the northern and southern sectors of the Loranca Basin around the Puerta–Pareja and El Hito anticlines, respectively (see Fig. 2). With respect to the El Hito area in the southern sector, this work benefits from the 3D geological model performed by Biete et al. (2012). After seismic interpretation, the conversion of time-domain to depth-domain data for both areas was carried out by generating a velocity model considering the sonic information from available well logs. The depth-converted seismic interpretations and surface data (i.e. construction of digital terrain model and data management) were integrated into a common 3D framework using the software gOcad®. From these 3D models, maps of structural contours were created for the top of the Lower Triassic and top of the Upper Triassic (Keuper facies) for each area (Figs 7 & 8).

In the northern sector, the only major structure deforming sediments filling the Loranca Basin is the Puerta–Pareja anticline (see cross-section in Fig. 1). In this case, surface data – bedding dip measurements, bedding and fault traces (Lendínez et al. 1989; Torres et al. 1990; Gabaldón et al. 1999a; Hernaiz et al. 1999a) – and subsurface data – 14 seismic reflection profiles (GEODE 2011) and three hydrocarbon exploration wells (Torralba-1, Santa Bárbara-1 and Belmontejo-1A; Lanaja 1987; GEODE 2011) – were used to create a 3D model. The detailed seismic interpretation of the Puerta–Pareja structure reveals the presence of a velocity pull-up seismic distortion (e.g. Gadallah & Fisher 2008) under the main Puerta–Pareja thrusts in the basement (Fig. 9a, b), discarding the existence of a possible basement structure controlling the nucleation of the Puerta–Pareja structure. This effect was already suggested by Muñoz-Martín & De Vicente (1998) based on gravimetric data. The 3D model shows how the geometry of the Puerta–Pareja structure varies along-strike from a relatively simple fault-propagation fold with a total fault displacement of c. 500 m in the south to a more complex geometry with two main thrusts following a breakthrough style and a total of 1200 m of fault displacement at its northern part (Fig. 7). No basement-cover structural relationships can therefore be inferred from this sector of the Loranca Basin in order to detect possible vertical-axis rotations.

Below the Altomira Range in the northern sector, stratigraphic and aeromagnetic data (Ardizone et al. 1989) indicate the presence of a large basement fault (Sacedón fault) which controlled the Triassic and Lower Cretaceous synrift deposition (Sopeña et al. 1988; Peropadre & Meléndez 2004) and the nucleation of the posterior Cenozoic compressional structures (Perucha et al. 1995; Muñoz-Martín & De Vicente 1998; Muñoz-Martín et al. 1998; Van Wees et al. 1996). However, the poor quality of available seismic data prevents analysis of its exact geometry and relationships with the cover structures there.

In the southern sector, the 3D geological model of El Hito area was performed using surface data (bedding dip measurements and bedding and fault traces from Albert & Ferrero 1990; Díaz de Neira & Cabra 1990; Díaz Molina & Lendínez 1992; Hernaiz et al. 1999b) and subsurface data, namely 21 seismic reflection profiles (GEODE 2011) and two hydrocarbon exploration wells (El Hito and Belmontejo-1A; Lanaja 1987; GEODE 2011). The El Hito area is characterized by several NNW–SSE-trending west-verging folds and thrusts that overlie several smooth basement highs (Figs 8 & 9c, d). The origin of these basement highs is related to the inversion, probably latest Cretaceous–Palaeocene in age, of Late Permian?–Early Triassic extensional faults (Biete et al. 2012). Taking into account the fact that inversion predated the formation of the cover Tertiary structures (i.e. formed mainly during the late Oligocene-early Miocene), these basement highs have been interpreted as mechanical perturbations controlling the nucleation of the posterior Tertiary structures (Biete et al. 2012). The orientation of these basement highs and the posterior Tertiary cover structures does not coincide exactly and highlights the existence of a partial decoupling between them (Fig. 8). The orientation of structures affecting the top of the basement (i.e. Lower Triassic) and the top of the Keuper facies shows an angle of 13° comparing the orientation of the main faults (see Fig. 8). Such an angle might be coherent with an anticlockwise vertical-axis rotation of the cover sediments with respect to a fixed basement in this sector. Other possible causes to explain the observed difference in the orientation of the basement and cover structures without implying vertical-axis rotation of the cover sediments could be: variation of thickness in the cover series; and/or the presence of anisotropies in the cover sediments as previous extensional faults. However, available subsurface data from this area do not show significant changes of thickness in the cover series and/or the presence of important previous extensional faults coinciding with these structures (Querol 1989).

**Discussion**

**Reliability of palaeomagnetic data**

Palaeomagnetism was chosen in this study as it is the only technique able to determine absolute vertical-axis rotations (e.g. Norris & Black 1961) and it is a robust technique to characterize the origin of obliquity (i.e. primary, progressive or secondary) in fold and thrust belts. However,
Fig. 7. Contour maps of the top of Palaeozoic–Lower Triassic basement and of the top of the Upper Triassic (Keuper facies) rocks in the Puerta–Pareja area. See location on Figure 2.
Fig. 8. Contour maps of the top of Palaeozoic–Lower Triassic basement and of the top of the Upper Triassic (Keuper facies) rocks in the El Hito area. Modified from Biete et al. (2012). See location on Figure 2. Rose diagrams represent the orientation of main faults.
Palaeomagnetic data have several limitations and sources of errors when applying them to understand fold and thrust belt kinematics (see Van der Voo 1990; Pueyo 2010): difficulties in the correct constraining of the age of magnetization and correct isolation of magnetic components often overlapped; internal deformation affecting the palaeomagnetic vector; and/or incorrect restoration of palaeomagnetic components in non-coaxial and/or complex structures. In this work, we assume that no important deformation affected the sampled rocks and palaeomagnetic vectors. Also, simple bed restoration of palaeomagnetic data was performed as we sampled in simple structures, avoiding periclinal terminations of folds or complex structures. However, our data still have the following two limitations: (1) a primary magnetization component is assumed; and (2) the scarcity of palaeomagnetic data that satisfy the statistics quality criteria.

A correct constraining of the age of magnetization acquisition is fundamental to obtain reliable structural interpretations. In most works, the

Fig. 9. Seismic profiles and cross-sections showing the geometry of (a, b) the Puerta–Pareja and (c, d) El Hito (modified from Biete et al. 2012) structures in the northern and southern sectors, respectively. The apparent antiform at the top of the Middle Triassic in (a) has been interpreted as a velocity pull-up seismic distortion.
primary magnetization components are distinguished based on the results of both the reverse and fold tests (e.g. Graham 1949; Van der Voo 1990; Weil & Van der Voo 2002). In this work we interpret the ChRM as a primary component because of: (1) the presence of normal and reverse polarity of this component; and (2) the mean directions acquire similar inclinations after the tectonic correction, despite declination scattering. On the other hand, we obtained a low number of reliable palaeomagnetic data for the calculation of vertical-axis rotations; only 6 sites from 45 can be considered, due to few suitable outcrops for sampling and the poor magnetic signal of most samples in the laboratory. However, as this work shows, the integration of other types of data with this palaeomagnetic dataset can help to characterize the origin of obliquity of the Altomira and Loranca fold and thrust belts.

**Vertical-axis rotations in the Altomira and Loranca fold and thrust belts deduced from palaeomagnetism**

Although scarce, some kinematic information can be deduced from the palaeomagnetic sites. The results of the palaeomagnetic analysis show that the present-day north–south orientation of the Altomira and Loranca structures at its central portion is a primary feature, that is, they were formed with a roughly north–south orientation already oblique with respect to the NW–SE orientation of the Iberian Chain as our results indicate non-vertical-axis rotations there or minor vertical-axis rotations (site AL07, Table 1). Sites located at the northern sector show a clockwise vertical-axis rotation up to 17°. It is worth noting that, despite being sparse, reliable sites in the northern sector (SA14, AL11 and SA07, Table 1) are not clustered and restricted to a particular region but distributed all along this sector, which makes us confident about the consistency of these results. In the southern sector, only site AL26 shows an anticlockwise vertical-axis rotation up to 21° (Fig. 5 & Table 1; location in Fig. 2). Site AL25, close to site AL26 but sampled in younger rocks, does not record any vertical-axis rotation, however (Fig. 5 & Table 1; location in Fig. 2). This might help to constrain the end of the vertical-axis rotation in this sector as it occurred before the deposition of site AL25 (Rupelian–early Aquitanian in age), although more data would be necessary to confirm it as its associated uncertainty is quite high. In the northern sector, site SA14 is the youngest site recording rotation (Fig. 5 & Table 1; location in Fig. 2), which suggests that the vertical-axis rotation would be posterior to the Aquitanian.

The 17° clockwise and 21° anticlockwise vertical-axis rotations inferred for the northern and southern sectors, respectively, would imply a secondary component to account for the subtle curved geometry of the Altomira and Loranca structures in plan-view (see Fig. 2), that is, the NNE–SSW and NNW–SSE orientation of structures in the northern and southern sectors, respectively.

**Integration of basement-cover relationships, theoretical calculations and palaeomagnetic data**

Kinematics of the Altomira and Loranca fold and thrust belts, mainly concerning the relative timing of formation of the different structures, has been well constrained by macro- and micro-structural data and tectonic–sedimentation relationships (Díaz Molina et al. 1995; Gómez et al. 1996; Muñoz-Martín 1997; Muñoz-Martín & De Vicente 1998; Hernaiz et al. 1999a, b). However, the characterization of the primary or secondary origin of its roughly north–south oblique orientation has not been analysed before by means of palaeomagnetism.

Previous works have postulated a primary origin (i.e. absence of vertical-axis rotations to explain their present-day trend) of structures of the Altomira Range and Loranca Basin based on the following features: variations in the basal detachment conditions in a roughly north–south direction; the existence of oblique normal basement faults that would have conditioned the oblique nucleation of the cover structures (Van Wees & Stephenson 1995; Muñoz-Martín & De Vicente 1998; Biete et al. 2012); and the influence of the double convergence of the Pyrenean–Iberian and Betic Chains added to these oblique anisotropies (Muñoz-Martín et al. 1998; Andeweg et al. 1999). Analogue and numerical modelling has proven that the localization of outer deformation fronts, such as the Altomira Range, is highly influenced by the boundary between sectors with different basal detachment conditions (e.g. Cotton & Koyi 2000; Schreurs et al. 2001; Bahroudi & Koyi 2003; Storti et al. 2007) and the nucleation of single thrusts is conditioned by pre-existing basement highs (e.g. Schedl & Wiltschko 1987). Our palaeomagnetic data confirm the absence of vertical-axis rotation to account for the north–south orientation of structures in the central sector of the Altomira Range and Loranca Basin. At this central sector, theoretical calculations of vertical-axis rotations from shortening based in balanced 2D cross-sections perpendicular to the principal structures from Muñoz-Martín & De Vicente (1998) show 9.7° of clockwise vertical-axis rotation (Fig. 6). These data would match well, as vertical-axis rotations under 10° are in the
limit of the resolution of palaeomagnetic measurements. Close to this central sector southwards (between sections V–V′ and VI–VI′, see Fig. 2), theoretical calculations of vertical-axis rotation indicate the absence of vertical-axis rotation for the Altomira and Loranca fold and thrust belts, supporting the primary origin of the north–south orientation of structures there.

Palaeomagnetic data also indicate the secondary acquisition of the slightly curved geometry of these two fold and thrust belts by clockwise and anticlockwise vertical-axis rotations in the northern and southern sectors, respectively. In the southern sector, basement-cover relationships analysed in the Loranca Basin (i.e. El Hito area) might be coherent with an anticlockwise vertical-axis rotation of the cover sediments with respect to a fixed basement of 13° (Fig. 8). This angle matches fairly well with data of the only available palaeomagnetic site (AL26) located there (Fig. 2; Table 1) that shows 21° (±8°) of vertical-axis rotation in the same sense. Data obtained from these two techniques would therefore indicate the same kinematic evolution in this southern sector.

With respect to the northern sector of the Loranca Basin, the absence of basement structures controlling the nucleation of the Puerta–Pareja antcline does not allow to inference of vertical-axis rotation there using this technique. Considering both the Altomira and Loranca fold and thrust belts, theoretical calculations of vertical-axis rotations yield a 3.6° clockwise vertical-axis rotation (Fig. 6). Despite a difference of 13° between the theoretical angle and that obtained from palaeomagnetic data (17°), both methods deduce clockwise vertical-axis rotations, supporting a similar kinematic model. We interpret the along-strike fault displacement differences of the Puerta–Pareja antcline in terms of accommodating the general slight clockwise vertical-axis rotation of the area.

In summary, the origin of the oblique orientation of structures of the Altomira and Loranca fold and thrust belts based on palaeomagnetic data, theoretical calculations and basement-cover relationships is primary in the central sector of the studied area (i.e. in sector with structures oriented north–south), and the origin of the small deviation structures with respect to the north–south direction is secondary at the northern and southern sectors.

Conclusions

This work deals with the integration of palaeomagnetic data and other two datasets to characterize the primary v. secondary obliquity of structures of the Altomira and Loranca fold and thrust belts (Iberian Chain, Central Spain).

Pre- and syntectonic Cretaceous–Lower Miocene rocks cropping out along the Altomira Range and Loranca Basin were sampled for palaeomagnetism. Scarce palaeomagnetic data (only 13% of sites satisfied the quality criteria) were obtained due to few suitable outcrops for sampling and rocks with unstable and/or very low intensities of the NRM. This makes the comparison of palaeomagnetic results with other data, from (1) theoretical calculations of vertical-axis rotations that must occur to accommodate the along-strike shortening variations and (2) basement-cover relationships, necessary. The integration of these three methodologies supports the conclusion that the origin of the oblique orientation of structures of the Altomira and Loranca fold and thrust belts is primary in the central sector of the studied area (i.e. in sector with structures oriented north–south). In the northern and southern sectors, the subtle curved geometry of the Altomira and Loranca structures in plan-view (i.e. the NNE–SSW and NWW–SSE orientation of structures in the northern and southern sectors, respectively) is secondary. This approach highlights the importance of integrating different datasets to characterize the obliquity of fold and thrust belts.

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