Three-dimensional gravity and magnetic modeling of crustal indentation and wedging in the western Pyrenees-Cantabrian Mountains

D. Pedreira,[1] J. A. Pulgar,[1] J. Gallart,[2] and M. Torné[2]

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[1] The complex crustal structure of the boundary zone between the Iberian and European plates, from the western Pyrenees to the Cantabrian Mountains, is probed by three-dimensional (3-D) gravity and magnetic modeling constrained by deep seismic profiles. The 3-D modeling results support the presence of a continuous Iberian crustal root and suggest that the geometry of the orogenic belt that formed in latest Cretaceous-Tertiary times along the northern margin of Iberia was conditioned by oblique structures separating areas characterized by different tectonic styles. In the western Pyrenees and the Basque-Cantabrian basin (a thick Mesozoic basin presently incorporated to the Pyrenean-Cantabrian belt), the relatively narrow thinning of the crust inherited from the Mesozoic rifting stage conditioned a structural style in which portions of the southward indenting European lower crust are interpreted to be back thrusted toward the north and uplifted to shallow depths, promoting the appearance of significant potential field anomalies. In the Basque-Cantabrian basin, the strongest aeromagnetic anomaly of the whole Iberian Mainland is superimposed on the eastern part of a well-defined positive gravity anomaly, similar in amplitude and wavelength to those located along the North Pyrenean Zone. These observations suggest that the eastern part of the dense, lower crustal causative body is strongly magnetized and may correspond to a gabbroic cumulate originated in the axis of the ancient Mesozoic rift. To the west, Tertiary compression affected the North Iberian (Cantabrian) passive continental margin, whose geometry and inherited structures conditioned the formation of a double crustal delamination and the uplift of the Cantabrian Mountains.

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1. Introduction

[2] In Late Cretaceous-Tertiary times, convergence between the European plate and the Iberian subplate gave rise to the inversion of the Mesozoic basins located between them and the uplift of basement blocks forming two E-W trending mountain chains: the Pyrenees and the Cantabrian Mountains. From a geographical point of view, the Pyrenees are located along the isthmus between the Iberian Peninsula and France, while the Cantabrian Mountains are located immediately to the west, bounded to the north by the North Iberian (or Cantabrian) coast, in the southern side of the Bay of Biscay (Figure 1). From a geological point of view, both mountain systems are in fact parts of the same doubly vergent Alpine belt, in which the south vergent branch can be continuously followed from the South Pyrenean Zone to Cantabrian Mountains, and the north vergent one is prolonged from the North Pyrenean Zone along the North Iberian continental margin. However, significant differences are observed along the strike of the Pyrenean-Cantabrian belt in terms of direction of structural trends, predominance of northern versus southern vergencies, involvement of the Mesozoic cover in the Alpine thrust sheets, exhumation of the Paleozoic basement, and the inferred amount of convergence, among others. Also, significant lower altitudes are found in the eastern part of the Cantabrian Mountains, which developed over a wide area, the Basque-Cantabrian basin, where particularly intense extensional deformation and sedimentation occurred during the Mesozoic in relation to the opening of the Bay of Biscay [e.g., *Rat*, 1988; *Vergés et al.*, 2002] (Figure 1).

[3] This complex transitional domain between an orogenic belt originated as a consequence of the collision between two vast continental masses (the Pyrenees) and a mountain chain raised up over a continental margin (the Cantabrian Mountains) constitutes a key element to understand in a global manner the Alpine structure and tectonic evolution of

[1]Departamento de Geología, Universidad de Oviedo, Oviedo, Spain.
[2]Departamento de Estructura y Dinámica de la Tierra, Instituto de Ciencias de la Tierra "Jaume Almera," Consejo Superior de Investigaciones Científicas, Barcelona, Spain.

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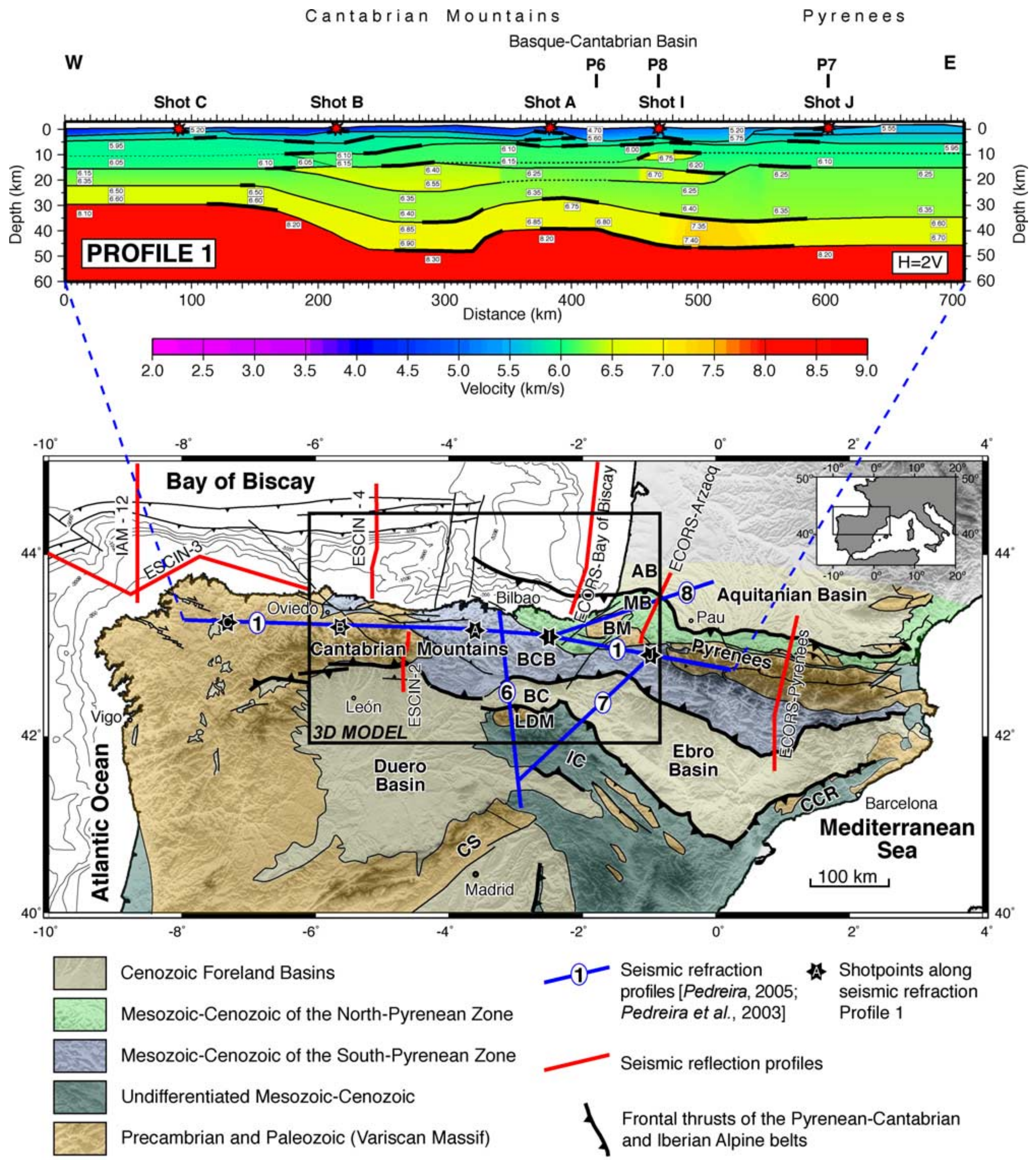


Figure 1. (bottom) Tectonic map of the northern Iberian Peninsula showing the location of the 3-D crustal model presented in this paper. AB, Arzacq basin; BC, Bureba Corridor; BCB, Basque-Cantabrian basin; BM, Basque Massifs; CCR, Catalan Costal Ranges; IC, Iberian Chain; LDM, La Demanda Massif; MB, Mauléon basin. (top) P wave velocity-depth model for seismic refraction wide-angle reflection profile 1, from *Pedreira* [2005] (slightly modified from *Pedreira et al.* [2003]).

the boundary zone between the Iberian and European plates. However, the geophysical knowledge of this domain was very scarce until the acquisition of a set of seismic refraction/wide-angle reflection profiles in 1997 [*Pedreira et al.*, 2003]. These profiles revealed a highly reworked crust in this area, with a continuous crustal root from the Pyrenees to the Cantabrian Mountains. The root reaches 46–48 km depth along E-W profile 1 (Figure 1), locally rising to

~40 km in the western part of the Basque-Cantabrian basin, and strongly contrasting with the 30–32 km thick, typical Variscan crust of the western end of the profile and other neighboring parts of the Iberian Variscan belt [*Córdoba et al.*, 1987, 1988; *Fernández-Viejo et al.*, 2000]. Both active seismic methods and passive seismic techniques, like teleseismic receiver functions analysis [*Díaz et al.*, 2003], are consistent in revealing that the root is developed by the northward underthrusting of the Iberian lower middle crust, forced by the southward drive of the thinner European/Cantabrian Margin crust [*Pulgar et al.*, 1996]. This indentation seems to be conditioned or affected by deep lateral structures, oblique to the strike of the chain, whose existence has been postulated to account for the discontinuous presence of a high-velocity intracrustal layer along the E-W profile 1 (Figure 1), attributed to the indenting lower crustal wedge from the northern domain [*Pedreira et al.*, 2003]. At a shallower level, E-W profile 1 also revealed the presence of a small body of high velocities, typical of lower crustal rocks (6.75 km/s) at only 9–10 km depth beneath shot point I in Figure 1. This was considered by *Pedreira et al.* [2003] to be the causative body of a remarkable positive gravity anomaly and the strongest aeromagnetic anomaly of the whole Spanish Mainland: the Basque Country Magnetic Anomaly [*Ardizone et al.*, 1989; *Aller and Zeyen*, 1996].

[4] All these interpretations, based on the resulting two-dimensional (2-D) velocity-depth profiles and the observation of potential field anomalies, will be fully tested in this work through the construction of a 3-D gravity and magnetic model for the transition zone between the Pyrenees and the Cantabrian Mountains. The modeling of potential fields will not only provide a more complete understanding of the crustal architecture and along-strike partitioning of deformation of this orogenic belt, but also of the physical properties and possible composition of anomalous crustal materials that are inferred.

[5] When describing the structure of this area, a terminology problem arises from the fact that the Alpine compressional deformation did not involve a true plate boundary between Iberia and Europe. Instead, a tectonic inversion took place over a wide zone of extended continental crust without evidences of oceanization. In the following sections, and for descriptive purposes, we adopted the criterion that 'Iberian crust' is used to designate the autochthonous crust of the Iberian Peninsula to the south and beneath the Pyrenean-Cantabrian southern frontal thrust, while 'European crust' refers to the overriding allochthonous crust.

2. Modeling Technique and Structural Constraints

[6] We used the interactive software IGMAS [*Götze and Lahmeyer*, 1988; *Schmidt and Götze*, 1998, 1999] to construct the model and calculate its 3-D gravity/magnetic response. The structure is introduced along parallel vertical sections, by defining layer boundaries separating bodies with different densities and/or magnetic susceptibilities. The program then interpolates the 3-D geometry by triangulation of equivalent layer boundaries between adjacent vertical planes, allowing a good representation of geological bodies and structures. Fitting between observed and calculated anomalies is achieved by forward modeling.

[7] In this work, the geological structure of the modeled area was defined along 22 vertical sections, N-S oriented, and 270 km long (Figure 2). Their E-W separation is variable, from 8 to 25 km, depending on the structural complexity of each zone of the model, covering a total length of 425 km. Although the studied area is limited to 425×270 km, the borders of the model are sufficiently extended to each side to avoid edge effects. In the vertical direction, the model is defined between 0 and 60 km depth. The gravity and magnetic stations are placed at their measurement heights above sea level, but the topographic body was not included in the model because it is virtually nonmagnetic and its effect on the gravity attraction was already subtracted by the Bouguer and terrain corrections. Small errors are to be expected in areas where the densities of the topographic masses significantly differ from that used in the Bouguer and terrain corrections, but these errors can hardly be greater than 3–4% of the total observed variation in the gravity field in this area and therefore can be disregarded for the purposes of this crustal-scale modeling.

[8] Several constraints were used to define the structure (Figure 2):

[9] 1. For the shallow structure, the base of the Cenozoic foreland basins was fixed from published depth contour maps [*Instituto Geológico y Minero de España* (*IGME*), 1990; *Gallastegui*, 2000]. In the case of the Duero basin, contours for the top of pre-Mesozoic basement were also used [*Gallastegui*, 2000]. Well log information helped to determine the thickness of Mesozoic-Cenozoic deposits, especially in the Basque Cantabrian basin [*IGME*, 1987; *Bois et al.*, 1997]. Finally, in some areas, the structure is based on published geological cross sections and shallow seismic reflection profiles (see situation and references in Figure 2).

[10] 2. For the deep structure, the base of the upper, middle, and lower crustal layers were fixed (±1 km) in the vertical planes at the crossing points with the seismic refraction/wide-angle reflection profiles shown in Figure 2. The velocity-depth models used were taken from *Pedreira* [2005], which are slightly modified versions of those presented by *Pedreira et al.* [2003]. Five deep seismic reflection profiles provide further constraints on the general crustal structure: ESCIN-1 [*Pérez-Estaún et al.*, 1994; *Gallastegui et al.*, 1997], ESCIN-2 [*Pulgar et al.*, 1996, 1997; *Gallastegui*, 2000], ESCIN-4 [*Gallastegui*, 2000; *Gallastegui et al.*, 2002], ECORS-Arzacq [*Daignières et al.*, 1994; *Teixell*, 1998] and ECORS-Bay of Biscay [*Pinet et al.*, 1987; *Bois and Gariel*, 1994].

3. Gravity Modeling

3.1. Origin and Processing of Gravity Data

[11] The gravity anomaly map used for the modeling was constructed from different data sets (Figure 3). Up to 3505 measurements in the northern Iberian Peninsula were provided by the Bureau Gravimétrique International (BGI), and 707 come from recent gravity surveys in the Cantabrian Mountains and northern Duero basin [*Pedreira*, 1998, 2005; *Gallastegui*, 2000]. All these data were referenced to the IGSN-71, converted to free-air anomalies using the Geodetic Reference System formula of 1967 (GRS-67), and to simple Bouguer anomalies considering the standard density

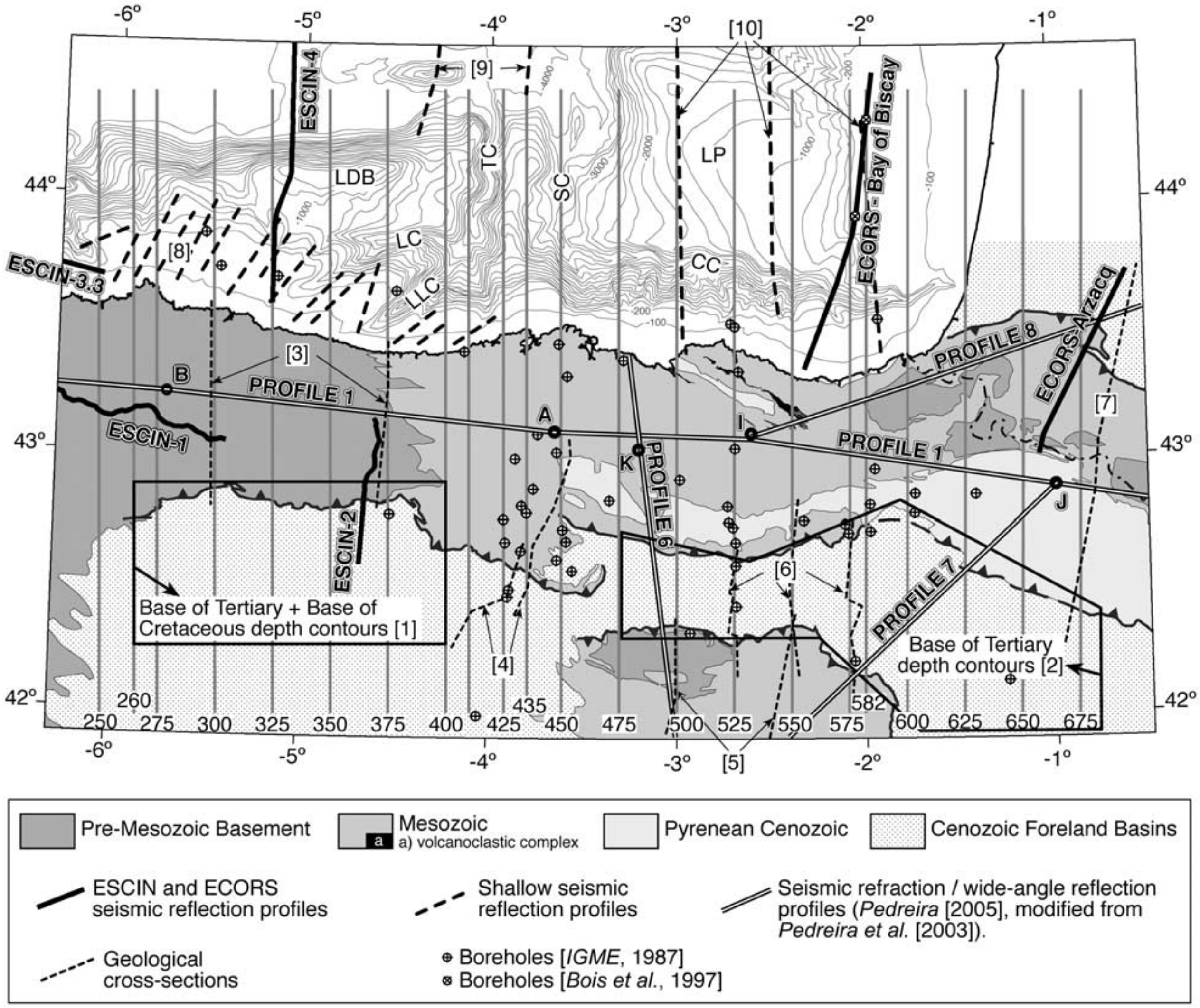


Figure 2. Schematic geological map showing the situation of the 22 N-S oriented vertical profiles (in grey) used to define the structure of the model and the constraints considered. Numbers at the bottom of each vertical plane indicate their UTM zone 30 easting coordinate (in km). Numbers within brackets indicate the following references: 1, *Gallastegui* [2000]; 2, *IGME* [1990]; 3, *Alonso et al.* [1996]; 4, *Hernaiz Huerta and Solé Pont* [2000]; 5, *Guimerà et al.* [1995]; 6, *Muñoz-Jiménez and Casas-Sainz* [1997]; 7, *Teixell* [1998]; 8, *Boillot et al.* [1971]; 9, *Derégnaucourt and Boillot* [1982]; 10, *Valéry et al.* [1971]. CC, Capbreton Canyon; LC, Lastres Canyon; LDB, Le Danois Bank; LLC, Llanes Canyon; LP, Landes Platform; SC, Santander Canyon; TC, Torrelavega Canyon.

of 2670 kg/m^3. Terrain corrections were computed out to 20 km around each station.

[12] In the easternmost part of the area chosen for modeling (southern France, Pyrenees and northern Ebro basin), Bouguer anomaly data come from a 4 × 4 km grid provided by the GeoFrance3D Project [*Grandjean et al.*, 1998]. The original data were also referenced to the IGSN-71 and calculated using the GRS-67 formula and Bouguer density of 2670 kg/m^3. Terrain corrections are variable, generally up to 22 or 167 km from the measurement point.

[13] Finally, free-air anomaly values in the Bay of Biscay were obtained from the satellite-derived database of *Sandwell and Smith* [1997] (version 9.2). Shipborne data is very scarce for this area, but comparison with available tracks shows very small differences except for an E-W track very close to the coastline, west of Santander, where mismatches up to 20–40 mGal are observed [*Pedreira*, 2005]. *Sandwell and Smith* [1997] point out that important errors are to be expected in coastal areas due to the short-wavelength noise produced by tide effects. This track is in fact located in a narrow (∼15–20 km), elongated band, immediately to the north of the coastline between Gijón and Santander, containing short-wavelength anomalies that are difficult to correlate with bathymetric or geological features. Moreover, strong discrepancies with land data are observed along the coastline in this region. Therefore data inside this band were omitted in the modeling (Figure 3).

3.2. Description of the Anomaly Map

[14] The resulting anomaly map, with Bouguer anomalies on land and free-air anomalies offshore, is shown in Figure 4a. Surprisingly, no negative anomaly is observed to be related to

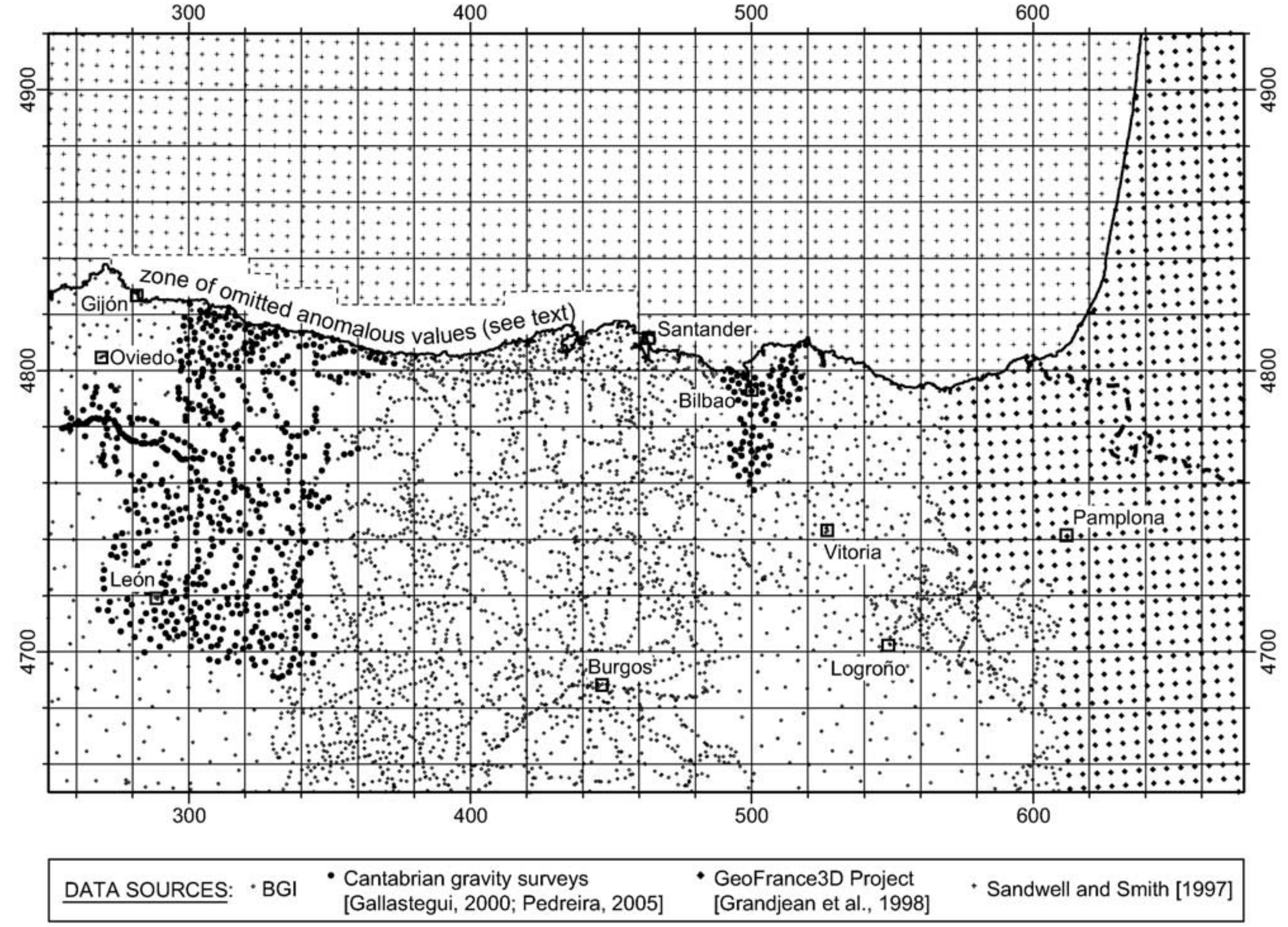
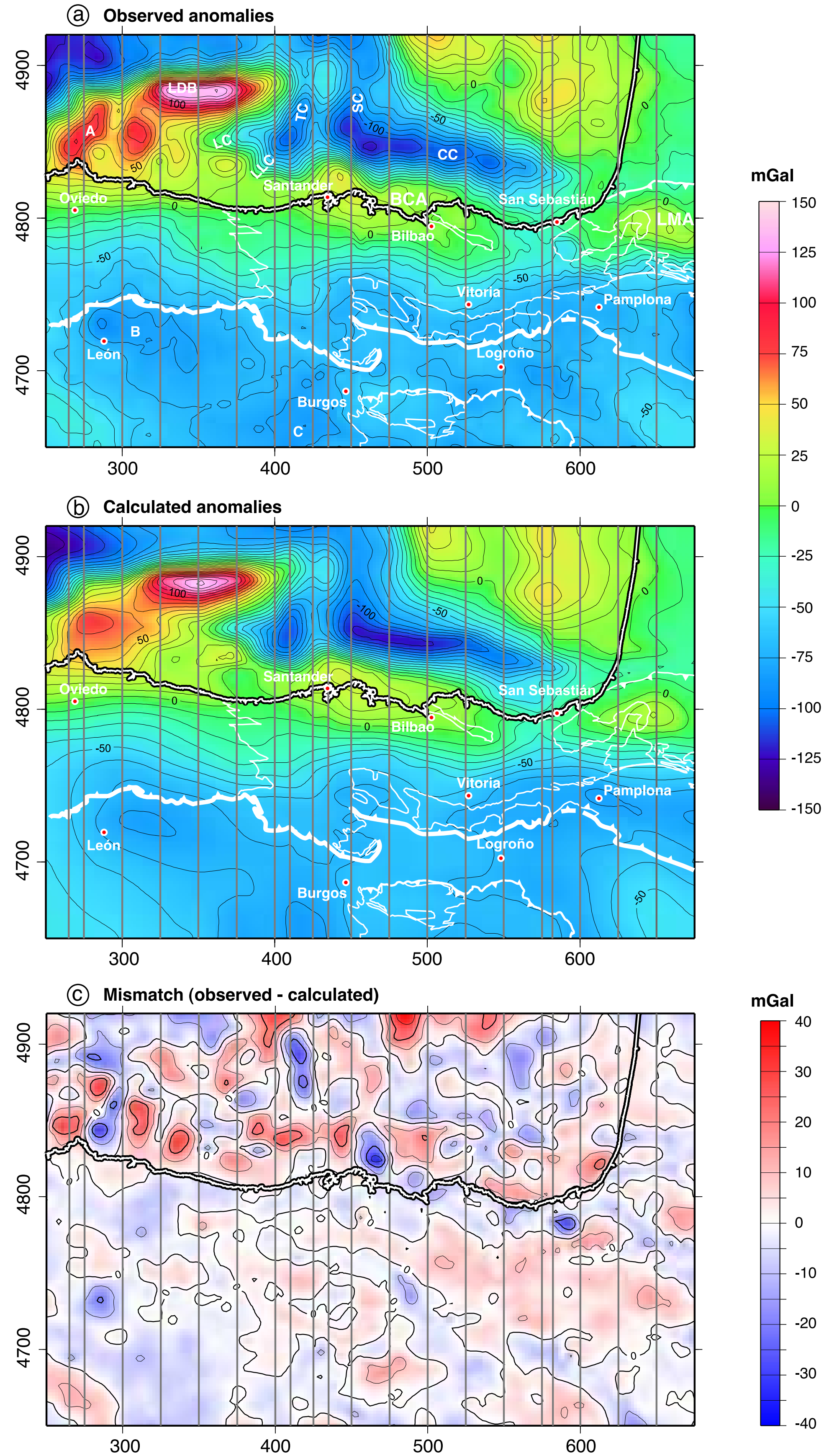


Figure 3. Location and source of gravity stations used in the modeling (UTM zone 30 coordinates, in km).

the presence of the crustal root under the Cantabrian Mountains (as it is the case in the Central Pyrenees [e.g., *Torné et al.*, 1989; *Casas et al.*, 1997; *Vacher and Souriau*, 2001]), even though this root is clearly revealed by different seismic experiments [*Pulgar et al.*, 1996; *Fernández-Viejo et al.*, 1998, 2000; *Gallastegui*, 2000; *Pedreira et al.*, 2003]. Thus exploring the requirements to reconcile gravity anomalies and seismic observations in this area becomes a very attractive problem.

[15] In the Bay of Biscay, free-air anomalies properly reflect the bathymetry. Minimum values are found in the abyssal plain (northwestern corner), and along the Torrelavega, Santander, Capbreton, Lastres and Llanes canyons (TC, SC, CC, LC and LLC, respectively, in Figure 4a). The highest free-air anomaly values, up to 140 mGal, are found over Le Danois Bank (LDB), where the water layer is reduced to 500–700 m and pre-Mesozoic crystalline rocks reach the seafloor [*Capdevila et al.*, 1974, 1980]. To the south of the Capbretron Canyon, a maximum is observed with an E-W orientation along the coast, from near San Sebastian to Santander, where values up to 20–40 mGal are found (Basque-Cantabrian Anomaly, BCA in Figure 4a). Toward the east, this regional maximum ends, but another positive anomaly with similar amplitude and wavelength (although with a shorter extent in E-W direction) is present near the eastern border of the modeled area: the Labord-Mauléon anomaly (LMA) [*Daignières et al.*, 1981; *Grandjean*, 1994; *Casas et al.*, 1997; *Vacher and Souriau*, 2001]. West of Santander, the Basque-Cantabrian positive anomaly (BCA) vanishes against a N-S alignment following the Torrelavega Canyon, although other positive anomalies are found along the Cantabrian continental platform. South of them, in the central Cantabrian Mountains, gravity values decrease from the coastline to the mountain front, to the south of which an E-W elongated minimum reaching −90 mGal (B in Figure 4a) is observed over a local depocenter in the Duero foreland basin [*Alonso et al.*, 1996; *Gallastegui*, 2000]. To the southeast, another negative anomaly reaching −80 mGal (C in Figure 4a) may be related to another local depocenter that could result from the flexure induced in the basement by the Alpine uplift of the Iberian Chain. The relationship between surface geology and gravity anomalies becomes especially confusing in the southeastern quadrant of the map, where an irregular pattern of local minima and maxima is observed within and along the edges of the Cenozoic foreland basin. These features might be related to several factors, including the presence of dense conglomerates at the borders of the basin and other



ⓐ Observed anomalies
ⓑ Calculated anomalies
ⓒ Mismatch (observed - calculated)
mGal
LDB
A
B
C
LC
LLC
TC
SC
CC
BCA
LMA
Oviedo
Santander
San Sebastián
Bilbao
Vitoria
Pamplona
León
Logroño
Burgos

Figure 4

Table 1. Densities and Magnetic Susceptibilities Used in the Modeling

Model Bodies	Density, kg/m^3	Magnetic Susceptibility, SI
Water	1030	-
Cenozoic sediments in the northern side of the Pyrenean-Cantabrian belt	2300	-
Tertiary of Duero basin (conglomerates, northern border)	2600	-
Tertiary of Duero basin (fine sediments)	2450	-
Tertiary of Ebro basin	2530	-
Tertiary of the South Pyrenean Zone	2630	-
Tectonized zone at the foot of the continental talus	2550	-
Mesozoic (post-Keuper)	2450–2650[a]	-
Mesozoic volcanoclastic complex (Biscay Synclinorium)	2650	0.04
Keuper	2250	-
Upper crust (pre-Keuper basement)	2670	0.001
Middle crust	2840	0.0035
Iberian lower crust	2930	0.005
European lower crust	2970	0.007
Anomalous (highly magnetized) lower crustal body	3000	0.09
Mantle	3300	-
Reference	2670	-

[a]See text for details.

lithological contrasts within it, a gradual covering of the Cenozoic deposits under long (>20 km), low-angle thrust ramps, a widespread presence of low-density salt deposits immediately above the frontal thrust of the inverted Basque-Cantabrian basin, and the presence of small Alpine reverse faults locally rising the basement under the Cenozoic sediments [e.g., *Muñoz-Jiménez and Casas-Sainz*, 1997].

3.3. Density Data

[16] Density values for the crustal layers differentiated in the model come from various sources and are summarized in Table 1.

[17] The crystalline crust was divided in three main layers (upper, middle and lower crust), following the interpretation of the four seismic refraction/wide-angle reflection profiles displayed in Figure 1 [*Pedreira et al.*, 2003; *Pedreira*, 2005]. Their densities were obtained from their mean P wave velocities, which were 5.75, 6.21 and 6.78 km/s for the undifferentiated (Iberian/European) upper and middle crustal levels and the Iberian lower crust, respectively. Density values finally adopted, lying within the envelopes defined by *Barton* [1986] in the *Ludwig et al.* [1970] velocity-density curve, were 2670, 2840, and 2930 kg/m^3, respectively. For the European lower crust, a slightly higher value was used (2970 kg/m^3), as it is suggested by the increase of seismic velocity of this level toward the north in the Bay of Biscay, where the crust becomes thinner [*Fernández-Viejo et al.*, 1998]. Also, for the basal part of the high-velocity body identified beneath shot point I at 9–10 km depth, where the velocity is less constrained than at its top, a slightly higher value was used: 3000 kg/m^3. The reason for this is that the potential field modeling requires a zone of increased density and magnetic behavior, as it will be discussed in more detail in the following sections. For the mantle, we assumed a density of 3300 kg/m^3.

[18] Direct density determinations in samples from the Paleozoic outcrops of the area give similar mean values for the upper crust: 2670 kg/m^3 in the central Cantabrian Mountains (unknown number of samples) [*Evers*, 1967], 2688 kg/m^3 in the Basque Massifs (61 samples), and 2642 kg/m^3 in the Demanda Massif (18 samples) [*Adam*, 1993]. Above this basement (in which we included the Permian and pre-Keuper Triassic), nine units were differentiated.

[19] 1. Triassic saline materials (facies Keuper) play an important role in the distribution of gravity anomalies due to the significant thickness (up to several km) they can reach in some parts of the Basque-Cantabrian and Mauléon-Arzacq basins (see Figure 1 for location), and their relatively low density. We adopted for these bodies a density of 2250 kg/m^3, which is the average value estimated by *Pinto et al.* [2005] after a detailed 3-D gravimetric study of Triassic salt diapirs located in the marginal areas of the Basque-Cantabrian basin.

[20] 2. The remaining Mesozoic materials (Jurassic and Cretaceous) were grouped in one single body. However, this body shows different density in the western and eastern parts of the model. In the eastern part, direct density measurements in Mesozoic samples of the North and South Pyrenean zones indicate average values of 2637 (48 samples) and 2666 kg/m^3 (12 samples), respectively [*Adam*, 1993]. Therefore we initially assigned a density of 2650 kg/m^3 to this body. However, these materials also continue toward the west within the study area along the North Iberian continental margin, where they seem to have lower densities. In the Le Danois Bank, *Gallastegui* [2000] differentiated several layers within the Mesozoic, with a mean velocity of ~3.6 km/s. Using the empirical relationship between P wave velocity and density of *Ludwig et al.* [1970], the Mesozoic should have a density between 2200 and 2500 kg/m^3 in this area. Moreover, in the western part of the modeled area, the Mesozoic is represented on land by thin Upper Cretaceous layers beneath the Cenozoic Duero basin, with a mean density of ~2450 kg/m^3 according to different density logs [*Gómez-Ortiz et al.*, 2005]. Therefore a density of 2450 kg/m^3 seems to be more appropriate for the western part of the modeled area, from plane 350 toward the west. Since the modeling software does not allow density gradients to be included within layers, a transitional zone was introduced between planes 350 and 400, where a density of 2550 kg/m^3 was assumed for this body.

[21] 3. Tertiary materials involved in the Pyrenean deformation and incorporated to the South Pyrenean Zone (Paleocene-Eocene) were assigned a density of 2630 kg/m^3,

Figure 4. (a) Observed and (b) calculated gravity anomalies in the studied area (Bouguer on land and free-air offshore). (c) Mismatch between observed and calculated anomalies. Contours are every 10 mGal. CC, Capbreton Canyon; LC, Lastres Canyon; LDB, Le Danois Bank; LLC, Llanes Canyon; LP, Landes Platform; SC, Santander Canyon; TC, Torrelavega Canyon; BCA, Basque-Cantabrian Anomaly; LMA, Labord-Mauléon Anomaly; A, B, and C are other anomalies referred in the text. White lines: main geological contacts. Thick black/white line indicates the coastline. Light grey lines indicate the vertical planes used to construct the geometry of the 3-D model (see text).

according to the mean value of 37 direct measurements carried out by *Adam* [1993].

[22] 4. Conglomeratic facies in the northern border of the Duero foreland basin, formed by Paleozoic clasts, are assumed to have a density of 2600 kg/m^3, the average value considered by *Torné et al.* [1989] for the Cenozoic conglomeratic series in their gravity model along the ECORS-Pyrenees profile.

[23] 5. For the nonconglomeratic Cenozoic sediments of the Duero foreland basin, a density of 2450 kg/m^3 was used, the same usually considered for the Ebro basin [*Torné et al.*, 1989; *Salas and Casas*, 1993; *Casas et al.*, 1997].

[24] 6. Outcrops of Cenozoic sediments in the NW Ebro basin and the Bureba corridor, which connects the Ebro Basin with the Duero basin to the west, are correlated with highly irregular distribution of local gravity highs and lows, revealing complex lithological contrasts. Instead of differentiating dense bodies and fine sediments as in the case of the Duero basin, we simplify the problem considering an intermediate density of 2530 kg/m^3. The boundary between this Cenozoic and that of the Duero basin is located in the plane 450.

[25] 7. Cenozoic sediments in the northern side of the Pyrenean-Cantabrian belt, within the modeled area are mostly present beneath the seafloor of the Bay of Biscay. On land, they form small outcrops in the Basque-Cantabrian and Mauléon basins, thickening toward the north in the Arzacq-Aquitaine basin. In the Mauléon and Arzacq basins, *Grandjean* [1994] obtained density versus depth curves from sonic logs, in which a mean density of ~2300 kg/m^3 can be derived for the Tertiary. The same density was used by *Álvarez-Marrón et al.* [1997] for the Cenozoic sediments of the abyssal plain in a gravity model along the ESCIN-4 transect, based on data from the DSDP boreholes 118 and 119, located some km to the west. Moreover, in Le Danois Bank, *Gallastegui* [2000] found mean P wave velocities as low as ~2.0 km/s for the sediments of this age. Therefore all Cenozoic sediments in the northern side of the belt were joined in one single body of density 2300 kg/m^3.

[26] 8. A strongly tectonized body located at the foot of the continental slope, with accretionary prism morphology and containing Paleozoic to Cenozoic rocks [*Gallastegui et al.*, 2002] was also included in the model. A density of 2550 kg/m^3 was inferred for this body by forward modeling, considering the geometry revealed by different seismic studies [*Montadert et al.*, 1971, 1974; *Derégnaucourt and Boillot*, 1982; *Gallastegui et al.*, 2002].

[27] 9. Finally, the standard density of seawater was used for the water layer (1030 kg/m^3), since free-air anomalies were modeled offshore.

3.4. Results of Gravity Modeling

3.4.1. North-South Crustal Cross Sections

[28] Figure 5 shows three of the most representative vertical cross sections used to define the structure, two of them crossing the Labord-Mauléon and Basque-Cantabrian anomalies.

[29] The western Pyrenees section (Figure 5a) runs from the Ebro basin to the Aquitaine basin, crossing the South Pyrenean Zone, the eastern border of the Basque Paleozoic Massifs, and the Mesozoic Mauléon basin. In the center of the section, the structure is well constrained by three crossing points with the seismic refraction/wide-angle reflection profiles 1, 7, and 8. The general structure shows the thinner European crust overriding the thicker Iberian crust and giving rise to a doubly vergent wedge. The frontal thrust of the South Pyrenean Zone can be directly connected to the main crustal ramp beneath which the Iberian crust is underthrusted. In the northern side of the doubly vergent wedge, the main frontal structure is interpreted to uplift a segment of the lower crust. This body of lower crustal rocks, extending 25 km to both sides of this profile, can explain the Labord-Mauléon positive anomaly, crossed by this section at its maximum values. Although a small contribution of mantle rocks cannot be ruled out, the presence of an anomalous body entirely composed of mantle rocks, as proposed by *Casas et al.* [1997], is not needed to fit the anomaly. On the other hand, a lower crustal body explains in a better way the seismic velocities of ~6.8 km/s documented by *Daignières et al.* [1981] for this area below 9–10 km depth. In summary, the picture is similar to the general structure of the Pyrenees across the ECORS-Pyrenees seismic profile, which crosscut the lateral termination of another uplifted body of lower crustal rocks, responsible for the positive gravity anomaly of St. Gaudens [*Torné et al.*, 1989; *Casas et al.*, 1997; *Vacher and Souriau*, 2001].

[30] The structure across the Basque-Cantabrian section, from the northern Iberian Chain to the Bay of Biscay, is shown in Figure 5b. This section crosses the seismic refraction/wide-angle reflection profile 1 close to shot point I, an interesting zone where two intracrustal high-velocity bodies were found one on top of the other (Figure 1). The general structure is similar to the one across the western Pyrenean transect, in the sense that the thinner European crust is overriding the Iberian crust promoting the development of the crustal root and the doubly vergent wedge. Again, a segment of the lower crust from the northern side is interpreted to be back thrusted toward the north, promoting the duplication of this high-velocity layer observed in profile 1. It must be noted that the basal surface of the back thrusted body is poorly constrained by the seismic modeling, and therefore it was lowered in the gravity model almost to the top of the European lower crustal level. Also, at least part of the back thrusted segment must have a slightly higher density than normal European lower crust, to achieve a proper fit of the Basque-Cantabrian positive anomaly. Since it must also have a high magnetic susceptibility, as it will be shown in section 4.3, the striped part of this body in Figure 5b is assumed to be composed of more mafic and denser lower crustal rocks. The meaning of this body will be discussed in section 5.3. The northern side of the Basque-Cantabrian anomaly shows a strong gradient (~6.5 mGal/km) down to −100 mGal due to the water column of the Capbreton canyon (~2.3 km) and, to a lesser extent, to the thick Mesozoic-Cenozoic sedimentary pile in the continental platform. In the northern end of the cross section, the crust starts thinning at the vicinity of the Parentis basin, while in the southern side the crust is thickened in relation to the Alpine deformation in the Iberian Chain [*Pedreira et al.*, 2003; *Pedreira*, 2005].

[31] The structure across the central Cantabrian Mountains is quite different, as it is shown in Figure 5c. In this

transect, the uplift of the Cantabrian Mountains is not a consequence of the collision between two continental masses, but of the compression affecting the North Iberian (Cantabrian) continental margin. According to interpretations of the ESCIN-2 and ESCIN-4 seismic reflection profiles by *Pulgar et al.* [1996, 1997] and *Gallastegui* [2000], the denser lower crust of the thinned Cantabrian margin is protruding into the Iberian crust forming a double indentation in the sense of *Moore and Wiltschko* [2004], but at a crustal scale. This lower crustal layer is cut in the km 4779 by the E-W seismic reflection profile 1 [*Pedreira et al.*, 2003; *Pedreira*, 2005] and protrudes further south than in the previous transects, reaching only 13–14 km depth. The relatively shallow emplacement of this lower crustal, dense material, together with the uplift of the middle and upper parts of the "Cantabrian" crust (with the resulting erosion of the Mesozoic cover and the exposure of the Paleozoic rocks) counteract the negative effect of the crustal root and give rise to a steep positive gradient from the northern border of the Duero foreland basin toward the north. The doubly vergent orogenic wedge is much wider in this area than in the previous transects, being the north directed structures restricted to the northern end of the continental platform and, especially, to the continental slope and to the complexly tectonized zone located at its foot [*Gallastegui et al.*, 2002]. A thick Mesozoic-Cenozoic basin is located in the continental platform, where a well-defined gravity low is observed. Toward the north, the thin water layer over the Le Danois Bank and the exposure of basement rocks by north directed thrusts, lead to a strong gravity high reaching 110 mGal.

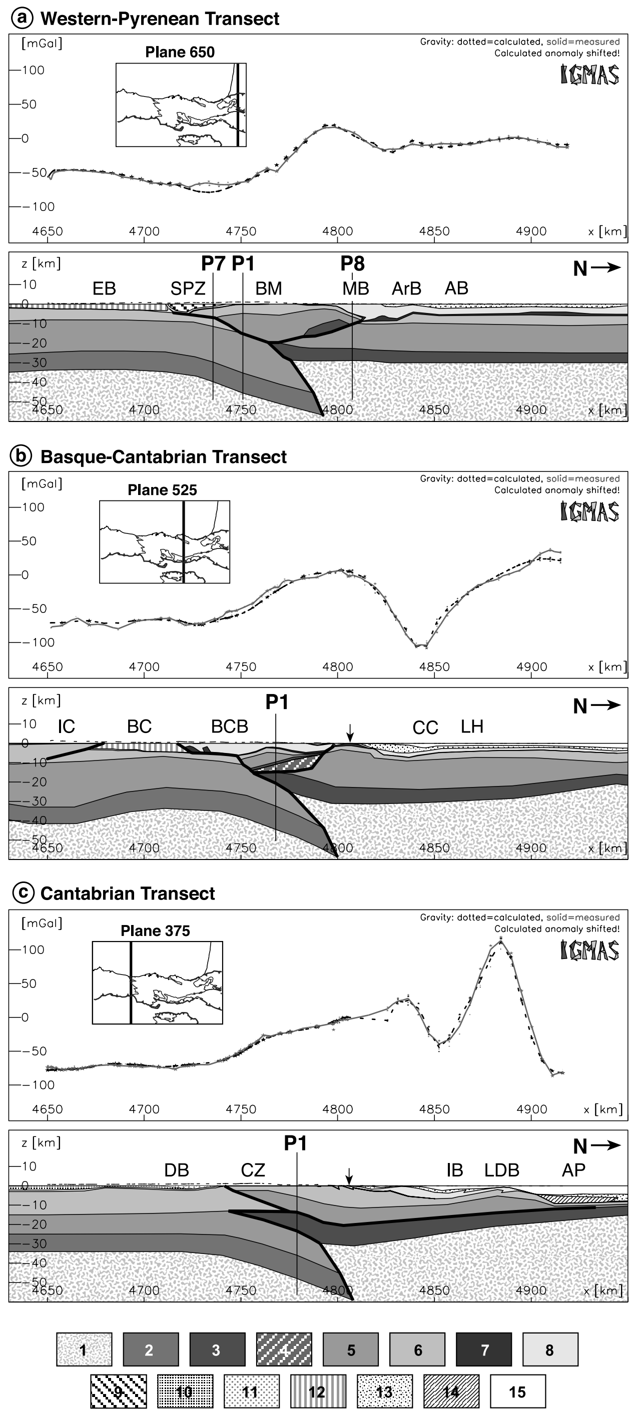


Figure 5. Vertical cross section of the 3-D model through (a) the western Pyrenees (plane 650), crossing the Labord-Mauléon anomaly; (b) the Basque Cantabrian basin (plane 525), crossing the Basque-Cantabrian anomaly; and (c) the central Cantabrian Mountains (plane 375). AB, Aquitaine Basin; ArB, Arzacq Basin; AP, Abyssal Plain; BC, Bureba Corridor; BCB, Basque-Cantabrian Basin; BM, Basque Massifs; CC, Capbreton Canyon; CZ, Cantabrian Zone; DB, Duero Basin; EB, Ebro Basin; IB, Inner Basin; IC, Iberian Chain; LDB, Le Danois Bank; LH, Landes High; MB, Mauléon Basin; SPZ, South Pyrenean Zone. Small arrows in Figures 5b and 5c indicate the coastline. P1, P7, and P8 mark crossing points with seismic refraction/wide-angle reflection profiles 1, 7, and 8, respectively (situation in Figure 2). Thick black lines outline major crustal structures. Dotted lines above the upper surface of the model mark the location of gravity stations. Gravity anomaly curves are grey solid, observed anomalies, and black dotted, calculated anomalies. Legend: 1, mantle (3300 kg/m^3); 2, Iberian lower crust (2930 kg/m^3); 3, European lower crust (2970 kg/m^3); 4, anomalous (dense and strongly magnetized) body of lower crustal rocks (3000 kg/m^3); 5, middle crust (2840 kg/m^3); 6, upper crust (2670 kg/m^3); 7, Triassic (Keuper) (2250 kg/m^3); 8, post-Keuper Mesozoic (2450–2650 kg/m^3); 9, Tertiary rocks of the South Pyrenean Zone (2630 kg/m^3); 10, nonconglomeratic Cenozoic sediments of the Duero foreland basin (2450 kg/m^3); 11, conglomeratic facies in the northern border of the Duero foreland basin (2600 kg/m^3); 12, Cenozoic sediments of the Ebro foreland basin and the Bureba Corridor (2530 kg/m^3); 13, Cenozoic sediments in the northern side of the Pyrenean-Cantabrian belt (2300 kg/m^3); 14, tectonized zone at the foot of the continental slope; 15, water layer (1030 kg/m^3).

3.4.2. Anomaly Maps

[32] A comparison between the observed and calculated gravity anomaly maps over the three-dimensional model is shown in Figure 4. The main positive anomalies of the contact zone between the Iberian and European plates are properly reproduced, as well as the negative anomalies of

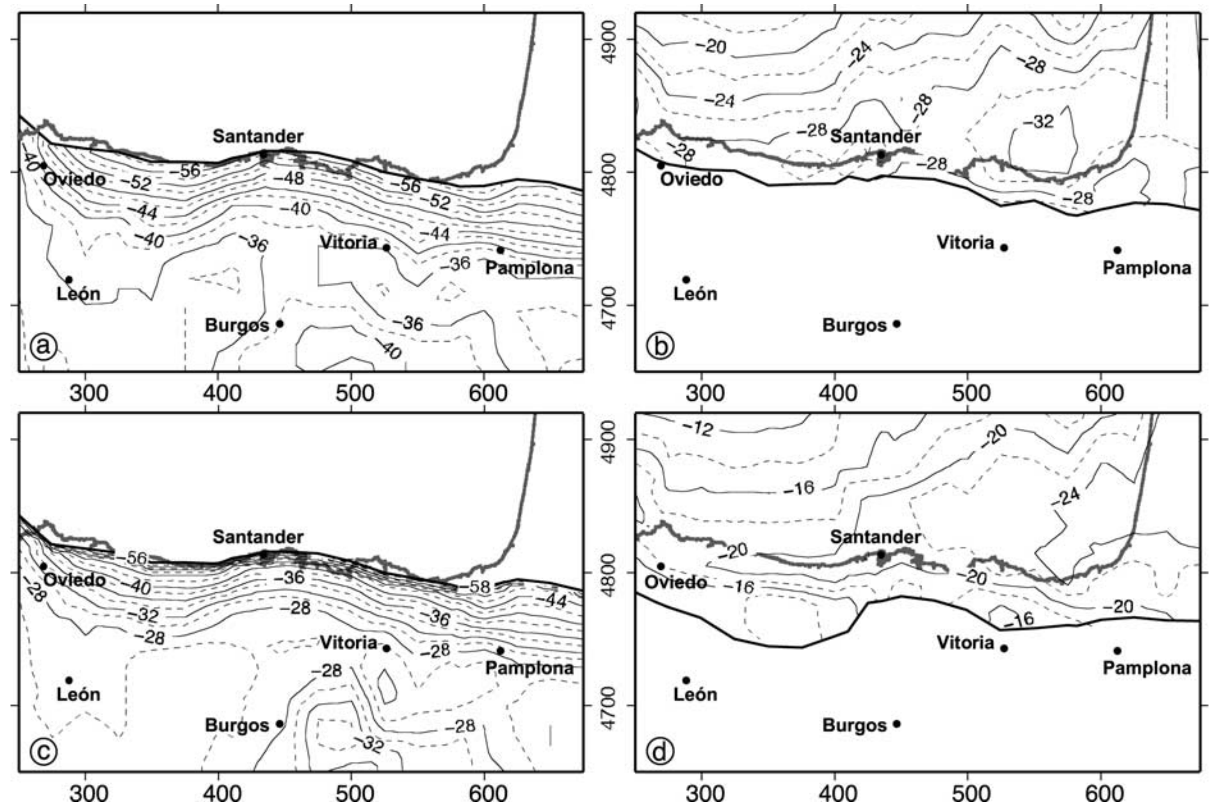


Figure 6. Model depth contours (Delauney triangulation) for (a) the Iberian Moho, (b) the European-Cantabrian Moho, (c) the top of the Iberian lower crust, and (d) the top of the European-Cantabrian lower crust. Numbers indicate depth below sea level in km.

the Duero basin and the Bureba corridor. The correlation coefficient between observed and calculated data is 0.99, with a standard deviation of 6.4 mGal. The highest differences are generally located between the cross sections used to define the structure, and in the offshore area, where the triangulation simplifies in excess the complex bathymetry of the North Iberian margin (Figure 4c).

3.4.3. Depth Contours

[33] Depth contours of layer boundaries are a useful representation of the 3-D geometry of the model. Figure 6 shows the depth contours for the top and bottom of the lower crust from the Iberian and European sides. The Iberian Moho (Figure 6a) reaches 60 km in the deeper part of the Pyrenean-Cantabrian root beneath the coastline, and up to 40 km beneath the northern border of the Iberian chain. The European Moho (Figure 6b) is located at ∼30–32 km depth beneath the Aquitaine basin and the southeastern corner of the Bay of Biscay and shallows toward the north and west to less than 18 km depth. The depth contours for the top of the Iberian lower crust are represented in Figure 6c. This crustal level has a fairly constant thickness of 10–12 km, except beneath the Iberian Chain, where it can be as thin as 6 km. The top of the European lower crust (Figure 6d) is located about 6–8 km above the European Moho and at less than 14 km depth beneath the central Cantabrian Mountains, where this level protrudes further south, promoting a delamination between the Iberian upper and middle crust [*Pulgar et al.*, 1997; *Gallastegui*, 2000].

[34] To visualize the along-strike variations in the degree of crustal imbrication, the northernmost position of the Iberian lower crust and the southernmost position of the indented European lower crust were traced in the structural sketch of Figure 7, which also shows the depth contours for the top of the Basque-Cantabrian and Labord-Mauléon anomalous bodies. In general, the degree of overlapping between the Iberian and European lower crustal levels increases from the western Pyrenees to the central Cantabrian Mountains, decreasing again toward the western border of the modeled area. Some remarkable changes both in the orientation of these traces and in the degree of overlapping, as well as the location of the Basque-Cantabrian and Labord-Mauléon thrusted anomalous bodies, hint at the existence of deep lateral structures that must have played a major role in controlling the tectonic style and degree of crustal imbrication during the N-S to NW-SE convergence between Iberia and Europe, supporting previous interpretations derived from the modeling of seismic refraction/wide-angle reflection profiles [*Pedreira et al.*, 2003]. While two of such structures displayed in Figure 7, namely, the Pamplona and Hendaya faults, can be easily identified at the surface, the presence of the other two is inferred from the modeling results and previous seismic findings. These are interpreted as basement structures beneath the Mesozoic sedimentary cover, aligned with the Torrelavega and Santander submarine canyons, which in their turn separate areas with significant structural differ-

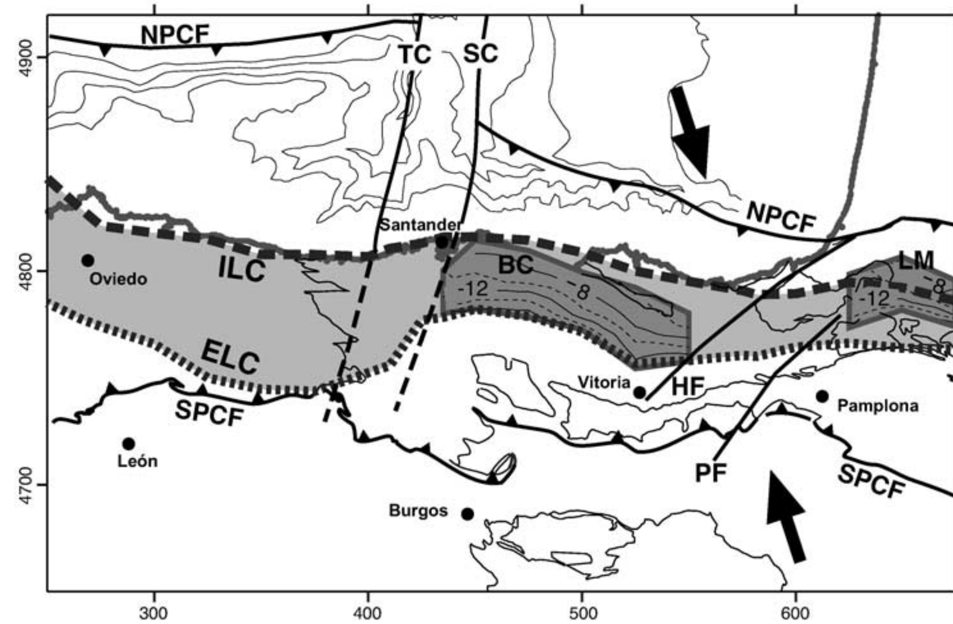


Figure 7. Tectonic sketch map with the structural interpretation and the depth contours for the top of the Basque-Cantabrian (BC) and Labord-Mauléon (LM) anomalous bodies (in dark grey; numbers indicate depth below sea level in km). ELC, southernmost position of the indented European lower crust; ILC, northernmost position of the Iberian lower crust; HF, Hendaya Fault; PF, Pamplona Fault; TC, Torrelavega Canyon; SC, Santander Canyon; NPCF, North Pyrenean-Cantabrian Front; SPCF, South Pyrenean-Cantabrian Front. Black arrows indicate the approximate direction of the mean Pyrenean-Cantabrian compressional phase. Light grey shading marks the area of overlapping between the Iberian and European lower crusts. Details are given in the text.

ences in the offshore continuation of the Pyrenean-Cantabrian belt [*Fernández-Viejo et al.*, 2006].

4. Magnetic Modeling

4.1. Preliminary Considerations

[35] The three-dimensional structure of the model is exactly the same as for the gravimetric model. However, the comparison of observed and calculated anomalies is restricted to the area occupied by the strong Basque Country Magnetic Anomaly, in the eastern part of the model. To the west, the magnetic anomalies are partially governed by the presence of thin but strongly magnetized Devonian ferruginous sandstones in a wide antiform over the frontal thrust [*Pedreira*, 1998] and well above sea level, that is, beyond the upper surface of the 3-D model. A proper anomaly fit in this western part could only be achieved by a more detailed modeling, which is out of the scope of this paper.

[36] The magnetic response of the model was calculated by the same modeling software (IGMAS), after assigning a value of magnetic susceptibility to each body. Königsberger ratios and declination and inclination of remanent magnetizations can also be defined, if desired. However, due to the unknown contribution and orientation of remanent magnetism, our modeling is based solely on the induced magnetization. We will describe the material properties and the modeling results in terms of susceptibilities, and afterward we will discuss the implications in terms of magnetizations and the possible contribution from the remanent magnetism. We assume that all the bodies lose their magnetization at the Curie temperature for magnetite (~580°C), and that this temperature is reached at 27 km depth, as in a previous model proposed by *Aller and Zeyen* [1996], after the thermal model of *Cabal* [1993]. Although this thermal model was developed before knowing the existence of the Cantabrian crustal root, the uncertainties in the estimation of the Curie depth are not significant since the main source of the anomaly lies within the upper ~18 km.

[37] Total field strength, declination and inclination values for the modeled area at the date of the aeromagnetic flight, used to calculate the induced magnetization, are: 45200 nT, −4° and 59°, respectively [*Ardizone et al.*, 1989; *Instituto Geográfico Nacional*, 1991].

4.2. Basque Country Magnetic Anomaly

[38] The Basque Country Magnetic Anomaly (BCMA) [*Aller and Zeyen*, 1996] is located in the Basque-Cantabrian basin, and is the highest aeromagnetic anomaly of the whole Spanish Mainland [*Ardizone et al.*, 1989]. *Aller and Zeyen* [1996] proposed a model to explain it by means of a SW dipping wedge composed of intrusive rocks related to the Cretaceous rifting stage and by lower crustal rocks, with a magnetic susceptibility of 0.07 SI. This ramp would reach only 5–7 km beneath the Basque-Cantabrian basin, and would be rooted in a flat lower crust, with its top located at ~20 km depth and the Curie isotherm at 27 km depth. However, the results of the seismic survey carried out in the Basque-Cantabrian basin [*Pedreira et al.*, 2003] revealed that the crustal structure is much more complex than previously considered by these authors. Thus an alternative

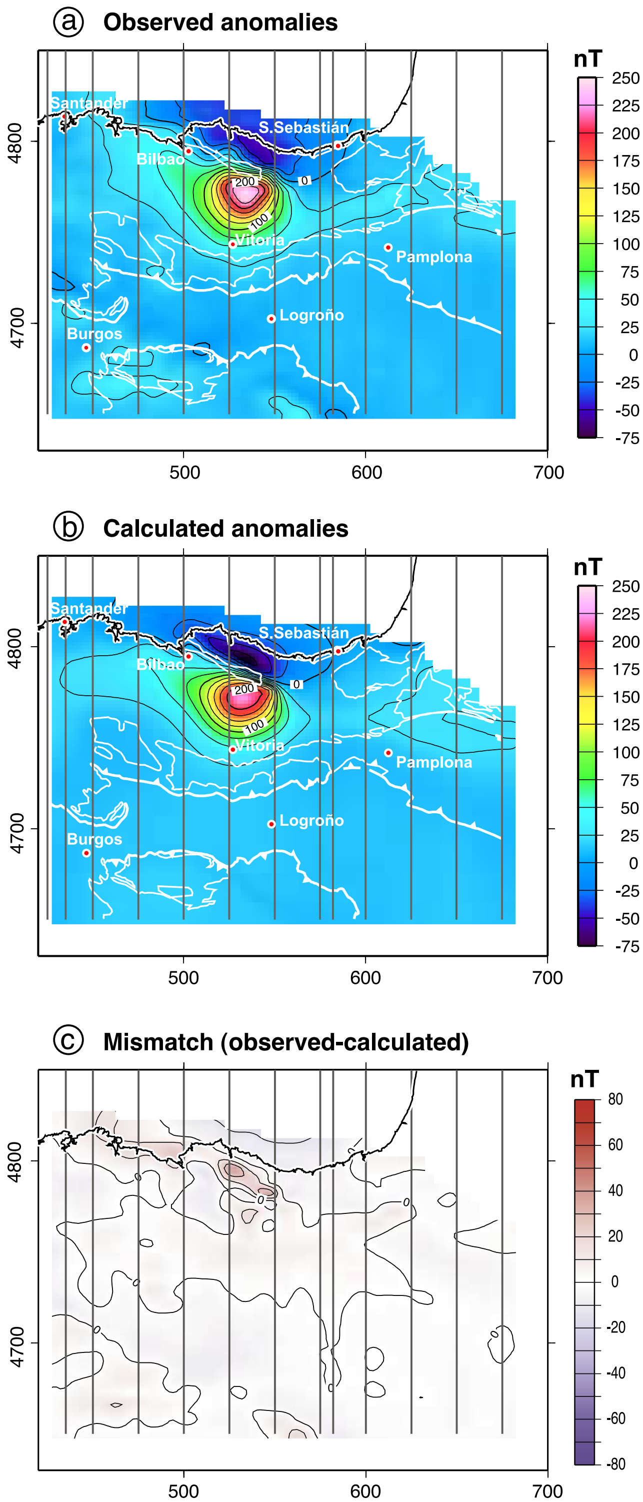


Figure 8. (a) Observed and (b) calculated magnetic anomalies over the studied area (measured at a height of 3000 m). (c) Mismatch between observed and calculated anomalies. Contours every 25 nT. White lines indicate the main geological contacts. Thick black/white line indicates the coastline. Light grey lines indicate the vertical planes used to construct the geometry of the 3-D model.

explanation must be found for this anomaly. We will show here that the structure proposed to explain the gravity anomalies and seismic data can also explain the origin of the BCMA.

[39] The magnetic anomaly data come from the aeromagnetic map of Spanish mainland [*Ardizone et al.*, 1989], recorded at 3000 m above sea level. The residual BCMA (Figure 8a) is composed of a minimum-maximum pair aligned in a N-S direction, which is also the direction of the regional field, suggesting that either the remanent magnetization is low, or it approximately follows the orientation of the present regional field. The positive part of the anomaly reach ~250 nT, and the negative part almost −60 nT near the shoreline. Although the shape of the strong positive part is almost circular, the ensemble of the anomaly shows a NW-SE orientation, the same as the Alpine structural trends, which in their turn follow the trends of previous Mesozoic extensional structures. This observation suggests that the emplacement of the causative body probably took place in Mesozoic or Tertiary times.

4.3. Susceptibility Data

[40] Rocks with magnetizations high enough to account for long-wavelength aeromagnetic anomalies in the continental crust are typically basic/ultrabasic lower crustal rocks with high magnetite content [e.g., *Wasilewski and Mayhew*, 1982]. Since the causative body of the BCMA must be located at a shallow depth between the positive and negative parts of the anomaly, it is straightforward to relate it to the anomalous body with typical lower crustal seismic velocities and densities found at only 9–10 km depth in this area, beneath shot point I. However, this interpretation needs additional refinement, since the BCMA is only partially superimposed to the positive gravity anomaly interpreted to be created by this lower crustal body, which extends westward up to Santander (Figures 4a and 8a).

[41] Disregarding the contribution of remanent magnetism and taking into account the dimensions of the whole back thrusted segment of lower crustal rocks revealed by the seismic and gravimetric modeling, this body must have a very high magnetic susceptibility around 0.09 SI in the eastern Basque-Cantabrian basin, but as low as 0.007 SI in its western part, in order to impede the continuation of the magnetic anomaly in this direction. It can then be assumed that both anomalies are created by a lower crustal body that only holds strong magnetization in the area located at present beneath the eastern part of Basque-Cantabrian basin. Although a pre-Mesozoic origin for this strong magnetization cannot be completely ruled out, we suggest that its most probable cause must be related to the injection of basic magma in the base of the crust during the Mesozoic rifting stage. In fact, the eastern part of the Basque-Cantabrian basin was probably the region of the basin that suffered a higher degree of crustal extension in Mesozoic times, with extrusion of volcanic material in the Late Cretaceous [*Olivé Davo et al.*, 1989]. Thus the injection of basic magma in the base of the crust was probably higher in that zone. Following this hypothesis, we divided the lower crustal anomalous body in two pieces: a lower part, with a high content of basic material and hence a high magnetic susceptibility (0.09 SI) and density (the body of 3000 kg/m^3 described in section 3.3), and an upper part with a low content in

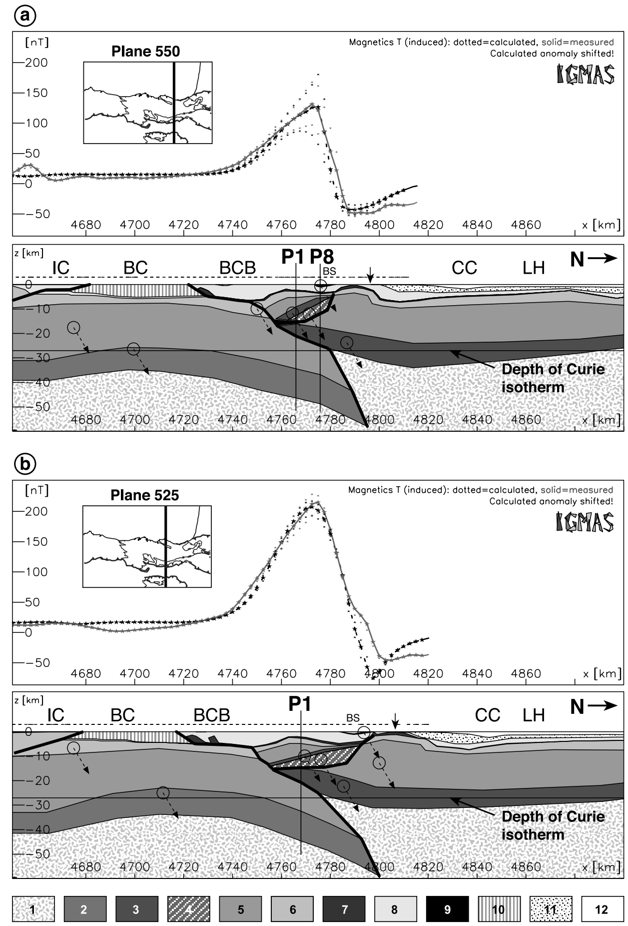


Figure 9. Two-dimensional magnetic sections through the Basque-Cantabrian basin, crossing the Basque-Cantabrian anomaly for (a) plane 550 and (b) plane 525. BC, Bureba Corridor; BCB, Basque-Cantabrian Basin (BS, Biscay Synclinorium); CC, Capbreton Canyon; IC, Iberian Chain; LH, Landes High. Legend: 1, mantle; 2, Iberian lower crust (k = 0.005 SI); 3, European lower crust (k = 0.007 SI); 4, anomalous (dense and strongly magnetized) body of lower crustal rocks (k = 0.09 SI); 5, middle crust (k = 0.0035 SI); 6, upper crust (k = 0.001 SI); 7, Keuper; 8, post-Keuper Mesozoic; 9, volcanoclastic complex in the Biscay Synclinorium (k = 0.04 SI); 10, Cenozoic sediments of the Ebro foreland basin and the Bureba Corridor; 11, Cenozoic sediments of the North Iberian continental margin; 12, water layer. P1 and P8 mark the crossing points with seismic refraction/wide-angle reflection profiles 1 and 8 (situation in Figure 2). Dotted lines at 3 km height mark the position of the stations.

magnetic minerals (susceptibility of 0.007 SI) and the density of the "standard" European lower crust. This simplistic division allows us to simulate the lateral variation in magnetic behavior by varying the size of each part along the model, to fit the magnetic anomaly without disrupting the gravimetric one. The value of 0.007 SI was also assigned to the remaining European lower crust, while for the Iberian lower crust, a better fit of the anomaly was obtained with a slightly lower value of 0.005 SI.

[42] Middle and upper crustal levels may also have a significant content of magnetic minerals and therefore an appreciable magnetic susceptibility [e.g., *Shive et al.*, 1992]. In our model, some magnetic susceptibility should be assigned to these layers; otherwise, a minimum would be created in the zone of the crustal root, where the Iberian lower crust sinks below the Curie isotherm. Susceptibility values of 0.001 SI and 0.0035 SI were assigned by trial-and-error for the upper and middle crustal layers, respectively.

[43] Finally, a magnetic susceptibility of 0.04 SI was attributed to a small folded body of magnetite-bearing volcanic, volcanoclastic, ophitic and basaltic rocks outcropping in the Basque-Cantabrian basin [*Olivé Davo et al.*, 1989] (Figure 2).

4.4. Modeling Results

[44] The observed and calculated anomalies for this model, with the geometry and magnetic susceptibility values described above, are shown in Figure 8. Considering the difficulties linked to this type of modeling, due to the dipolar nature of magnetism, the unknown undulations in the Curie temperature isotherm and the unknown influence of remanent magnetism, a reasonably good fit is achieved. The correlation coefficient is 0.95, and the standard deviation, 9.18 nT.

[45] Figure 9 shows the fit between observed and calculated anomalies along two of the vertical planes crossing the zone of higher amplitudes of the BCMA. Plane 550 (Figure 9a) is the first one from the east where the Basque-Cantabrian lower crustal anomalous body is present. Note that another well-defined anomaly, although of short wavelength and small amplitude, can be identified in the southern end of this plane. Its origin is probably related to the presence of large basaltic sills intruded during the Triassic-Jurassic rifting stage in the northern border of the basin that was subsequently inverted to form the Iberian Chain [e.g., *Simón et al.*, 2002]. In the area of interest, crossing points with seismic refraction/wide-angle reflection profiles 1 and 8 give useful constraints on the crustal structure. The anomaly profile can be fitted allowing for slightly more than half the Basque-Cantabrian anomalous body occupied by the strongly magnetized rocks (susceptibility of 0.09 SI). However, these must occupy almost the whole body in plane 525, 25 km to the west, in order to explain the anomaly at its highest values. As for the model proposed by *Aller and Zeyen* [1996], the anomalous body reaches only ~6 km depth beneath the Biscay Synclinorium and it deepens toward the SW, although it is not rooted in the Iberian lower crust. From this plane toward the west, the volume of strongly magnetized rocks within this body diminishes again, ending at plane 475 (Figure 10 shows the depth contours for the top and base of this piece), while the rest of the body continues 40 km further west with a magnetic susceptibility of 0.007 SI.

[46] The inferred magnetic susceptibility value of 0.09 SI imply a total magnetization of ~3.26 A/m for the basal part of this lower crustal body. Long-wavelength magnetic anomalies from many parts of the world require considerable volumes of rocks with magnetizations typically ranging between 2 and 6 A/m to exist deep in the crust [*Wasilewski and Mayhew*, 1982; *Mayhew et al.*, 1985; *Shive et al.*, 1992]. Hence the BCMA does not place unusual require-

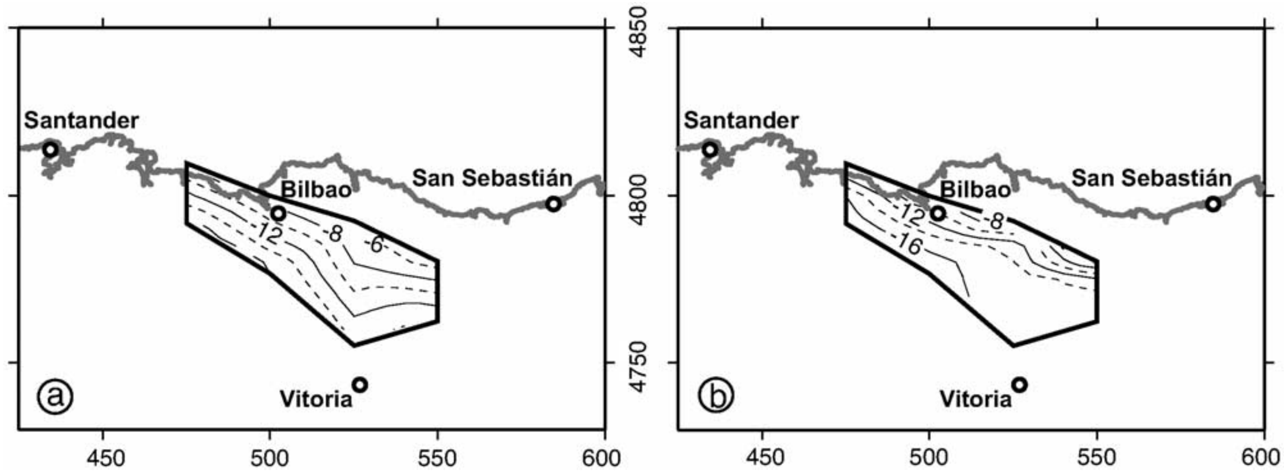


Figure 10. Model depth contours (Delauney triangulation) for (a) the top and (b) the base of the strongly magnetized part of the Basque-Cantabrian anomalous body (susceptibility of 0.09 SI). Numbers indicate depth below sea level in km. Contour interval is 2 km.

ments on source intensities for the lower crustal rocks. The way this total magnetization is decomposed into the induced and remanent components is unknown in this case, although the intensity of the latter is expected to be significant if the anomalous body is composed of gabbroic intrusions. In this case, the orientation of the mean remanent magnetization vector must be close to the orientation of the actual field. Most magnetic studies of exposed lower crustal rocks show that natural remanent magnetization intensities are normally comparable to or less than the induced magnetization intensities [*Shive et al.*, 1992, and references therein]. Whether those ratios of remanent to induced magnetization (Königsberger ratios) can be extrapolated to the deep crust is still an open question. In any case, it is obvious that a substantial contribution from the remanent magnetism could reduce in a significant way the extreme value of magnetic susceptibility needed for the anomalous body to explain the BCMA. For example, Königsberger ratios of 0.5 and 1 would reduce the susceptibility to 0.06 SI, and 0.045 SI, respectively (providing again that the mean remanent vector closely follows the orientation of the actual field). Still, susceptibility values of 0.045–0.09 SI are close to the upper limit of the range of susceptibilities usually measured in samples from different outcrops of lower crustal rocks [e.g., *Schlinger*, 1985; *Wasilewski and Warner*, 1988; *Carmichael*, 1989; *Belluso et al.*, 1990]. This apparent excess of magnetization inferred for the anomalous body is in fact a common feature in the vast majority of the models proposed up to date to explain crustal long-wavelength magnetic anomalies around the globe, and its explanation lies out of the scope of this paper.

5. Discussion and Conclusions

[47] A 3-D crustal model has been derived for the transition zone between the Pyrenees and the Cantabrian Mountains. The model is seismically constrained and explains the main gravimetric and aeromagnetic anomalies over the area. The tectonic implications of this study are discussed hereafter.

5.1. Style of Crustal Deformation Between Iberia and Europe

[48] This modeling provides further support to previous seismic results [*Pedreira et al.*, 2003] suggesting that the northward underthrusting of the Iberian crust beneath the European crust is a continuous feature from the Pyrenees to the Cantabrian Mountains. The style of crustal deformation is, however, somehow different from east to west, and this difference is evidenced in the gravity anomalies. In the Central Pyrenees, beyond the study area, the ECORS-Pyrenees deep seismic profile (Figure 11a) suggests that the Iberian underthrusting takes place beneath a continuous crustal ramp that extends from the South Pyrenean frontal thrust to the mantle [e.g., *Muñoz*, 1992]. The European lower crust shows little uplift over this crustal ramp, which favors the existence of a wide negative anomaly over the crustal root [*Torné et al.*, 1989; *Casas et al.*, 1997; *Vacher and Souriau*, 2001]. In the northern branch, several authors inferred the presence of a body of lower crustal rocks uplifted from the European plate in the area where the positive gravity anomaly of St. Gaudens is observed [e.g., *Torné et al.*, 1989; *Muñoz*, 1992; *Vacher and Souriau*, 2001].

[49] A similar crustal structure is proposed here for the western Pyrenees, in the area sampled by the ECORS-Arzacq seismic profile [*Daignières et al.*, 1994], including the uplift of a lower crustal segment that is interpreted to be responsible for the Labord-Mauléon anomaly (Figure 5a). The gravity modeling in this zone also supports the presence of a continuous crustal ramp from the southern mountain front to the mantle, which was recently proposed by *Muñoz* [2002] (Figure 11b). This ramp may be considered as the actual boundary between the sinking Iberian plate and the overriding European plate. The structural interpretation by *Muñoz* [2002] and this study is contrary to most previous interpretations, which proposed that this crustal ramp reaches the surface in the northern border of the Basque Massifs (Figure 11c) [*Daignières et al.*, 1994; *Grandjean*, 1994], or considered a double crustal wedge or delamination (Figure 11d) [*Teixell*, 1998, 2004].

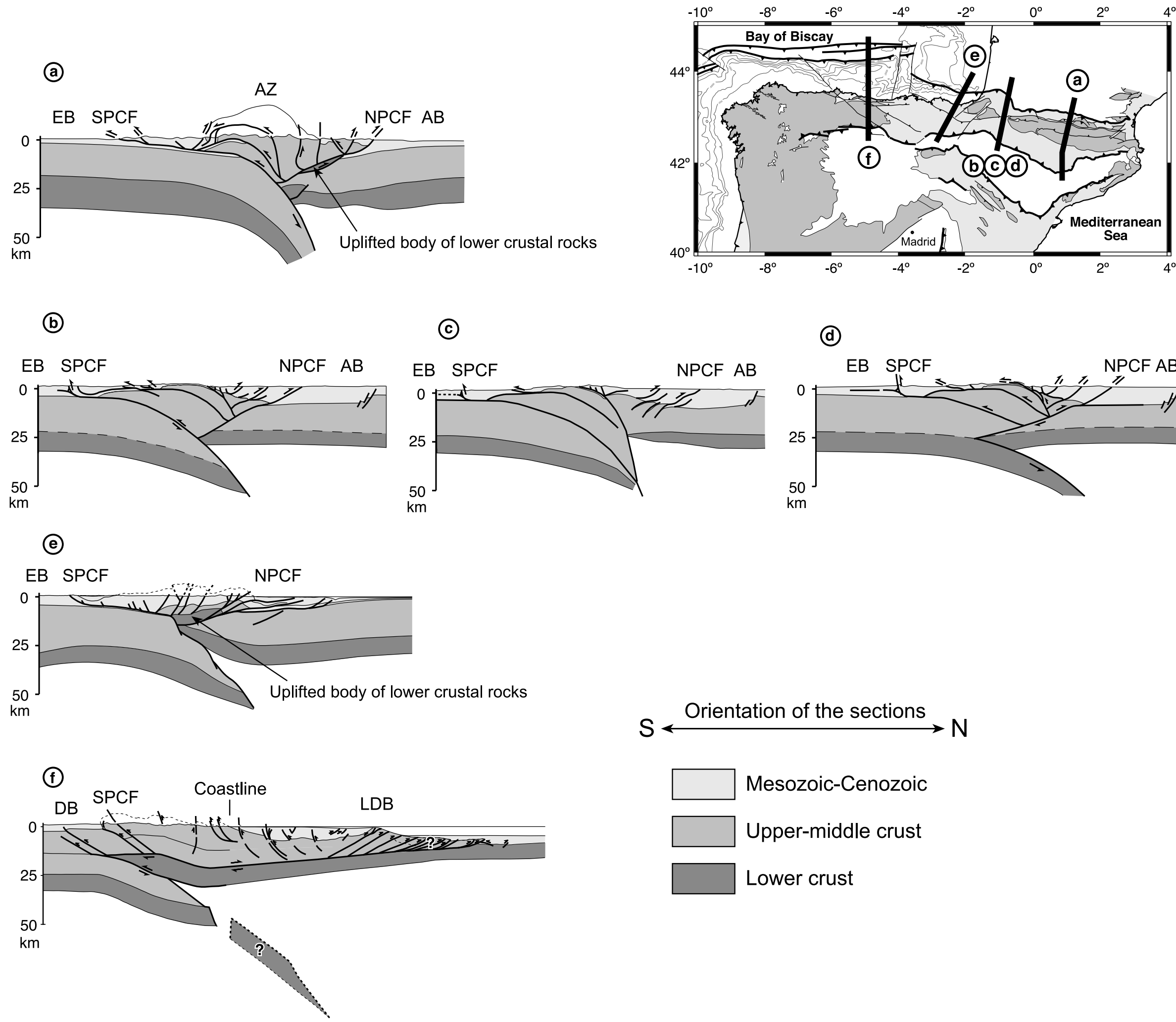


Figure 11. Schematic crustal cross sections along the Pyrenean-Cantabrian belt. (a) Section across the Central Pyrenees [*Muñoz*, 1992]. (b), (c) and (d) Different interpretations of the western Pyrenees section, by *Muñoz* [2002] (the position of the lower crust has been added), *Daignières et al.* [1994] and *Teixell* [2004], respectively. (e) Cross section across the Basque-Cantabrian basin [*Pedreira*, 2005]. (f) Crustal transect across the central Cantabrian Mountains [*Gallastegui*, 2000]. AB, Aquitaine Basin; AZ, Axial Zone; EB, Ebro Basin; LDB, Le Danois Bank; NPCF, North Pyrenean-Cantabrian Front; SPCF, South Pyrenean-Cantabrian Front.

[50] In the easternmost part of the Cantabrian Mountains (the Basque-Cantabrian basin) no seismic reflection profiles are available on land, and therefore the potential field modeling, constrained by seismic refraction data, provides very relevant information. Here the contact between the Iberian and European crusts is also interpreted to follow a continuous crustal ramp connecting the southern frontal thrust with the mantle, but with the lower crust of the northern side uplifted to shallower depths (Figures 5b, 6, and 11e). In some parts of the Basque-Cantabrian basin the uplifted European lower crust dips steeply to the north. This is interpreted to be related to the inherited geometry of the main extensional fault limiting the Mesozoic basin in the southwest. The steepness of this structure might impede the southward displacement of the European crust, promoting the back thrust of the lower crustal segment, which in turn creates the Basque-Cantabrian gravity and magnetic anomalies.

[51] Finally, in the western side of the modeled area, (the central Cantabrian Mountains), the ESCIN-2 seismic profile revealed that the Iberian crust is not sinking into the mantle beneath a unique continuous crustal ramp. Instead, a double wedge or double delamination is inferred (Figure 11f), in which the lower crust from the Cantabrian margin side is uplifted and protrudes into the Iberian crust [*Pulgar et al.*, 1996, 1997; *Gallastegui*, 2000]. This configuration places high-density material in the thickened area, counteracting the negative effect of the crustal root and giving rise to a positive gravity gradient toward the north. A longitudinal view of this European lower crustal wedge beneath the central Cantabrian Mountains is provided by seismic refraction profile 1 (Figure 1).

[52] These three regions of different tectonic styles (western Pyrenees, Basque-Cantabrian basin and central Cantabrian Mountains) are separated by the N-S to NE-SW lateral structures displayed in Figure 7, the two westernmost of

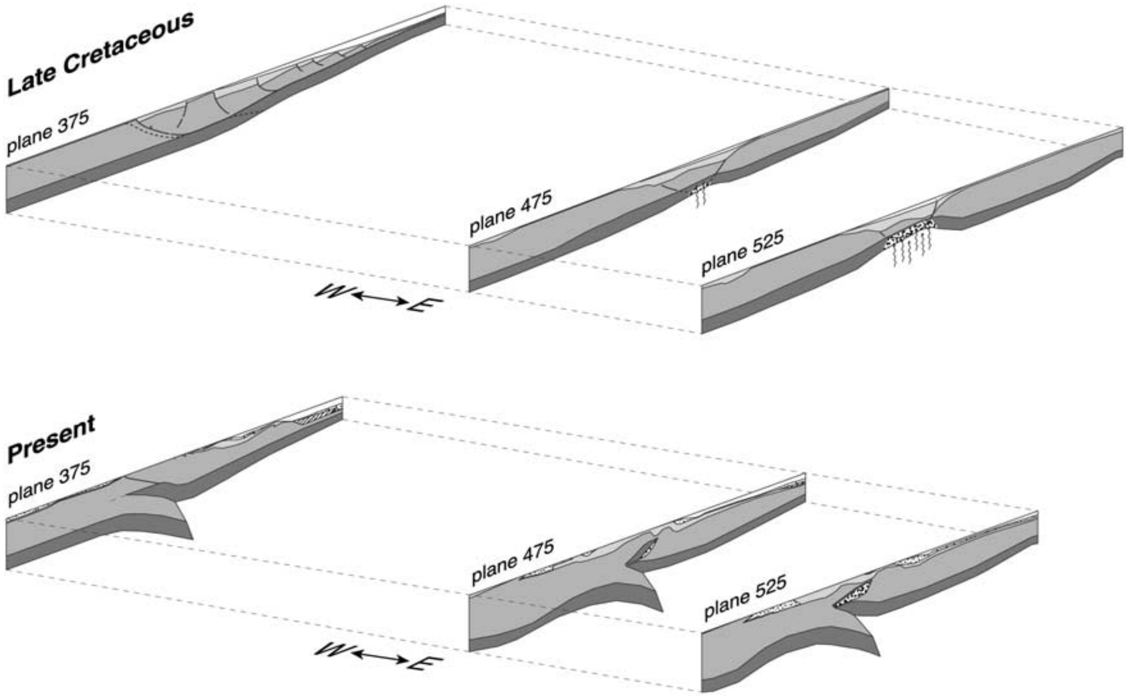


Figure 12. Schematic model proposed to explain the different magnetization of the back thrusted piece of lower crustal rocks beneath the Basque-Cantabrian basin. During the Late Cretaceous, the thinnest part of the crust in the eastern transect (plane 525) is subjected to pervasive injection of basic magmas (some of them reaching the seafloor) leading to magnetite enrichment. Toward the west (plane 475), the crustal thinning is less focused, the intrusion of basic magmas is less pervasive, and hence the lower crust in the axis of the rift is less dense and magnetized, globally, than in the eastern part. 100 km further to the west (plane 375), the situation at the end of the Cretaceous was that of a typical passive continental margin (reconstruction simplified from *Gallastegui et al.* [2002]), such that at present no anomalously magnetized body is present.

which were inferred to be present in the basement from the three-dimensional structural reconstruction achieved with the gravity modeling and previous seismic findings [*Pedreira et al.*, 2003]. These lateral structures must have played a major role in partitioning the deformation along the Pyrenean-Cantabrian belt during the plate convergence.

5.2. Extent of the Crustal Root

[53] Although the gravity modeling is of great help to define the general crustal structure in the contact zone between Iberia and Europe, this method is barely sensitive to certain geometric details, especially in the deeper parts of the crustal root. This was modeled down to ~60 km depth, based on seismic reflection and wide-angle results in the Cantabrian Mountains [*Pulgar et al.*, 1996; *Fernández-Viejo et al.*, 1998; *Gallastegui*, 2000] and the Pyrenees [*Gallart et al.*, 1981; *ECORS Pyrenees Team*, 1988]. Other geological and geophysical studies, including restorations of crustal cross sections, magnetoteluric modeling or seismic tomography suggest the existence of an Iberian lower crust subducting down to 80–100 km in the Pyrenees [*Muñoz*, 1992; *Teixell*, 1998; *Pous et al.*, 1995; *Souriau and Granet*, 1995; *Vergés et al.*, 1995; *Ledo et al.*, 2000] and in the Cantabrian Mountains [*Gallastegui*, 2000]. However, these deep crustal roots are hardly identified by gravity modeling since they are eclogitized at depths below ~50 km, acquiring a density similar to that of the surrounding mantle [e.g., *Vacher and Souriau*, 2001]. In any case, one clear and relevant conclusion is the absence of a local, Airy type, isostatic equilibrium in this area, since a crustal root down to ~60 km depth is present under the coastline.

[54] Concerning the western prolongation of this root, the model proposed can explain a remarkable feature observed in the ESCIN-3.3 marine seismic reflection profile, located in the western edge of the modeled area (location in Figures 1 and 2). This profile shows the presence of two subhorizontal reflective bands, with their basal surfaces located by wide-angle modeling at 29 and 41 km depth, interpreted by *Ayarza et al.* [1998] as a duplication of lower crustal levels and the Moho. These authors discussed the origin of this duplication, proposing three hypotheses: a preserved Variscan root, a post-Variscan lower crustal delamination and partial assimilation into the mantle, or an Alpine imbrication in N-S direction. We consider that the gravity model presented in this study (see the depth contours for the Iberian and European Moho in Figures 6a and 6b) favors interpretation of an Alpine imbrication.

5.3. Nature of the Anomalous Body Beneath the Basque-Cantabrian Basin

[55] Three strong positive gravity anomalies are observed along the Pyrenean-Cantabrian belt related to the presence

of high-density bodies at upper crustal and midcrustal levels: the St. Gaudens (beyond the study area), Labord-Mauléon and Basque-Cantabrian basin anomalies. The first two anomalies were studied by several authors, but the nature of the causative bodies is still subject to debate. Some authors [*Grandjean*, 1994; *Vacher and Souriau*, 2001] consider they are composed of lower crustal rocks, others point to a mantle origin [*Casas et al.*, 1997], and a third group acknowledges both possibilities [*Torné et al.*, 1989]. For these two anomalies, we consider that their origin must be related to the presence of shallow bodies composed of lower crustal rocks, although only the one that gives rise to the Labord-Mauléon anomaly was included in the model presented in this study.

[56] To our knowledge no crustal modeling has ever attempted to explain the Basque-Cantabrian gravity anomaly. In this work, we propose that it is also related to a body built up of lower crustal rocks rather than of mantle material, as constrained by its seismic velocities around 6.75 km/s [*Pedreira et al.*, 2003], its inferred density (2970–3000 kg/m^3) and also by its strongly magnetic behavior. *Vacher and Souriau* [2001] suggest that the most likely range of densities and P wave velocities for the causative bodies of the North Pyrenean anomalies are 2800–3100 kg/m^3 and 6.5–7.0 km/s, respectively, that is, bracketing the values we infer for the causative body of the Basque-Cantabrian anomaly. They also point out that these values correspond to lower crustal rocks, following the experimental results of *Christensen and Mooney* [1995] for a mean geotherm and pressure equivalent to 10 km depth. The magnetic modeling provides further support for a lower crustal composition, since unaltered peridotites are essentially paramagnetic [*Wasilewski and Mayhew*, 1982; *Shive et al.*, 1992]. These rocks can only achieve a susceptibility high enough to explain the BCMA when serpentinized in the presence of fluids at temperatures below $\sim$550°C. Alternatively, this type of alteration could also have taken place in the upper mantle during the Mesozoic period of crustal extension, driven by percolation of fluids through extensional faults reaching the base of the crust [e.g., *O'Reilly et al.*, 1996]. However, an extensive serpentinization would also reduce in a drastic way the density and seismic velocity of the original peridotites [*Saad*, 1969; *Christensen*, 1965, 1978; *Toft et al.*, 1990; *Kern and Tubia*, 1993; *Oufi et al.*, 2002] down to values that are clearly not supported by the seismic and gravimetric observations.

[57] Although the partial contribution of serpentinized peridotites cannot be ruled out, we consider that the Basque-Cantabrian anomalous body is most likely a thrusted piece of the lower crust that was subjected to an extensive intrusion of basic magmas from the mantle during the Mesozoic period of crustal extension in the neck of the rift. This may have led to the generation of gabbroic cumulates that can explain the combined increase in density, seismic velocities and magnetization of this portion of the lower crust. Toward the west, the extension was probably less focused, with less magmatic intrusions, according to the lower magnetization of the back thrusted piece in the western part of the Basque-Cantabrian basin (Figure 12). An inherited, pre-Mesozoic origin for the magnetization of the crust may also be possible, but we consider this interpretation to be less likely in view of the geological location of the anomalous body within the highly extended crust of the Mesozoic Basque-Cantabrian basin, and the orientation of the magnetic anomaly following the Mesozoic-Cenozoic structural trends. Finally, the localized intrusion of gabbroic magmas could also be favored by the creation of transtensive spaces during the left-lateral movement between the Iberian Peninsula and stable Europe that ended in the Late Cretaceous (at the time of the extrusion of volcanic material in the Basque-Cantabrian basin), although no clear arguments are available yet to validate this hypothesis.

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J. Gallart and M. Torné, Departamento de Estructura y Dinámica de la Tierra, Instituto de Ciencias de la Tierra "Jaume Almera," CSIC, c/Lluís Solé i Sabarís, s/n, E-08028 Barcelona, Spain.

D. Pedreira and J. A. Pulgar, Departamento de Geología, Universidad de Oviedo, c/J. Arias de Velasco, s/n, E-33005 Oviedo, Spain. (david@geol.uniovi.es)