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Lithospheric structure of the Western Pyrenees-Cantabrian Mountains based on 3D modelling of gravity anomalies and geoid undulations: preliminary results

D. Pedreira[1*], J. Ebbing[2] and J. A. Pulgar[1]

[1]*Departamento de Geología, Universidad de Oviedo. Equipo CONSOLIDER Topo-Iberia, Spain.*

[2]*Geological Survey of Norway (NGU), Trondheim, Norway.*

[*]*e-mail: david@geol.uniovi.es*

Abstract: The lithospheric structure of the contact zone between the Iberian and European plates in the transition from the Western Pyrenees to the Cantabrian Mountains is investigated by 3D modelling of gravity anomalies and geoid undulations. The main target of this study is to gain insight into the deep geometry of this plate boundary, especially into the topography of the lithosphere-asthenosphere boundary. The results, still preliminary, suggest that the lithospheric thickness is similar on the Iberian and European sides, with a small and discontinuous lithospheric root in the contact zone between the two plates.

Keywords: Cantabrian Mountains, Pyrenees, lithospheric structure, gravity modelling, geoid modelling.

The Pyrenees and the Cantabrian Mountains are two E-W-trending mountains ranges located in the northern edge of the Iberian Peninsula (Fig. 1). In fact, from a geological point of view, they constitute a continuous mountain belt formed in Late Cretaceous-Tertiary times as a consequence of the collision between the Iberian and European plates, after an important period of crustal extension in the Mesozoic.

The crustal structure of the transition zone between the Pyrenees and the Cantabrian Mountains was investigated in recent years by seismic refraction/wide angle reflection profiling (Fernández-Viejo *et al.*, 2000; Pedreira *et al.*, 2003), teleseismic receiver functions (Díaz *et al.*, 2003) and 3D gravity/magnetic modelling (Pedreira *et al.*, 2007). The results of these previous studies evidence the presence of a continuous crustal root (down to minimum depths of 55-60 km) formed by the northward underthrusting of the Iberian crust, while segments of the European-Cantabrian lower crust are identified as high-velocity/high-density (and in some cases highly magnetized) bodies at mid-crustal depths in the thickened region, with a disrupted pattern that suggests the participation of lateral structures during the ~N-S Alpine compression.

However, neither the seismic refraction/wide angle reflection profiles nor the previous deep seismic reflection profiles in the Cantabrian Mountains (e.g. Pulgar *et al.*, 1996; Gallastegui, 2000) sampled the deeper parts of the crustal root. Several authors suggest that the crustal root in the Pyrenees reach 80-100 km in depth, based on geological balancing of crustal cross sections (e.g. Muñoz, 1992; Verges *et al.*, 1995; Teixell, 1998), seismic tomography (Souriau and Granet, 1995) and magnetotelluric results (Pous *et al.*, 1995; Ledo *et al.*, 2000). To the west, the restoration of the crustal cross section across the Cantabrian Mountains also suggests that some lower crustal material may be subducted into the mantle to depths of ~90 km (Gallastegui, 2000). Deeper in the lithosphere, the uncertainties concerning the structure greatly increase. For example, based upon teleseismic arrival times, Poupinet *et al.* (1992) concluded that the thickness of the Iberian lithosphere must be approximately twice the thickness of the European one (140 and 70 km, respectively), while Ledo *et al.* (2000), based on electromagnetic results, propose almost the opposite picture: the Iberian lithosphere being 80 km thick and the European one, 115 km thick. On the other hand, a two-dimensional integrated lithospheric modelling along the Pyrenees combining thermal, gravity and local isostasy analysis proposes a lithospheric thickness of 105-115 km on the European side, 120-130 km beneath the Pyrenees, progressively shallowing up to 60-65 km in the Mediterranean Valencia Trough (Zeyen and Fernàndez, 1994). To the west, a similar 2D study across the western Cantabrian Mountains recently proposed a lithosphere of similar thickness (110-120 km) both in the central part of the Bay of Biscay (oceanic lithosphere) and beneath the Cantabrian Mountains, with a lithospheric root of ambiguous sense in the contact zone, down to depths of 150 km (Ayarza *et al.*, 2004).

An ongoing three-dimensional joint modelling of gravity anomalies and geoidal undulations is presented here as a tool to investigate the possible presence of deep crustal or lithospheric roots in this area (the modelled area is marked in figure 1). The modelling of gravity anomalies alone (e.g. Pedreira *et al.*, 2007) offers a poor resolution in the deeper parts of the crustal root and, especially, in the deeper topography of the lithosphere-asthenosphere boundary (LAB), as gravitational acceleration decays at a rate of $1/d^2$ (where d is the distance from the source). However, it

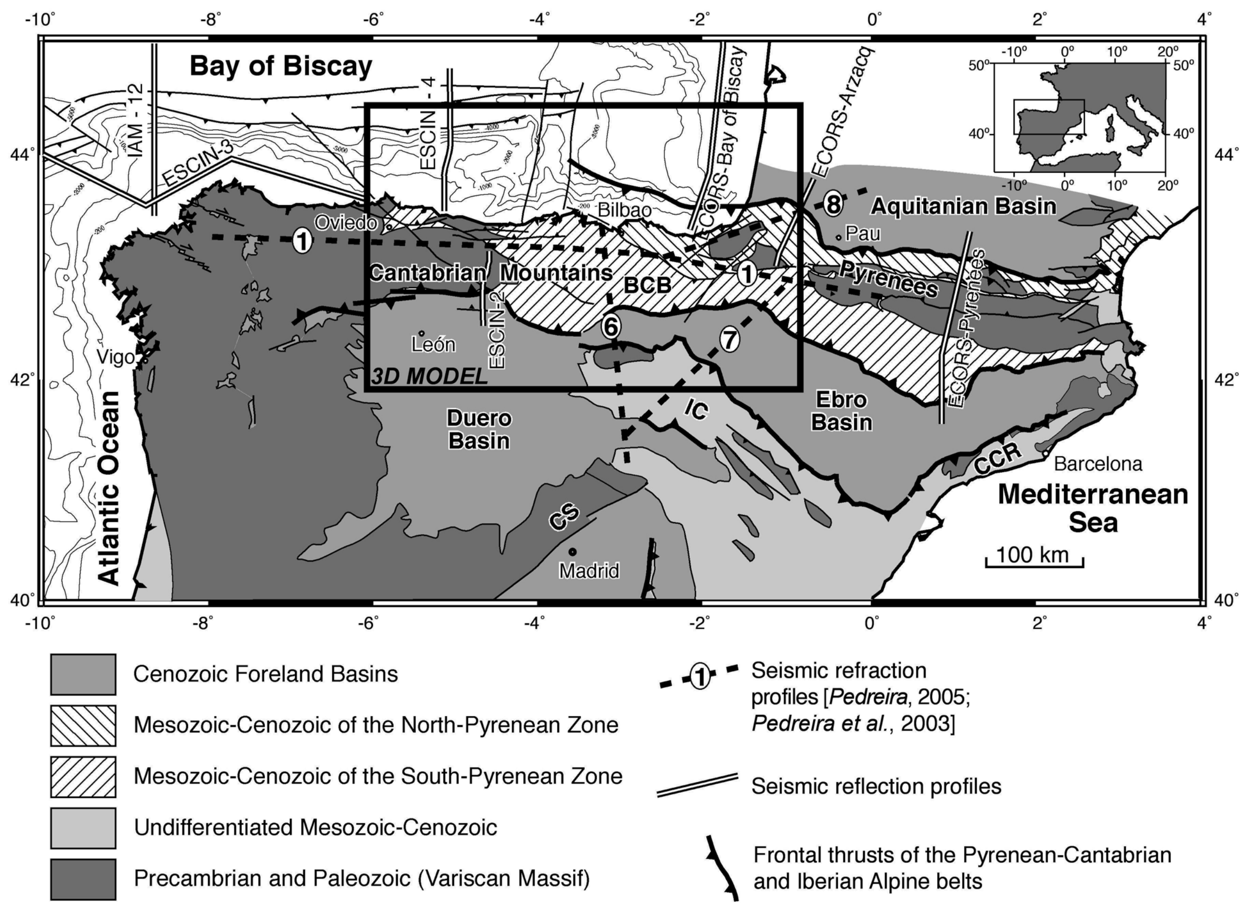

Figure 1. Tectonic map of the northern Iberian Peninsula showing the location of the 3D lithospheric model and some of the seismic profiles used to constrain the crustal structure. BCB: Basque-Cantabrian basin; IC: Iberian Chain; CCR: Catalan Coastal Ranges; CS: Central System.

could be a powerful tool when combined with the modelling of geoidal undulations, which are more sensitive to deeper (or more distant) sources, as the gravitational potential in this case decays at a rate of 1/d. Due to the different spectral content and depth (distance) dependence, the joint modelling of gravity anomalies and geoid undulations reduces the ambiguity of the final model and provides stronger constraints on the deep crustal/lithospheric structure.

Modelling strategy

We used the IGMAS interactive software (Götze and Lahmeyer, 1988; Schmidt and Götze, 1998, 1999) to construct the 3D model and calculate its potential field response. The structure is introduced along parallel vertical sections, and the volumes are obtained by triangulation of equivalent layer boundaries between adjacent vertical planes. Fitting between observed and calculated anomalies is achieved by forward modelling.

The starting model is the 3D crustal model already published by Pedreira *et al.* (2007). A detailed explanation on the geological and geophysical data used to constrain the structure is given in that publication. The geometry of the initial model was extended in depth to 400 km in order to allow a proper modelling of the upper mantle. It has also been extended with a more careful determination of the general crustal structure from all the borders of the model to a distance of 400 km, with a smooth transition to a uniform reference model from 400 to 800 km. The reference density model extends far beyond that distance to avoid edge effects and is composed of five layers: upper crust (0-14 km depth, 2670 kg m^{-3}), middle crust (14-24 km depth, 2840 kg m^{-3}), lower crust (24-32 km depth, 2950 kg m^{-3}), lithospheric mantle (32-100 km depth, 3315 kg m^{-3}) and asthenosphere (100-400 km depth, 3210 kg m^{-3}).

At this first stage of the study, the crustal structure of the model by Pedreira *et al.* (2007) was kept fixed inside the area marked in figure 1, and efforts were centered on the fitting of the longer wavelength component of the geoid created by the topography of the LAB. Further detailed adjustments will probably require some modifications of the Moho depths in areas not constrained by seismic profiles.

Density values

Densities used in the modelling are listed in table 1. A detailed explanation on the sources of these density values for crustal materials is given in Pedreira *et al.* (2007). Two new density bodies were added in this new model: the first one is located outside the studied area and represents the Cenozoic sediments in the Mediterranean Sea (Ayala *et al.*, 2004), whose elevated thickness and relatively low density (2400 kg m^{-3}) impose a noticeable lateral effect on the geoidal undulations; the other one is the asthenosphere, whose density of 3210 kg m^{-3} was derived from the best-fitting model. The density of the lithospheric mantle has been slightly increased with regard to the previous crustal model from 3300 to 3315 kg m^{-3}, which implies a higher density contrast at the LAB than those commonly accepted in similar types of studies. Further tests, including lateral and vertical variations in the density values of both the lithosphere and the asthenosphere, must be accomplished in order to reduce the high density contrast between them.

	Model bodies	Density (kg m^{-3})
1	Water	1030
2	Cenozoic sediments in the northern side of the Pyrenean-Cantabrian belt	2300
3	Cenozoic sediments in the Mediterranean sea (outside the studied area, see text)	2400
4	Tertiary of Duero basin (conglomerates, northern border)	2600
5	Tertiary of Duero basin (fine sediments)	2450
6	Tertiary of Ebro basin	2530
7	Tertiary of the South Pyrenean Zone	2630
8	Tectonized zone at the foot of the continental talus	2550
9	Mesozoic (post-Keuper)	2450-2650*
10	Mesozoic volcanoclastic complex (Biscay Synclinorium)	2650
11	Keuper	2250
12	Upper crust (pre-Keuper basement)	2670
13	Middle crust	2840
14	Iberian lower crust	2930
15	European lower crust	2970
16	Anomalous (highly magnetized) lower crustal body	3000
17	Lithospheric mantle	3315
18	Asthenosphere	3210

* Vary from east to west. See Pedreira *et al.* (2007) for details.

Table 1. Densities used in the modelling.

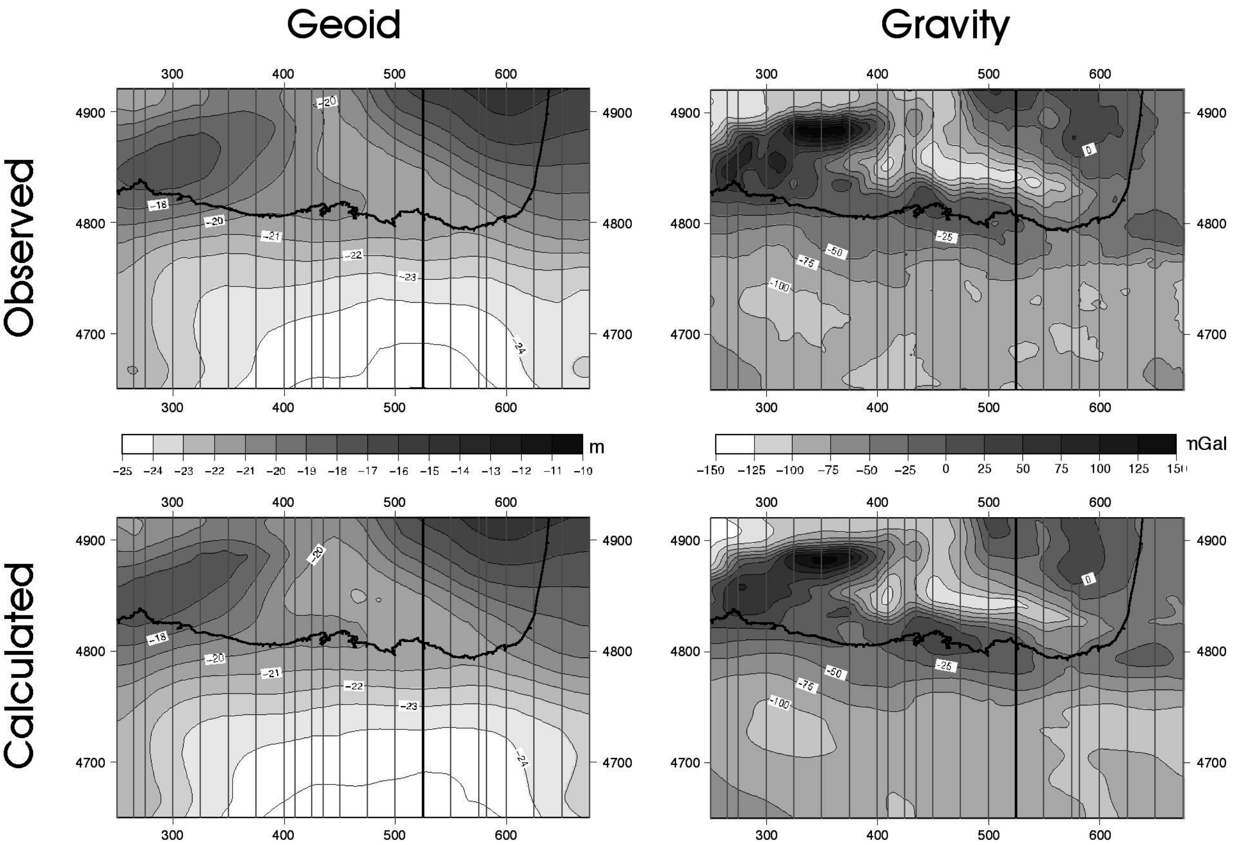

Figure 2. Observed and calculated geoid undulations and gravity anomalies over the 3D model (UTM Zone 30 coordinates in km). N-S grey lines: location of the cross sections used to construct the 3D model by triangulation of equivalent layer boundaries between adjacent planes. N-S black line: location of the cross section across the Basque-Cantabrian Basin shown in figure 3.

Gravity data

Gravity data used to create the map of observed gravity anomalies (Bouguer anomalies –with a reduction density of 2670 kg m^{-3}– on land and Free Air anomalies off-shore) were obtained from different sources (Pedreira *et al.*, 2007): the Bureau Gravimétrique International, the GeoFrance3D Project (Grandjean *et al.*, 1998), data collected during several projects carried out by the Geophysics and Lithospheric Structure Research Group of the University of Oviedo, and off-shore data from the database of Sandwell and Smith (1997).

Geoid data

The local geoid model corresponds to the IBERGEO-95 model for the Iberian Peninsula (Sevilla, 1995). In order to eliminate the effects of very deep sources, a regional geoid model derived from the global EGM2008 model (Pavlis *et al.*, 2008) developed up to degree and order 14 was subtracted from the local IBERGEO-95 geoid. The resulting residual geoid undulations have a wavelength of <2800 km and reflect the effect of the crustal and upper mantle density structure down to ~500 km depth (Featherstone, 1997).

The effect of the topography must also be subtracted, as it was done with the gravity data, in order to fit both types of anomalies with the same density model. We subtracted the effect of the topography out to a distance of 170 km from each side of the model. Due to the slow decay of the gravity potential with the distance, we also tested the effect of the topography from 170 to 400 km, but the undulations created by such distant topography have a very long wavelength that is considered to be well represented by the regional geoidal undulations, already subtracted from the local geoid.

Preliminary results

Figure 2 shows the observed and computed geoidal undulations and gravity anomalies over the 3D model. The distribution of highs and lows on the

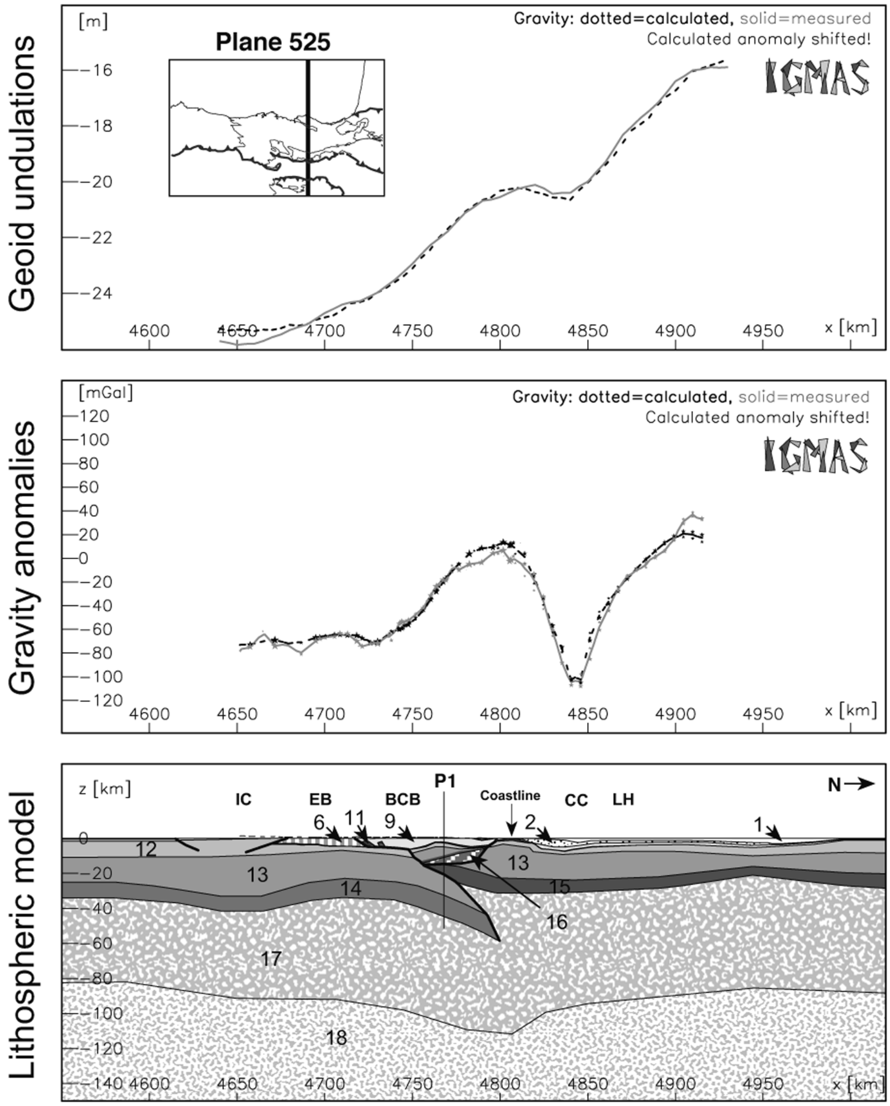

Figure 3. Observed (grey solid lines) and calculated (black dashed lines) geoid undulations and gravity anomalies over one of the vertical planes used to construct the 3D model, through the Basque Cantabrian basin (plane X = 525; north to the right). BCB: Basque-Cantabrian Basin; CC: Capbreton Canyon; EB: Ebro Basin; IC: Iberian Chain; LH: Landes High. Numbers indicate model bodies listed in table 1. P1 marks the crossing point with seismic refraction/wide-angle reflection profile 1 (Pedreira *et al.*, 2003; situation in figure 2).

map of observed geoidal undulations approximately follows the distribution of long-wavelength highs and lows on the gravity map, suggesting that the main sources for the geoid anomalies lie at the crust-mantle boundary or above it. The effects of such crustal sources reproduce very well the shorter wavelength components of the geoidal undulations, placing additional constraints on the structure proposed by Pedreira *et al.* (2007) for this area. The longer wavelength components of the residual geoidal undulations were adjusted by trial and error modification of the lithospheric mantle and asthenospheric densities, and the topography of the boundary layer between these two bodies. The correlation coefficients between observed and computed geoid and gravity anomalies are 0.99 and 0.98, respectively, with standard deviations of 0.36 m and 8.06 mGal.

Figure 3 shows an example of the fitting of gravity anomalies and geoid undulations along one of the N-S crustal profiles used to construct the 3D model. This profile, marked by a thick black line in figure 2 (coordinate X = 525), runs across the Basque-Cantabrian Basin, a thick Mesozoic basin inverted during the Alpine orogenic event and incorporated into the Pyrenean-Cantabrian belt. The structure proposed, with an uplifted piece of lower crustal material, is also able to explain the Basque Country Magnetic Anomaly (Pedreira *et al.*, 2007), which is the strongest aeromagnetic anomaly of the whole Spanish Mainland (Ardizone *et al.*, 1989; Aller and Zeyen, 1996). Apart from the Alpine crustal root of the Pyrenean-Cantabrian belt, other noticeable features in the Moho topography in this section are the crustal thickening in the northern Iberian Chain to the South (Pedreira *et al.*, 2003) and the crustal thin-

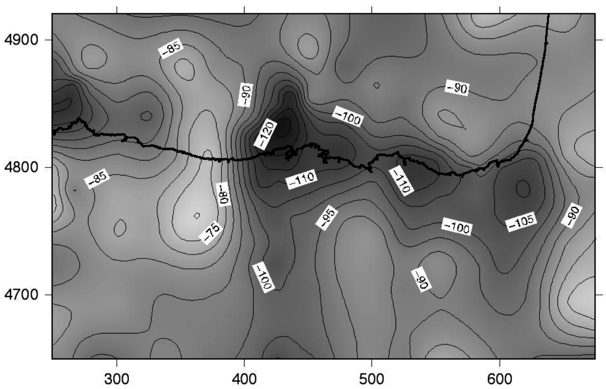

Figure 4. Preliminary low-pass filtered depth contour map of the lithosphere-asthenosphere boundary over the studied area.

ning in the Parentis Basin to the North (e.g. Pinet *et al.*, 1987).

A preliminary low-pass filtered map of the LAB is shown in figure 4. Thicknesses in both the Iberian and European-Cantabrian plates generally range between 85 and 95 km, with a small and discontinuous lithospheric root down to 110-125 km depth beneath the shoreline (approximately coincident with the trend of the crustal root).

Conclusions and future work

The results of this preliminary study suggest that the lithosphere in both the Iberian and European-Cantabrian plates has a similar thickness of 85-95 km, with a small and discontinuous root of an extra ~20-30 km maximum in the contact zone, approximately beneath the crustal root.

The trend of this lithospheric root seems to be disrupted by ~N-S lineaments, although we must emphasize that several factors still need to be tested in order to achieve reliable results on the topography of the LAB, especially the influence of variable density values for the lithospheric and asthenospheric mantle and the effect of possible eclogitized crustal roots.

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