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Crustal transition between continental and oceanic domains along the North Iberian margin from wide angle seismic and gravity data

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Abstract. Deep crustal features of the transition between the North Iberian mainland and the Bay of Biscay are constrained from new wide-angle seismic and gravity data. Velocity-depth models are derived from far-offset recordings onshore of two N-S marine profiles, complemented with new refraction data inland and tested against models that fit the gravity anomalies. Important lateral variations are inferred along the North Iberian margin. In the western transect, a Variscan crust is documented from the mainland across the continental shelf, and a rapid crustal thinning beneath the slope marks the transition to the oceanic domain. The eastern transect shows an outstanding crustal thickening beneath the coastline (Moho depths around 50 km) and a gradual thinning across the shelf. Differences are related to the V-shape of the Bay of Biscay that causes a W-E transition along the margin, from a short-lived oceanic subduction to continental collision during the Tertiary oblique convergence between Europe and Iberia.

1. Introduction

The North Iberian (NI) margin is a rifted continental margin that originated during the Mesozoic opening of the Bay of Biscay. It was affected later on by the Alpine convergence between the Iberia and Europe plates, clearly expressed in the eastern side by an intracontinental collisional orogen, the Pyrenees. The moderate convergence of about 40 km [*Roest and Srivastava*, 1991] in the NI margin enables the comprehension of processes responsible for continental rifting-early drifting, early subduction and continental collision. However, crucial to achieve these goals is an accurate knowledge of the crustal architecture of the transition between continental and oceanic domains. In contrast to a crustal structure extensively studied in the Pyrenees [*Muñoz*, 1992], the deep features from the Cantabrian range northwards, across the NI margin, were poorly constrained. New insights were provided by deep vertical reflection and refraction profiles in selected areas of the Cantabrian Mountains and foreland Duero basin [*Pérez-Estaún et al.*, 1994; *Pulgar et al.* 1996; *Fernández-Viejo* 1997], and by marine reflection profiles within the IAM and ESCIN experiments [*Banda et al.*, 1995; *Alvarez-Marrón et al.*, 1996]. Two N-S marine profiles have also been recorded on land (Fig. 1). These new wide-angle seismic and gravity data will be analyzed in this paper, to deriver a first model of the internal distribution of velocities and densities across the western and central part of the NI margin, from mainland to the oceanic domain. The geophysical transects will also illustrate the importance and westward extent of the Alpine deformations on a crustal scale.

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2. Geotectonic Setting

The V-shaped Bay of Biscay formed as one of the arms of the North Atlantic rift system during the Mesozoic rupture between Europe and North America. Models that invoke a counter-clockwise rotation of Iberia with respect to the Eurasia and Africa plates in Mesozoic and Tertiary times [see in *Sibuet*, 1989] involve sea-floor spreading in the Bay of Biscay simultaneously with compression in the eastern Pyrenees. Magnetic anomalies led *Roest and Srivastava* [1991] to propose a kinematic model with a plate boundary that jumped from the Bay of Biscay (prior to anomaly 34) to the NI margin (between anomalies 21 and 13) and later on, to the Azores-Gibraltar fracture zone.

The NI margin (Fig. 1) shows a narrow continental shelf (30-40 km wide) that pass to the abyssal plain (depths around 4500 m) through a very steep continental slope (10-15 km wide). North of the slope, the NI trough is infilled by a northward thinning wedge of sediments interpreted as an accretionary prism produced by short-lived subduction along the margin [*Boillot et al*, 1979; *Grimaud et al.*, 1982; *Álvarez-Marrón et al.*, 1997]. Inland, the Cantabrian Mountains constitute the western extension of the Pyrenean chain, and represent a block of Variscan basement uplifted over the foreland Duero basin as a result of the Eocene-Oligocene convergence between Europe and Iberia along this margin [*Alonso et al.*, 1996].

3. Seismic Data

The air-gun shots of the IAM-12 and ESCIN-4 marine profiles [*Alvarez-Marrón et al.*, 1997] were recorded at far offsets by 7 portable stations on land, in-line with the N-S profiles and spaced about 10 km (Figure 1). The aperture of the seismic experiments is

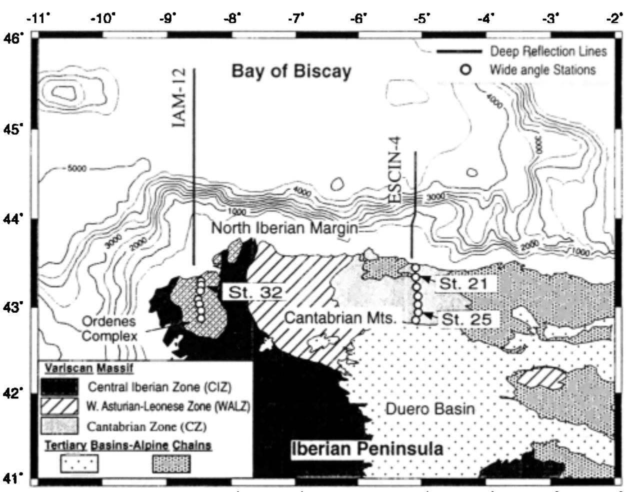

Figure 1. Simplifed geological map and bathymetric chart (contours in meters) of the study area and location of seismic profiles and land-recording stations

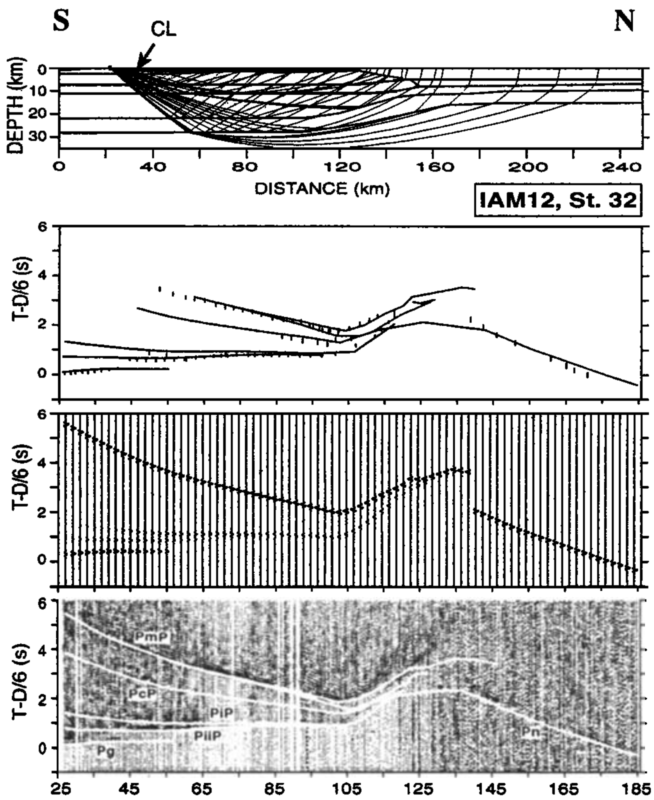

Figure 2. Example of wide-angle data (station 32) and interpretation for profile IAM-12. Panels from top to bottom show respectively, ray-tracing, fitting between observed and calculated traveltimes, synthetics and data (receiver gathers). Record sections shown in trace-normalized amplitudes, 3-12 Hz band-pass filter and Vr=6 km/s. The abrupt continental slope produces strong delays in arrivals and diffractions. Seismic phases labeled are Pg, Pn: refractions at basement and upper mantle; PiiP, PiP, PcP: reflections within upper crust, and at upper-middle and middle-lower crust boundaries, respectively; PmP: reflection at the Moho beneath the margin. CL marks the coastline. Model velocities are shown in Fig. 4.

thus extended 50-60 km to the mainland by these wide-angle recordings. Data have been plotted for each station as receiver gathers. A velocity-depth model has been developed through iterative combination of forward modeling and traveltime inversion [*Zelt and Smith*, 1992]. The relative amplitudes of the phases used in the inversion were compared with the observed ones and adjusted by forward modeling where necessary.

3.1. The IAM-12 Transect

The marine reflection profile IAM-12 runs in a N-S direction at 8.5°W (Fig.1). The vertical section shows, apart from the sedimentary sequence, a reflective band between 8-10 s TWT under the continental shelf [*Alvarez-Marrón et al.*, 1997]. Previous refraction work on land, in the Galicia domain had evidenced a three-layered crust with a total thickness of 30-32 km, thinning towards the coast [*Córdoba et al.*, 1987]. The wide-angle recordings of profile IAM-12 (Fig. 2) show several seismic phases that fit a velocity-depth model that corroborates the existence of a Variscan crustal structure southward of the continental slope.

A relevant feature in the upper crust is the seismic signature of the Ordenes complex, a mafic-ultramafic allochthonous body tectonically placed in the Variscan orogeny over the autochthonous Variscan Massif. This body explains the high velocities observed in the first arrivals at short distances. It extends from the surface down to 2-3 km depth and appears to continue beneath the sedimentary basin of the shelf, up to 40 km offshore. The Moho is located at 29 km depth in the sampled part inland. It is imaged as a subhorizontal feature under the continental shelf, starting a rapid shallowing beneath the slope toward the abyssal plain, where it is located at 15 km depth. Upper mantle velocities of 8.0-8.1 km/s are interpreted throughout.

3.2. The ESCIN-4 Transect

The wide-angle data of the ESCIN-4 profile at 5°W have been preliminary interpreted in *Pulgar et al.* [1996]. The PmP phases from the shots between the shoreline and the continental slope, which were recorded by all the land stations, constrain the Moho beneath the continental shelf. In the four stations on the northern part, the arrivals observed at offsets larger than 100 km are interpreted as the PmP and Pn phases associated also with this margin Moho (Fig. 3A). The sections from the three southernmost stations show an additional, energetic seismic phase, PmP', about 2 s after the Pn arrivals (Fig. 3B). Several explanations for this positive polarity reflection have been checked. It could not correspond to a multiple along the continental shelf, nor to a primary reflector below the margin Moho as it is not observed, from the same shots, on the northernmost stations. The arrival times and relative amplitudes of this PmP' phase can be fitted in a 'Pyrenees-like' structural model [*Choukroune et al.*, 1989] that includes a deep Moho onshore, steeply dipping northwards up to the shoreline (Fig. 3B). The existence of this type of Iberian Moho is also supported by two independent seismic experiments inland, in the same area of the Cantabrian Zone. A N-S vertical profile parallel to the ESCIN-4 transect showed a reflectivity pattern dipping northwards from 12 to 16 s TWT [*Pulgar et al.*, 1996], and an E-W refraction profile constrained a crustal root beneath the main topographic heights of the Cantabrian Mountains, where the Moho reaches 45-48 km depths [*Fernández-Viejo*, 1997].

In the velocity-depth model obtained (Figure 4) the lower crust is considerably thickened inland, with a steeply dipping Moho to more than 50 km depth beneath the shoreline. This structure is relayed oceanwards by a Moho beneath the margin that shallows gradually from 31 km depth near the coast to 18 km in the abyssal plain. Low velocities of 7.7-7.8 km/s are interpreted in the upper mantle beneath the shelf and slope. Although the present data are unreversed and there is obviously a trade-off between velocities and dips in the interpretive models, the observation of both PmP and Pn phases and PmP critical distances at different stations spaced up to 60 km along the N-S transect constrains the range of admissible mantle velocities, and values of 8.0-8.1 km/s could not be retained. However, more seismic data, especially from OBS recordings along- and across-strike of structures are needed to establish the deep structure of this complex area that may have resulted from a southward subduction of the oceanic crust and a northward underthrusting of the continental crust during the Alpine convergence.

4. Gravity Constraints

A gravity map has been compiled by considering Free-air anomalies offshore [data from *Sandwell and Smith*, 1995] and Bouguer anomalies onshore (Bureau Gravimétrique International data, complemented with new data collected in a ESCIN related campaign). Modeling of the gravimetric transects has been performed with an algorithm [*Talwani et al.*, 1959] that calculates the gravimetric contribution of 2-D polyhedra. The P-wave velocities obtained in the seismic modeling were converted to densities [*Ludwig et al.*, 1970] and used as initial models.

In the IAM-12 transect, gravimetric and seismic models are in good correspondance (Fig. 4). In the gravity model, a local positive anomaly in its southern part has been associated with the

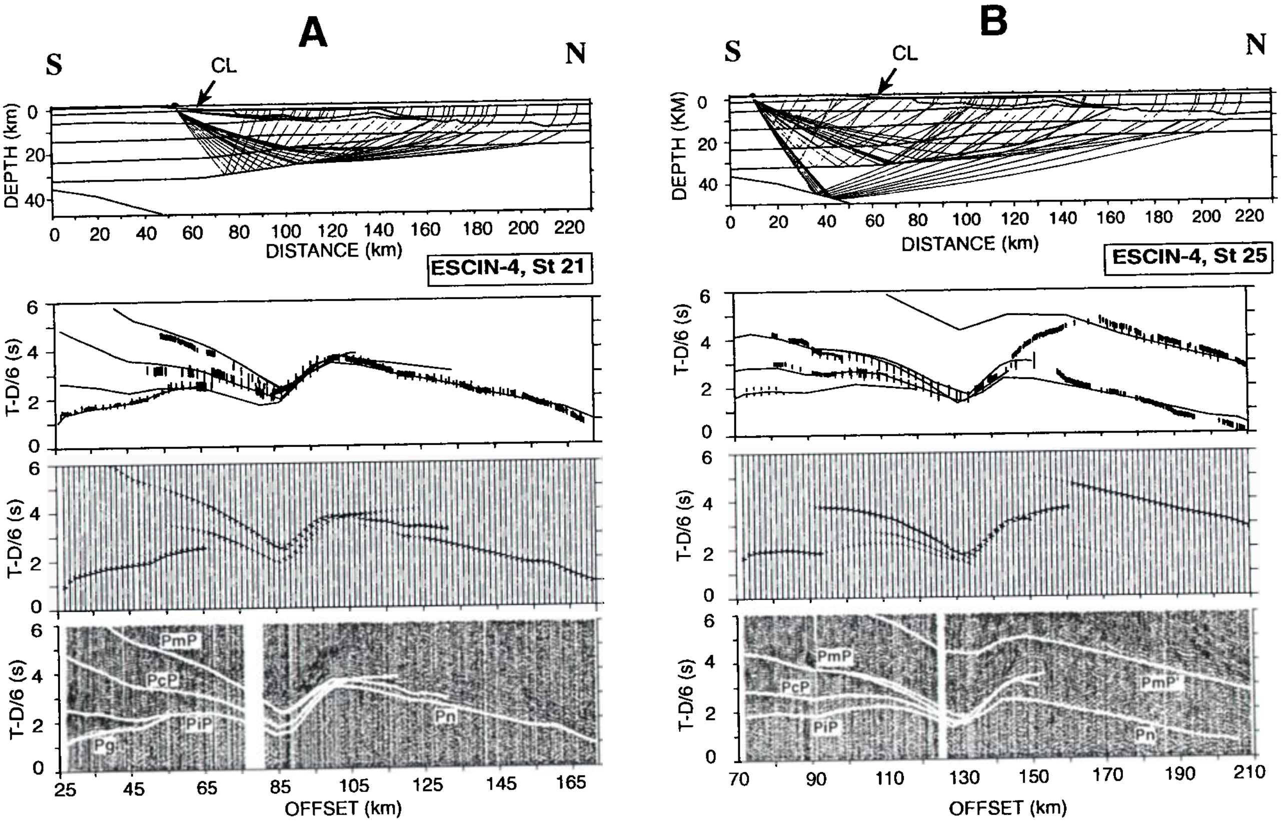

Figure 3. Examples of wide-angle data and interpretation for profile ESCIN-4. Fig. 3A (left): station 21; Fig 3B (right): station 25. PmP': Moho reflection inland. Other features as in Fig. 2.

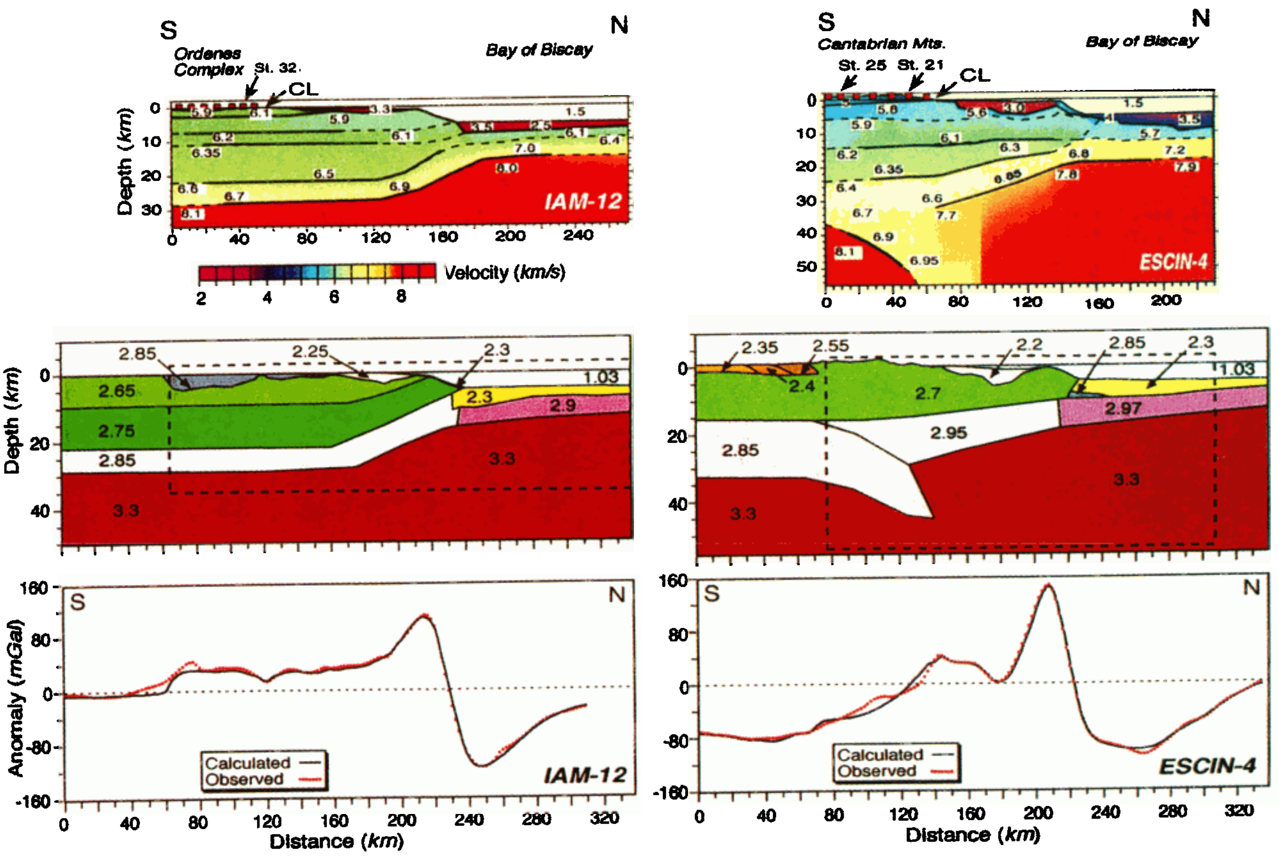

Figure 4. Velocity-depth models (upper panel), density models (middle panel) and fitting of the gravity anomalies (lower panel) in the IAM-12 (left) and ESCIN-4 (right) transects. Velocities in km/s and densities in g/cm^3. The dashed boxes in gravity models indicate the parts constrained from the seismic models. CL marks the coastline.

Ordenes complex. The transition to the oceanic domain in this transect is abrupt, within a short distance below the continental slope. Northward of this feature, velocities and densities increase, marking the transition to oceanic crust.

In the eastern gravity transect, densities and depths of the main layers have been derived from the velocity models of profile ESCIN-4 and two seismic refraction profiles in land [*Fernández-Viejo*, 1997]. Gravity values are around -70 mGal beneath the Cantabrian mountains, with a steep positive gradient towards the coast. On the marine side, gravity increases to a maximum of 140 mGal under the shelf then abruptly descends to a minimum of -120 mGal in the NI trough, increasing again to the North up to -10 mGal at the end of the transect. The observations are fitted by a model (Fig. 4) in which the crust thickens from 32 km depth in the southern part of the transect, to more than 45 km depth near the shoreline, in agreement with the seismic model.

5. Conclusions and Discussion

A major conclusion from the seismic and gravity models developed is that the deep crustal structure along the NI margin is marked by significant lateral variations (Fig 4). Such variations affect not only crustal and upper mantle velocities but also the type of transition from continental to oceanic domains. In the western part (IAM-12 transect) the transition is very abrupt beneath the continental slope and the Moho is subhorizontal beneath the shelf, whereas in the eastern part of the margin the transition is smoother, and the Moho deepens gradually southwards from around 18 km depth beneath the abyssal plain of the Bay of Biscay to 30 km depth near the coastline. The transition to mainland is very complex in this eastern part, showing an imbrication of two continental blocks that led to an important thickening of the crust beneath the Cantabrian Mountains. In contrast, at the longitude of IAM-12 transect, the onshore-offshore transition is smooth, and the Moho displays almost no variations from mainland to the continental slope suggesting that a much less important Alpine reactivation has affected the Variscan crust in this area.

These differences can be attributed to the role and nature of the northern plate subducted in the Tertiary convergence along this margin. In the eastern part, the magnetic anomalies suggest that the subducted slab was probably not really oceanic, but a thinned continental one [*Derégnaucourt and Boillot*, 1982], being quite resistant to subduction, hot and buoyant, as this area was at the vertex of the V-shaped Biscay oceanic basin. The structural features interpreted suggest that this slab was underthrusted beneath the continental margin giving rise to anomalous mantle velocities beneath this segment of the transect. Toward mainland, the slab indented the Iberian continental crust in a tectonic interwedging that promotes a detachment of the Iberian upper crust and a related underthrusting of the Iberian lower crust northwards below the European crust, resulting in an important crustal thickening and uplift of the Cantabrian Mountains. A similar deep structural relationship between Iberian and European crusts has been inferred further East, from the ECORS-Pyrenees [*Choukroune et al.*, 1989] and ECORS-Arzaq [*Daignières et al.*, 1994] profiles.

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