The eastern end of the Pyrenees: Seismic features at the transition to the NW Mediterranean.

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Abstract. The deep crustal features at the transition from the Pyrenean range to the NW Mediterranean basin have been investigated by onshore/offshore recording of Ligurian Sardinian (LISA) seismic profiles. The predominance in this area of the Neogene extensional tectonics over the Paleogene compressional one is revealed from the present-day deep structure sampled by the new wide-angle data. The existence of a crustal root beneath the Pyrenean Axial Zone and the outstanding differences in Moho depths between the Iberian and European domains, well established from previous seismic studies on central and western Pyrenees, are not observed anymore at the easternmost part of the range. This area is marked by a continued crustal thinning seawards (the Moho rises about 10 km along distances of 60 km) that affects already the mainland. Further evidences on lateral variations and topography of the crust-mantle boundary are indicative of the extent of the different tectonic episodes.

1. Introduction

The Pyrenees constitute a well known case-history concerning the signature on a lithospheric scale of compressional (Alpine) tectonics involving two continental plates: Iberia and Europe. Numerous seismic studies, particularly reflection and refraction profiles along and across the range [Gallart *et al.*, 1980; Hirn *et al.*, 1980; Daignières *et al.*, 1982; 1989; ECORS-Pyrenees Team, 1988; Choukroune *et al.*, 1989; Suriñach *et al.*, 1993] complemented by teleseismic [Poupinet *et al.*, 1992], tomography [Souriau and Granet, 1995] or gravity [Casas *et al.*, 1997] analyses, have revealed the existence of a crustal root beneath the Axial zone where the Moho reaches depths of about 50 km, as well as outstanding variations of 15-20 km in Moho depths within short distances between the Axial and North Pyrenean zones. This crustal architecture clearly delineates a northward subduction or imbrication of the Iberian crust beneath the European one [Daignières *et al.*, 1989; Roure *et al.*, 1989; Muñoz, 1992]. Contiguous to the Pyrenean domain eastward, the NW Mediterranean basins (Gulf of Lyon, Provençal basin, or Valencia trough) have developed in a very different tectonic regime, dominated by Neogene extensional processes. Marine seismic profiles have shown that the crust beneath these basins is predominantly of thinned continental type, the oceanic crust being restricted to the central part of the Algero-Provençal basin [Le Douaran *et al.*, 1984; de Vooch *et al.*, 1991; Pascal *et al.*, 1993; Mauffret *et al.*, 1995; Vidal *et al.*, 1998]. The deep features at the eastern end of the Pyrenean chain and the crustal evolution towards the NW Mediterranean basin, and hence the structural transition between domains dominated by compressional versus

extensional tectonics were poorly constrained to date, and are the object of the present paper.

2. Wide-angle seismics at the Pyrenees-Mediterranean transition

In the framework of the seismic study of the Ligurian Sardinian (LISA) margins project conducted in 1995 on the Western Mediterranean, five marine profiles were performed nearby the Pyrenean range (Figure 1). The air-gun shots were also recorded by 5 portable land stations placed so as to sample the easternmost part of the different Pyrenean domains: Axial, North and South Pyrenean zones. The corresponding wide-angle data constrain the deep crustal features around the onshore-offshore transition, and are analyzed here.

Examples of data are shown in Figures 2 to 5. The record sections are presented with a 6 km/s reduction velocity, a 5-12 Hz band-pass filtering and a normalisation in terms of maximum trace-amplitude. Main seismic phases identified on the sections are interpreted as refractions on the sedimentary cover and basement (Ps and Pg phases) and reflections from within the crust and at the Moho boundary (PiP, PcP, and PmP phases, respectively). Fitting of travel-times and amplitudes in a forward modelling procedure (Zelt and Smith, 1992) has resulted in 2D velocity-depth models that illustrate main structural features of the sampled area (Figures 2, 3 and 6).

3. Crustal structure along an onshore-offshore transect

Profile 4 recorded on stations F, A and C (see Figure 1) maps the transition from the Pyrenean mainland towards the margin.

Figure 1. Tectonic map of the eastern Pyrenees showing the location of the LISA seismic profiles 1 to 5 and the recording stations on land (A), (B), (C), (F) and (P). NPF stands for North Pyrenean Fault. The dotted lines indicate the midpoints for respective wide-angle profiles and station pairs shown in Figs. 2 and 3.

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Figure 2. Wide-angle data and interpretation for Profile 4. (a): station (A) on the South Pyrenean Zone; (b): station (C) on the Axial zone. Panels from top to bottom show, respectively the fitting between observed data (crosses) and synthetics calculated from model (c), and the record sections, reduced with 6 km/s and with main seismic phases labelled. (c): velocity-depth model obtained, showing main P-velocity values (km/s). The parts of the model directly sampled by ray-tracing are shown in white segments. The arrow marks the shoreline.

The energy reflected at the Moho boundary dominates the section from station A (Figure 2a), in contrast to the image from station C (Figure 2b) at shorter recording offsets, where Ps, Pg, and PiP phases are better defined than PcP and PmP. The interpreted model (Figure 2c) shows a 5 km-thick sedimentary sequence where two layers are differentiated. The uppermost one has velocities of 4.8 km/s on land and 2.5 km/s at sea, below which the sediments have values of 5.5 km/s and 4.0 km/s, respectively. The crystalline basement has velocities ~ 6.1 km/s. The lower crust is characterized by velocities of 6.4–6.5 km/s onshore, and seawards higher values of 6.8–7.1 km/s have been introduced in the model to account for the relative amplitudes between reflected phases, particularly the low energies observed for PcP and PmP phases on station C. A W-E lateral change in the configuration of the lower crust is hence documented. This crustal structure offshore is in agreement with the coincident near-vertical section [Nercessian *et al.*, 2001] that shows beneath the sedimentary sequence three crustal reflectors at 4, 6, and 8 s TWT, respectively. Velocities of 8.0–8.1 km/s are interpreted at the upper mantle throughout the profile.

Another significant result from profile 4 is the continued crustal thinning seawards. The Moho depths vary from ~ 32 km beneath point A to 25 km beneath point C, and to 22 km at ~ 25 km offshore. The crustal thickness is thus reduced by 10 km in ~ 50 km horizontal distance and the thinning affects already the mainland. On the other hand, the far-offset recordings of this profile at point F (not shown in Fig. 2) suggest that farther inland than point A, the Moho remains at ~ 32 km depth.

4. Differences in crustal thickness along the margin and between Pyrenean domains.

The lateral variations of the deep crust along the margin can be evaluated from profile 5 recorded on stations A and C (Figure 3). Considering the lack of a simple 2D recording geometry specially for short distances, we have assumed most upper crustal features as for profile 4, and focused on the Moho level. A progressive crustal thinning along the margin can also be inferred,

Figure 3. (a): Wide-angle data and interpretation for Profile 5 from station (C). Top panel: ray-tracing. Other panels as in Fig. 2; (b): velocity-depth model. The dotted line indicates the Moho as derived from modelling of the same profile on station (A). Comparison between Moho locations from both stations illustrates the progressive thinning of the crust seawards.

Figure 4. Examples of the PmP seismic phase from profile 5 recorded on station (C) (top) and station (A) (bottom). Note that in both cases the PmP correlation does not show up as a single hyperbola, but rather suggests local jumps in arrival times.

as the Moho is located at depths of ~28 km and 25 km at the areas sampled from stations A and C respectively (see Figures 1 and 3), which is however deeper than further NW under profile 4 (see Figure 2). Moreover, the PmP phase can not be correlated with an unique hyperbola, but seem to split at some offsets into different wavefronts detected in both sections (Figure 4). This may be attributed to throws and dips that affect locally the Moho in relation with deep crustal faulting, as was already suggested in former seismic profiles at the eastern Pyrenees and western Mediterranean margins [Gallart *et al.*, 1980; 1994].

Constraints on the crustal depths at the easternmost part of the Pyrenean units are provided by the different profiles recorded at stations P and B on the North Pyrenean and Axial zones, respectively (see Figure 1). The PmP arrivals at station B recorded from three different profiles (Figure 5) indicate a remarkable S-N thinning of the crust. This is documented by the earlier PmP arrival times associated to the northern EW profile 1, with respect to the ones observed for profile 2 (Figure 5c, d). This northward thinning can also be inferred at a different level from the steep slope of the PmP phase along the NW-SE profile 5 (Figure 5e). On the other hand, PmP phases in stations P and B at comparable offsets are observed at about the same arrival times (Figure 5). Modelling of these data, taking also into account previous velocity-depth results on land [Gallart *et al.*, 1980], led to crustal thicknesses of 27 and 28 km, respectively north and south of the North Pyrenean fault zone that separates these two main Pyrenean domains (Figure 6). Therefore, the outstanding differences in crustal thickness between the Axial and North Pyrenean zones, ranging from 10 to 20 km, well established in more central parts of the range since pioneering work by broadside seismic profiling [Hirn *et al.*, 1980], do not persist at the eastern end of the Pyrenees.

5. Discussion and Conclusions

The predominance of the Neogene extensional tectonics over the Paleogene compressional one at the transition from the Pyrenean domain of NE Iberian Peninsula to the adjacent Mediterranean margin can be assessed from the new wide-angle data presented here. No evidences of thickening or existence of a crustal root extending into the Mediterranean are inferred from the seismic results. The dominant feature found in the study area is a

marked crustal thinning, the Moho rising progressively by ~10 km within horizontal distances of 60 km along the onshore-offshore transition (Figure 6). Moreover, the crust thins for ~7 km already within the mainland, and the Moho is found at 25 km beneath the shoreline. This is at variance with results reported for this transition southwards [Vidal *et al.*, 1998], which indicate that the thinning associated with the formation of the Valencia trough starts seaward from the shoreline, where the Moho is still located at 32 km depth.

The well constrained crustal image along the Pyrenees in terms of a thickening with subduction or imbrication of the Iberian crust beneath the European one [Daignières *et al.*, 1989; Roure *et al.*, 1989; Muñoz, 1992] does not persist at the eastern end of the range, where similar crustal depths of 27–28 km are obtained beneath the North Pyrenean and Axial zones (Figure 6). Gravity constraints [Casas *et al.*, 1997] also minimise the crustal differences at the easternmost Pyrenees. All these results suggest that the shortening in relation with the Alpine compressional tectonics has been probably smaller here than in more central parts of the range, and it has been reabsorbed on a crustal scale by the Neogene extensional processes that produce the western Mediterranean basins. The Upper Oligocene–Early Miocene extension associated to the opening of the Provençal basin and the anti-clockwise rotation of the Corsica–Sardinia block [Gueguen *et al.*, 1998] and the Upper Miocene–Recent active extension [Lewis *et al.*, 2000] have produced the corresponding crustal thinning at the NE Iberian mainland and continental margin.

Onshore, velocities of 6.4–6.5 km/s are interpreted at the lower crust, in agreement with values obtained in the adjacent Catalan margin [Gallart *et al.*, 1994; Vidal *et al.*, 1998] or at the Betics-Alboran domains [Banda *et al.*, 1993] where the absence of high velocities at deep levels was attributed to the removal of part of the lower crust across extensional detachments during the rifting process. The tilted block tectonics along the Catalan margin associated to normal faulting [Roca and Guimera, 1992] may have an expression on a crustal scale, as our data suggest that throws and dips may affect locally the Moho, in agreement with previous observations further southwards [Gallart *et al.*, 1994]. All these features are indicative of the importance and lateral

Figure 5. Examples of PmP recordings at stations P on the North Pyrenean zone from marine profile 5 (b), and B on the Axial zone from marine profiles 1, 2, 5 (c, d, e). Location is outlined in (a).

Figure 6. Compilation of main results concerning crustal thicknesses in the study area. Numbers inside boxes correspond to Moho depth in km. Values in circles around points (B) and (P) are taken from previous studies in the eastern Pyrenees (Gallart et al., 1980).

extent of the different successive tectonic episodes that affected the NE Iberian-Mediterranean transition.

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