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The deep roots of the western Pyrenees revealed by full waveform inversion of teleseismic P waves

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ABSTRACT

Imaging the architecture of mountain roots is required to understand the support of topography and for kinematic reconstructions at convergent plate boundaries, but is still challenging with conventional seismic imaging approaches. Here we present a three-dimensional model of both compressional and shear velocities in the lithosphere beneath the western Pyrenees (southwest Europe), obtained by full waveform inversion of teleseismic P waves. This tomographic model reveals the subduction of the Iberian crust beneath the European plate, and the European serpentinized subcontinental mantle emplaced at shallow crustal levels beneath the Mauléon basin. The rift-inherited mantle wedge acted as an indenter during the Pyrenean convergence. These new results provide compelling evidence for the role of rift-inherited structures during mountain building in Alpine-type orogens.

INTRODUCTION

Collisional orogens require deep roots to support their topography over millions of years (Watts, 2001). However, the deep internal structure and nature of these orogenic roots have long been the focus of debates and contrasting interpretations. According to local (Airy) isostasy, high topographic reliefs of mountain ranges are compensated by deep crustal roots. However, the crust in orogens does not respond to surface loads locally but rather by flexure over a broad region (Karner and Watts, 1983). Departure from the Airy model is often observed, with a shift of maximum crustal thickness with respect to topographic highs, the gravity field displaying a positive-negative anomaly couple. The positive anomalies have been classically ascribed to buried loads, whereas the broad gravity lows reflect the downward flexure of the underthrust crust produced by the combined effects of surface (i.e., topography) and internal loads. This simple conceptual model has been successfully applied to reproduce the pattern of Bouguer anomalies in various orogenic belts (e.g., Karner and Watts, 1983; Royden and Karner, 1984). However, owing to the insufficient spatial resolution of classical seismic tomography, the nature and origin of these buried loads have so far remained elusive.

The Pyrenees (southwest Europe) are an intracontinental orogen that result from the tectonic inversion of an Early Cretaceous rift system formed between the Iberia and European plates (e.g., Choukroune et al., 1989). Tectonic restorations and kinematic models of plate convergence indicate a moderate shortening of <200 km since the Late Cretaceous (Roure et al., 1989; Muñoz, 1992; Teixell, 1998; Mouthereau et al., 2014) that ended ~20 m.y. ago. The Pyrenees can thus be considered as a fossilized plate boundary. This has been confirmed by recent GPS studies that did not find any measurable relative motion between Iberia and Europe (Nocquet and Calais, 2004). Precollisional rift-related structures are particularly well preserved in the western Pyrenees, where extension was greatest and collision reached a less advanced stage (Masini et al., 2014). This region thus offers a unique opportunity to study a crustal section across an embryonic stage of a collisional orogen. Here we present a lithospheric section of the western Pyrenees constructed from full waveform inversion of vertical and radial component records of teleseismic P waves that enables us to decipher the enigmatic nature and structure of buried loads.

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DATA AND WAVEFORM INVERSION METHOD

Seismological data are from a dense transect deployed during the temporary PYROPE (Pyrenean Observational Portable Experiment) project (Chevrot et al., 2014) in 2012–2013 (Fig. 1). We selected the vertical and radial components of 5 earthquakes recorded by the 29 stations deployed along the transect. The full waveform inversion (FWI) method (Monteiller et al., 2015; for details on the method, see the GSA Data Repository[1]) searches for three-dimensional compressional and shear velocity models that minimize the misfit between observed and synthetic seismograms computed with the hybrid direct solution method–spectral-element technique (Monteiller et al., 2013). We use 50-s-long time windows from the vertical and radial component records around the P wave arrivals, low-pass filtered at 5 s. We thus include in the inversion all the crustal reverberations that arrive in the coda of the P waves. These arrivals are crucial to constrain the sharp velocity gradients associated with the main crustal interfaces such as the crust-mantle boundary (Moho). The final model obtained after nine iterations provides an excellent fit of both vertical and radial component waveforms (Figs. DR1–DR5 in the Data Repository). A synthetic resolution test performed on a checkerboard model (Fig. DR6) demonstrates that our imaging technique is able to resolve lateral and vertical variations of seismic velocities in the crust with a spatial resolution of a few kilometers, even with a limited number of teleseismic

[1]GSA Data Repository item 2016159, description of the model, forward modeling, full inversion method, resolution tests, modeling of Bouguer gravity anomalies, supplemental table with event information, and plots of vertical and radial waveform fits, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

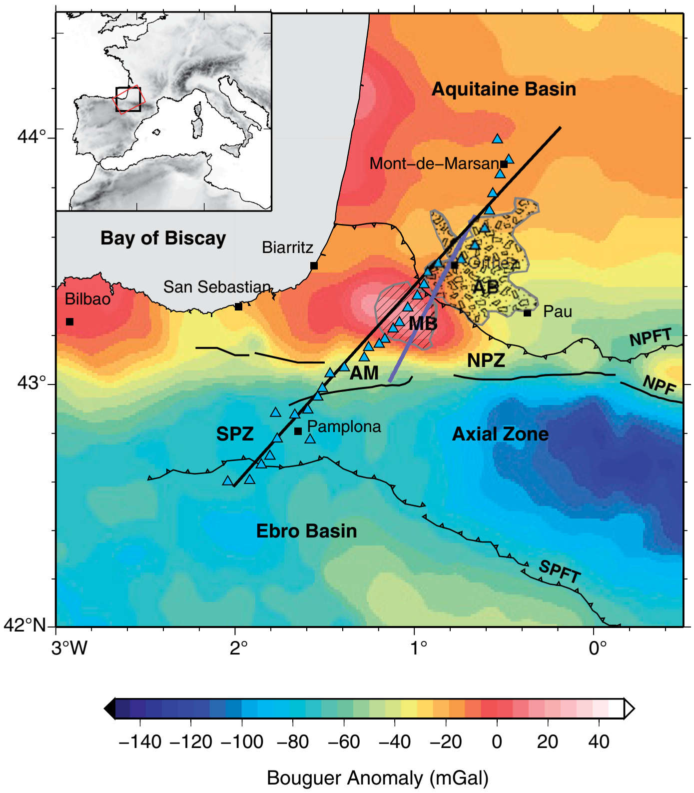

Figure 1. Map of Bouguer gravity anomalies with the locations of seismic stations (blue triangles) in the Pyrenees. The black and purple solid lines show the positions of the western PYROPE and ECORS-Arzacq transects, respectively. NPF—North Pyrenean fault, NPZ—North Pyrenean zone, SPZ—South Pyrenean zone, SPFT—South Pyrenean frontal thrust, NPFT—North Pyrenean frontal thrust, MB—Mauléon Basin, AB—Arzacq Basin, AM—Aldudes Massif. Inset shows location of the study region (black square) and limits of the spectral-element grid (red square).

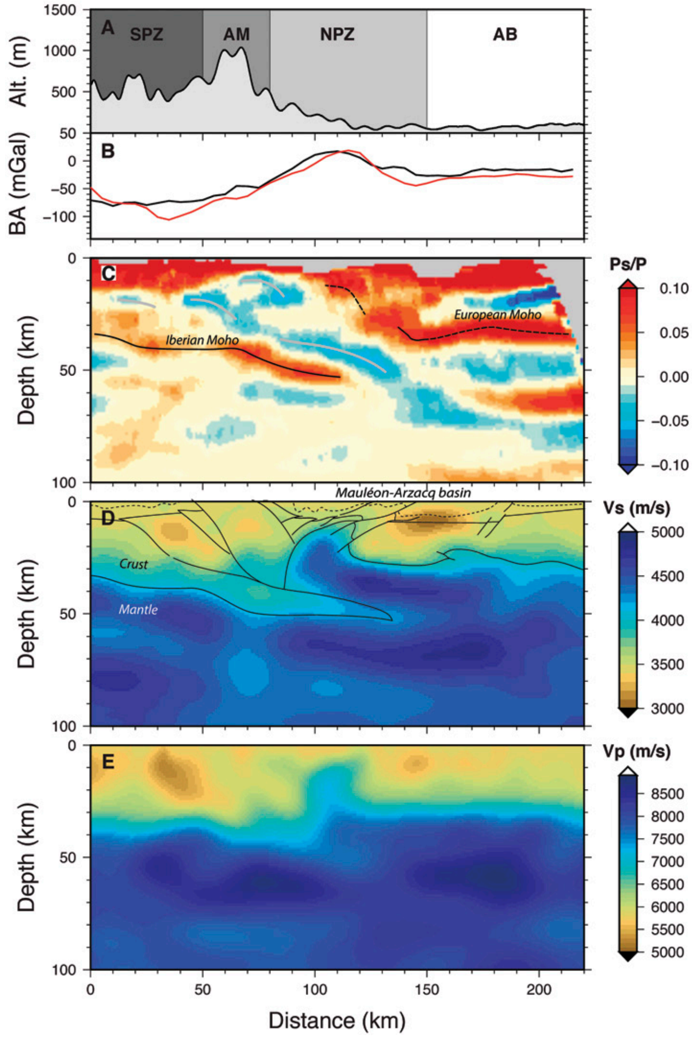

Figure 2. A: Topography (Alt—altitude) along the western PYROPE seismic transect. The gray areas delimitate the South Pyrenean zone (SPZ), the Aldudes Massif (AM), the North Pyrenean zone (NPZ), and the Aquitaine Basin (AB). The North Pyrenean frontal thrust (NPFT) marks the limit between NPZ and AB. B: Profiles of observed (black line) and modeled (red line) Bouguer gravity anomalies (BA). C: Common conversion point stack of receiver functions for the western transect (from Chevrot et al., 2015). D: Vs model obtained by full waveform inversion. E: Vp model obtained by full waveform inversion.

sources. The FWI inversion approach reveals structural details that could not be seen with conventional regional traveltime (Chevrot et al., 2014) or ambient noise (Macquet et al., 2014) tomography.

TOMOGRAPHIC MODEL

The vertical cross sections through our Vp and Vs models along the transect (Figs. 2C and 2D) show striking similarities, even though Vp and Vs were allowed to vary freely and independently during the inversion. This is remarkable because the Vp model is mostly constrained by transmitted P waves on the vertical component, while the main contribution to the Vs model comes from the P to S conversions and multiple reflections on crustal interfaces recorded on the radial components. However, the structures are more sharply defined in the Vs model. Because in FWI, as in any tomographic method, the spatial resolution scales with the seismic wavelength, this simply results from the shorter wavelengths of shear waves compared to compressional waves.

The crust-mantle boundary, expressed as a sharp velocity gradient in both the Vp and Vs models, exhibits a very complex geometry, which is in remarkable agreement with the results of receiver function migration (Chevrot et al., 2015) shown in Figure 2B. We observe two distinct Mohos, belonging to the Iberia and European plates, that are superposed beneath the North Pyrenean zone. The Iberian Moho dips gently from a standard depth of 30 km at the southern end of the profile to a depth of 40 km. Further north, it deepens and flattens to reach a depth of 50 km, delimiting a slice of Iberian material that underthrusts the European mantle. The Moho of the European plate is shallower and has much stronger topography. However, beneath the Arzacq basin, the different images may be contaminated by the reverberations inside shallow unconsolidated sedimentary layers.

A salient feature in the tomographic model is the north-dipping low-velocity anomaly observed beneath the European plate, located at ~50 km depth. The top of this anomaly coincides with a negative polarity interface observed in the migration section. This strongly suggests the underthrusting of a fragment of the Iberian crust beneath the European plate, topped by the European subcontinental mantle, as proposed in a receiver function migration study (Chevrot et al., 2015). Seismic velocities in that subducted body (Vp ~ 7.2 km/s, Vs ~ 4 km/s) are typical of a mafic lower crust (Rudnick and Fountain, 1995), but could also be compatible with a serpentinized mantle (Christensen, 2004).

Another prominent anomaly is observed beneath the Mauléon basin, between 10 and 30 km depth, expressed in both the Vp and Vs models, that coincides with the strong positive Labourd-Mauléon Bouguer gravity anomaly (Fig. 1). The top of this fast velocity anomaly also corresponds to a strong Vs contrast observed in the migrated section. We have built a density model from the Vp model using a standard Birch law (see the Data Repository). The Bouguer anomalies predicted by this density model are in excellent agreement with the observations (Fig. 2B; Figs. DR6 and DR7). This suggests that the details of the deep architecture revealed with our new imaging technique are robust and can be exploited to propose a new geological model for the western Pyrenees.

GEOLOGICAL INTERPRETATION

Discriminating the nature of rocks from seismic velocities is a difficult problem. The seismic velocities beneath the Mauléon basin (Vp ~ 7.3 km/s and Vs ~ 4.2 km/s), although not incompatible with a mafic lower crust, would be close to the extreme values reported for this type of material (Rudnick and Fountain, 1995). However, the compressional velocities observed at the base of the European crust are significantly lower, ~6.9 km/s, and in excellent agreement with those typically found in the lower crust of Cenozoic convergent margins by seismic reflection or refraction surveys (Rudnick and Fountain, 1995). We thus think that it is very unlikely that the velocity anomaly beneath the Mauléon basin reflects a thick accumulation of mafic rocks in the lower crust.

The alternative is that this fast velocity body is made of serpentinized mantle. This hypothesis is supported by many recent geological studies in the western Pyrenees that describe remnants of a hyperextended rifted margin with the presence of an exhumed mantle locally exposed within small outcrops along the southern reactivated border of the Mauléon basin as well as reworked in the Albian–Cenomanian sediments filling the Mauléon basin (e.g., Jammes et al., 2009; Lagabrielle et al., 2010).

The top of the serpentinized mantle body, which corresponds to the European petrological Moho beneath the North Pyrenean zone, is very close to the surface, at ~10 km depth. Recent studies estimate that as much as 8 km of sediments accumulated in the Mauléon basin since the Triassic (Vacherat et al., 2014), while drilling has shown that the depth of the basement is now found at ~6 km depth, suggesting that ~2 km of sediments were eroded during the Pyrenean convergence. This would imply that the crust beneath the Mauléon basin is <4 km thick, and may correspond to the continuation of a hyperextended crust of the European rifted margin (Tugend et al., 2014). The tomographic model also suggests that shortening in the North Pyrenean zone involved deep-seated folding and thrusting of the European subcontinental mantle of the previously thinned European lithosphere. Our geological interpretations of the tomographic model are summarized in Figure 3.

DISCUSSION AND CONCLUSIONS

Our geological model differs notably from published crustal sections built from the interpretation of the Étude Continentale et Océanique par Réflexion et Réfraction Sisimique (ECORS) Arzacq profile (Daignières et al., 1994) and surface geology (Teixell, 1998; Masini et al., 2014; Daignières et al., 1994; Jammes et al., 2009). The main reason for this discrepancy stems from the difficulty to detect the Moho on the migrated section presented in Daignières et al. (1994). Beneath the Arzacq basin there is a clear deep reflector at ~10 s, which probably corresponds to the Moho. Sporadic reflectors at ~9 s are also detected beneath the northern part of the Mauléon basin, but not further south. This means that the previous interpretations of the ECORS-Arzacq section were not constrained by the seismic reflection data in their central part. However, our geological model is consistent with the ECORS Arzacq section, with a rather flat European Moho at~30 km depth beneath the Arzacq basin. It also explains why deep reflectors are not observed beneath the southern Mauléon basin and the Arbailles massif. One key observation in serpentinized mantle domains is that the Moho reflections are usually absent (e.g., Minshull, 2009); thus the lack of a well-defined Moho beneath the Mauléon basin may be additional evidence for serpentinized mantle.

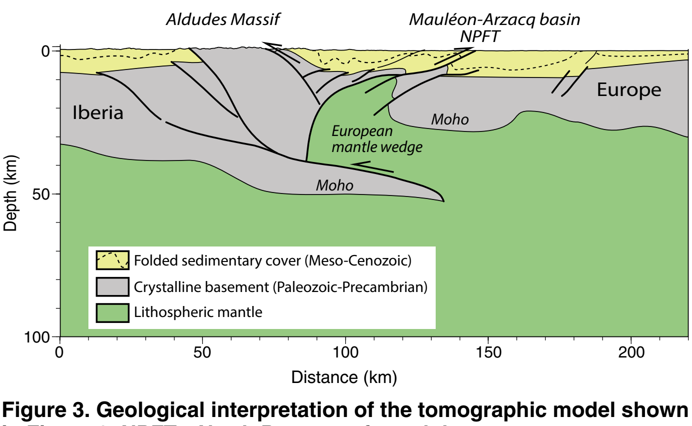

Figure 3. Geological interpretation of the tomographic model shown in Figure 2. NPFT—North Pyrenean frontal thrust.

Our new structural model could also explain why Lg seismic waves are strongly attenuated when they cross the western Pyrenees (Chazalon et al., 1993; Sens-Schöenfelder et al., 2009), a puzzling observation that numerical modeling has so far been unable to reproduce. It is interesting that similar observations have been made in the Alps, where the attenuation of Lg waves has been related to the dense Ivrea body (Campillo et al., 1993). It is well known that crustal thickness has an important effect on the propagation of Lg waves by limiting the number of overtones in a given frequency range (Zhang and Lay, 1995). For this reason, Lg waves are almost never present in oceanic paths. The crust that we image beneath the Mauléon basin is extremely thin, perhaps even locally absent, which should strongly impede the propagation of Lg waves.

To explain the strong positive Bouguer anomaly of the Mauléon basin, former studies invoked a block of European mantle (Casas et al., 1997) or lower crust (Grandjean, 1994; Vacher and Souriau, 2001; Pedreira et al., 2007; Jammes et al., 2010). Our model would rather suggest that this anomaly is the signature of an exhumed mantle, inherited from the precompressional hyperextended Pyrenean rift system. The mantle wedge beneath the Mauléon basin loads and causes flexure of the underlying Iberian plate, which explains why the Pyrenees appear isostatically overcompensated, and why the deep crustal roots are shifted 50 km northward with respect to the topographic highs.

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