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Seismic diffraction from the North Pyrenean Fault: a depth-migrated line-drawing of the ECORS profile

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Abstract

We present here a complete depth-migrated line-drawing of the ECORS Pyrenees profile. The main feature of the migrated section is an important diffraction zone generated by the North Pyrenean Fault. We image several inhomogeneities in both the Iberian and the European upper crust. Some of them can be linked to Proterozoic materials that have been affected by Hercynian tectonics. Deeper, around 25 s two-way time (TWT), several dipping reflectors initially identified below the Aquitaine basin migrate to the south. They form the northern limit of the Iberian lower crust dipping beneath a wedge consisting of European crust and upper mantle, a previously described but now better imaged feature of the lithosphere beneath the Pyrenees.

1. Introduction

The ECORS Pyrenees profile is a 250-km-long deep seismic survey which was acquired in 1986 across the Pyrenees from the Aquitaine basin to the Ebro basin (Fig. 1). From north to south, this profile crosses the entire orogenic belt. Detailed descriptions of the geological and geographical context were presented by Choukroune et al. (1989).

Several interpretations of this profile have already been published. The different models are always based on the continuity, dip and localization of the reflectors. Some of the interpretations focus on the Axial Zone and they mainly deal with the reflectors situated below the North Pyrenean Fault. However, these models are usually based on partially migrated or even unmigrated data. As many intra-crustal reflectors have a strong dip (35–40°), sometimes at great depth, migration is vital to the creation of reliable balanced cross-sections.

2. Some very deep dipping reflectors

Any interpretation of vertical seismic data usually makes use of a line-drawing to extract the geological information from the seismic section. Following a first presentation of the results (ECORS Pyrenees Team, 1988), a complete line-drawing of the ECORS Pyrenean profile was produced (Choukroune et al., 1989). For objectiv-

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ity's sake, the section was independently analysed by a group of geologists and geophysicists, in order to pick the most energetic events. The final result (Fig. 2a) corresponds to a synthesis of their independent line-drawings.

The high quality of the data is responsible for the line-drawing showing a great density of reflectors. Very deep reflections (around 25 s TWT) could be picked below the Aquitaine basin. They dip to the north, and, if we take into account the geometrical principles of the vertical seismic reflection method, these reflectors will be shifted to the south, to a shallower position but with an increased dip. The magnitude of such a migration will depend on the depth and dip of the reflectors. Migration is very important here because these reflectors migrate to the contact between Iberian and European crust. These reflectors are used in various balanced cross-sections where they constrain the shortening estimate (Daignières et al., 1989; Davy et al., 1990). The shape of the contact between the Iberian and the European Moho determines: first, the extension of the imbrication between both lithospheres; and second, the geometry at depth of the North Pyrenean Fault.

3. With or without migration?

Methods of numerical migration have been mainly developed for oil exploration (McQuillin et al., 1979). They give good results only for short travel times (4–5 s TWT). For continental deep seismic data, the low signal-to-noise ratio and the poor knowledge of the velocity distribution frequently create artefacts and noise that degrade the sections (Warner, 1987). This is probably the reason why many authors use only line-drawings of the unmigrated section (Fig. 2a). This has led some authors to base their interpretations on unmigrated time sections, which might have been adequate near the surface (Baby, 1988; Choukroune et al., 1989; Déramond et al., 1990) but is certainly not so at depth in the presence of dip. Others have concentrated on the migration of a few selected reflectors (Daignières et al., 1989; Roure et al., 1989).

Different intermediate solutions to the migration of deep continental reflection data have been proposed in the last few years. One of these is a ray-tracing migration of the line-drawing (Raynaud, 1988), tested on few reflectors by Roure et al. (1989). Marthelot obtained a full migrated

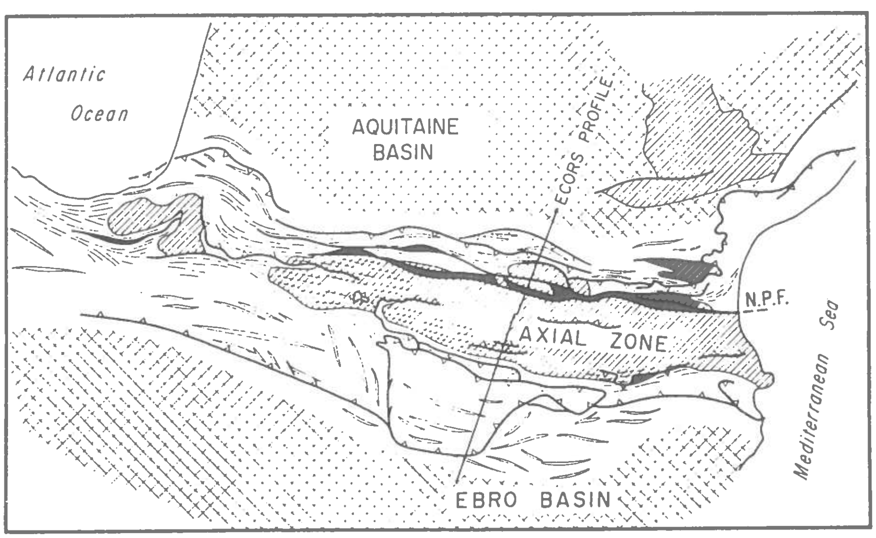


Fig. 1. Structural sketch map of the Pyrenees and position of the ECORS profile (after Choukroune et al., 1989). *N.P.F* = North Pyrenean Fault.

section of the Iberian part of the section (Surinach et al., 1993) using a coherency-weighted migration with a constant velocity. Nevertheless, the different results are not fully satisfactory and many published interpretations do not take into account the effects of migration.

We use here a geometrical approach that computes the tangent common to two wavefronts (Sénéchal and Thouvenot, 1991). This method was first tested with the ECORS Alps data, and proved very efficient compared with other migrations. Moreover, we can handle both lateral and

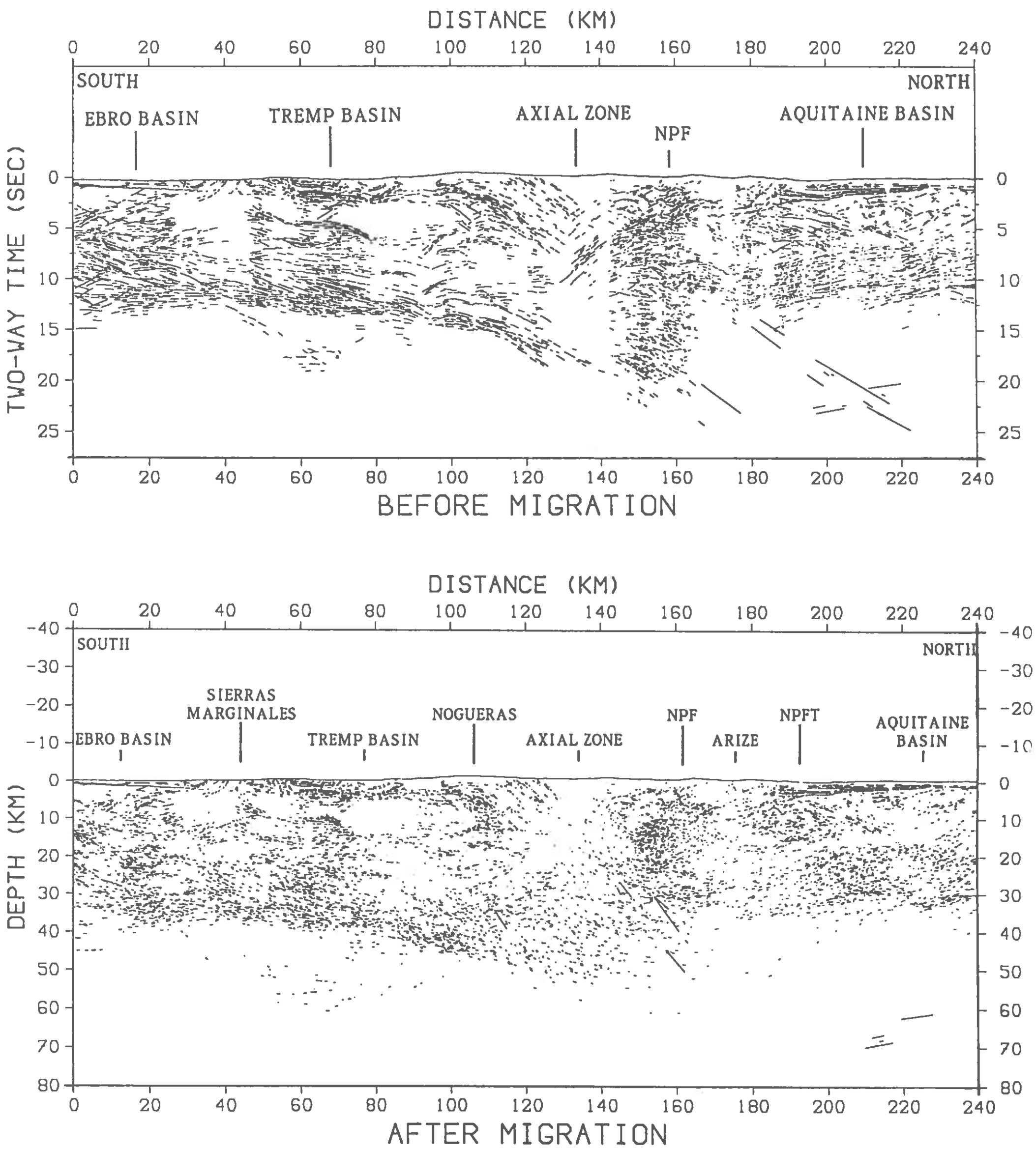


Fig. 2. (a) Unmigrated time line-drawing (after Choukroune et al., 1989) and (b) Migrated depth line-drawing obtained by geometrical migration, using the velocity model shown in Fig. 3. Deep reflectors below the European crust are shown unsplitted after migration. *NPF* = North Pyrenean Fault; *NPFT* = North Pyrenean Frontal Thrust.

vertical velocity variations. The migrated depth-section can be directly used for interpreting and constraining balanced cross-sections.

4. A depth-migrated line-drawing

Using the unmigrated time line-drawing and a velocity model, we obtain a depth-migrated cross-section (Fig. 2b). It is well known that the migration of a line-drawing is more subjective than a numerical migration. Our aim is limited here to a comparison between migrated and unmigrated line-drawings. The time-to-depth transformation and the migration are performed using a two-dimensional velocity model. Considering the P-wave velocity distribution, we compute mean velocities between the surface and each point of the section. Based on the synthesis of the previous studies (Gallart et al., 1980, 1981; Daignières et al., 1981, 1982; Roure et al., 1989; Berastegui, 1992), we define the velocity model used for migration (Fig. 3).

Each reflector is split into 50-m-long segments, and each segment is migrated using the mean surface-to-reflector velocity (V_{mean}) which can be computed before migration. For horizontal or low-dipping reflectors, the difference between this velocity and that which can be computed when the reflector is in its migrated position is usually negligible. The problem is more critical for deep, very dipping reflectors (Fig. 4) where the difference in velocity before and after migration (segments A and B, Fig. 4) can be very large. We first migrate segment A into B, and we determine the surface-to-reflector velocity (V_{mean}) for this migrated position. Taking this velocity into account, we "de-migrate" segment B into a new unmigrated position (C). We iterate the migration (segment D) until the difference in velocity before and after migration is acceptable, which is the case after two or three iterations. For example, with the velocity model described above, deep reflectors located below the Moho, at more than 12 s TWT, (V_{mean} = 6.7 km/s) migrate into the lower crust, at a depth of about 30 km (V_{mean} = 6.05 km/s). Using the algorithm described above, we chose a mean velocity of 6.15 km/s to migrate these reflectors.

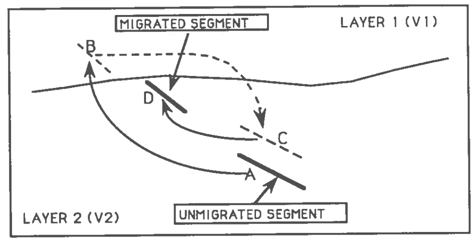


Fig. 4. For migrating deep reflectors, one must take into account the important velocity gradient between the unmigrated and the migrated position.

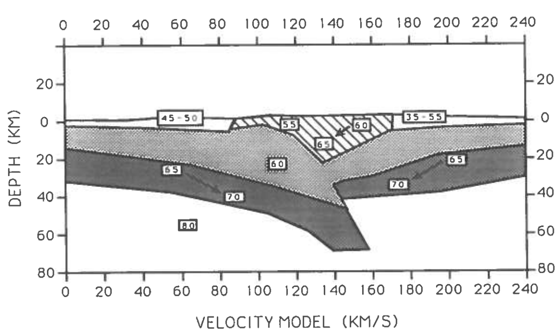


Fig. 3. Velocity model used for the time-to-depth transformation and for the migration (modified from Berastegui, 1992). Velocities are true P-wave velocities.

The line-drawing is digitized before migration and each reflector is split into several segments, which are later individually migrated. It is possible to migrate the entire reflector, but it would not then be possible to take into account the small variations in dip that occur over its length. The separate migration of the segments of each reflector allows us to take account of these variations. The appearance of the migrated section is similar to that of other migration processings (see, for example, Surinach et al., 1993), and we interpret much of our information from the concentration of the migrated line segments.

5. Interpretation of the migrated data

Some features of the unmigrated section are still present after migration. The geometry of the

Mesozoic and Cenozoic sedimentary cover is unchanged, which still makes a detailed interpretation of surface tectonics valid, as proposed by Choukroune et al. (1989). The Iberian crust is definitely thicker than the European crust, with a Moho at 35-km depth in the south, which dips to the north to reach a 55-km depth beneath the North Pyrenean Fault. The European crust is about 30 km thick. Both crusts show a high density of reflectors in their lower parts, which makes the lower crust about 11 km thick.

We will focus our discussion of the migrated cross-section on the following four observations which were not distinct before migration:

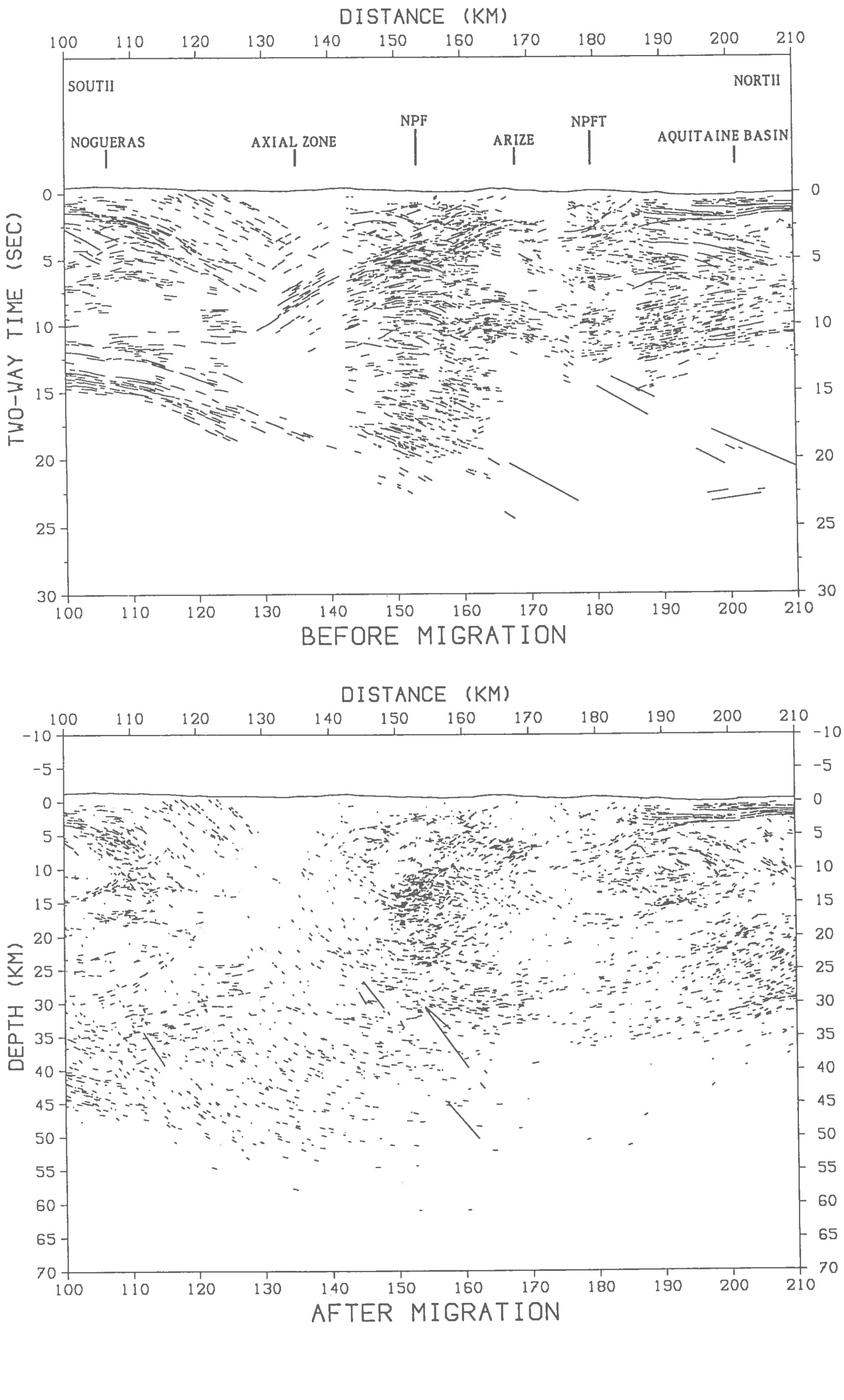
(1) The Iberian upper crust shows many reflectors which clearly delimit three important units in the 3–12-km depth range below the Sierras Marginales and the Tremp Basin (Fig. 2). These units can be interpreted as structural markers corresponding to ramps and flats associated to Hercynian movements (Choukroune et al., 1989; Roure et al., 1989). However, the lack of reflections within these units leads us either to support a change in lithology within the Paleozoic formations, or to consider these units as cores unaffected by orogenic motions and apparently more homogeneous than the crust situated directly below them.

(2) The northern limit of the axial zone beneath the North Pyrenean Fault shows numerous intersecting reflectors, characteristic of a large diffraction zone at about 12-km depth (between km 150 and 160, Fig. 2). The central part of the axial zone does not contain many reflections even at shallow depth (km 130–150, Fig. 2), though its northern part can be considered the most reflective zone of the unmigrated section. After migration, these reflections are focused on a narrow vertical band. The way they intersect is characteristic of a diffraction zone. No real continuity of reflectors can be claimed after migration under the Arize massif. Taking into account the location of the North Pyrenean Frontal Thrust at the surface, we do not believe that this thrust really extends deep into the crust and it does not seem to affect the North Pyrenean Fault as proposed by Choukroune et al. (1989).

Different interpretations of this part of the profile have been proposed, with a North Pyrenean Fault more or less affected by the post-Hercynian tectonics (Roure et al., 1989; Mattauer, 1990; Choukroune et al., 1990). The hypothesis of a deep continuation of the south-dipping North Pyrenean Frontal Thrust is not supported by the migrated section. No coherent reflections can be associated with the thrust, which corresponds to the northern limit of the Arize massif (Fig. 5). We believe that the numerous reflectors located at depths between 10 and 20 km below the northern part of the axial zone are generated by diffractions along the vertical North Pyrenean Fault (Fig. 5). The diffraction zone is characterized, after migration, by numerous localized intersecting reflectors. The North Pyrenean Fault is nearly vertical at the surface and the presence of this diffraction zone indicates that the fault is close to vertical at depth. The alternative hypothesis of a segment of lower crust at such a shallow depth is not supported by gravity data (Torné et al., 1989).

(3) The European upper crust presents more north-dipping reflectors than south-dipping ones. Under the southern sedimentary cover of the Aquitaine Basin we identify two north-dipping alignments of reflectors. They can be associated to ramp anticlines or pre-Mesozoic tilted blocks as proposed by Choukroune et al. (1990). A few south-dipping and flat reflectors characterize the deep crust of the Arize massif (Déramond et al., 1990).

(4) The deep reflectors below the axial zone define the top of the Iberian lower crust, underlying part of the European lithosphere. The geometry of the Moho can be better imaged after migration. The Iberian crust dips progressively under the European mantle wedge, showing some reflectors as deep as 55 km. The deep reflectors located under the European crust before migration now define the top of the Iberian lower crust (Fig. 5) dipping under the European mantle wedge (Hirn et al., 1980). At this depth, the poor density of reflectors may be due to a change in the mechanical behaviour of the materials which are more ductile and generate less diffractions, or it may be due to the increasing attenuation of the signal as a function of depth.


DISTANCE (KM)
SOUTH
NORTH
NOGUERAS
AXIAL ZONE
NPF
ARIZE
NPFT
AQUITAINE BASIN
TWO-WAY TIME (SEC)
BEFORE MIGRATION
DISTANCE (KM)
DEPTH (KM)
AFTER MIGRATION

6. Conclusion

The migration of the line-drawing of the ECORS Pyrenean profile provides us with a more accurate picture of the real geometry of the geological structures. This processing is indispensable when reliable, balanced cross-sections have to be built. On both parts of the axial zone, the different aspects of the upper crust express the existence of Hercynian structures. The axial zone is characterized by a high density of diffractions that are due to several vertical faults in the crust, such as the North Pyrenean Fault. The geometry of the northern wedge of the Iberian crust is better imaged. The hypothesis of a possible extension at depth of the North Pyrenean Frontal Thrust is not supported by the migrated data.

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Fig. 5. Comparison between unmigrated and migrated sections in the central part of the profile. Deep reflectors below the European crust shown unsplitted to check the effect of migration.