Constraints on the deep structure of the Pyrenees from new magnetotelluric data

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Abstract: Magnetotelluric data registered along a N-S profile in the central Pyrenees as well as along-strike indicate the existence of very high conductive zones at lower crustal and mantle depths. This deep conductor is interpreted as partial melted Iberian subducted lower crust. It is present all along the Axial Zone. Westwards the western termination of the Axial Zone it seems to disappear. This has been interpreted as a smaller volume of subducted lower crust as a result of the westwards decrease of orogenic contraction accompanied by an increasing of the Mesozoic extensional thinning.

Keywords: Pyrenees, magnetotelluric survey, partial melting, lower crust, subduction.

Resumen: Varias campañas de magnetotelúrica en los Pirineos han detectado la presencia de un conductor profundo a nivel de corteza inferior y manto litosférico bajo la Zona Axial. Este conductor se interpreta como fusión parcial de la corteza inferior ibérica subduciendo bajo la placa europea. Más al oeste de la Zona Axial este conductor tiende a desaparecer. La ausencia del mismo se interpreta como una disminución del volumen de corteza inferior subducida debido al decrecimiento, en dirección oeste, de la contracción orogénica, junto con un aumento del adelgazamiento extensional mesozoico.

Palabras clave: Pirineos, magnetotelúrica, fusión parcial, corteza inferior, subducción.

Pous, J., Ledo, J.J., Queralt, P. and Muñoz, J.A. (1997): Constraints on the deep structure of the Pyrenees from new magnetotelluric data. *Rev. Soc. Geol. España, 8 (4), 1995:395-400.*

In the Pyrenees abundant geophysical data strongly constrain the crustal structure of the chain. The refraction and deep reflection seismic profiles show that the Iberian crust thickens progressively from the southern foreland to the hinterland, from 35 km to 50-60 km respectively. By contrast, the thickness of the European crust is in the range of 30-35 km (Gallart *et al.*, 1981; Pinet *et al.*, 1987; Choukroune & ECORS Team, 1989; Daignières *et al.*, 1994). This difference in crustal thickness is the result of the subduction of the Iberian plate below the European one and a greater amount of deformation of the former (Muñoz, 1992). The Bouguer anomaly map in the Pyrenees shows a strong negative anomaly centred in the Pyrenees accounting for the large increase in the crustal thickness. Modelling of a N-S profile along the ECORS Pyrenees line discloses an Iberian crust of 65 km in the Axial zone (Torné *et al.*, 1989).

In the central Pyrenees a simple mass balance together with the geometry of the imaged lower crust suggests that this lower crust was attached and subducted with the lithospheric mantle. The calculated shortening for the upper crust and the no exhumation of lower crustal rocks as well as of Cenozoic metamorphic rocks (apart from those outcropping along the North Pyrenean fault) suggest that a lower crustal slab of up to 100 km long was subducted into the mantle, which represents a subducted volume greater than that imaged by the seismic reflection data (Muñoz, 1992). The existence of this subducted lower crustal slab has been corroborated by a magnetotelluric N-S profile roughly coinciding with the ECORS Pyrenees deep seismic reflection profile (Pous *et al.*, 1995a, 1995b). The magnetotelluric profile detected a deep conductor on the boundary between the Iberian and European plates. This was interpreted as partial melting of the subducted continental lower crust. This model accounts for the total shortening deduced in the central Pyrenees.

The Pyrenees show a significant along-strike variation of the deformation style as a consequence of longitudinal differences in the amount of orogenic contraction and the inherited crustal geometry. The shortening decreases westwards as the amount of the previous Mesozoic crustal thinning increases in the same direction. Moreover, the age of the structures also decrease westwards (Choukroune, 1976). In the eastern Pyrenees deformation was probably completed by Middle Oligocene times, whereas in the western Pyrenees it lasted until the Middle Miocene (Vergés, 1993). In order to investigate the westwards continuation of this conductor and to correlate the deduced amount of shortening and the amount

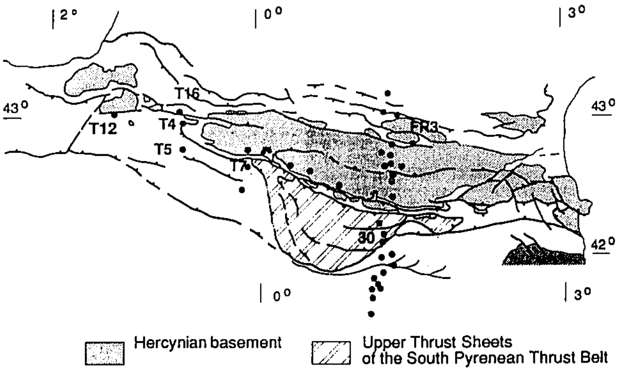

Figure 1.- Structural sketch of the Pyrenees. Dots in the map refer to the magnetotelluric stations.

of subducted crust, new magnetotelluric stations located along the chain were set up (Fig. 1). This paper deals with these new data as well as with their relationship with the N-S profile across the central Pyrenees.

Magnetotelluric data analysis

Given that the magnetotelluric method measures the electrical conductivity (which is independent of other geophysical parameters), a new independent constraint of the earth is obtained. Advances in the processing and data acquisition of magnetotelluric recordings have resulted in a wider use of this method to obtain electrical images of the crust and upper mantle. Modern robust processing techniques of the time series (Egbert & Booker, 1986; Chave & Smith, 1994) and the control of galvanic and magnetic distortion (Groom & Bailey, 1989, 1991; Chave & Smith, 1994; Smith, 1995) have enabled us to obtain reliable transfer functions. Furthermore, modelling and inversion algorithms have been developed resulting in an improvement in interpretations, mainly in 2-D earth models (Wannamaker *et al.*, 1987; de Groot-Hedlin, 1995). 3-D algorithms are currently being developed (Mackie *et al.*, 1993) and complex 3-D structures are starting to be interpreted (Pous *et al.*, 1995c).

In the magnetotelluric method the time series of the five magnetotelluric field components are recorded. The horizontal electric field E and the magnetic field B are measured simultaneously at the earth surface, the relation between them, in the frequency domain, being:

$$E_x = Z_{xx} B_x + Z_{xy} B_y$$
$$E_y = Z_{yx} B_x + Z_{yy} B_y$$

which hold for every period T. x and y are the horizontal axes and the subindexes represent the corresponding field components. The vertical magnetic field component is related to the horizontal components, also in the frequency domain, as follows:

$$B_z = Z_x B_x + Z_y B_y$$

z being the vertical axis.

The coefficients in these equations are the period dependent complex transfer functions. These transfer functions depend on the resistivity distribution of the earth and are used for interpretation. Apparent resistivities and phases are defined from the tensor components in the following way:

$$\rho_{xy} = (\omega \mu)^{-1} |Z_{xy}|^2 \text{ and } \phi_{xy} = \mathrm{tg}^{-1} (\mathrm{Im}\, Z_{xy} / \mathrm{Re}\, Z_{xy}),$$
$$\rho_{yx} = (\omega \mu)^{-1} |Z_{yx}|^2 \text{ and } \phi_{yx} = \mathrm{tg}^{-1} (\mathrm{Im}\, Z_{yx} / \mathrm{Re}\, Z_{yx}),$$

where ω is the frequency in radians per second and μ is the magnetic permeability.

Over a 2-D dimensional earth, with x as the strike resistivity direction and y the perpendicular, Z_{xy} and Z_{yx} correspond to the E-polarisation and B-polarisation respectively.

Magnetotelluric responses are distorted by local surface anomalous conductivity. The Groom and Bailey decomposition method (Groom & Bailey, 1989), allows us to recover the regional responses, to define the regional dimensionality and to obtain the direction of the strike. This method is based on the decomposition of the measured impedance tensor $\mathbf{Z}_m$ as follows:

$$\mathbf{Z}_m = \mathbf{C}\, \mathbf{Z}_r$$

where $\mathbf{Z}_r$ is the regional impedance tensor and $\mathbf{C}$ the local distortion tensor. This factorises as:

$$\mathrm{C} = \mathrm{g}\, \mathbf{T}\, \mathbf{S}\, \mathbf{A}$$

where the scalar g is the site gain and the matrices **T**, **S** and **A** are the twist, shear and anisotropy matrices respectively. In a 2-D regional structure, the twist and shear matrices are period independent when one measured axis coincides with the strike direction. Thus, the rotation of the impedance tensor is a common procedure for finding the strike direction of the resistivity structure. This decomposition analysis must be performed before an interpretation is made in order to obtain the regional tensor, which is the real response of the regional model.

The N-S magnetotelluric profile in the central Pyrenees

Thirty-six magnetotelluric stations along a N-S profile across the Central Pyrenees were carried out (Fig.1). The five components were recorded from 0.0128 s to about 2000 s. The horizontal ones were measured in N-S and E-W directions and the time recorded for the longest periods was 4 days per station. The time series data were processed using the robust processing method (Egbert & Booker, 1986). The Groom and Bailey analysis indicated that the electrical structure is 2-D striking E-W, coinciding with the general trend of the range. Levelling due to the static shift distortion was made by constraining the geometry of the conductive sediments from the seismic

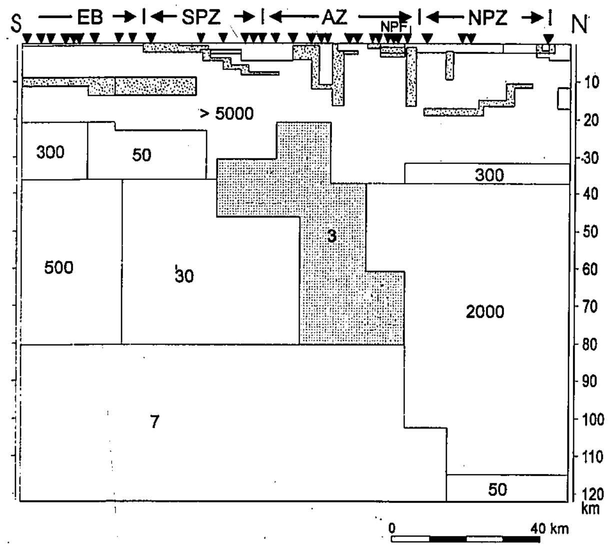

Figure 2.- Two dimensional electrical resistivity model across the central Pyrenees. The numbers are the resistivity in Ω.m. Dotted patterns indicate the conductors in the upper and middle crust and grey pattern the deep conductor. EB: Ebro Basin, SPZ: South Pyrenean Zone, AZ: Axial Zone, NPZ: North Pyrenean Zone and NPF: North Pyrenean fault. The black triangles indicate the location of the magnetotelluric stations.

data as well as their resistivity from well logs. A 2-D resistivity model was obtained along the N-S profile across the central Pyrenees, from the Aquitaine basin up to the Ebro basin. Fig. 2 shows the two-dimensional resistivity model which fits jointly the regional apparent resistivities, phases and geomagnetic transfer functions. This was constructed by trial and error using the finite element code by Wanamaker *et al.*, (1987). (For further details of model calculations see Pous *et al.*, 1995b).

The first kilometres, in the upper part of the model, show different resistivities varying from 5 Ω.m of the Eocene Ebro sediments to more than 1000 Ω.m for the Variscan rocks of the Axial Zone. The upper and middle crusts are largely of high resistivity (more than 5000 Ω.m). However, some subvertical conductors appear in the central part of the chain, revealing major fracture zones, as for example the North Pyrenean fault located on the boundary between the Axial and the North Pyrenean Zone. Moreover, there are two dipping conductors in the middle crust which are related to the sole thrusts of the double orogenic wedge. The low resistivity of the areas along major faults is attributed to the presence of fluids in the fractures and, in some cases, to the high graphite content of Silurian rocks which commonly occur along the faults involving the Variscan basement. On the other hand, the significance of the subhorizontal conductor under the Ebro basin is not sufficiently clear. It could be related to ancient Variscan thrusts and needs further investigation.

The lower crust and lithospheric mantle away from the subducted Iberian crust show normal resistivity values (Hjelt & Korja, 1993; Jones, 1992). However, one of the most striking results of the magnetotelluric model is the progressive decrease in the resistivity of the Iberian lower crust and upper mantle from the Ebro basin to the interior of the chain where the Iberian plate is subducted (Fig. 2). The subducted lower crust shows a resistivity value as low as 3 Ω.m. The European upper mantle is more resistive (more than 2000 Ω.m) than the Iberian one. The anomalous conductive Iberian upper mantle, as well as its thinner thickness with respect to the European one, could be the result of some delamination process and the replacement of cold upper mantle by astenosphere. The bottom of the model is characterised by a resistivity of 7 Ω.m in the Iberian plate and 50 Ω.m in the European one.

In the Axial and South Pyrenean zones, the E-polarisation mode decreases continuously up to the longest periods (2000 s). By contrast, in the North Pyrenean Zone, there is a change in the slope of the E-polarisation at 80 s. From this period to higher values the apparent resistivity increases. A sensitive test revealed that this behaviour is due to the presence of the deep conductor (Pous *et al.*, 1995b). Hence, magnetotelluric data along-strike of the chain can be used to confirm the presence of this deep conductor and to evaluate its lateral extension.

Magnetotelluric data along the strike

Twelve new stations were registered along-strike, from the N-S profile westwards (Fig. 1). The westernmost measured site is located north of Pamplona and more stations further west are currently being collected. The stations were strategically located close to the Axial Zone and its western continuation in order to register the deep conductor. The range of periods and the measurement axes as well as the processing data were as in the previous N-S profile. The Groom and Bailey decomposition method indicated a general E-W striking. Fig. 3 shows the twist and shear distortion parameters of site T7 corresponding to the measured axes (N-S and E-W), the behaviour being period independent. Fig. 4 shows the apparent resistivities corresponding to site T4 and the comparison with site 30 of the N-S profile. The E-polari-

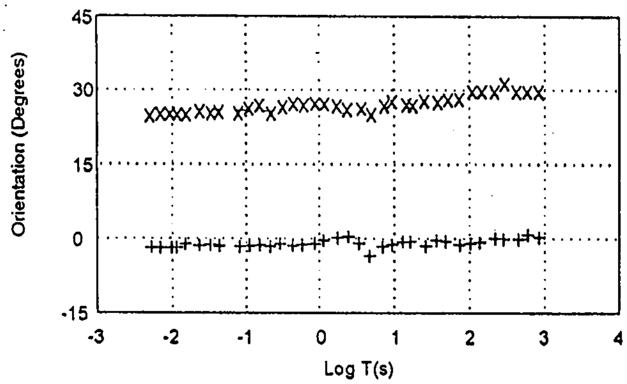

Figure 3.- Twist and shear distortion parameters of site T7. The strike is fixed to 0°.
(+: twist, x: shear).

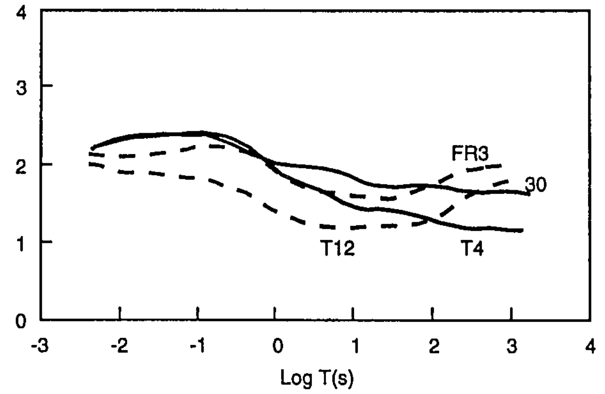

Figure 4.- Apparent resistivity E-polarisation curves for sites 30, T4, FR3 and T12.

sation behaviour at sites T4 is similar to that of the sites revealing the presence of the deep conductor in the N-S profile (e.g. site 30). The apparent resistivity decreases continuously up to the longest periods as at sites located in the Axial and the South Pyrenean zones in the N-S profile. This behaviour is typical for the new sites located to the East of the transversal of site T4, but it does not prevail further West at site T12, whose E-polarisation mode is typical of the North Pyrenean Zone in the N-S profile. Fig. 4 also shows the apparent resistivities (E-polarisation) of sites FR3 from the N-S profile and T12 north of Pamplona. Both sites undergo a change in the slope at 80 s, indicating the absence of the deep conductor beneath them.

In accordance with the E-W strike, a two-dimensional model along a short N-S profile consisting of sites T5, T4 and T16 (Fig. 1) was obtained. Regardless of the small number of sites, this model (Fig. 5) shows the main geometrical features of the conductive bodies. Fig. 6 shows the apparent resistivity and phase data as well as the model responses. The upper kilometres are moderately resistive, the southern lower resistivity area corresponds to the Jaca basin clastic sediments, and the northern one, which is slightly higher resistive, corresponds to Paleogene and Mesozoic limestones. Below these limestones, at 4 km depth, a subhorizontal conductor could correspond to a high content water zone below the karstified limestones. In the high resistive upper crust the two north dipping conductors coincide with the basement involved thrusts (Teixell, 1996). As far as the deeper structure is concerned, a high conductive zone exists at upper mantle depth, although its northern limit is not well constrained. This deep conductor correlates with the partial melted subducted lower crust interpreted in the central Pyrenees N-S profile. We conclude that the deep conductor is documented along strike as far West as site T4.

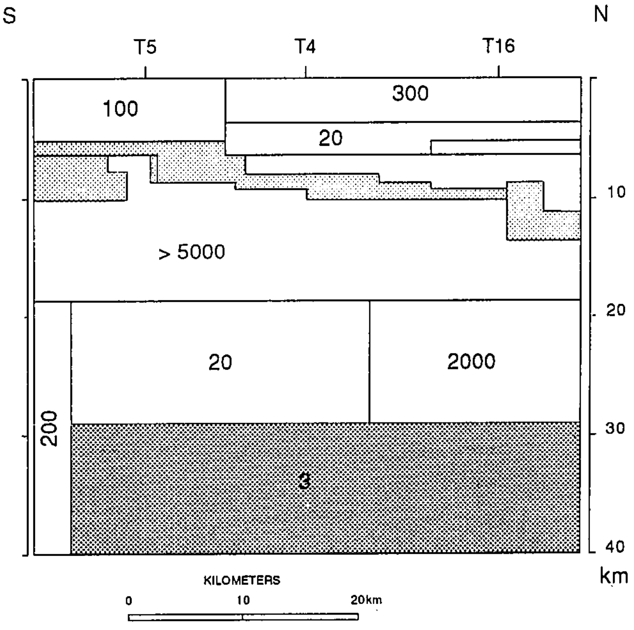

Figure 5.- Two dimensional electrical resistivity model along the western N-S profile. The numbers are the resistivity in Ω.m. Dotted patterns indicate the conductors in the upper and middle crust and grey pattern the deep conductor.

Discussion and conclusions

The magnetotelluric data provide new constraints on the knowledge of the Pyrenean crustal structure in two ways. First, they measure a physical parameter which is independent of those measured by seismic, gravity and other geophysical methods. Second, they show different sensitive responses to the models and therefore, prove to be a good complement to other geophysical techniques. Thus, magnetotelluric data restrict the possible geodynamic models. For instance, the main subvertical fractures in the Pyrenean upper crust were not detected as reflectors since vertical reflections are lost. By contrast, the presence of fluids in the fractures causes the resistivity to fall dramatically and therefore these structures are suitable for detection by the magnetotelluric method.

The presence of the deep high conductive zone has been interpreted as the result of partial melting of the subducted Iberian lower crust (Pous *et al.*, 1995a). The geometry of this conductor in the central Pyrenees (Fig. 2) indicates that the subducted lower crust reaches at least 80 km depth. However, this is only the minimum amount of subduction since the low resistivity area of 3 Ω.m merges with the bottom of the model whose 7 Ω.m is interpreted as the asthenosphere in accordance with studies elsewhere (Hjelt & Korja, 1993). This image shows a volume of subducted material greater than that imaged by the seismic data as predicted by the restoration of the upper crustal thrust sheets (Muñoz, 1992). Partial melting of the subducted lower crust appeared when lower crustal granulites, having a solidus of about 700 °C at lower crustal depths, were heated during the postorogenic rising of the isotherms since Early Miocene times. A recent study by teleseismic tomography in the Pyrenees has revealed a low seismic velocity zone down to 80-100 km in line with the idea of partial melting (Souriau & Granet, 1995). Delamination of the Iberian crust, favoured by the geometry of the inherited Variscan and Mesozoic structural geometry, resulted in subduction of the lower crust during the collision between Ibe-

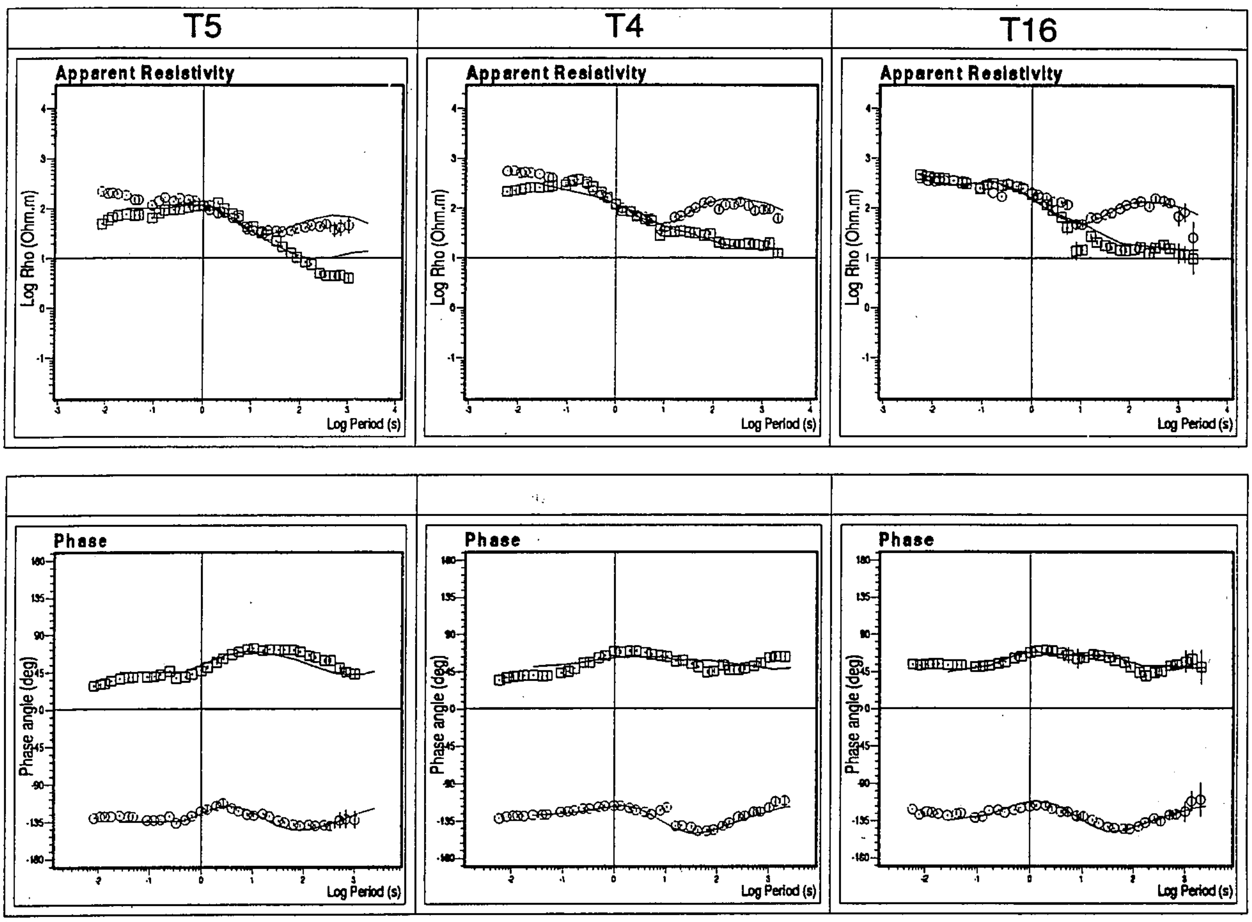

Figure 6.- Apparent resistivities and phases of sites T5, T4 and T16. Circles: B-polarisation; squares: E-polarisation. Solid lines: responses of the model of Fig. 5.

rian and European plates (Muñoz, 1992). The amount of subducted crust depends mainly on the amount of orogenic contraction and the geometry of the double orogenic wedge thrust system. It also depends on the geometry of the lower crust before the collision and its capability to accommodate the orogenic contraction without subduction. Geodynamic numerical models of collision orogens have shown that subduction of the lower continental crust is in agreement with the geometry and the style of deformation observed in the central Pyrenees (Beaumont & Quinlan, 1994).

The deep conductor is present along-strike as far west as the transversal of site T4 (Fig. 1), as evidenced by the new magnetotelluric data. Further to the West, the westernmost site T12 indicates the absence of this conductor although new data are needed in order to quantify its westwards decrease. The absence of this deep conductor, more to the West, could be attributed to the following four factors: 1) decrease of the orogenic contraction, and as a consequence, decrease (or absence) of the subducted lower crust, 2) increase of Mesozoic crustal thinning before the onset of the collision in which case the contractional deformation would have recovered the normal crustal thickness without significant subduction, 3) deformation and thickening of the whole crust without delamination of the lower crust, and 4) younger contractional structures and consequently, less time for a thermal re-equilibration and for the onset of melting.

In the transversal of site T4, the westernmost site showing the deep conductor (Fig. 1), shortening of the Iberian is less than that of the central southern Pyrenees as evidenced by restored cross-section construction (Teixell, 1992, 1996; Alonso *et al.*, 1995). Accordingly, a possible subducted lower crust would be a slab shorter than the one in the central Pyrenees. Shortening continues to decrease westwards of the transversal of site T4 and the amount of crustal thinning increased in the same direction during the transtensional Early Cretaceous rifting event (Canerot, 1989; Daignières *et al.*, 1994). Thickness of the synrift Early Cretaceous sequences revealed a significant amount of crustal thinning in the western Pyrenees. This has been accommodated in the upper crustal level by extensional faults. The lower crust below the extensional basins could have been extremely thinned by pure shear as imaged by seismic profiles in non deformed areas during the Pyrenean collision, e.g. the Parentis basin and the north Biscay Gulf margin (Pinet *et al.*, 1987; Le Pichon & Barbier, 1987; Marillier *et al.*, 1988). A combination of a smaller amount of orogenic contraction together with an initial very thin or inexistent lower crust in the inner parts of the chain could account for the absence of a subducted lower crust in the westernmost areas where magnetotelluric data have been recorded (Fig. 1). A very thinned or inexistent lower crust could also have favoured the involvement of all the crust during the crustal thickening. Regardless of the previous considerations, which explain the absence of the deep conductor, a younger age of the western Pyrenean structures can not be ruled out as another possible contributing factor. The end of the deformation occurred in a range of 5-10 Ma later in the western Pyrenees than in the central Pyrenees (Vergés, 1993). As a consequence, the time span for a thermal re-equilibration of a possible subducted lower crust in the western Pyrenees would be significantly less and this process could not have been completed. If isotherms were still rising, and consequently a hypothetical partial melting of a subducted lower crust had not yet been generated, the deep conductor would not be visible by magnetotelluric techniques. All these facts support the idea that the volume of the subducted lower crust is variable along the chain, being smaller in the West.

This work was supported by the DGICYT project PB92-0808 and by the "Comissionat per Universitats i Recerca de la Generalitat de Catalunya-Grup de qualitat GRQ94-1048".

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