Electrical conductive structure of the central Betics from magnetotelluric data

J. POUS, P. QUERALT, J. J. LEDO, E. ROCA, X. GARCIA, and A. MARCUELLO

Universitat de Barcelona. Departament de Geologia Dinàmica, Geofísica i Paleontologia, Zona Universitària de Pedralbes. 08028 Barcelona.

Abstract: A magnetotelluric survey was carried out in the central part of the Betic range. We present the interpretation along a NW-SE profile across the chain. The periods recorded range from 0.0128 s to approximately 2000 s. Analysis of the data indicates that the electrical structure along this profile is roughly two-dimensional striking NE-SW. Accordingly, a two-dimensional resistivity cross-section along the profile was obtained by two-dimensional inversion. The most striking results are: (1) detection of shallow conductors, one of which is associated with the base of the External Betics; (2) the middle and lower crust in the Internal Betics are more conductive than those beneath the External Betics; (3) detection of a very high conductive zone at lower crustal and upper mantle depths beneath the Sierra de los Filabres.

Keywords: magnetotellurics, impedance tensor, electrical conductivity, Betics.

Resumen: Se presenta la interpretación de un perfil de magnetotelúrica de 140 km de longitud de dirección NW-SE que atraviesa las principales unidades de la Cordillera Bética en su zona central. Los períodos registrados abarcan desde 0.0128 s a poco más de 2000 s. El análisis de los datos indica que la estructura eléctrica a lo largo de este perfil es aproximadamente bidimensional con una dirección de NE-SW. La interpretación se realiza a partir de la inversión bidimensional de las componentes del tensor de impedancias. Los resultados más relevantes son: (1) presencia de conductores superficiales a lo largo del perfil, uno de ellos asociado a la base de las Béticas Externas; (2) existe un marcado contraste de conductividad eléctrica entre la corteza media e inferior de las Béticas Externas y la de las Béticas Internas, siendo en éstas más conductoras; (3) presencia de una zona muy conductora a partir de unos 20 km de profundidad bajo la Sierra de los Filabres.

Palabras clave: método magnetotelúrico, tensor de impedancias, conductividad eléctrica, Béticas.

Pous, J., Queralt, P., Ledo, J.J., Roca, E., Garcia, X. and Marcuello, A. (1997): Electrical conductive structure of the central Betics from magnetotelluric data. *Rev. Soc. Geol. España, 8 (4), 1995: 513-517.*

The Betic range is located in the area of interaction between the Eurasian and African plates in the western part of the Alpine orogenic belt. A number of geological and geophysical studies have been carried out to investigate the structure and the kinematics of this complex region. As regards the Central part of the Betic Chain, the seismic refraction profiles (Banda & Ansorge, 1980) provided data of the deep crustal structure. Recently, two deep seismic reflection profiles (García-Dueñas *et al.*, 1994) and a new seismic refraction/wide angle survey (Banda *et al.*, 1993) reported new findings concerning the crustal configuration. With the aim of obtaining new constraints from the electrical conductivity, which is a physical parameter independent of seismic parameters, a magnetotelluric survey was carried out in the central part of the Betic Chain. Analysis of the data reveals the complexity of the structure in this region. Among the sites measured there is one profile along which the structure is approximately two-dimensional. In this paper we present, as preliminary results, a NW-SE electrical resistivity cross section along this profile. The model was obtained by simultaneous two-dimensional inversion of all the impedance tensor components by using the Rapid Relaxation Inverse (RRI) algorithm of Smith & Booker (1991).

Geological setting

The Betic chain and the Rif chain form an arcuate belt (Gibraltar Arc) which constitutes the westernmost part of the Alpine orogen (Fig. 1). Its structure resulted from two episodes: 1st. A Mesozoic transtensional regime, related to the SE displacement of Africa in relation to Europe, which accounted for the formation of the Tethys ocean and extensional systems of horsts and grabens in its passive margins. 2nd. A Cenozoic N-S convergent regime between the Iberian and African plates, which first led to the building of a late Cretaceous-Palaeogene orogen between Africa and the Balearic islands (Monié *et al.*, 1991) and, subsequently to the displace-

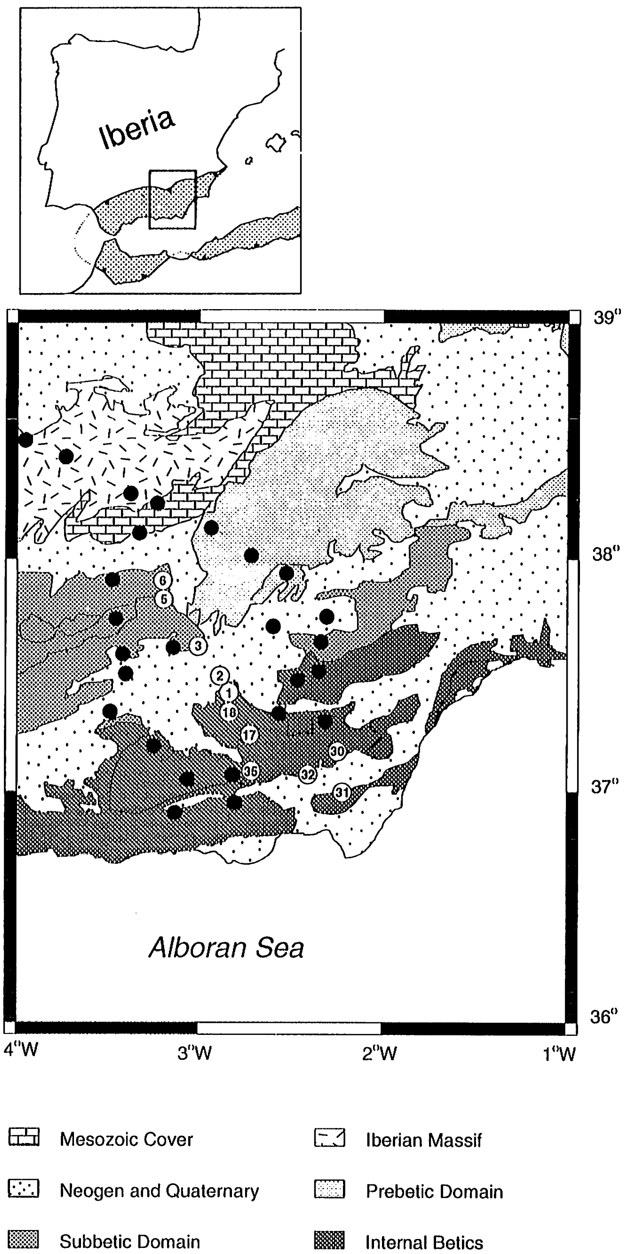

Figure 1.- Geological map showing the locations of magnetotelluric sites. Numbered circles indicate the sites along the profile presented.

ment of a fragment of this orogen (the so- called Alborán crustal domain) westwards. In connection with this motion, the Betic-Rif arcuate fold-and-thrust belt developed during the Miocene as a result of the collision of this crustal domain against the old Mesozoic Maghrebian and south-Iberian passive margins. Synchronously, the inner parts of the Alborán crustal domain thinned resulting in the formation of the extensional Alborán basin (Platt & Vissers, 1989; García-Dueñas & Balanyá, 1991).

In this context, the Betic chain forms the northern branch of the Betic-Rif arcuate orocline, which overthrust upon the Iberian plate. It is classically divided into an Internal Zone in the South and an External Zone in the North, which are separated at their westernmost point by the oceanic or semioceanic Campo de Gibraltar Complex.

The Internal Zone forms a great allochthonous crustal wedge composed mainly of Triassic and older metamorphic rocks belonging to the Alborán crustal domain (Torres-Roldán, 1979; Bakker *et al.*, 1989). Its regional structure is very complex and includes both compressive and extensional structures. According to recent works (Galindo-Zaldivar *et al.*, 1989; Azañón *et al.*, 1994; Crespo-Blanc *et al.*, 1994) it consists of a stack of four NNW-directed nappe complexes (Veleta, Mulhacén, Alpujárride and Maláguides complexes) which, emplaced during the late Cretaceous-Palaeogene, were affected by Miocene low-angle extensional faults or shear- bands.

Partially backthrusting the Internal Zone, the External Zone comprises the allochthonous foreland fold-and-thrust belt of the orogen and the cover of the former Mesozoic continental margin of southern Iberia (García-Hernández *et al.*, 1980). It consists of a deformed wedge of Mesozoic to Lower Miocene carbonates and marls detached above Triassic evaporite and mudstone layers (Vera, 1983; Banks &Warburton, 1991). On the basis of tectonic and stratigraphic criteria, the External Betics can be subdivided into a Prebetic Zone in the North, characterised by shallow marine facies, and a Subbetic Zone in the South, where pelagic facies prevail (Fallot, 1948). Both zones were strongly deformed during the Miocene thrust-emplacement of the Internal Zone onto the southern Iberian margin. It is thought that this intense Miocene compressive deformation of the External Zone, like the Internal Zone, was also affected by younger extensional structures (García-Dueñas, 1995).

In the central and western Betics, the Prebetic and Subbetic thrust sheets border the Miocene Guadalquivir Basin, which is generally regarded as the foreland basin of the Betics (e.g. Vegas and Banda, 1982). This basin is infilled by Lower Miocene to Quaternary marine sediments (Sanz de Galdeano & Vera, 1992) which unconformably overlie the Variscan Iberian Massif to the West and its thin Triassic cover to the East.

Magnetotelluric data

Magnetotelluric data were acquired at forty-one stations in the central part of the Betic chain. In this paper one profile in a NW-SE direction consisting of eleven magnetotelluric stations is discussed (Fig. 1). The profile is 140 km long and crosses the chain perpendicularly from the southern boundary of the Guadalquivir basin to the Internal Betics. Its northwestern part coincides with the deep seismic reflection profile ESCI-Béticas1. The five magnetotelluric components were recorded in the period range 0.0128 s to 2000 s. The time series were processed using the robust processing method by Egbert & Booker (1986). The time recording was 3-4 days per station for the highest periods. Along the profile, the induction arrows obtained from the vertical magnetic component pointed roughly to the northwest indicating a two-dimensional structure striking NE-SW. The Groom & Bailey decomposition method (Groom & Bailey, 1989) also suggests such a behaviour. However, it does

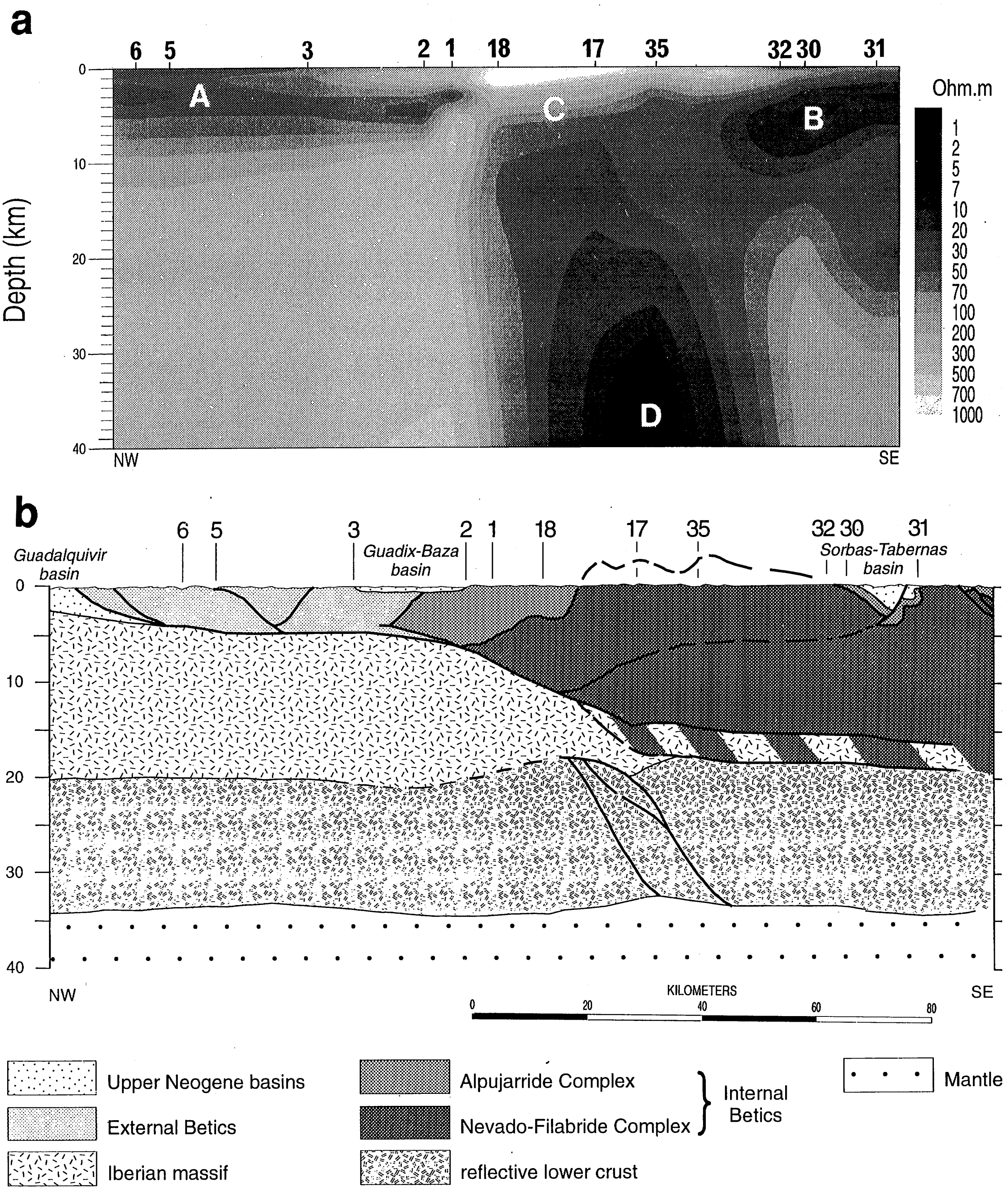

Figure 2.- (a):Two-dimensional electrical resistivity model obtained by two-dimensional inversion. A, B, C and D indicate the most striking features (see text for details); (b): schematic geological cross-section along the magnetotelluric profile.

not hold for the other sites outside this central profile, which is an indication of three dimensional effects outside this profile. Accordingly, we present the interpretation of this profile by using two-dimensional techniques. The E-polarisation mode will be the apparent resistivities and phases which detect currents in the northeast direction and the B-polarisation mode will be those detecting currents in the perpendicular northwest direction. The static shift distortion was corrected by levelling the apparent resistivities from the resistivity measured in the sediments of the Guadalquivir basin. This resistivity was obtained from wells drilled in the External Betics (i.e. Guadalquivir H-1).

Apparent resistivities and phases for both polarisations of all the sites along the profile were interpreted by using the two-dimensional inversion algorithm by Smith & Booker (1991) and Wu *et al.* (1993). This algorithm known as Rapid Relaxation Inverse produces a smoothed

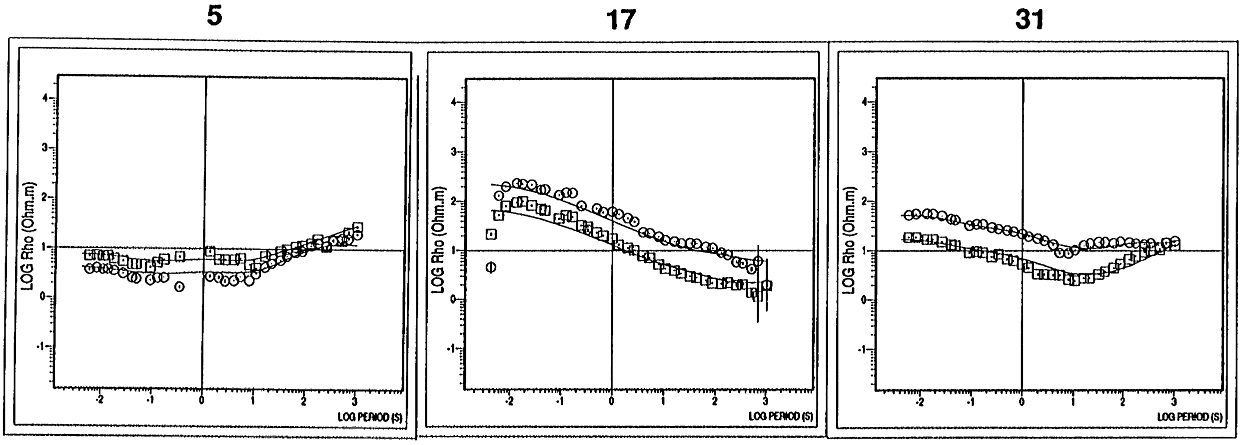

Figure 3.- Apparent resistivity curves for sites 5, 17 and 31. circles: E-polarisation experimental data; squares: B-polarisation experimental data. Bar errors are showed. Solid line: responses of the 2-D model.

image displaying the main features of the conductive structure minimising the spatial roughness of the conductivity. Fig. 2a shows the two-dimensional model obtained by the inversion. The effect of the sea was considered in the final model. The inversion resulted in a good fitting of the data. The corresponding root mean square for the E-polarisation was 5.1 (apparent resistivity) and 3.7 (phases) and for the B-polarisation it was 3.1 (apparent resistivity) and 3.1 (phases), the error floor being 5%. The profile can be divided into three zones, each zone being characterised by the shape of the impedance tensor components. Fig. 3 shows the model responses and data for three sites, each one corresponding to one zone. At site 5 located in the External Betics both polarisations roughly coincide. They are characterised by an abrupt change in the slope of the apparent resistivity before 10 s where the minimum reveals the presence of a shallower conductor associated with the base of the sedimentary layer whereas the increase in the apparent resistivity for periods longer than 10 s reveals a higher resistivity for the middle and lower crust. Site 17, located in the Internal Betics, shows a continuous decrease in the apparent resistivities up to the longest periods in both polarisations, indicating a higher conductivity at depth. Finally, site 31 in the Internal Betics but at the southeastern end of the profile, shows a divergence between both polarisations from 10 s. The B polarisation has a relative minimum at 10 s and it increases for longer periods. This indicates a shallow conductive layer beneath which there is an increase in the resistivity. On the other hand, the slope of the E-polarisation is less than that of the B-polarisation for periods longer than 10 s, thus indicating the presence of lateral conductors at greater depths and at a distance from the site (that located beneath site 17).

The main features depicted by the model are labelled A, B, C and D in Fig. 2a. A corresponds to a shallow conductor along the External Betics with the highest conductivity at 3 km depth beneath site 6 and dipping slightly to the southeast, where it reaches a depth of 5 km beneath site 2. B is a conductor in the Internal Betics located on the right side of the model. From site 31, it dips northwestwards reaching approximately 7 km beneath site 32. The shallowest structure between sites 32 and 18 shows resistivities higher than 100 Wm. (above C in Fig. 2a), which correlates with the metamorphic complex of Sierra Nevada and Filábrides. At deep crustal depth, the marked difference in the resistivity, corresponds to the boundary between the autochthonous Iberian crust (more resistive) and the Internal Betics (more conductive). Another striking result is the presence at the bottom of the model beneath sites 17 and 35 of a very high anomalous conductive zone (D in Fig. 2a). From 20 km downwards the resistivity of this conductor is lower than 5 Ω.m.

Discussion and conclusions

In order to highlight the features of the magnetotelluric model, a schematic geological cross-section along the magnetotelluric profile was constructed (Fig. 2b). The shallower part was obtained from known structural data. The deep structure beneath the External Betics is derived from the interpretation of ESCI-Béticas1 deep seismic reflection profile (García-Dueñas *et al.*, 1994) and the seismic refraction profile I (Banda *et al.* 1993). The deep structure beneath the Internal Betics was obtained from the interpretation of the NE-SW ESCI-Béticas2 seismic reflection profile (García-Dueñas *et al.*, 1994) which was projected over the NW-SE magnetotelluric profile.

As regards the surface structure, the conductor emerging in the Guadalquivir basin and dipping southeastwards (A in Fig. 2a) reveals a fluid rich level. In the External Betics this level is formed by the Triassic evaporite and lutite rocks of the bottom of the Subbetic and Prebetic thrust units. The great thickness of this level, is attributed to the incorporation of Neogene sediments of the autochthonous Guadalquivir basin. This conductive level continues beneath the Internal Betics where it could be attributed to the presence of overthrust sedimentary rocks of the External Betics, although it could also be explained by an increase in fracturation. Therefore, this conductive level shows the geometry of the main detachment level of the Betics northwestwards of site 1. Southwestwards of this site, probably the conductive level associated with the main detachment merges with the upper zones of the conductor D. Comparing with Fig. 2b, this level A would connect with the change in resistivity beneath sites 32 and 30 at about 20 km depth dipping southeastwards.

The shallow northwest dipping conductor (B in Fig.2a) is interpreted as having been generated by fluid circulation along active extensional faults. In Fig. 2b the fault cropping out in the Sorbas-Tabernas basin and dipping northwestwards correlates, at depth, with this conductor.

The presence of the deep conductor (D) is one of the most striking results and its interpretation is still unclear. Nevertheless, a number of considerations must be kept in mind: 1) the deep conductor is located just beneath the sierra de los Filabres at lower crustal and upper mantle depths and not along the profile; 2) comparison with the ESCI-Béticas2 seismic profile shows correlations with reflectivity in the lower crust and the upper mantle in the same location; 3) a seismic tomography study performed recently in the Betics and Alborán Sea detected a low seismic velocity zone beneath Sierra Nevada (Sallarès *et al.*, 1996), which correlates with the deep conductor. Three-dimensional modelling of the other magnetotelluric sites and new geophysical data (i.e. heat flux) will shed more light on the interpretation of this enigmatic deep conductor.

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

References

Azañón, J.M., García-Dueñas, V., Martínez-Martínez, J.M. and Crespo-Blanc, A. (1994): Alpujarride tectonic sheets in the central Betics and similar eastern allochthonous units (SE Spain). *C.R. Acad. Sci. París,* 318, Série II: 667-674.

Bakker, H.E., De Jong, K., Helmers, H. and Biermann, C. (1989): The geodynamic evolution of the Internal Zone of the Betic Cordilleras (south-east Spain): a model based on structural analysis and geothermobarometry. *Jour. Metamorphic Geology.,* 7: 359-381.

Banda, E. and Ansorge, J. (1980): Crustal structure under the central and eastern part of the Betic Cordillera. *Geophys. Jour. Roy. Astr. Soc.,* 63: 515-532.

Banda, E., Gallart, J., García-Dueñas, V., Dañobeitia, J. and Makris, J. (1993): Lateral variation of the crust in the Iberian Peninsula. New evidence from the Betic Cordillera. *Tectonophysics,* 221: 53-66.

Banks, C.J. and Warburton, J. (1991): Mid-crustal detachment in the Betic system of southeast Spain. *Tectonophysics,* 191: 275-289.

Crespo-Blanc, A., Orozco, M. and García-Dueñas, V. (1994): Extension versus compression during the Miocene tectonic evolution of the Betic chain. Late folding of normal fault systems. *Tectonics,* 13: 78-88.

Egbert, G.D., and Booker, J.R. (1986): Robust estimation of geomagnetic transfer functions. *Geophys. Jour. Roy. Astr. Soc.,* 87: 173-194.

Fallot, P. (1948): Les Cordillères Bétiques. *Estudios Geol.,* 8: 83-172.

Galindo-Zaldívar, J., González-Lodeiro, F. and Jabaloy, A. (1989): Progressive extensional shear strucutres in a detachment contact in the Western Sierra Nevada (Betic Cordilleras, Spain). *Geodinamica Acta,* 3: 73-85.

García-Dueñas, V. and Balanyá, J.C. (1991): Fallas normales de bajo ángulo a gran escala en las Béticas occidentales. *Geogaceta,* 9: 29-33.

García-Dueñas, V., Banda, E., Torné, M., Córdoba, D. and ESCI-Béticas Working Group (1994): A deep seismic reflection survey across the Betic Chain (southern Spain): first results. *Tectonophysics,* 232: 77-89.

García-Dueñas, V. (1995): Sobre la extensión longitudinal en las Béticas y su hipotética incidencia en la estructura cortical (Perfiles ESCI-Béticas 1 y 2). In *Reunión-Estudios Sísmicos de la Corteza Ibérica,* Resúmenes,Barcelona.

García-Hernández, M., López-Garrido, A.C., Rivas, P., Sanz de Galdeano, C. and Vera, J.A. (1980): Mesozoic palaeogeographic evolution of the External Zones of the Betic Cordillera. *Geol. Mijnb.,* 59: 155-168.

Groom, R.W. and Bailey, R. (1989): Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distorsion. *Jour. Geophys. Res.,* 94: 1913-1925.

Monié, P., Galindo-Zaldivar, J., González-Lodeiro, F., Goffé, B. and Jabaloy, A. (1991): 40 Ar/ 39 Ar geochronology of Alpine tectonism in the Betic Cordilleras (southern Spain). *Jour. Geol. Soc. (London),* 148: 289-297.

Platt, J. and Vissers, R.L.M. (1989): Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alborán Sea and Gibraltar Arc. *Geology,* 17: 540-543.

Sallarès, V., Dañobeitia, J.J. and Martínez-Solaros, J.M. (1996): A regional tomographic approach of the velocity structure beneath the Betics-Alborán region using local earthquake data. *XXI General Assembly of the European Geophysical Society. The Hague*

Sanz de Galdano, C. and Vera, J.A. (1992): Stratigraphic record and palaeogeographical context of the Neogene basins in the Betic Cordillera, Spain. *Basin Research,* 4: 21-36.

Smith, J. T. and Booker, J.R. (1991): Rapid inversion of two- and three-dimensional magnetotelluric data. *Jour. Geophys. Res.,* 96: 3905-3922.

Torres-Roldán, R.L. (1979): The tectonic subdivision of the Betic Zone (Betic Cordilleras, southern Spain): its significance and one possible geotectonic scenario for the westernmost Alpine belt. *Amer. Jour. Sci.,* 279: 19-51.

Vegas, R. and Banda, E. (1982): Tectonic framework and Alpine evolution of the Iberian Peninsula. *Earth Evol. Sci.,* 4: 320-343.

Vera, J.A. (1983): Las zonas externas. In: *Libro Jubilar J.M. Ríos. Geología de España.II* (J.A. Comba, Coord.): 218-250. Inst. Geol.Min. España., Madrid.

Wu, N., Booker, J.R. and Smith, J.T. (1993): Rapid two-dimensional inversion of Coprod2 data. *Jour. Geomagnetism and Geoelectricity,* 45: 1073-1087.

Received 15 November 1995;
revised typescript accepted 28 June 1996.