The ESCI-Béticas: a seismic reflection image of the Betics orogen

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Abstract: New processing of the two deep seismic reflection normal incidence data acquired across the Betic Cordillera provides an image of the main tectonic features, that probably have been active during the development of the orogen. The new processing and the detailed study of the shot gathers reveals an almost transparent upper crust, with only a few prominent reflectors. The most prominent upper crustal reflector, appears to be subparallel to the thick mylontic contact between the Alpujárride and the Nevado-Filábride. The surface wave attenuation by means of wave equation datuming has revealed shallow reflectivity. A prominent reflector appears at approximately 6 s TWTT (Two Way Travel Time) that seems to mark the boundary between the upper crust and the lower crust. Below this level, the crust presents a high reflectivity pattern. Elastic finite difference modelling supports that the high amplitude 6 s reflector is probably due to a highly laminated structure. Between the highly reflective top of the lower crust and the crust mantle transition, anastomousing bands of reflectors have been imaged, suggesting boudinage like structures. The shot gathers present a high amplitude event that can be correlated with the base of the crust (Moho discontinuity). The multicyclic nature of the event, the high amplitude, and the frequency peaks, suggest that it is probably the response of a layered structure. The analysis of the shot gathers indicated a low average velocity of 6.3 ± 0.2 km/s for the crust and an average crustal thickness of 35 ± 2 km where the crust-to-mantle transition is marked by a prominent reflected event. These results are consistent with older seismic refraction data. These results constitute the key features for the development of a tectonic model characterised by structures which can physically accommodate the complicated tectonics that have affected the area.

Keywords: Betic Cordillera, seismic reflection, tectonic model, geodynamics

Resumen: El reprocesado de las perfiles de sísmica de reflexión profunda adquiridos a través de la cordillera Bética, proporcionan una imagen de los elementos tectónicos que muy probablemente han estado activos durante el desarrollo del orógeno. El nuevo procesado y el estudio detallado de los los registros sísmicos de los disparos, revela una corteza superior transparente con sólo algunos reflectores importantes. El reflector de mayor amplitud aparece como subparalelo a una estructura milonítica relativamente gruesa que hace de contacto entre el Alpujáride y el Nevado Filábride. La atenuación de las ondas superficiales a través de la prolongación a un nivel de referencia mediante la ecuación de ondas ha permitido la visualización de reflectividad a niveles superficiales. Un reflector muy prominente aparece a unos 6 s DTR (Doble Tiempo de Recorrido) y que podria corresponder al límite entre la corteza superior y la inferior. Por debajo de este nivel, la corteza presenta una alta reflectividad. Simulaciones mediante diferencias finitas del campo de ondas sugieren que el reflector localizado a 6 s es, probablemente, la respuesta de una estructura laminar. Entre la estructura altamente reflectante que marca el limite superior de la corteza inferior y la transición corteza-manto se han visualizado unas bandas entrelazadas que sugieren estructuras en boudinage. Los registros de los disparos presentan un reflector de gran amplitud que puede correlacionarse con la base de la corteza (Moho), La naturaleza multicíclica, la elevada amplitud, y los máximos del espectro de frecuencias, sugieren que corresponde a la respuesta sísmica de una estructura laminar. La distribución de velocidades determinada a partir de los datos de sísmica de reflexión sugiere velocidades medias para la corteza de 6.3 ± 0.2 km/s y el grosor medio de la corteza limitado por un prominente reflector es de unos 35 ± 2 km en concordancia con datos de sísmica de refracción. La imagen sísmica permite desarrollar un modelo tectónico con los mecanismos físicamente razonables para acomodar la actividad tectónica que ha afectado a este area.

Palabras clave: Cordillera Bética, símica de reflexión, modelo tectónco, geodinámica

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The Spanish program for Seismic Studies of the Iberian crust (ESCI) was designed to image the most characteristic lithospheric structures within the Iberian peninsula. The Betics orogen is one of the most enigmatic lithospheric structures in the Iberian peninsula. The Betics complicated tectonics, with periods of compression overprinted by extension episodes, has puzzled the earth scientists since the early seventies and it has been the aim of a large number of geologic and geophysic studies.

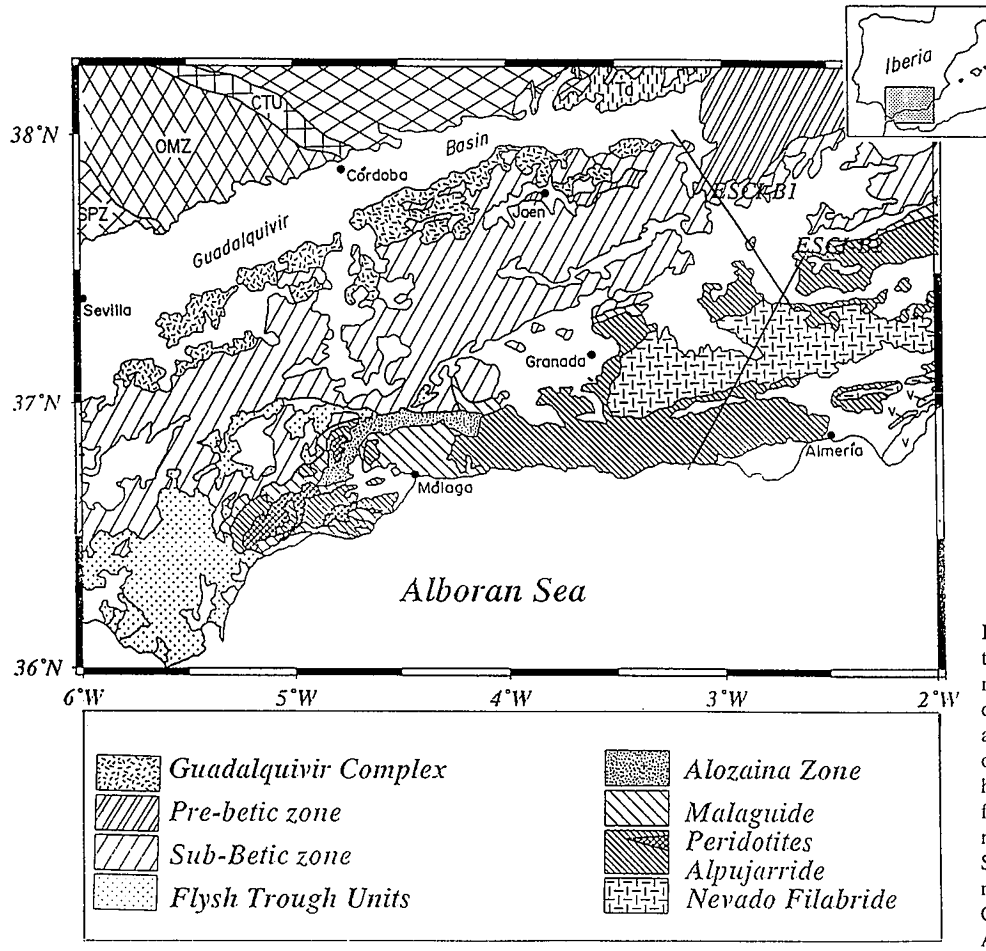

Figure 1.- Map showing the location of the refraction/wide-angle reflection and deep normal incidence seismic reflection profiles across the Betic cordillera. The geological, lithologic and metamorphic complexes are indicated in the figure. Abbreviations: IEZB Internal External Zone Boundary; SPZ Sub-Portuguese Zone; OMZ Ossa-morena Zone; CTU Central units; CIZ Central Iberia Zone; SA Sierra Alhamilla.

The precise pattern of plate motions that led to Betics orogen is unclear, although it certainly involved dextral motion of Iberia with respect to Africa as well as convergence (Dewey *et al.*, 1989). The strike slip plate motion is emphasised by Leblanc & Olivier (1984) and Vauchez & Nicolas (1991). Unravelling the plate-tectonic scenario of the region is complicated by the fact that the orogen follows a 180° curve around the Gibraltar arc connecting with the Rif mountain chain (Didon *et al.*, 1973). The Rif and Betics cordilleras, with the Gibraltar arc trap the Alborán microplate whose relative motion has apparently also contributed to the present geometry (Adrieux *et al.*, 1971).

A key feature in the analysis of the plate motions is the clear definitions of plate boundaries, and/or suture zones within the orogens. A broad (15 m in some outcrops), highly deformed shear zone, known as the Internal-External Zone Boundary (Lonergan *et al.*, 1994) has been proposed as the plate boundary between the Alborán domain and the Iberian plate. This contact juxtaposes rocks of the uppermost, nonmetamorphic, Maláguide complex of the Internal Zone on Subbetic rocks of the External zone, an equivalent boundary has been suggested in the African plate close to the Rif mountain chain in Morocco, the Jebha fault. Another postulated crustal scale shear zone is a broad mylonitic contact (of ductile high-strain deformation) between two highly metamorphosed geologic units, the Alpujárride and the Nevado-Filábride. Models for the geodynamic evolution of the Betic mountain chain can not be validated because of the lack of knowledge on the depth extent and geometry of these shear zones. Therefore, two deep seismic reflection profiles were acquired across the main geologic structures within the ESCI-Béticas project (García Dueñas *et al.*, 1994). The present study reveals the main features of the internal architecture based on evidence from new processing of the multichannel deep seismic data set. These features play key roles in the development of a geodynamic model for the area.

Background: tectonic setting, geology and geophysics

The Betics represent part of the western-most circum-Mediterranean Alpine range, and constitutes the southernmost deformed palaeo-margin of the Iberian plate. It was formed by the interaction of the European and African plates in Late Mesozoic and Early Tertiary time.

The Meso-Cenozoic evolution of the Betics is associated to the opening of the Atlantic ocean and the convergence between the Iberian and African plates (Decourt *et al.*, 1986). An extensional episode during Late Triassic-Middle Cretaceous times, mainly due to a left-lateral transtensional movement between Africa and Eurasia-Iberia, originated a rifted margin on the southeastern border of the Iberian continent. Presently, a compression tectonic environment has affected the region since Late Cretaceous times mainly due to plate convergence (Buforn *et al.*, 1988). Within this collisional setting numerous spatially and temporally localised extension episodes led to the initiation of a number of rifted basins in the western Mediterranean (the Gulf of Lions, Valé ncia trough and Alborán basin).

Like most of the Alpine mountain chains the Betics orogen can be subdivided into a non-metamorphic external zone and a metamorphic and highly deformed internal zone (Fig. 1). The external zone of the Betic Cordillera represent the Mesozoic-Palaeogene rifted continental margin of Iberia (García-Hernández *et al.*, 1980). The external zones are subdivided into Prebetic domain, which represents the shelf of the margin, and the Subbetic slope and basin. The differentiation between the Prebetic and Subbetic probably took place during the break up of the platform in Early Jurassic. Three main units can be distinguished in the internal zone on the basis of their tectono-metamorphic evolution (Torres-Roldán, 1979). The internal zone is made up of mainly pre Mesozoic and Triassic terranes. The palaeogeography of these units is not well known but they are clearly allochthonous to the Iberian continent (MSkel, 1985).

Additionally, geologic mapping of the southeastern most part of the Iberia peninsula from the Gibraltar arc to the external Betics illustrates that the Betics zone represents a crustal scale cross section, with rock units coming from all different depths, including the world largest exposure of high density peridotitic rocks (300 km^2) (Dickey, 1970; Obata, 1980).

The contacts between these units represent major thrusts, and/or suture zones. Detailed outcrop descriptions of these suture and shear zones can be found in Platt *et al.* (1984), Galindo-Zaldívar *et al.* (1989), Lonergan *et al.* (1994), Platt & Behrmann (1986), among others. The three main units of the internal Betics are known as: the Maláguide, the Alpujárride and the Nevado-Filábride. The latter corresponds to the deepest part of the crustal section followed by the Alpujárride. The Maláguide would correspond to the shallowest representative of the crust. However, the Alpujárrides can be found in a few locations on top of units of unknown age. Detailed descriptions of the units, their stratigraphy, and the descriptions of their metamorphic fabrics can be found elsewhere (Aldaya *et al.*, 1979; Torres-Roldán, 1979; Behrmann & Platt, 1982; Platt *et al.*, 1983; García-Dueñas, 1987; Galindo-Zaldívar *et al.*, 1989; Tubía *et al.*, 1992; Tubía *et al.*, 1993).

Since 1974, seismic refraction measurements where carried out across the Betics and surrounding area covering from the Gibraltar arc to the eastern most part of the Betics orogen. The velocity depth functions derived from these refraction data sets can be summarised as a 30 ± 2 km thick crust with an average velocity of 6.2 ± 0.2 km/s. The velocity-depth functions derived beneath the highest topographic elevations suggest a slight thickening going up to 37 ± 2 km indicative of a crustal root. In summary, the refraction data suggest a crust consisting of three layers of relatively low velocities. A few velocity-depth profiles include a low velocity channel. Gravity studies were also carried out in the area. The Bouguer anomaly seems to support this crustal root (Casas & Carbó, 1990; Torné & Banda, 1992). Potential field data specially gravity is crucial in defining the Ronda peridotite body as a thin tectonic flake (Torné *et al.*, 1992). García-Dueñas *et al.*, (1994) presented the first interpretation of the commercially processed normal incidence seismic data and compared it with the latest refraction/wide-angle seismic data set.

The ESCI-Béticas deep seismic reflection profiles: processing and description

The ESCI-Bé ticas deep seismic reflection profiles were acquired across the most peculiar features mapped by the surface geology of the complex Betic cordillera (Fig. 1). The main purpose was to image the transition from the Variscan Iberian lithosphere across the Betics mountain chain to the Alborán, allochthonous terranes. The profiles cross the most prominent surface lineaments: the postulated plate boundary (Internal-External Zone Boundary suture); and, a crustal shear zone that presumably outcrops in the Sierra Alhamilla. The latter

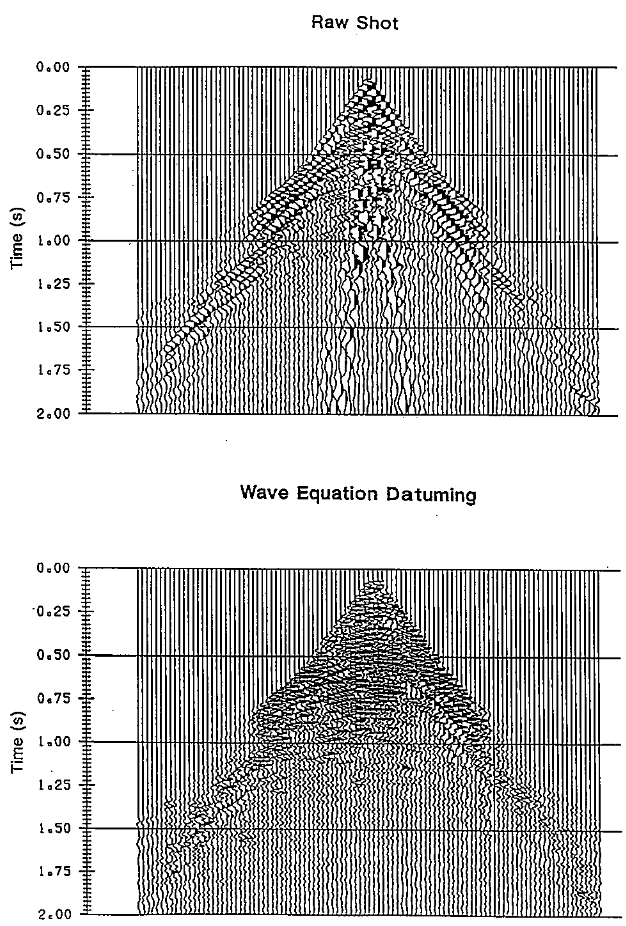

Figure 2.- Shot record before (top) and after (bottom) the application of the wave equation datuming algorithm (Berryhill, 1979). This scheme suppressed the surface wave energy and revealed upper crustal reflectivity.

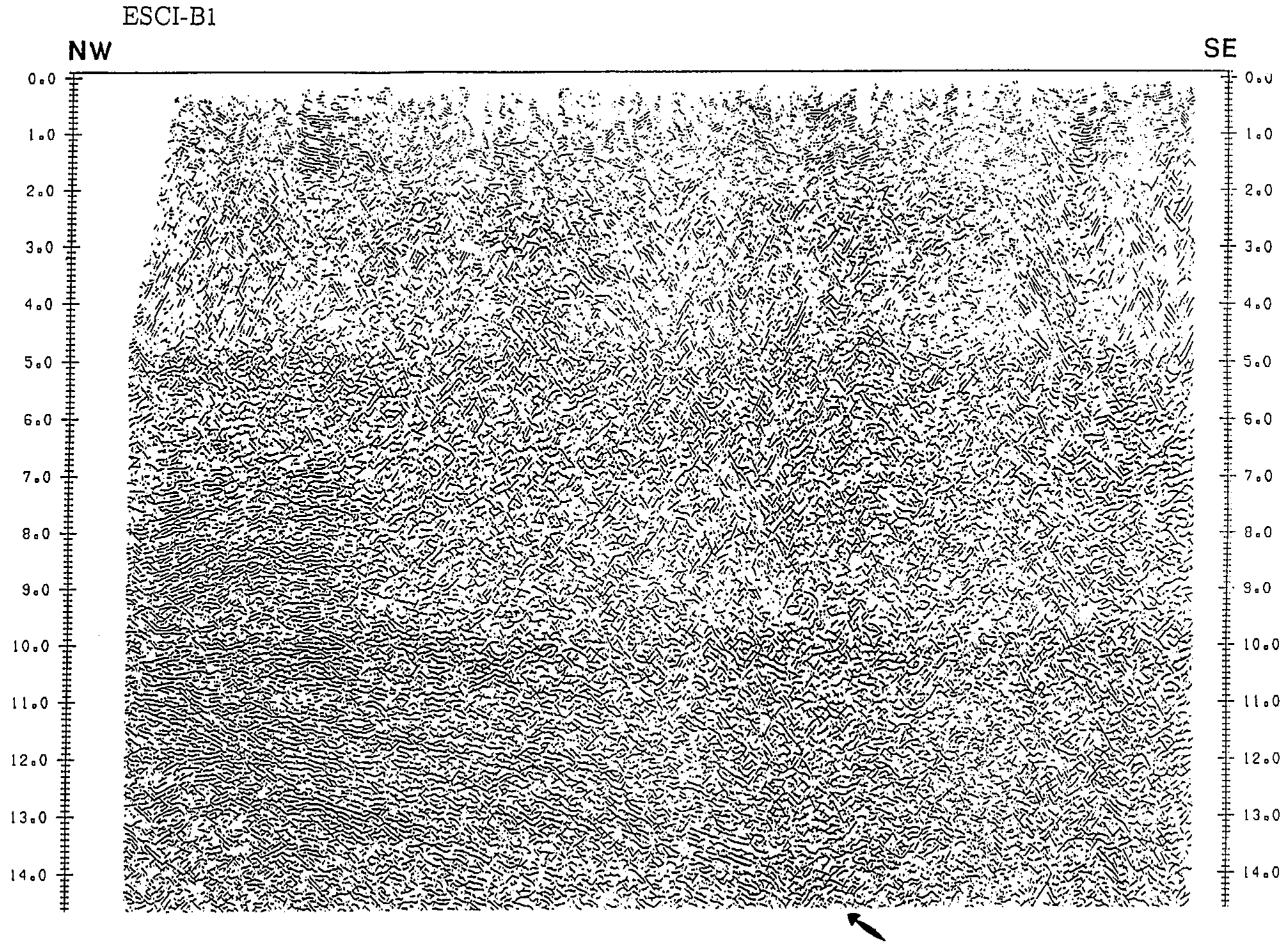

Figure 3.- Commercially processed seismic reflection stack sections of ESCI-Béticas1. UCR indicates the Upper Crustal Reflector; TLC refers to the Top of the Lower Crust; PmP indicates the Moho discontinuity, crust-mantle transition. Note that the banded appearance of the section with marked limits at 5 and 10 s. across the section is mainly due to an artefact of the commercial processing.

is interpreted as a crustal scale thrust (or movement zone) that juxtaposes two metamorphic units, the Alpujárride and the Nevado-Filábride.

The seismic reflection normal incidence data consist of two transects. ESCI-Béticas1 oriented Northwest-Southeast and ESCI-Béticas2 oriented Northeast-Southwest (Fig. 1). These data were acquired using explosive sources; the energy released by the explosions (every 250-300 m in average) was recorded by single component vertical geophones with a station spacing of 60 m. In order to achieve a well resolve subsurface image the new processing focused in increasing the signal-to-noise ratio and estimating a velocity model. Despiking, and trace editing were applied to reduce the cultural and weather generated noise. Because this dataset was acquired using explosive sources the data are characterised by significant differences in amplitudes, waveforms and frequency content. The amplitude differences from shot to shot due to source coupling variations were compensated for by ensemble balancing. A root mean square (RMS) amplitude normalisation scheme, where each trace is normalised by the RMS amplitude of the background noise, was used to compensate for the receiver coupling differences. The amplitudes before the first breaks, or the last second of recorded data provide a reliable estimate of the background noise.

A frequency filtering, spectral balancing and deconvolution help homogenise the wave forms and compensate for the frequency differences. The phase differences were also corrected for. A quality factor (Q) derived from surface wave studies (Canas *et al.*, 1992) was used to compensate for the amplitude decay due to attenuation.

Static corrections are fundamental in this data set due to the high topographic relief. A newly designed wave-equation (Berryhill, 1979) datuming algorithm was used to correct for statics and attenuate the high amplitude low frequency surface waves. The wave-equation datuming algorithm proved very efficient in revealing the shallow reflectivity masked by the surface waves (Fig. 2).

The seismic reflection Common Mid-Point (CMP) profiles present very distinctive seismic signatures ESCI-B1 shows an almost featureless crust for the entire 15 s (Fig. 3). A relatively weak Moho, or crust to mantle transition zone can be identified in the semblance filtered section. The PmP arrival dips into the mantle in the southwestern most part of the profile. Apparently there is

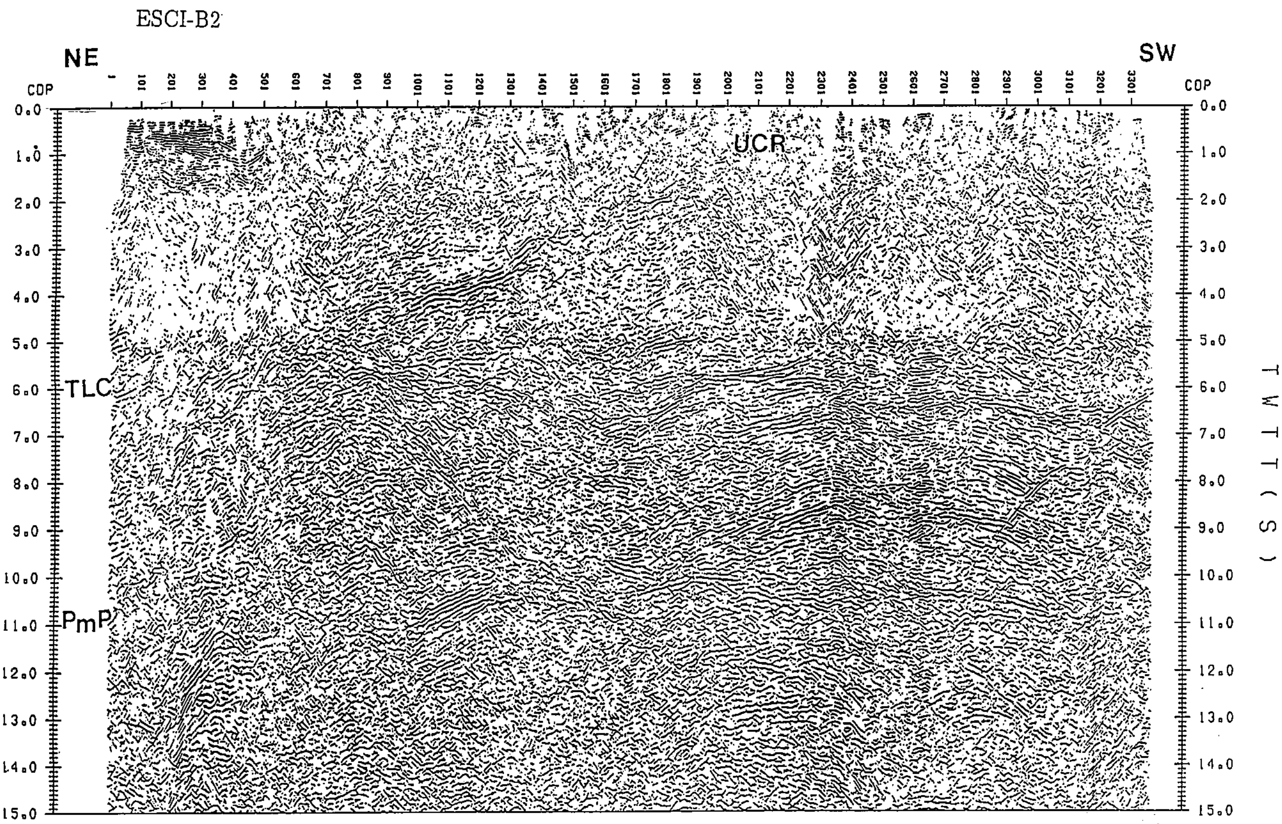

Figure 4.- Seismic reflection stack sections of ESCI-Béticas2 (obtained for the present study). UCR indicates the Upper Crustal Reflector; TLC referees to the Top of the Lower Crust; PmP indicates the Moho discontinuity, crust-mantle transition.

no differentiation between the upper and the lower crust in the shot gathers and in the CMP stack.

The spectacular differences between ESCI-Béticas1 and ESCI-Béticas2 are mainly the high amplitude lower crustal reflectivity observed in ESCI-Béticas2 (Fig. 4). In ESCI-Béticas2 the upper crust exhibits a few reflectors. The horizontal reflectors (Fig. 5) at the northwestern part of the profile (CMP 101), mostly display the sedimentary layering of a basin (southern end of the Guadix-Baza). A prominent multicyclic spoon shaped reflector, labelled UCR (Upper Crustal Reflector) can be observed between 2 and 4 s, this northwest dipping event flattens out at 1-2 s TWTT (Fig. 6). At 6 s a prominent 0.5 s thick multicyclic reflector can be identified almost across the entire profile, this event is undulating in the stacked image. This event exhibits a small southeastern dip and is labelled TLC (Top of the Lower Crust). The event labelled PmP and located at approximately 11 s is identified as the Moho discontinuity. In the stack image this event exhibits an undulated pattern. There are a few events beneath this prominent structure below CMP # 2201 (Fig. 4). ESCI-Béticas2 displays a highly reflectivity between the TLC and the PmP events, with arcuate series of events which can reach up to 50 km in length.

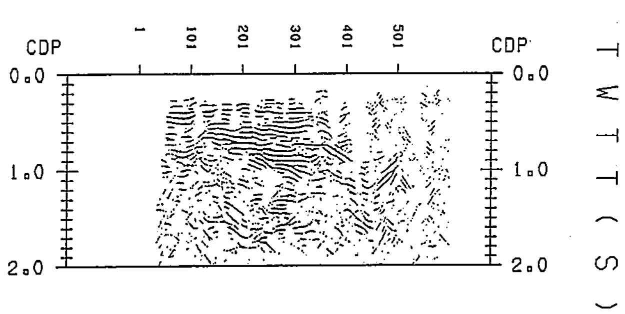

Figure 5.- Detailed view of the shallow reflectors of the northwestern end of ESCI-Béticas2, (southernmost part of the Guadix-Baza basin).

There are significant differences between the average frequency contents of the UCR, TLC and PmP events. The UCR is characterised by low frequencies with significant frequency peaks between 10-15 Hz. The TLC shows a broader spectra with high amplitude contribution between 10 to almost 25 Hz, while the PmP features a narrower band between 15 to approximately 20 Hz (Fig. 7).

Discussion

The three most prominent events (UCR, TLC and PmP) exhibit different amplitude spectra (Fig. 7) indicating different internal structures. For example: UCR has a prominent frequency peak at 13 Hz and 20 Hz; TLC has a higher frequency content with maxima at 12, 17-20, and 35 Hz; PmP has a prominent maxima are 17 Hz. For an average velocity of 6.2 km/s constructive interference considerations suggest that frequencies of 12, 17, 20 and 35 hz could correspond to a layered pattern of, approximately, 125, 100, 75 and 45 m, respectively. Additionally, the multicyclic and dispersive character of the TLC event can be appropriately simulated by a highly la-

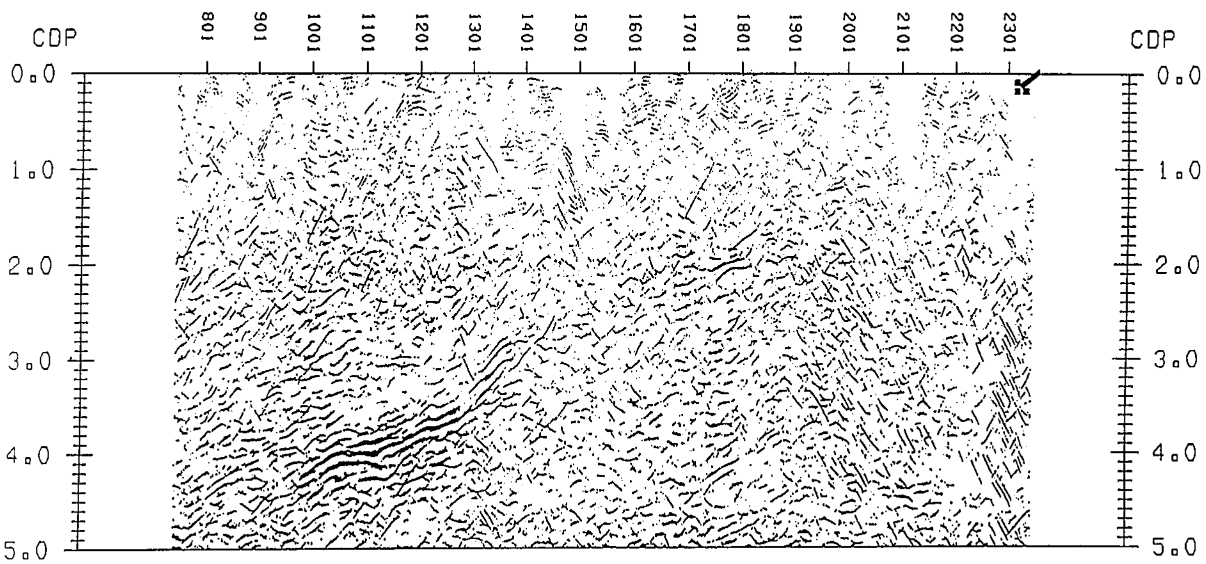

Figure 6.- Detailed view of the UCR (Upper Crustal Reflector) illustrating its possible extrapolation to shallower levels (arrow).

minated and laterally heterogeneous structure (Fig. 8). The lateral changes of the seismic signature is indicative of lateral thickness variations, or the existence of lateral heterogeneities.

In ESCI-Béticas2 the UCR event extrapolated to the surface it closely parallels an outcropping mylonitic shear zone that separates two highly metamorphic units (the Alpujárride and the Nevado-Filábride). The TLC event,

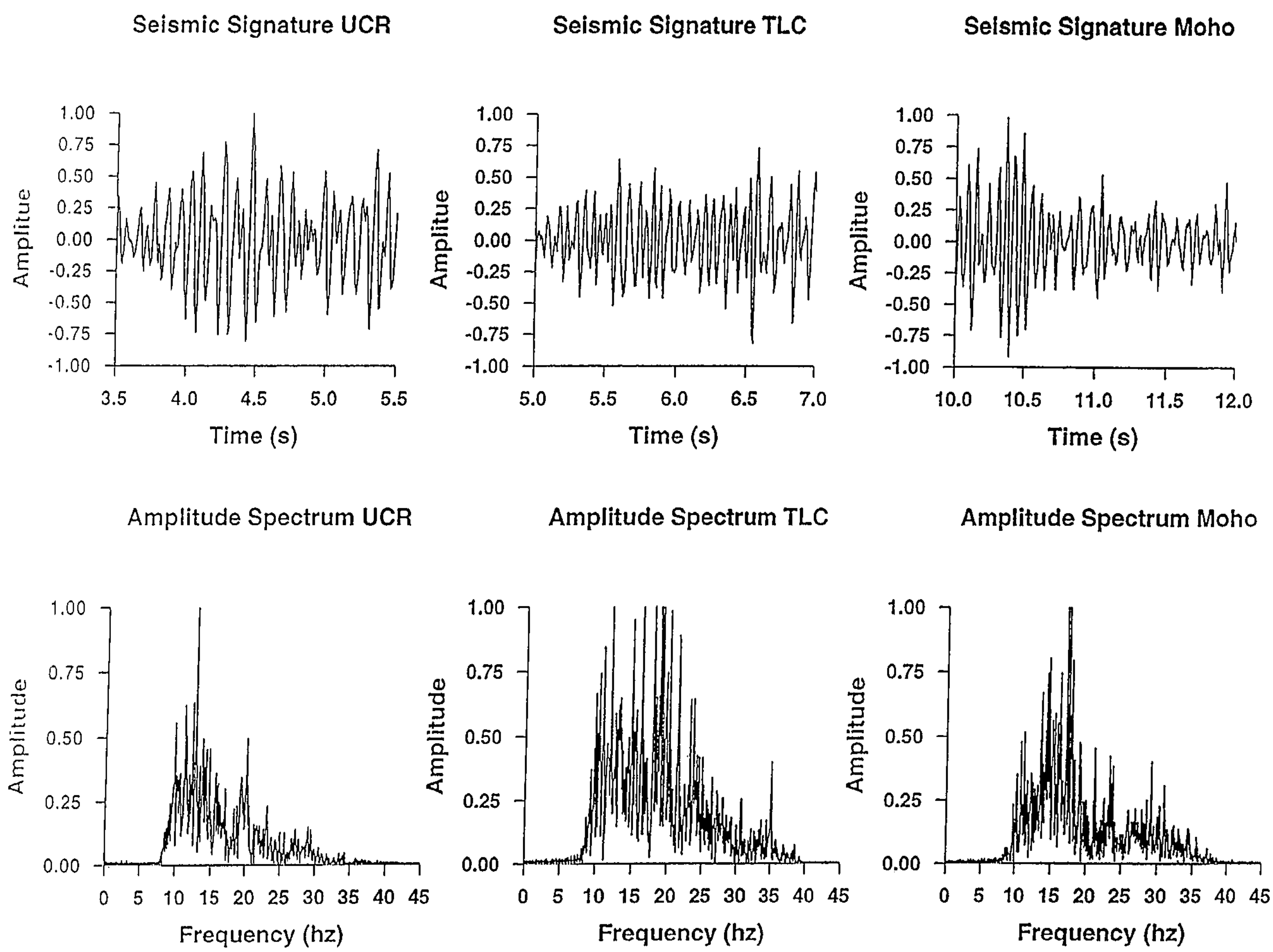

Figure 7.- Frequency spectra of the UC, TLC, and M events. The differences in the frequency content illustrate possible differences in the internal structure. The amplitude spectra corresponds to a 1 s long window centred around the UCR, TLC, and Moho events between (3.5-5.5 s; 5.0-7.0 s and 10.0-12.0 s).

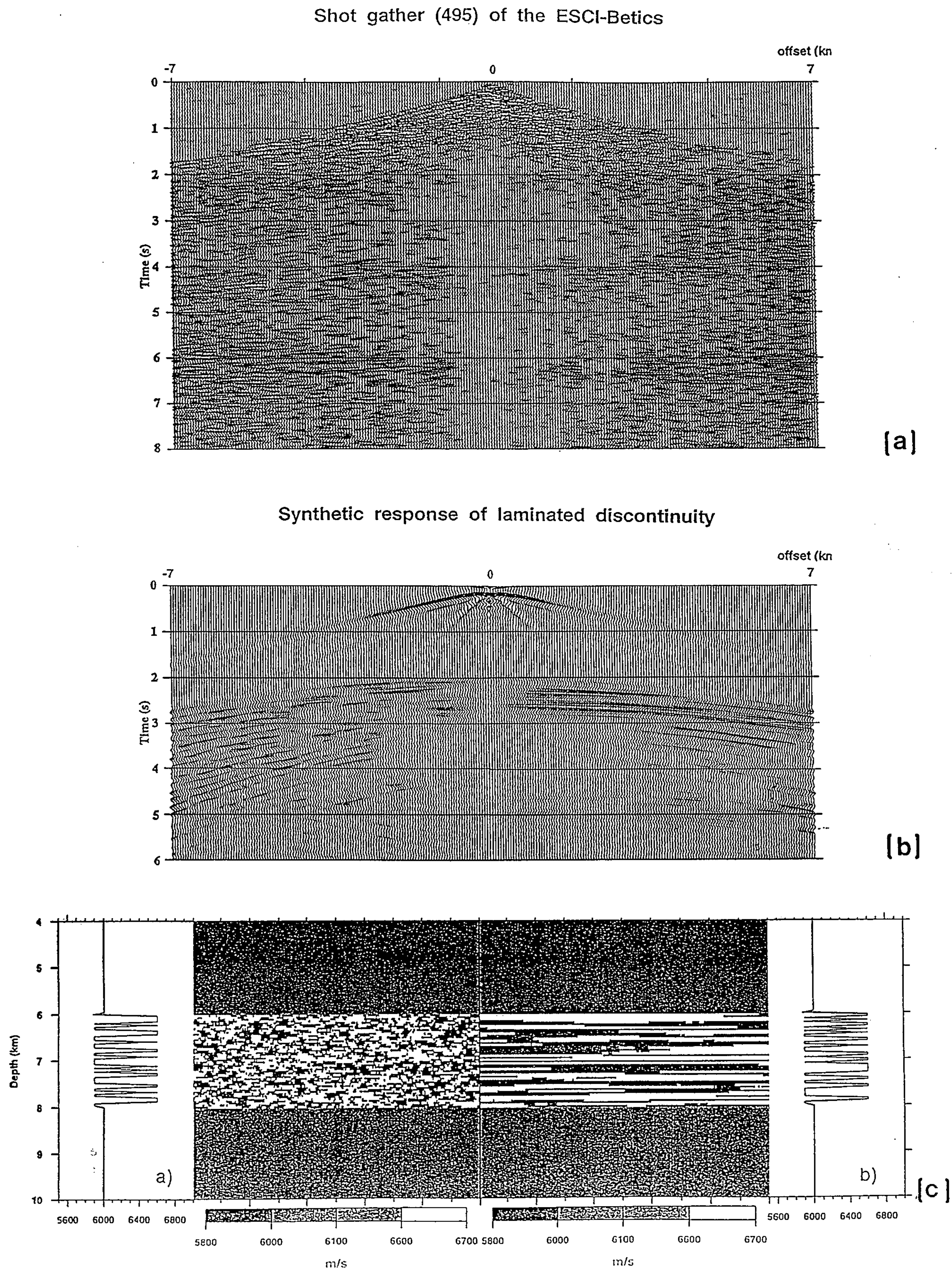

Figure 8.- (a) Shot gather of the ESCI-Béticas, ESCI-Béticas2, illustrating the details of the seismic signature of two multicyclic and dispersive events. (b) Finite difference simulation of a laminated 4 km thick structure. The geological model © has been generated using a fractal velocity distribution with a dimension of 2.5 and velocity variation that range from 5.9-6.5 km/s. The right and left columns of c show a vertical-depth curve illustrating the velocity depth distribution for both sides of the synthetic model. This figure illustrates effects of the lateral variable thinly layered structure.

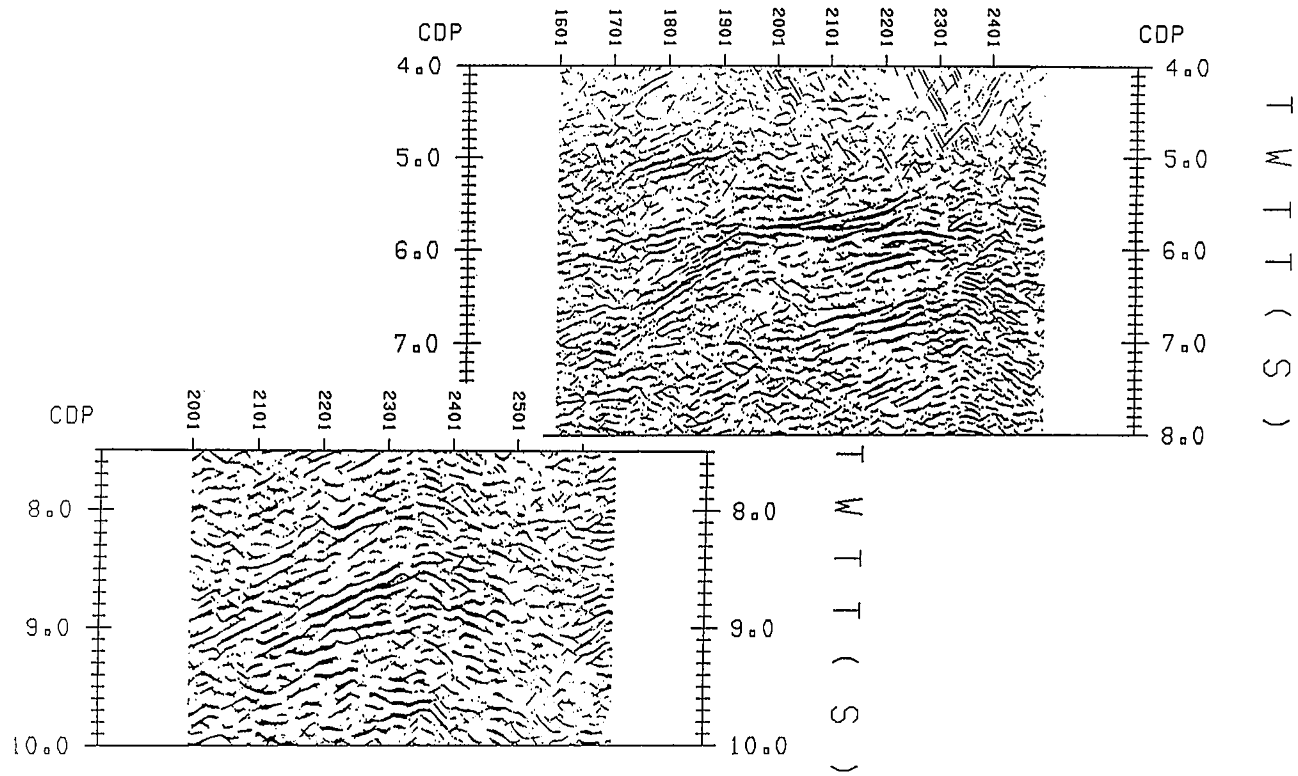

Figure 9.- Seismic boudinage structures extracted from the stacked section of ESCI-Béticas2. The bottom lenses exhibits indications of deformation.

dips to the Southeast in the stacked section (Fig. 4), the smooth dip suggest that it should outcrop at the southeastern end of ESCI-B1, beneath the Guadix-Baza basin. If this is the case, this event would be a reasonable candidate for the postulated Internal-External Zone Boundar (the continental suture zone between the Variscan and the Alborán domains).

The PmP reflection is a multicyclic arrival, which can reach 0.5 s in thickness. The PmP phase in ESCI-Béticas1 dips to the Southeast, while in ESCI-Béticas2 the Moho discontinuity exhibits a small undulation pattern at the base of the crust at, approximately, 11 s. In the shot gathers, the PmP phase is a continuous event across each gather at 11 s in average. In the stack section a small root can be identified beneath the main topographic elevations (CDP 1001, Fig. 4).

The 5-6 s thick reflective band limited by the TLC and the PmP events is considered to be the lower crust. Within this broad zone, the arcuate reflectors suggest boudinage like structures (Fig. 9). The seismic boudins are limited by multicyclic arcuate events. This events are similar in pattern to the ones generated by thinly layered models. Thus suggesting, a series of boudins (boudinage structures) limited by anastomousing shear zones which have localised the deformation (Hamilton, 1987). The layering and/or fabrics of this bands are considered responsible for the reflectivity (Carbonell & Smithson, 1991b).

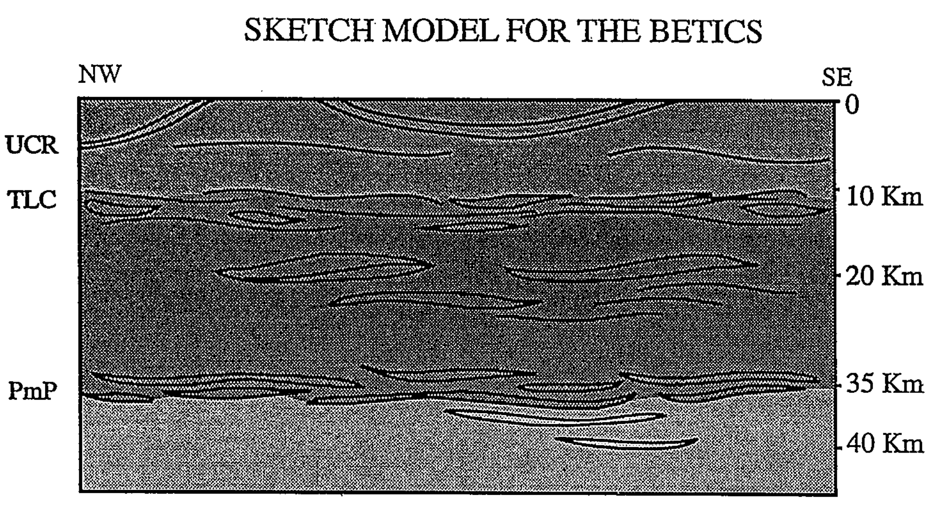

Figure 10-. Sketch of a geodynamic model for the Betic Cordillera based on a composite interpretation of ESCI-Béticas1 and ESCI-Béticas2. This model exhibits the most characteristic features that have been identified in the deep seismic reflection seismic data. UCR, a strong Upper Crustal Reflector; TLC a detachment zone located at 10-14 km; Lenses or boudins at lower crustal depths, immersed in a matrix of weak deformable shear zones; a PmP Moho discontinuity; and, a few structures in the upper mantle.

The shape of the crust mantle transition suggest that this is a recent structure probably generated during the extension tectonic environment. At TWTT greater than 11 s horizontal and/or slightly arcuate events can be identified beneath CDP 2051-2401 in ESCI-B2 (Fig. 4). This upper mantle reflectivity can be a remnant of a sandwiched boudin which has indented in the mantle. The lenses or boudins will flatten with increasing depth and temperature deforming internally at great depths, this process will produce long, flat and horizontal reflection segments.

Tectonic model

Fig. 10 represents a sketch of the tectonic model that can be derived from the seismic reflection data. The model consist of a main detachment level, located at approximately 10-15 km (TLC), and which dips to the Southeast. A shallower spoon shaped reflector which can be extrapolated to the surface, and which is parallel to the main suture zone that separates the two highly metamorphic terranes (the Alpujárride and the Nevado-Filábride). This structure probably corresponds to the mylonitic shear zone that outcrops in the Sierra de Alhamilla.

The boudinage appearance of the seismic section suggests lenses within the lower crust, between the TLC event and the Moho. Such boudins could be delineated by a network of anastomousing shear zones (Reston, 1987; Carbonell & Smithson, 1991a), or simply "float" in a matrix that underwent greater plastic deformation. During extension these boudins or lenses are probably pulled apart, and the stretching is taken up dominantly by simple shear within the narrow zones separating the lenses. Lenses will flatten with increasing depth and temperature (for instance boudins themselves become less competent and so deform internally at greater depth). Compression, would reactivate the narrow zones limiting the lenses, the boudins would come together again, deforming the top and bottom limits of this boudinage layer, the TLC and the PmP (Moho) in our case. This geodynamic model consisting of a matrix of plastic and more competent boudins would accommodate the complex extension and compression tectonics that have affected the area. The localised deformation within the anastomousing shear zones is probably a result of a change in the physical properties of the rocks causing a strong decrease in the viscosity (Meisner & Kusznir, 1987). The presence of fluids is a physically reasonable way to achieve a decrease in viscosity. Fluids could also account for the high conductivity measured by magnetotelluric soundings (Pous *et al.*, this vol.).

Conclusions

In this study we present a structural model for the crust beneath the Betics orogen. The recently reprocessed ESCI-Béticas deep seismic reflection images constitute the basis for this model. The lithosphere beneath the Betic cordillera is characterised by a featureless crust to the North (below ESCI-Béticas1), in the Variscan crust, as one follows South, the weak PmP arrival dips slightly into the mantle, suggesting a collision, or flower like structural zone suggesting the crustal suture between the Iberian plate and the Alborán domain. South of the suggested suture zone in ESCI-Béticas2 a high amplitude reflective lower crust is imaged. The reflectivity starts at approximately 6 s TWTT. This reflectivity displays an internal structure. The 6 s event labelled TLC is continuous along the southern profile, up to the coast line. An upper crustal reflector, UCR, is interpreted as a major mylonite zone that separates two geologic metamorphic units, the Alpujárride and the Nevado-Filábride. ESCI-Béticas2 also shows reflections in the upper crust mainly produced by lithological and/or sedimentary contacts. This is supported by surface geology mapping. The newly obtained images display boudin like structures in the lower crust, as well as localised shear zones. The PmP arrival for the southern profile is very well imaged, at least in the shot gathers, is multicyclic with frequencies up to 35 Hz, suggesting a layered structure with a bimodal velocity distribution in order to achieve the high amplitude reflectivity by means of constructive interference due to layering. This layering at the Moho level is laterally variable, we suggest that the observed short horizontal reflections observed below 12 s below CMP 2001-2701 are probably due to this layering.

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