The base of the crust at the Betics-Alborán Sea transition: evidence for an abrupt structural variation from wide-angle ESCI data

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Abstract: The deep vertical seismic reflection ESCI experiment in the Betic Cordillera and Alborán Sea basin was designed to constrain a structural transect in an area marked by lithospheric thickening and thinning episodes, related to different compressional, extensional and transcurrent processes since Mesozoic times. The vertical stacks, however, lack resolution in imaging the transition between stretched and unstretched crust at the Alborán domain. Complementary wide-angle data recorded in the same experiment and analysed here reveal the lateral variations of the Moho. Five stations located along the Betics-2 profile up to 60 km inland recorded the air-gun shots of the Alborán-1 profile. The conventional processing of these data had to overcome some technical deficiencies prior to the generation of high-density receiver-gathers, which show conspicuous reflections from the bottom of the crust along most of the profile. In addition to a classical interpretation by forward modelling, we developed a multichannel processing of the wide-angle Moho reflections, as large-offset multifold is achieved for a 60 km-long section. In the final wide-angle stack, the crust shows a moderate thinning seawards. The strong reflections observed between 6-7 s along the 35 km offshore segment are associated to the Moho beneath the Alborán Sea basin. This horizon penetrates up to 10 km inland where it is imaged at 8 s. Further north, this reflective level vanishes and a more diffuse reflectivity evidenced after 11 s is attributed to the crust-mantle transition beneath the Internal Betics. The wide-angle stack merged with the land and marine vertical sections completes a seismic transect across the Alborán domain. The composite section confirms that the transition from stretched to unstretched crust is marked by an abrupt Moho-jump of more than 3 s. This seismic image agrees with gravity interpretations in the same area. The geophysical results seem to enhance the role of shear tectonics. Lateral westward movements may have juxtaposed two blocks of different crustal thicknesses, before the Neogene-dominating compressional and extensional tectonics between the African and Iberian plates.

Keywords: ESCI profiles, Betics-Alborán Sea transition, wide-angle seismics, multichannel processing, unified seismic section, crustal transect.

Resumen: Uno de los objetivos del experimento ESCI de sísmica de reflexión vertical en la cordillera Bética y la cuenca del mar de Alborán era el establecer una transecta estructural en un área marcada por episodios de engrosamiento y adelgazamiento de la litosfera, en relación con los diferentes procesos compresionales, extensionales y transcurrentes acaecidos desde el Mesozoico. En la práctica, las secciones (*stacks*) de la sísmica vertical carecen de resolución respecto al control de la transición entre corteza deformada y no deformada en el dominio de Alborán. En cambio, los datos complementarios de gran ángulo registrados en el mismo experimento y analizados en este trabajo, sí permiten inferir las variaciones laterales del Moho. Estos datos se obtuvieron al registrar los disparos de aire comprimido del perfil Alborán-1 en cinco estaciones en tierra, a lo largo del perfil Béticas-2 hasta unos 60 km al norte de la línea de costa. Durante el procesado convencional de los datos, ha sido preciso paliar algunas deficiencias en los tiempos origen de los tiros, antes de poder construir los ensamblajes para las distintas estaciones. En ellos, la alta densidad de registros permite correlacionar con claridad fases reflejadas en la base de la corteza a lo largo de casi todo el perfil. Además de una interpretación clásica en términos de modelización directa, se ha desarrollado un procesado multicanal de los datos de gran ángulo, puesto que se dispone de cobertura múltiple para las reflexiones en el Moho a lo largo de una sección de unos 60 km de longitud. En el stack final obtenido, se observa un adelgazamiento cortical moderado hacia el centro de la cuenca. Las reflexiones con gran energía visibles entre 6 y 7 s a lo largo del segmento marino de 35 km se asocian con el Moho bajo la cuenca del mar de Alborán. Este horizonte penetra unos 10 km en tierra, donde se observa a unos 8 s. Más al norte, este nivel reflectivo desaparece, y se pone de relieve, en cambio, una reflectividad más difusa a partir de 11 s, atribuída a la transición corteza-manto bajo las Béticas Internas. Se ha elaborado una transecta sísmica completa a través del dominio cortical de Alborán combinando el stack de gran ángulo con las secciones verticales en tierra y en mar. La sección compuesta confirma una transición cortical marcada por un salto brusco de unos 3 s en el Moho. Esta imagen sísmica coincide con las interpretaciones gravimétricas en la misma zona. Los resultados geofísicos parecen acentuar el papel de una tectónica de cizalla, que habría ocasionado movimientos laterales de envergadura hacia el oeste, juxtaponiendo dos bloques de diferente espesor cortical, antes de la tectónica neógena dominada por extensión y compresión entre las placas ibérica y africana.

Palabras clave: perfiles ESCI, transición Béticas-Mar de Alborán, sísmica de gran ángulo, procesado multicanal, sección sísmica unificada, transecta cortical.

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The structural and evolutionary framework of the westernmost Mediterranean is particularly complex. The kinematic regime between the Iberian and African plates since Mesozoic times is marked by different compressional, extensional and transcurrent processes, some of them coeval (García-Dueñas *et al.*, 1994). The interac-

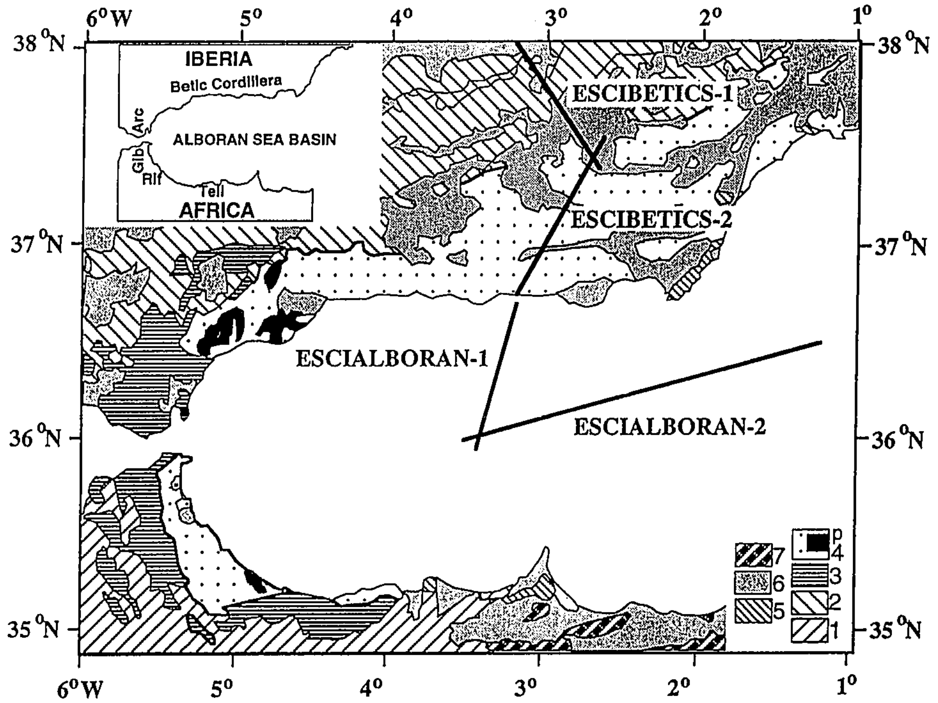


Figure 1.- Location of the ESCI profiles in the southern part of the Iberian Peninsula: lines ESCI-Alborán1 and 2 on the marine basin and ESCI-Béticas1 and 2 on the Iberian mainland. Geological scheme on land adapted from Docherty and Banda (1995). 1: Maghrebian domain; 2: South Iberian domain; 3: Flysch Trough; 4: Alborán domain (p: peridotites); 5: volcanic rocks; 6: onshore marine deposits and Quaternary sediments; 7: African foreland.

tion between these large plates takes place at the western end of the Alpine orogenic belt, formed by the Betics and Rif-Tell chains, separated by the Alborán Sea basin. This basin opens eastwards to the Algerian and South Balearic basins, and is limited westwards by the Gibraltar Arc.

Many geotectonic studies have been developed in the area. Classical analysis focusing on Betics units (Internal Betics, Subbetics and Prebetics) have been replaced nowadays by more general approaches based on the Gibraltar Arc setting. This arc resulted (García-Dueñas *et al.*, 1994) from continental collision and juxtaposition of tectonic complexes and palaeogeographic elements belonging to pre-Miocene crustal domains. The internal zones of the Gibraltar Arc constitute the Alborán domain, including the Alborán basin, and the external zones refer to the South Iberian and Maghrebian domains.

Restoration of the relative positions between the different blocks have been attempted in a number of evolutionary models (Dercourt *et al.*, 1986; Dewey *et al.*, 1989; Srivastava *et al.*, 1990), and mechanisms of extensional collapse (Vissers *et al.*, 1995) or delamination (Docherty and Banda, 1995) are invoked to explain the formation of extensional basins within a regime of continental collision.

However, plate tectonic concepts are difficult to apply in this case, as basic features regarding lithospheric structure, or seismotectonics are still poorly understood. The occurrence of very deep earthquakes, at depths about 650 km beneath the Betics is very uncommon in a continent-continent interaction context. Moreover, major fault structures or plate limits cannot be inferred from the present-day seismicity, which is abundant but appears broadly distributed. This fact could be related, to some extent, to uncertainties in event location, due to an uneven distribution of monitoring stations. In the Betics, seismicity is controlled by a permanent network since recent times, but few 3-component stations operate in an area with strong lateral variations of crustal structure.

The present knowledge on the lithospheric structure is also limited and uneven. Several seismic refraction experiments have been carried out in the Betics realm since the seventies (Banda & Ansorge, 1980; Medialdea *et al.*, 1984; Barranco *et al.*, 1990; Banda *et al.*, 1993), complemented in cases by gravity modelling (Torné & Banda, 1992), as well as regional tomography (Blanco & Spakman, 1993) and surface waves analysis (Paulssen & Visser, 1993). A number of lateral variations in lithospheric structure have been inferred, although structural models often lack resolution due to the limited quality/density of the available data with respect to the dimensions of the Betics internal heterogeneities. Lithospheric thinning in the Alborán Sea has been reported from a few regional seismic studies and thermal modelling (Poliak *et al.*, *in press*), but details on the crustal velocity distribution or Moho location are not constrained by the seismic refraction or reflection data available up to now (Watts *et al.*, 1993).

The ESCI-Beticas/Alborán seismic reflection experiment (García Dueñas *et al.*, 1994; Comas *et al.*, this vol.) was intended to provide a first complete structural transect of the northern flank of the Gibraltar Arc, from the external to the internal domains. Two profiles totalling about 200 km were recorded on land, respectively across the South Iberian domain (ESCI-Béticas1, in a NW-SE direction) and the Alpine metamorphic complexes of the Betics (ESCI-Béticas2, in a NNE-SSW direction). Another two profiles were recorded in the Alborán Sea basin, one continuing 90 km seawards the NNE-SSW line (ESCI-Alborán1), and the other (ESCI-Alborán2) in a 400 km WSW-ENE line from the axis of the Alborán basin towards the South Balearic basin (Fig. 1).

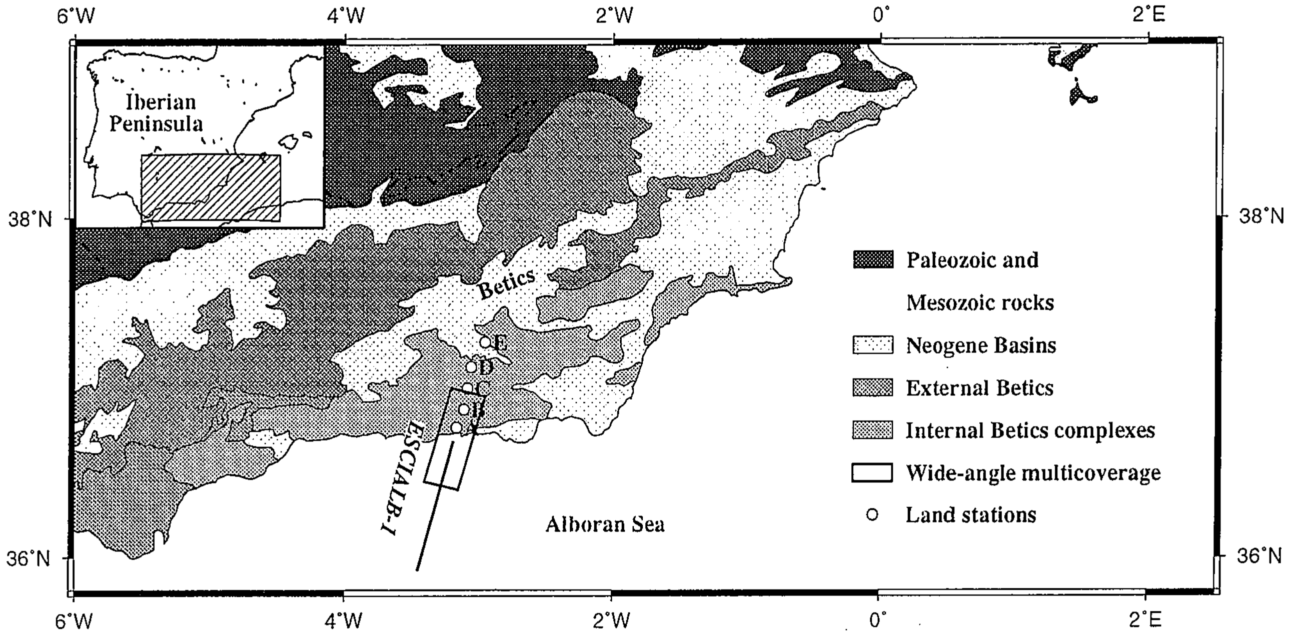


Figure 2.- Location of 5 land stations, A to E, that recorded the shots of the marine profile ESCI-Alboránl. The white square indicates the area where wide-angle multicoverage is achieved.

Remarkable crustal features are imaged in the transect, specially after detailed reprocessing of the data inland (Carbonell *et al.*, this vol.), but the base of the crust at the onshore/offshore transition and along the marine segment lack resolution (Comas *et al.*, this vol.). Therefore, onshore wide-angle recording of the marine ESCI-Alboránl profile provides a complementary dataset that constrains the lateral variation of the crust-mantle transition along the NNE-SSW transect. These data are analysed in the present paper.

The wide-angle data of the ESCI experiment: processing difficulties and classical interpretation

The air-gun shots of the marine profile ESCI-Alboránl, running from the coast to 90 km seawards have been piggy-back recorded by 5 portable 3-component land stations, placed along the ESCI-Béticas2 profile (Fig. 2), at an average station spacing of 15 km.

The classical processing of these large-offset recordings has raised some difficulties. Due to an unexpected technical failure in the time storage system onboard the Bin-Hai vessel (GECO company) during this marine profile, the shooting break-times were stored in tapes only up to full seconds, although the shooting rate was based on distance rather than time intervals (shots every 75 m, not at a fixed time sequence). Therefore, the accuracy in travel times between any successive shots was not better than 1 s, and the corresponding receiver-gather sections (see example in Fig. 3a) display continuous random jumps in arrival times that difficult the correlation of any seismic phase. This seemed to prevent us from any valuable interpretation of those data.

However, the high signal-to-noise ratio observed in the individual wide-angle recordings, together with the poor resolution in the images of the deep crust provided by the vertical reflection profiles compelled us to develop further analysis on the large-offset data. In fact, they constrain in a unique way the Moho along a transect where the crustal thickness seems to be reduced by a factor of two. Moho depths previously reported in that area range from 38 km beneath the internal Betics (Banda *et al.*, 1993) to less than 20 km in the Alborán basin (Hatzfeld, 1976).

A detailed inspection of the record-section for station A, closer to the coast and with the best signal-to-noise ratio (Fig. 3a) shows that a rather consistent correlation can be established among those traces (approximately one tenth of the total number of traces) that display the earliermost arrivals. In fact, up to two branches can be distinguished in this way along the first half of the profile. We may then assume that these traces correspond statistically to the shots for which the break-time does not exceed a full second in more than, say, one tenth. The time delay observed in the remaining traces with respect to the correlated branch should then correspond to the number of tenths that any particular shot exceeds a full second.

Under this assumption, we painstakingly corrected the break-times of the different shots in order that the first arrivals lay within the correlated branches. All the applied corrections were found to be consistent, i.e. not exceeding one second. In any case, these corrections can be considered as conservative, in the sense that real corrections, if not equal to, can only be higher than the applied ones (the real travel time curve might be earlier than the reference curve, but not later than this one). An accuracy better than 0.2 s is estimated in the final travel times from shots along the first 50 km of the profile.

The corrected record-section (see Fig. 3b) shows strong coherency not only in first arrivals but also in la-

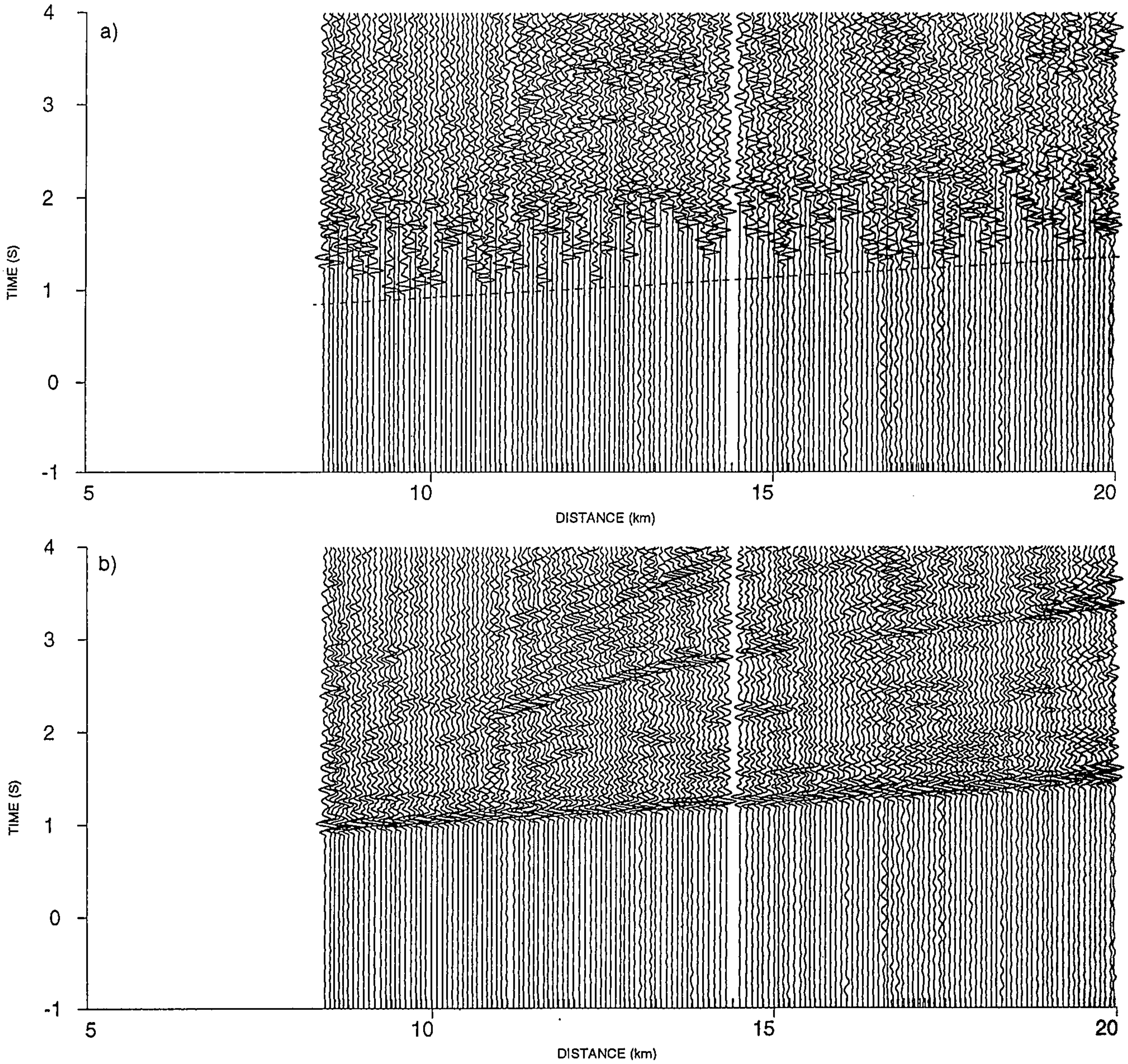
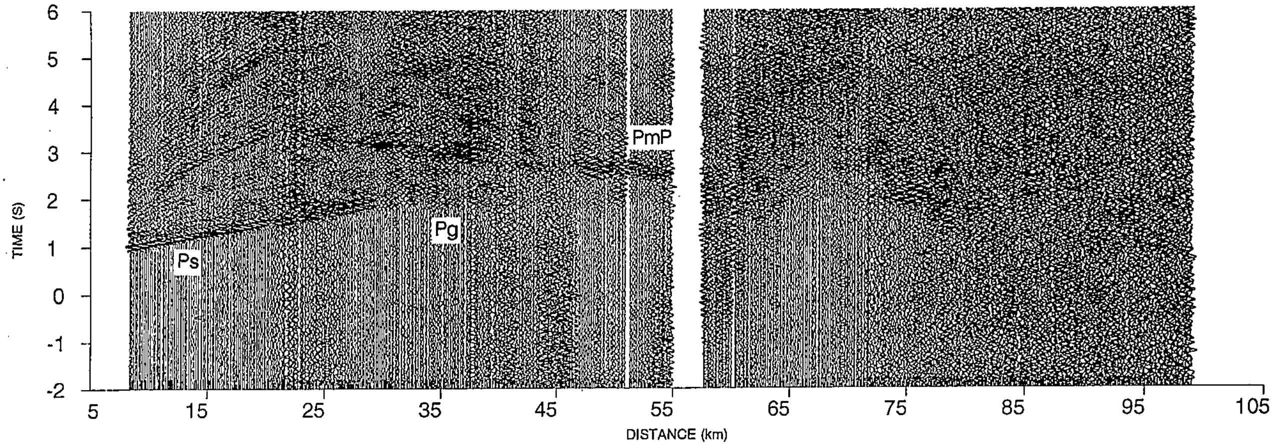


Figure 3.- Example of data recorded on station A, near the shoreline. 3a (top panel): first part of the record-section (Reduction velocity of 6 km/s) obtained from the original available break-times, the accuracy of which is limited to full seconds. This causes the observed scattering in first arrivals. The dotted line indicates a consistent correlation that can be established among the fist arrivals. 3b (bottom panel): shows the same section once the break-times have been modified to fit the correlation. Note the high degree of coherency in secondary phases.

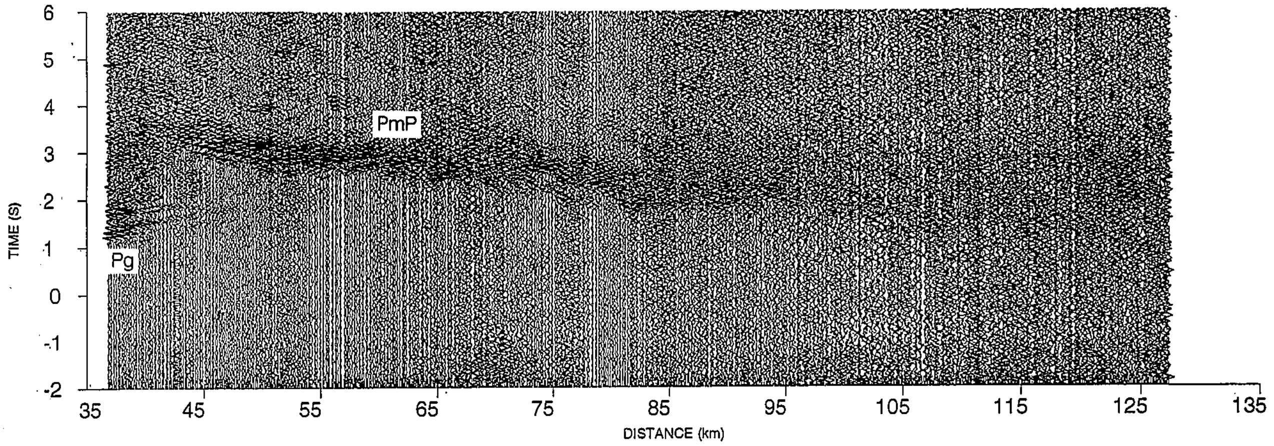
ter, secondary phases, specially on a high energetic reflected phase from the bottom of the crust (Fig. 4) which is of particular interest to complete a structural transect. Using the corrected break-times file, we then built up the record-sections for the 5 stations onland, which all show a consistent seismic pattern (see examples in Fig. 4).

As a first step in data interpretation, we applied the classical forward modelling scheme. Considering the uncertainties inherent to our data indicated above and the lack of refracted phases, like Pn, observed in this unreversed profile, we have not focused the interpretation in establishing a very detailed velocity-depth distribution. We rather searched for most relevant features of a velocity model that explains the main seismic phases at the different stations. In such a model, the velocity errors can be estimated around 0.2 km/s. Fig. 5 shows an example of appropriate fitting for station C, in the middle of the line. Beneath a sedimentary sequence that may be characterised by an average velocity of 5.1 km/s, crustal velocities of 6 km/s are found after 8 km depth. The main reflected phase observed with continuity in the record-sections after distances of 40 km is interpreted as the reflection in a Moho which is located around 21 km depth beneath the shoreline and shows a moderate, progressive thinning seawards.

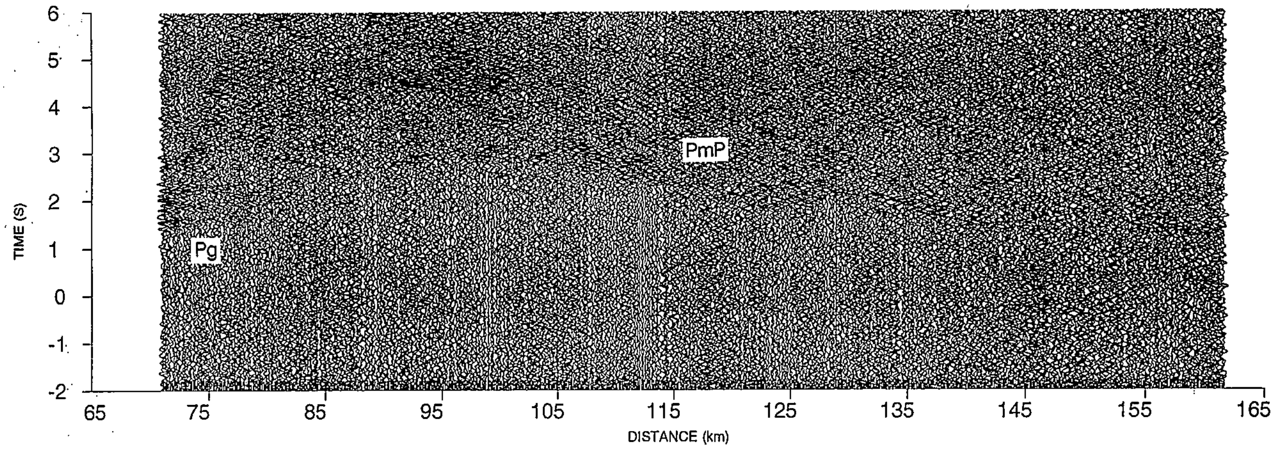
According to the geographical location of the recording stations and the critical distances of the PmP observations, this “Alborán Sea Moho” must be continued some 10 km onshore. The continuation of this reflector further inland can not be evidenced in view of the diffuse



ESCIALBORAN - 1 / STATION A



ESCIALBORAN - 1 / STATION C



ESCIALBORAN - 1 / STATION E

Figure 4.- Receiver gathers (Vr=6 km/s) showing the marine profile ESCI-Alborán1 recorded on three land stations: A (Fig. 4a); C (Fig. 4b) and E (Fig. 4c). In the sections, the conspicuous secondary energy correspond to reflections at the bottom of the "Alborán Sea" crust.

reflective pattern observed at short distances in the northernmost stations D and E (see Fig. 4c).

Multichannel analysis of the large-aperture data

The geometry of the piggy-back recordings onland, i.e. on 5 stations in-line with the marine profile, provide large-offset multifold for a 60 km-long segment around the onshore/offshore transition (see Fig. 2). Usually, such zones are poorly constrained in the conventional stacked sections due to their location at the edge of the vertical recording profiles, both onland and at sea. In addition, the vertical penetration of seismic energy at the Betics-Alborán Sea transition may be perturbed by the

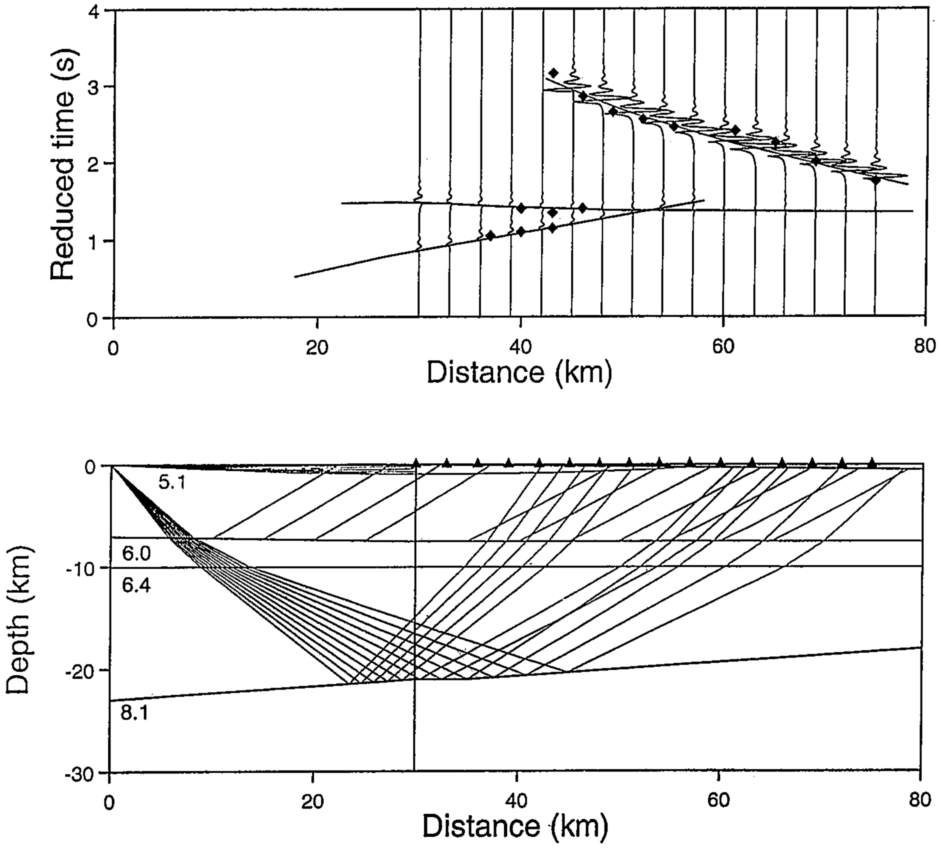


Figure 5.- Example of forward modelling developed for station C, in the middle of the line (see Fig. 2). Bottom: ray-tracing and velocity-depth model. Crustal velocities in km/s. Top: synthetic seismograms, calculated travel times and fitting with the observations (black squares, see also Fig. 4b).

heterogeneities in the uppermost sedimentary sequences and the strong lateral variations in deep crustal structure.

Additionally, a large-offset geometry undershots the zone of interest, deals with high-energetic post-critical reflections, and minimises the scattering of energy by obstacles above the investigated Moho reflector. In the multicoverage wide-angle procedure a CMP is composed of recordings from very different seismic paths.

Taking into account the advantages of the large-aperture geometry, we propose to generate a wide-angle stack section using the multifold processing methodology developed by our group (Gallart *et al.*, 1995; Vidal *et al.*, 1995; Vidal *et al.*, this vol.) that extends the conventional sequence to larger offset range.

In practice, the ITA-Landmark software was used, starting from the 5 receiver-gathers with data in SEG-Y format. The highly variable distances range requires an accurate management of relevant parameters such as the geometry or the bin width. For the latter, a value of 500 m has been adopted as a trade-off for the differences in spacing between sources and receivers.

Pre-processing of the data in the receiver-gathers include edition of traces, muting, energy equalisation and band-pass filtering. Energy preceding the PmP reflections (essentially refracted Pg phases) has been eliminated by direct mute, as f-k filtering distort the signal and is not very efficient in this case. Velocity analysis in the Common Mid Point (CMP) gathers leads to static and dynamic corrections applied prior to the generation of the wide-angle stacked section. Differences in station elevations and water depths beneath the shots are accounted for by applying topographic corrections. A single CMP may consist of traces resulting from very different, large offsets, and the Normal Move Out (NMO) correction is a fundamental step. Contrary to the near-vertical reflection case, the NMO in our Moho reflected data strongly depends on the average velocity considered. For the Betics-Alborán data, the NMO velocities oscillate between 5.8 and 6.0 km/s and, in each CMP, they can be usually constrained up to 0.1 km/s. After the NMO correction, some far-offset traces may be affected by important stretching, and mute must be applied accordingly.

The final stacked section is shown in Fig. 6. Along the 35 km segment in the Alborán Sea basin, the reflections at the bottom of the crust are imaged with continuity, indicating a moderate thinning seawards, from 7 s beneath the shoreline to 6 s at the SW end of the sampled section.

An outstanding feature inferred from the section is the continuity of this horizon (the “Alborán Sea Moho”) onshore, up to about 10 km inland where it is imaged at 8 s. This reflectivity vanishes abruptly further inland. In the northernmost 15 km of the section it is replaced by a more diffuse reflective pattern after 11 s which can be attributed to the crust-mantle transition beneath the Internal Betics. This reflectivity around 11-12 s seems to be imaged almost to the shoreline, although it is difficult to constrain such horizon with the available recording geometry, as only subcritical wide-angle reflections with low energy content can be expected from that deep reflector. The main features in the reflective image of the

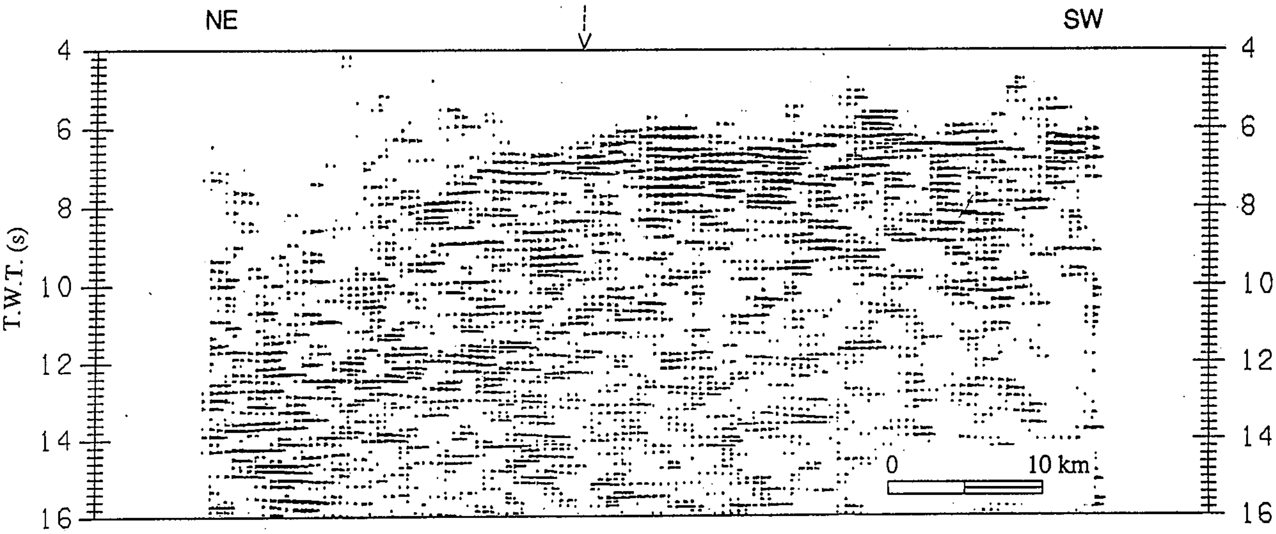


Figure 6.- Wide-angle stacked section obtained at the Betics/Alborán transition. The arrow marks the shoreline. In the 35 km-long marine segment (SW) the reflectivity at 6-7 s is associated to the "Alborán Sea Moho", which penetrates about 10 km inland. In the 15 km further NE (Internal Betics), continuity of the reflective level is interrupted, and a diffuse reflectivity after 11 s is observed.

wide-angle section, when converted to depths using appropriate crustal velocities, are consistent with the Moho location constrained in the forward modelling (Fig. 5).

Discussion: a Moho transect at the Betics/Alborán transition by combining the wide-angle and the near-vertical stacks

A complete structural transect in a NNE-SSW direction from the Internal Betics towards the axis of the Alborán Sea basin can be obtained by merging the vertical sections of the profiles ESCI-Béticas2 and ESCI-Alborán1 with the wide-angle section. The latter section fills in the gap between the two normal incidence profiles. Fig. 7 illustrates the procedure. The two land and marine vertical stacks are first juxtaposed (Fig. 7a) and then decimated to a CMP spacing compatible with the wide-angle stack (Fig. 7b). Finally, the three sections are merged (Fig. 7c), considering a common datum plane at sea level and a datum velocity of 4.5 km/s.

The image of the base of the crust is significantly enhanced along the marine segment, for which the vertical stack lacks resolution (Comas *et al.*, this vol.) due to the presence of water multiples and absorption of energy within the sedimentary cover. The land segment of the composite section seems rather confusing, and differences in the frequency content and relative amplitude scaling should be invoked to properly decipher the seismic pattern. On the vertical section of the profile ESCI-Béticas2 a strongly reflective lower crust is imaged between 6-7 s and 11-12 s (García-Dueñas *et al.*, 1994; Carbonell *et al.*, this vol.). According to the seismic refraction results in the Internal Betics (Banda *et al.*, 1993), the Moho should correspond to the end of this reflective band. Within 10 km of the shoreline, the quality of the image decreases. The composite section shows in that area the energy reflected from the bottom of the "Alborán Sea crust", and this reflectivity appears as time coincident (7-8 s) with the laterally juxtaposed energy reflected from the top of the lower crust in the vertical stack. A more detailed analysis of the composite stack can confirm the compatibility between both sections, as well as the existence of a lateral jump in the Moho level inland.

The full-aperture stacked image at the Betics/Alborán transition differs significantly from the images obtained with the same technique in comparable margins around Iberia, like the València Trough at the NE Iberian Peninsula. An important steady thinning of the crust has been evidenced along the Catalan flank of the València Trough where the Moho shallows for more than 10 km in about 60 km horizontal distance (Vidal *et al.*, 1995; Vidal *et al.*, this vol.). In the Alborán domain, the shallowing of the Moho takes place very abruptly; the jump is located some 10 km inland, and a very moderate crustal thinning is further evidenced along the northern flank of the Alborán basin.

Hence, the thinned crust at the central part of the Alborán Sea basin extends to the northern mainland and penetrates beyond the shoreline. The transition to the thickened crust of the Internal Betics is marked by an abrupt change of 3-4 s in the Moho level.

The seismic image at the Betics/Alborán transition fully agrees with gravity interpretations in the same area (Torné & Banda, 1992; Watts *et al.*, 1993). The density model requires a steplike lateral variation of the crust/mantle transition (depth change of 15 km in less than 20 km distance) to fit the strong gradient of about 10 mGal/km in the Bouguer anomaly. In contrast, the gravity anomaly pattern in the eastern Alborán basin is fitted by a much more smooth lateral transition along 100 km distance. Subsidence analyses (Watts *et al.*, 1993; Docherty & Banda, 1995) indicate also that subsidence rates clearly increase towards the western Alborán basin.

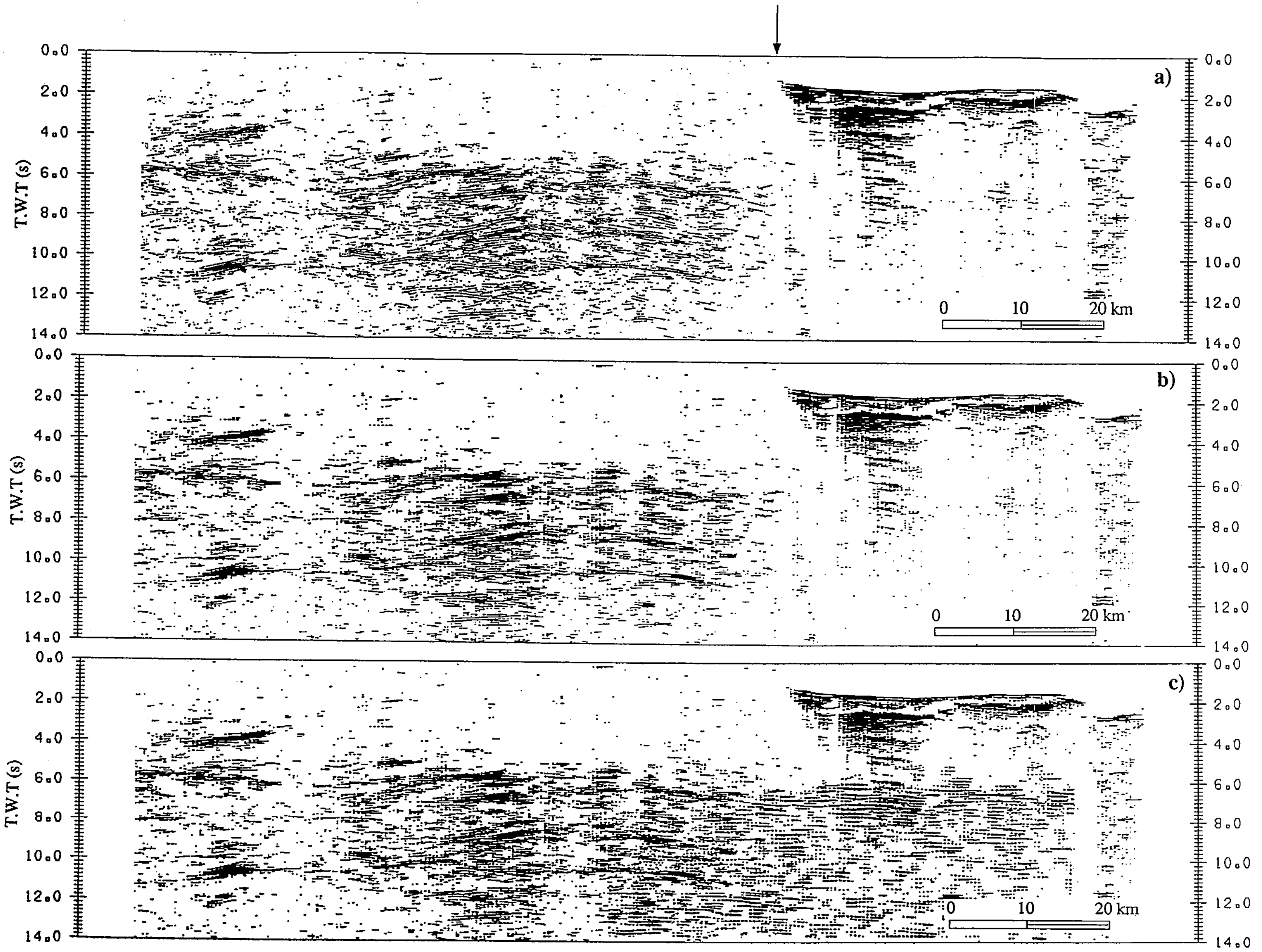


Figure 7.- A composite, full-aperture stacked section along the Betics/Alborán transition. 7a (Top): juxtaposition of vertical stacks: profiles ESCI-Béticas2 on land (left) and ESCI-Alborán1 at sea (right). The arrow marks the shoreline. 7b (Middle): same section decimated to a CMP spacing of 500 m, comparable to the one of the wide-angle section. 7c (Bottom): final stack after merging of the wide-angle section (Fig. 6). The bottom of the crust in the marine segment is clearly enhanced. Onland, the rather confuse image at the superposed zone is related to the abrupt jump in the Moho location.

The steplike transition between stretched and unstretched crust evidenced in this work, associated to the onshore-offshore transition at the Alborán domain, suggest that shear tectonics (Scrutton, 1986) could be taken into account, in addition to the extensional processes interacting with a surrounding convergent regime and increasing the differences in crustal thicknesses. Lateral westward movements that may have juxtaposed two crustal blocks of different thicknesses could have played a significant role, prior to the Alpine-to-Recent compressional and extensional dominating tectonics between the African and Iberian plates. Post-collisional delaminating processes in the lower crust could also originate important variations in the present-day deep crustal structure. Further informations on the lithospheric distribution of seismic velocities are needed to constrain the geodynamic evolution of the Betics-Alborán Sea domains.

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