Contribution of the ESCI-València Trough wide-angle data to a crustal transect in the NE Iberian margin

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Abstract: The ESCI-València Trough seismic experiment was designed to provide a crustal transect of the NE Iberian margin. The vertical reflection profiles have evidenced strong lateral variations in crustal structure, but complex areas like the Catalan and Balearic onshore/offshore transitions lack resolution at depth. However, the passage from thick to thin crust could be constrained by dense-spaced wide-angle reflection data collected by recording on land the ESCI marine profile. Our analysis of these data includes classical velocity-depth forward modelling and development of a wide-angle multichannel processing, by adapting the entire sequence of the conventional reflection seismics. This new approach led to large-aperture stacked sections that clearly image Moho reflected energy beneath the crucial areas. The lateral variation of the wide-angle results is tested by developing a similar analysis on a former refraction profile parallel to the ESCI one. The two approaches provide coincident results regarding the crust/mantle transition, and evidence a steady thinning of the continental crust in the flanks of the València Trough. Low velocities are regularly found in deep levels of the crust. A combined crustal transect between the Pyrenees and the South Balearic basin is obtained by merging the near-vertical and wide-angle stacked sections, which show consistent Moho depth images in the common areas resolved for both data sets. This transect documents a thinning by a factor of two of the continental crust in 50 km horizontal distance. The continent-ocean transition seems to be associated with the South Balearic basin although the lithospheric structure of the Balearic area needs to be further constrained. The image of this seismic transect is clearly different from those reported in comparable Mediterranean or Atlantic passive margins, and has to be related to the complex Cenozoic tectonics at the NE Iberian margin.

Keywords: ESCI profiles, wide-angle, València Trough, velocity-depth modelling, multichannel processing, combined section, crustal transect.

Resumen: El experimento sísmico ESCI-Surco de València está encaminado a completar una transecta cortical en el margen NE de Iberia. Los perfiles de sísmica de reflexión vertical proporcionan en general imágenes bien contrastadas de la estructura interna que muestran claras variaciones laterales en la corteza. No obstante, los resultados de la sísmica vertical carecen de un control adecuado de la distribución interna de velocidades, y no resuelven la estructura profunda en zonas complejas como las transiciones tierra-mar en los márgenes catalán y balear. En cambio, la evolución de corteza gruesa a delgada puede establecerse a partir de los datos de reflexión de gran ángulo obtenidos al registrar en tierra, con estaciones autónomas, la alta densidad de disparos de aire comprimido del perfil ESCI marino. El análisis efectuado de este tipo de datos incluye la interpretación clásica de la distribución velocidad-profundidad por métodos de ajuste directo (trazado de rayos y sintéticos), así como el desarrollo de un procesado multicanal de gran ángulo, aprovechando que la geometría de registro permite alcanzar cobertura múltiple en las zonas de las transiciones tierra-mar. Para dicho procesado, se ha adaptado la secuencia típica de la sísmica de reflexión convencional, es decir: edición, aplicación de filtros pasabanda, eliminación de fases refractadas, deconvolución predictiva y ordenación de los registros en grupos de CMPs. La sección sumada (*stack*) de gran ángulo se ha obtenido tras realizar las correcciones estáticas y dinámicas, y sobre la misma se ha aplicado un tratamiento post-stack, con migración en tiempo/profundidad y filtrado de coherencia lateral. Las secciones finales obtenidas muestran claramente la variación de la base de la corteza a lo largo de la zona de interés. Los resultados son consistentes con la geometría del Moho obtenida en el modelo de velocidades, y ponen de relieve un adelgazamiento notable pero continuado de la corteza continental en los flancos del Surco de València. Para verificar la variación lateral de estructuras, a lo largo del Surco de València, se ha realizado el mismo tipo de análisis para datos de gran ángulo de un perfil marino de refracción ya existente, paralelo al ESCI y desplazado unos 30 km al NE. Los niveles profundos de corteza presentan en toda la zona velocidades bajas, de 6.4-6.5 km/s. Las imágenes de reflexión vertical y de gran ángulo se han combinado en una misma sección unificada, que muestra una buena consistencia en las zonas comunes en que ambos tipos de datos tienen reflexiones en el Moho. Esta sección conjunta permite completar una transecta cortical continua de 600 km, desde los Pirineos hasta la cuenca Sud Balear. La transecta pone de relieve que la corteza continental se adelgaza en un factor dos, en 50 km de distancia horizontal. El adelgazamiento asociado a la transición continente-océano parece producirse en la cuenca Sud Balear, aunque el conocimiento actual de la estructura litosférica del área Balear es insuficiente para precisar cualquier modelo evolutivo. La imagen de esta transecta sísmica es muy diferente de las obtenidas en márgenes pasivos comparables, mediterráneos o atlánticos, y debe atribuirse a la complejidad de la tectónica cenozoica en el margen nor-oriental de Iberia.

Palabras clave: perfiles ESCI, gran ángulo, surco de València, distribución velocidades, procesado multicanal, sección sísmica unificada, transecta cortical.

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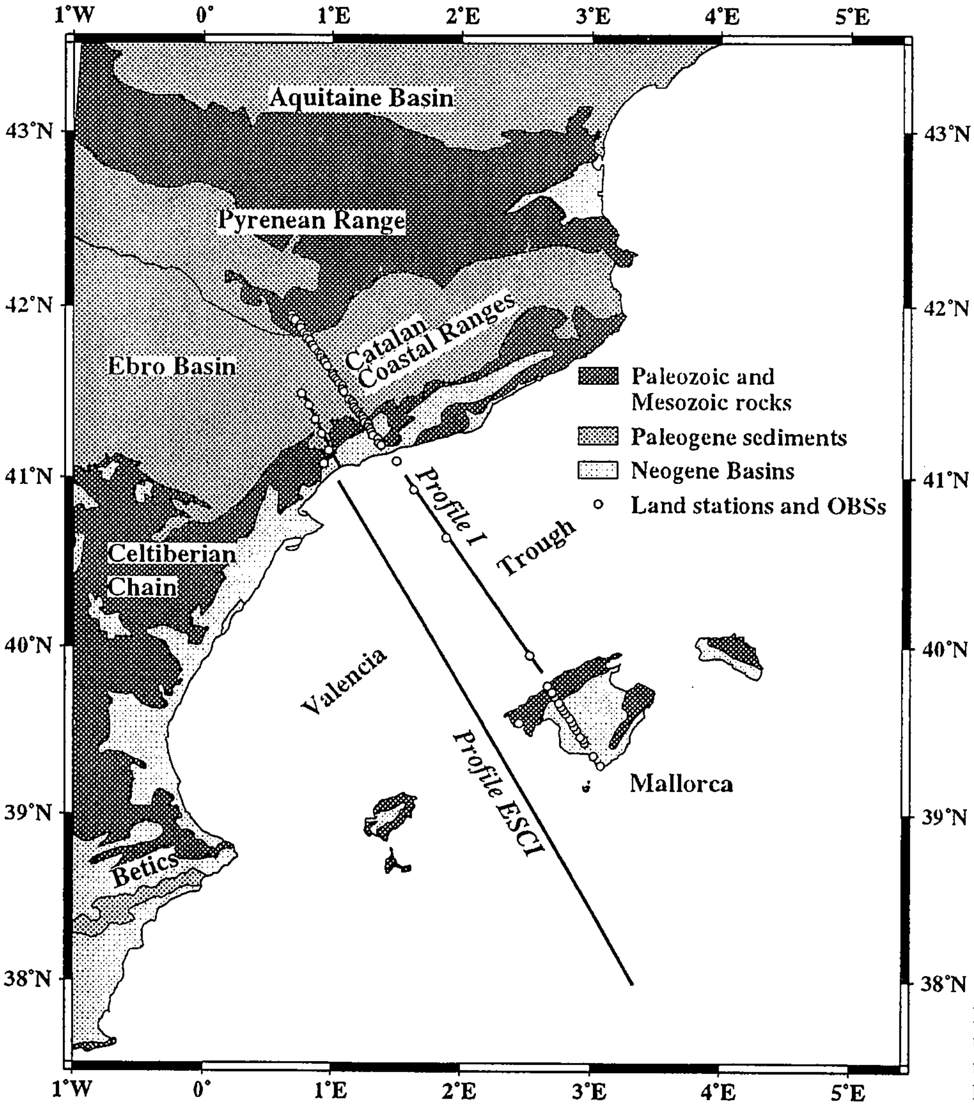

Figure 1.- Geological scheme of the NE Iberian Peninsula including the ESCI seismic profiles and the land stations considered.

In continental margins associated with strong lateral variations of velocity distribution and crustal thickness, near-vertical seismic profiles may often lack resolution at depth. However, the crust-mantle transition in these areas can still be constrained by dense-spaced wide-angle reflection data (Gallart *et al.*, 1995).

The ESCI-València Trough seismic experiment was designed to provide a crustal transect at the NE Iberian margin (Gallart *et al.*, this vol.). In this region, at the western end of the Alpine orogenic belt, the Neogene extension developed within an overall convergence between the African and European plates originated the València Trough. This basin is characterised by a rather small size, stretched continental features and presumably high-average strain rates during rifting (Watts & Torné, 1992a, b; Roca & Guimerà, 1992).

Significant variations in crustal structure have been reported for the València Trough and surrounding areas (Banda & Santanach, 1992a, b; Collier *et al.*, 1994) and are clearly imaged in the new seismic sections of the ESCI experiment (Gallart *et al.*, this vol.). However, a number of parameters essential to complete any structural transect (geometry of the Moho or reflectivity changes in the lower crust at the onshore-offshore transitions) are not well defined in the near-vertical seismic sections. Hence, the complementary structural information available from wide-angle measurements may be decisive, and is investigated in this paper.

During the ESCI-València Trough marine profile, six autonomous stations (10 km spaced) were deployed along the land segment to record at far offsets the 7118 cu. in. airgun shots. Another station was operating at Mallorca island. This wide-angle experiment gives new insight on the deep structure of the area. Firstly, it provides velocity-depth control. Secondly, the large-aperture geometry favours higher energy returns from post-critical Moho reflections and allows us to "undershot" the uppermost crustal obstacles to the vertical penetration of energy. Thirdly, the recording/shooting geometry results in multifold at the onshore/offshore transitions, and enables the building-up of large-aperture stacked sections through a multichannel processing adapted to the wide-angle data set.

To test the lateral consistency of the velocity models and crustal sections a second wide-angle data set is considered in our study. It comes from an experiment carried

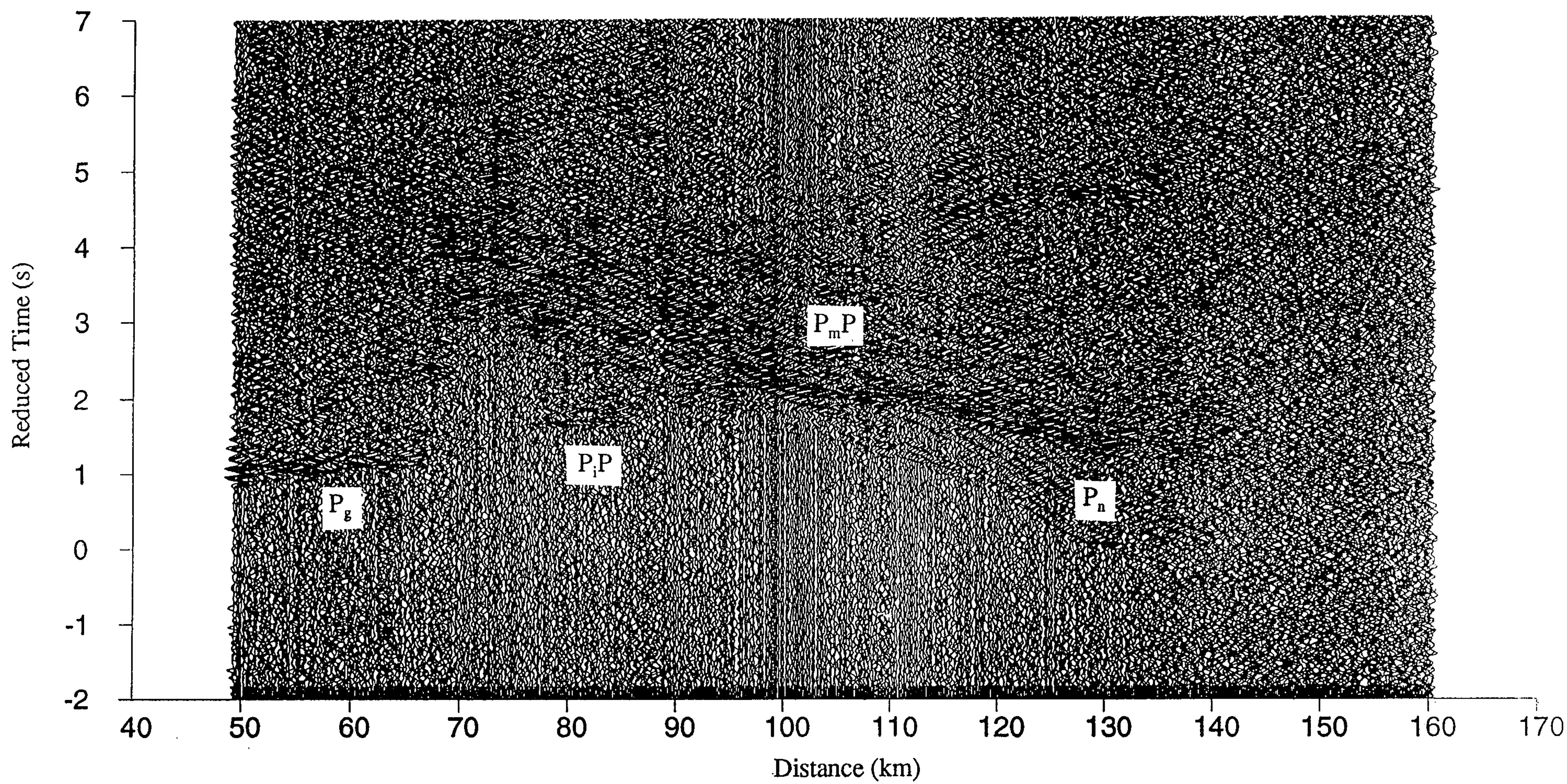

Figure 2.- Receiver-gather from the air-gun shots of the marine ESCI-València Trough profile recorded at one station located 45 km inland on the Catalan margin. A 3-15 Hz bandpass filter, a reduction velocity of 6 km/s and the bathymetric correction have been applied.

out in 1989 (Dañobeitia *et al.*, 1992). In a marine profile (Profile I in Fig. 1) lying about 30 km NE and almost parallel to the ESCI one, 20 kg-explosive shots, spaced every 1.5 km, were recorded by 50 stations up to 100 km in the Iberian mainland, 20 stations on Mallorca island and a few OBSs in the València Trough.

Wide-angle data analysis

High-quality recordings were obtained from the six land stations deployed along the ESCI-land profile and the station in Mallorca island (Fig. 1). Figs. 2 and 3 show some examples of these data sets. Main refracted phases P_g and P_n, as well as P_mP and P_iP reflections can be correlated easily on the record sections sampling the VT and its flanks. To the SE of Mallorca, more diffuse intracrustal and Moho-reflected energy can be observed.

The data analysis developed includes classical velocity-depth forward modelling and a new structural approach by multichannel processing.

Velocity-depth forward modelling

As a first step, we performed for profiles I and ESCI velocity-depth modelling through classical forward analysis of arrival times and amplitudes (Gallart *et al.*, 1994). Main results are shown on Fig. 4. The requirement of fitting the data for all the land stations and OBS along the two lines severely restricts the acceptable models. However, the velocities within the sedimentary sequence and the upper-lower crustal transition in the València Trough are not fully constrained, because the profiles are not reversed. In all the cases, significant crustal thinning beneath the trough has been inferred. The Moho shallows seawards, from about 32 km beneath the mainland, either continuously up to 14-15 km depth at the València Trough axis (Profile I), or keeping rather constant depths around 17-18 km in the trough (Profile ESCI). The thinning affects mainly the lower crust. Low-velocities of 6.4-6.5 km/s are found in deep levels of the crust, and best-fitting velocities in the uppermost mantle range between 7.8 and 8.0 km/s. Lower velocities which could confirm the existence of an anomalous upper-mantle in the València Trough were not evidenced. Forward modelling of gravity data performed along the two profiles (Gallart *et al.*, 1994) are in agreement with the seismic results.

Possible lateral variations on the velocity-depth structure which could be related to the continent-ocean transition of the crust at the South Balearic basin (Gallart *et al.*, 1996) can not be constrained by the presently available wide-angle data, due to low ray coverage along the southern end of the ESCI profile.

Multichannel wide-angle processing

Significant differences in the reflectivity pattern have been observed in the adjacent onshore-offshore segments of the ESCI-València Trough vertical reflection profiles (Gallart *et al.*, 1996). On the Iberian mainland, abundant reflections are present between 5.5 and 11 s TWT beneath the Catalan Ranges. The 12 km-wide low-velocity Neogene El Camp (Reus) basin onshore attenuates the energy and causes a pull-down effect in the reflectivity. Offshore, deep reflections are not imaged in the first 20 km of the profile. Where present, they lie at 7.5-8 s TWT and are attributed to the Moho, according to the lower crustal reflectivity recognisable in some places at the Catalan margin between 5 and 8 s TWT (Torné *et al.*, 1992; Gallart *et al.*, this vol.). This seismic picture (see Fig. 6a) may suggest an imbrication and shortening of two crusts of different thickness, in a similar way to that reported in the Pyrenees, between the Iberian and the European crusts at the North Pyrenean fault level (Suriñach *et al.*, 1993). This would have strong implications for geodynamical modelling of the area. However, as there is a gap of 20-30 km in the image of the deep reflectivity, the transition between the thick to thin crust is not well resolved by the near-vertical data. Similar structural problems arise on the Balearic flank (Gallart *et al.*, 1996), where a lack of reflectivity on the near-vertical sections does not allow us to characterise the onshore/offshore transition.

The geometry of the marine reflection profile and the piggy-back recordings on land shows that wide-angle multiple coverage is achieved in some places (Fig. 5a), concerning mainly the onshore/offshore transition. With the aim of improving the near-vertical images that lack resolution in these areas, we decided to undertake a multichannel processing of the wide-angle data in terms of the conventional sequence for vertical reflection data (Gallart *et al.*, 1995; Vidal *et al.*, 1995). This analysis has been focused on the PmP Moho reflected phase, clearly observable on the sections for offsets ranging between 40 and 160 km. An intermediate PiP reflection from the top of the lower crust is also correlated in the individual record-sections along distances of 20-30 km, but has not been considered in the analysis, since multiple coverage for this phase is only achieved in a short area near the coast, due to the 10 km spacing between the recording stations.

The main steps in the processing sequence applied to the wide-angle data are summarised on Table I. In order to compare and merge the final small and large-aperture stacked sections, the processing techniques applied to both data sets have been kept as similar as possible. In the middle part of the table are listed common steps and differential features are described within each column.

Preprocessing in the receiver gathers include geometry and bin-width definition. Editing of traces, muting, energy equalisation and bandpass filtering were also applied. Predictive deconvolution attenuated the ringing of the signal and mute of refracted phases was necessary to avoid possible mixing with the reflection arrivals. Common mid-point (CMP) gathers built up have an average fold of 30 which includes traces coming from 3-4 different stations on land. Static and dynamic corrections were also applied before stacking. The large-offsets involved on the CMP gathers provide a strong velocity

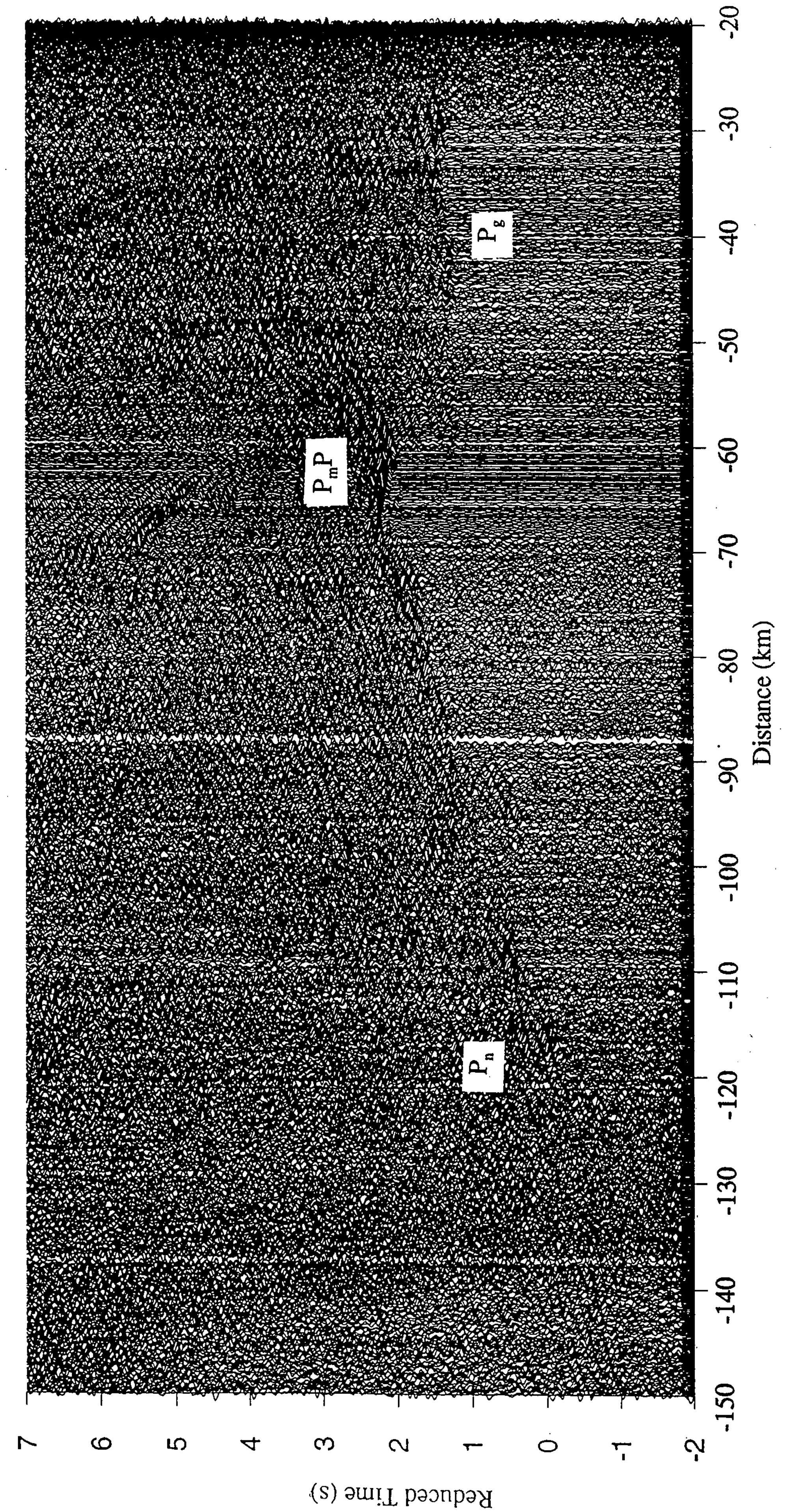

Figure 3.- Receiver-gather from the air-gun shots of the marine ESCI-València Trough profile recorded at the station in Mallorca island. A 3-15 Hz bandpass filter, a reduction velocity of 6 km/s and the bathymetric correction have been applied.

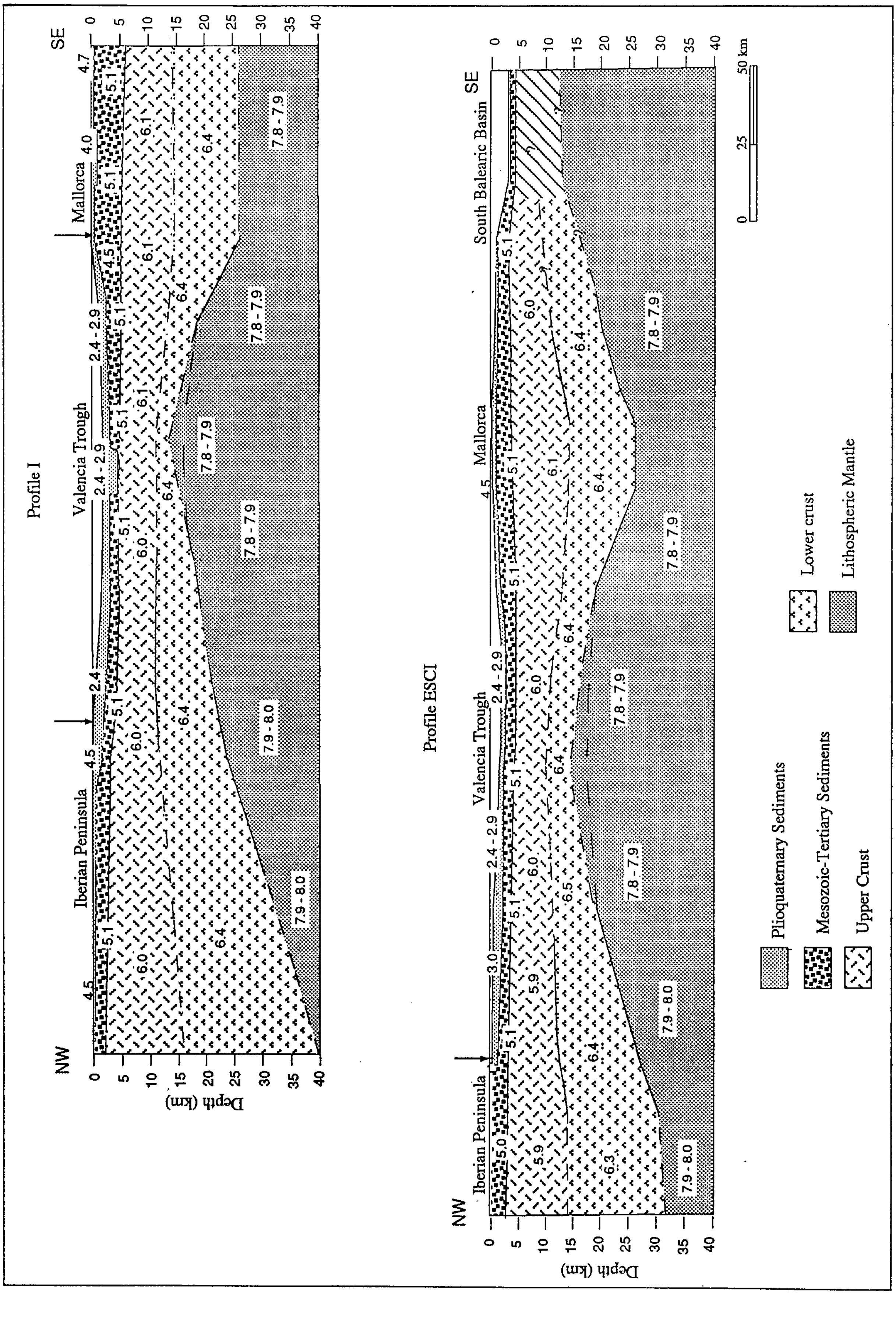

Figure 4.- Forward modelling results for profiles I and ESCI across the NE Iberian margin, that fit best the recorded data on the different land stations (Fig. 1).

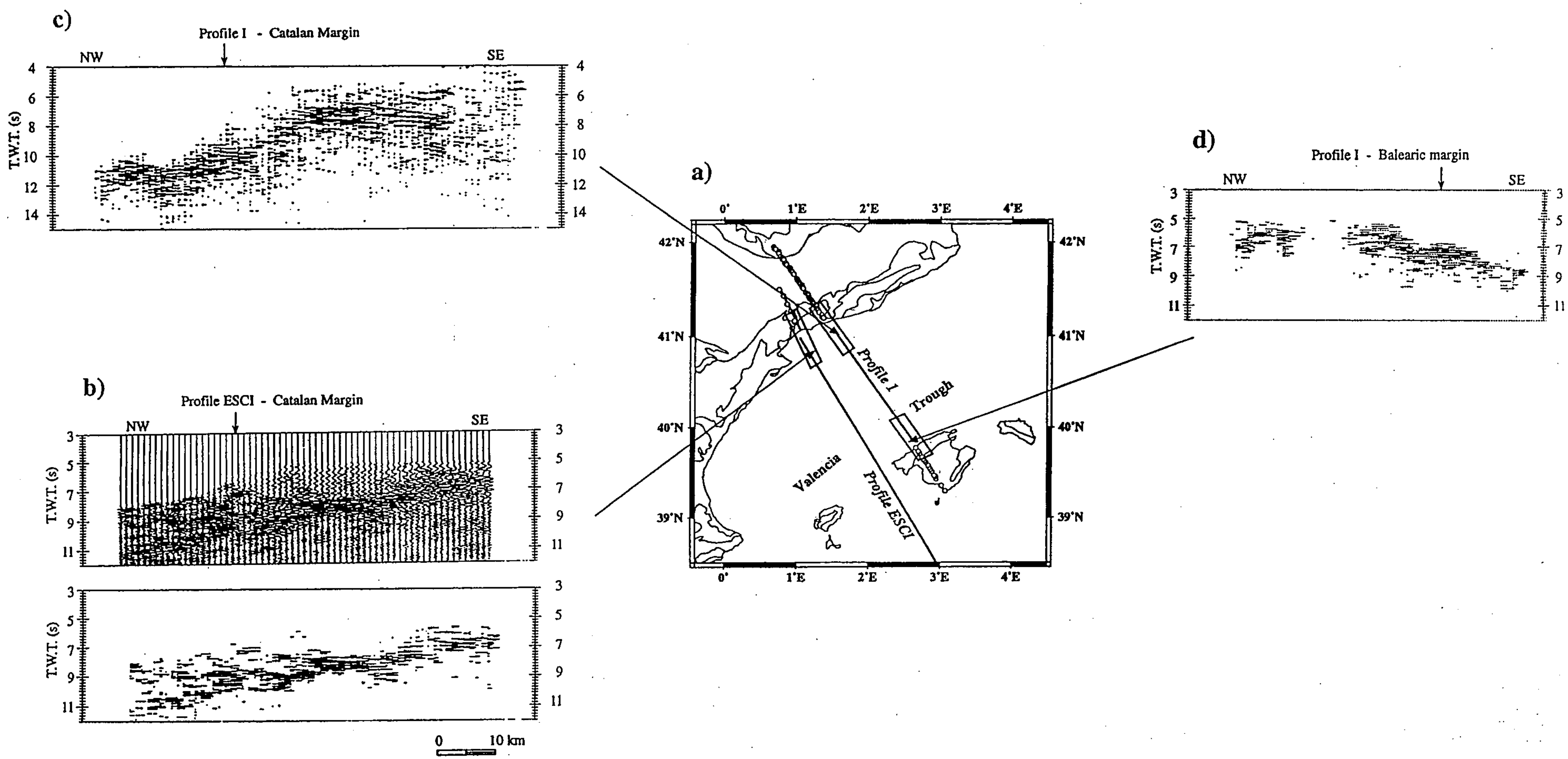

Figure 5.- (a) Scheme of the NE Iberian margin including the seismic profiles considered, the land stations and the wide-angle multicoverage areas (boxes). (b) Wide-angle stacked section for profile ESCI at the Catalan margin. A continued reflectivity from the bottom of the crust is clearly imaged across the onshore/offshore transition (the arrow marks the shoreline). Semblance/coherency filtering (low panel) enhance the signature of the Moho and the crustal thinning seawards. (c) Coherency filtered wide-angle stacked section for profile I at the Catalan and (d) Balearic margins.

Table I.- Summary of parameters and steps characteristic of near-vertical and wide-angle multichannel processing. Common techniques for both data sets are in the middle, and differential features within each column.

Near vertical processing		*Wide angle processing*
-- 4 ms	**Sampling rate**	-- 8 - 16 ms
Resampling		
-- 30 m bin width	**Geometry**	-- 1000 m bin width
	Data edition	
-- 0-50 Hz	**Bandpass filtering**	-- 3 - 20 Hz
	F-K filtering	-- Not useful for refracted phases
Amplitude compensation		**Mute of refracted phases**
-- Spherical divergence correction		-- Pg and Pn
	Energy balance	
Refraction statics		
Demultiple	**CDP sorting**	
-- 90 m - 7200 m	-- Distances	-- 10 km - 140 km
	Elevation statics	
	-- floating datum plane	
	Predictive deconvolution	
-- operator length 300 ms predictive gap 32 ms		-- operator length 1 s predictive gap 0.1 s
	NMO correction	
-- maximum correction (30 km depth) 0.07 s		-- maximum correction (30 km depth) 15 s
		-- High resolution in velocities
	-- mute application	
Residual statics	**Stack**	
-- fold 30		-- fold 10 - 30
	Elevation statics	
	-- final datum 400 m	
Time and space variant bandpass filter		
	Scaling	
	Time and depth migration	
-- Finite differences algorithm		-- Time shift algorithm
	Semblance coherency filter	
-- 20 traces	-- all velocity ranges	-- 3 traces

constraint on the NMO corrections (up to 0.1 km/s). Finally, a semblance/coherency filtering as well as time and depth migrations were performed using a constant velocity in agreement with the forward modelling results.

Wide-angle stacked sections at the Catalan and Balearic margins

The multichannel wide-angle processing described above was applied for the wide-angle data sampling the Catalan and Balearic margins (Fig. 5a).

The large-aperture stacked section from profile ESCI is displayed in figure 5b. A 30 fold was achieved for most of the section. Despite the spacing of 1 km between CMPs, strong laterally coherent energy coming from the bottom of the crust is observed along the profile. The Moho shallows steadily from 11 s TWT at 20 km inland up to 6 s TWT about 40 km seawards. Consistency on the wide-angle stacked image of the Moho across the onshore-offshore transition at the Catalan margin of the València Trough is supported by results from Profile I, which had a more homogeneous spacing between shots (1.5 km) and stations (2 km) than profile ESCI, but a lower coverage ranging from 5 to 20 fold. The stacked section is shown in Fig. 5c, and the Moho-reflections display a pattern similar to profile ESCI: they are located at 11 s TWT inland, and shallow across the shoreline to around 6 s TWT at about 30 km offshore. At larger distances seawards, the reflectivity becomes diffuse, probably due to the low-fold and highly stretched NMO-corrected traces in that area.

On the Balearic margin of the València Trough wide-angle multichannel analysis is feasible for Profile I, recorded in 20 stations on the island of Mallorca. Using the best defined PmP data, a fold between 5 and 15 is achieved along the onshore-offshore transition, in a section covering 15 km landwards and 35 km seawards (Fig. 5d). Deep reflectivity is reasonably imaged for most of the section, displaying a continued crustal thinning towards the València Trough. Moho-reflections are less sharply identified than in the Catalan margin, but range from 9-10 s beneath Mallorca to around 6 s at the western end of the section.

A combined small and large aperture crustal section in the València Trough

Up to now, near-vertical and wide-angle stacked sections have been analysed independently. Next step towards a direct comparison of results is to combine both crustal images. As a first approach this is illustrated on Fig. 6 for the Catalan flank of the València Trough. The composite stacked section of the vertical ESCI-València Trough land and marine profiles is displayed on Fig. 6a. A trace decimation has to be applied to this section to be comparable to the large-aperture section, due to differences on CMP spacing with respect to the wide-angle data set. An intertrace of 1 km has been adopted (Fig. 6b). The final merged image (Fig. 6c) is obtained after unifying sampling rates and applying lateral and depth energy data balancing. A remarkable coherency between the near-vertical and wide-angle results has to be pointed out for the areas where both methods provide good images of Moho-reflected energy.

A complete stacked and depth migrated image has been obtained for the València Trough area and its flanks (Fig. 7). It maps for the first time the lateral evolution at depth across strike and reveals that the crust undergoes a strong but continuous thinning towards the centre of the basin. In the transition seawards of the NE Iberian Peninsula, almost half of the crustal thickness (up to 14-15 km) is lost in less than 60 km horizontal distance. At the Balearic margin the combined section (Fig. 7, lower panel) also improves the lateral image of the Moho, documenting a continuous thinning seawards that reaches about 8 km in 20 km horizontal distance. The geometry of the Moho obtained in the stacked sections along profiles I and ESCI is consistent with the independent results coming from the velocity-depth forward modelling (Gallart *et al.*, 1995).

Discussion and conclusions

Coincident near-vertical and wide-angle reflection data sets are now available in the NE Iberian margin after the ESCI experiment. A classic, independent analysis of the former in terms of stacked crustal sections, and of

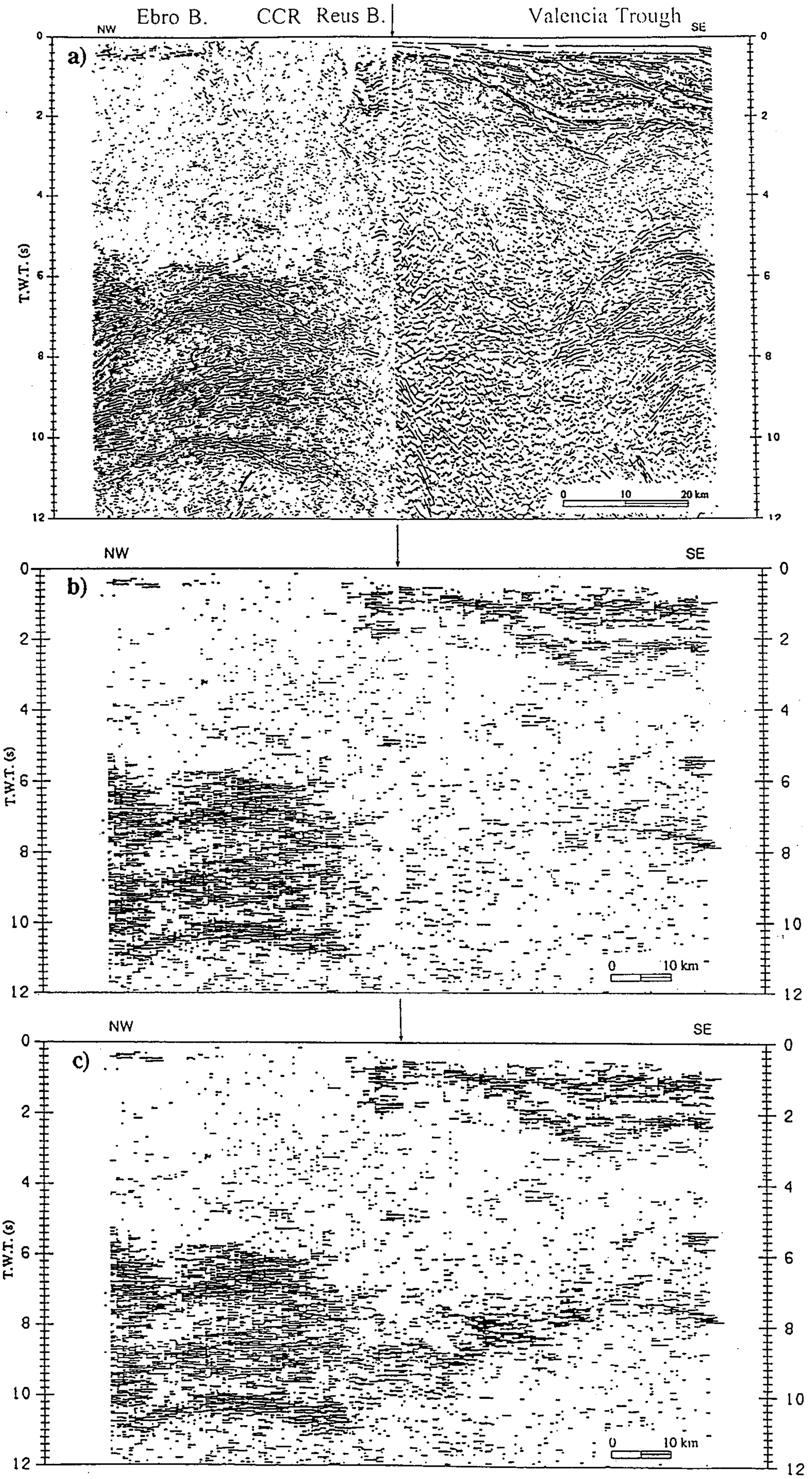

Figure 6.- Onshore-offshore transition at the Catalan margin. (a) Composite near-vertical section of the ESCI land (left) and sea profiles (right). The arrow marks the shoreline. (b) The section is decimated to a 1 km spacing before merging the wide-angle multichannel data set (c).

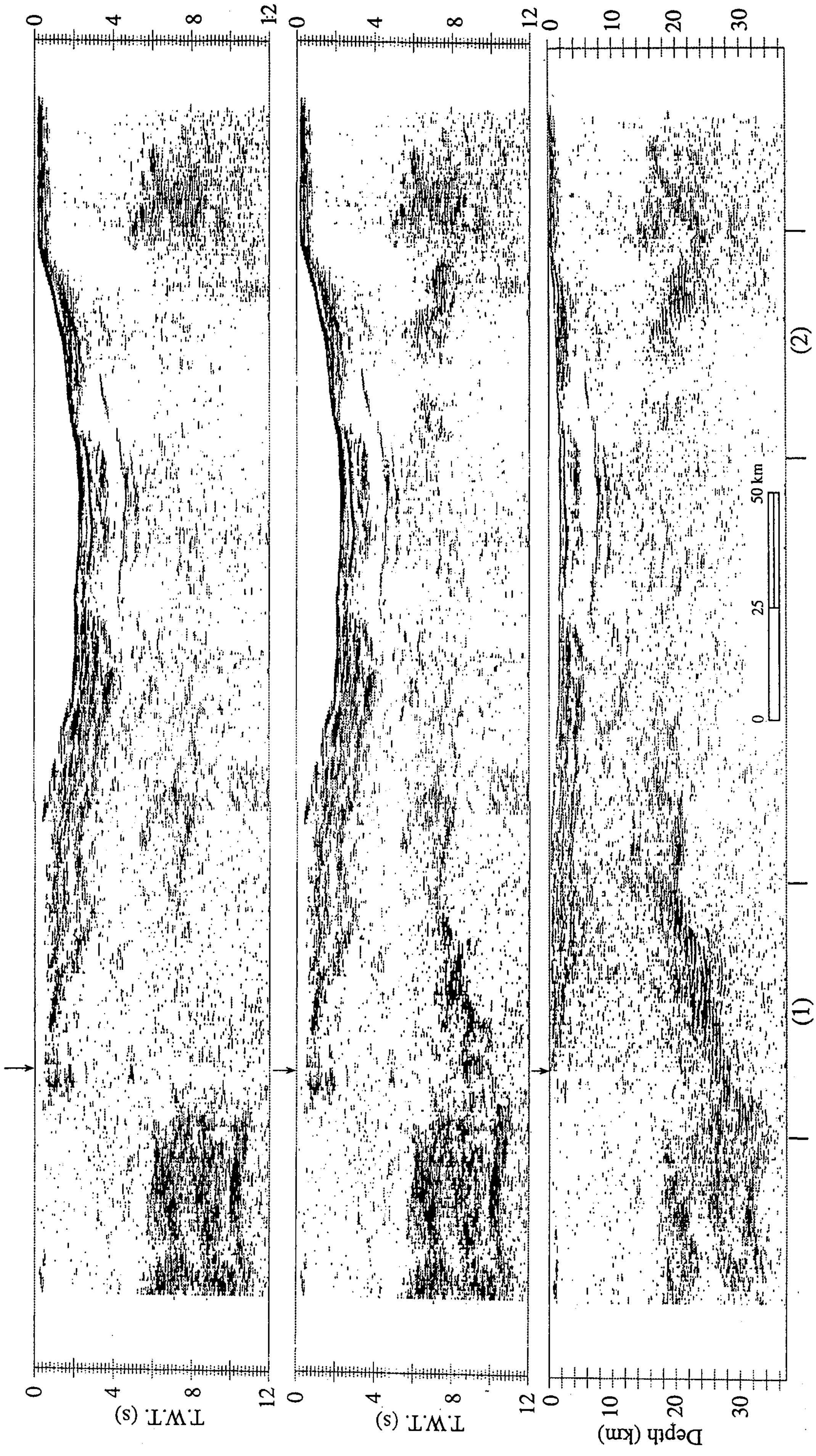

Figure 7.- A 250 km-long seismic crustal transect from the Ebro basin (left), across the València Trough (middle), up to the Balearic promontory (right). The upper panel shows the near-vertical stacked section, decimated to a common spacing of 1 km. Middle and lower panels show the stacked and depth-migrated sections after processing and merging the near-vertical and the wide-angle reflection data sets. (1): wide-angle data from profile ESCI; (2): wide-angle data projected broadside from profile I.

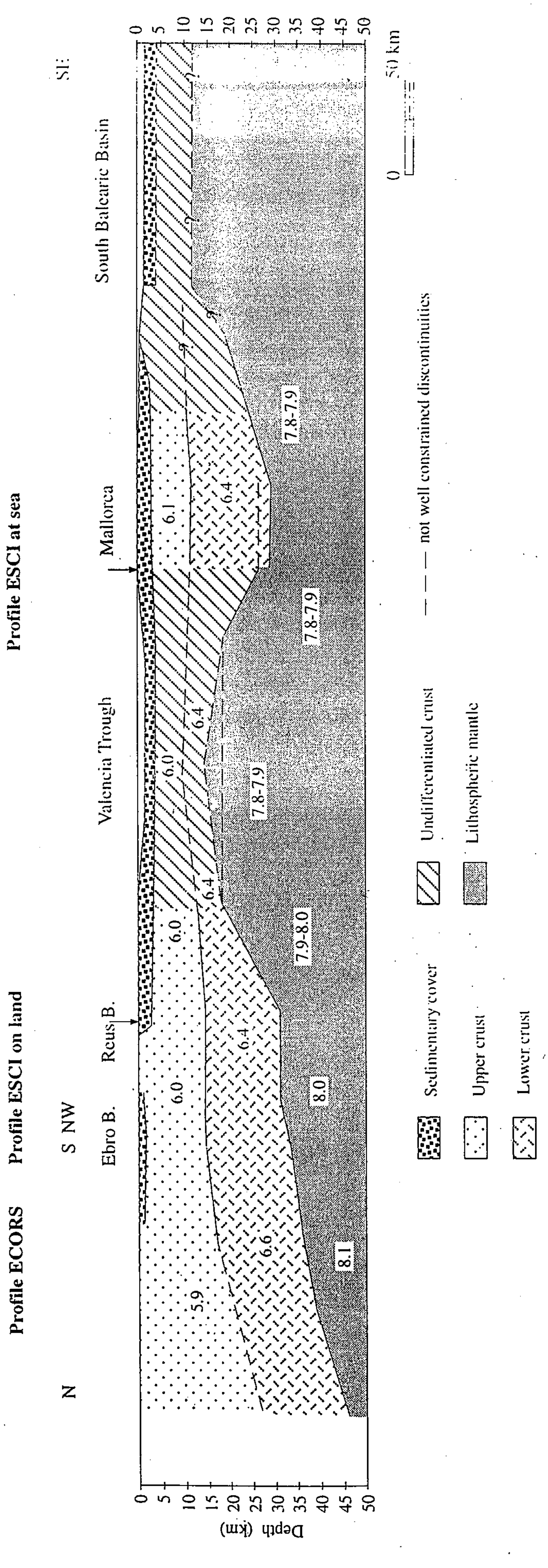

Figure 8.- Schematic crustal transect from the Pyrenees up to the South Balearic basin summarising the results obtained from the ESCI-València Trough seismic experiment. Arrows mark shorelines. Dashed lines correspond to boundaries not clearly constrained, and in hatched areas the upper and lower crustal levels can not be differentiated from the seismic data. Numbers indicate velocities in km/s.

the latter through velocity-depth forward modelling was performed as a first step. A thorough comparison of the results is perturbed by the lack of resolution in complex areas, such as the onshore/offshore transitions. Therefore, a more homogeneous, readily comparable analysis of normal incidence and large-aperture data has been attempted by developing merged stacked sections.

Both data-sets altogether provide a continuous crustal transect mapping the lateral evolution between a thickened continental crust (Pyrenees), a thinned continental crust (València Trough) and an oceanic-type crust (South Balearic basin).

Fig. 8 is a schematic drawing that summarises the major features for the whole transect. The image is based on depth-migrated near-vertical and wide-angle multichannel sections. Velocities have been taken from forward modelling in the area (Fig. 4). In this transect, the sedimentary cover, upper/lower crust and lithospheric mantle have been differentiated. We have also indicated the areas in which some boundaries are not well constrained, as for instance the bottom of the crust in the central part of the València Trough or beneath the South Balearic basin. In other areas, it is not possible to differentiate the upper and lower crustal levels, and the velocities reported correspond to average crustal values.

In the crustal transect (Fig. 8) the structure in the Iberian mainland is well resolved from profiles ECORS and ESCI, which map a progressive thinning of the crust from 48 km in the Pyrenees to 32 km around the coastline. From this point, a strong and continuous thinning is associated to the València Trough. Velocity-depth results show that the crust remains of continental type in the whole area.

The Balearic promontory is characterised by a 26-30 km thick crust which thins up to 12 km at the South Balearic basin where a 6 km thick crust beneath the sediments has been interpreted (Gallart *et al.*, this vol.). Nevertheless, the lack of reliable information on velocity-depth distribution does not allow us to constrain its possible oceanic nature.

The present-day deep structure of the NE Iberian margin shows significant differences with respect to comparable passive-type margins. The strong steady thinning of the crust by a factor of two, associated to the València Trough (15 km lost in 50 km horizontal distance), the continental nature of this thin crust and the low velocities (6.4-6.5 km/s) found at deep crustal levels are the most relevant distinctive features.

Seismic results reported for another western Mediterranean margin, the Gulf of Lion-Provençal basin (Le Douaran *et al.*, 1984; de Voogd *et al.*, 1991; Pascal *et al.* 1993) indicate that a crustal thinning of 15 km in 80 km distance is associated to a continent-oceanic structural transition. In Atlantic margins as the US East margin (LASE study Group, 1986; Holbrook, 1994a, b), Nova Scotia margin (Bassi *et al.*, 1993; Keen *et al.*, 1994) or at the conjugate margins of Newfounland and the West-Iberian (Keen *et al.*, 1994; Whitmarsh *et al.*, 1993), crustal thinnings of 15-20 km take place over large horizontal distances (200-250 km). At the East Newfounland margin, a thinning similar to the one at the València Trough has been observed (Reid, 1994) but involving the continent-ocean transition. In all these margins, higher velocities than in the València Trough are reported for the deep crust, as well as underplating in some cases.

The importance of successive compressional and extensional processes occurred at the NE Iberian margin since the Mesozoic, and the role of the Balearic promontory in the margin architecture and in the continent-ocean transition are main features to be further investigated, to constrain the evolution of this part of the Western Mediterranean from its present-day lithospheric configuration.

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