

Deep structure of the transition between the Cantabrian Mountains and the North Iberian Margin from wide-angle ESCI-N data

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Abstract: In the northern Iberian Peninsula, a N-S lithospheric transect along the Cantabrian Mountains and the continental margin can be constrained not only from the seismic images of the vertical reflection ESCI-N profiles but also from the analysis of complementary large-aperture reflection data. The seismic velocities interpreted from a refraction profile in the land segment confirm a Variscan-type crust beneath the Duero basin, which has been reworked and thickened in the Cantabrian Mountains as a result of the Alpine tectonics. Forward modelling of high-quality wide-angle reflections, obtained by piggy-back recording onland the ESCI-N4 marine shots on 7 stations in a N-S line, indicates the existence of two different Moho levels. The deeper one is an "Iberian Moho" located in the sampled segment inland, strongly deepening northwards and defined up to the coast where it reaches about 60 km depth. A much shallower "Cantabrian margin Moho" is found in the marine segment, at depths ranging from 30 km beneath the coast to 22 km at the continental slope. The extend and location of this Moho is confirmed in a large-offset stacked section, obtained by multichannel processing of the wide-angle data. However, this technique cannot properly image the deeper Moho inland. The N-S seismic section that is built up by combining the different ESCI-N data sets suggests a wedge-type pattern of crustal subduction northwards, similar to the image given by the ECORS Pyrenees profile.

Keywords: ESCI profiles, Cantabrian Mountains-Cantabrian Margin transition, wide-angle seismics, multichannel processing, unified seismic section, crustal root.

Resumen: En el margen norte de la Península Ibérica es posible completar una transecta litosférica N-S, a través de la cordillera Cantábrica y el margen Cantábrico, a partir de las imágenes sísmicas de los perfiles ESCI-N de reflexión vertical, así como del análisis de los datos complementarios de reflexión de gran ángulo. Las velocidades sísmicas deducidas de la interpretación de un perfil de refracción en el segmento terrestre de la transecta confirman la existencia de una corteza de tipo varisco bajo la cuenca del Duero. Esta corteza ha sido retrabajada y engrosada en los montes Cantábricos como consecuencia de la tectónica alpina. Por otra parte, se dispone de datos de reflexiones de gran ángulo, con una alta calidad y densidad de información, a partir de los disparos con cañones de aire del perfil marino ESCI-N4 registrados en tierra, en 7 estaciones dispuestas según una línea N-S hasta unos 60 km al sur de la línea de costa. La modelización por métodos directos (trazado de rayos y sintéticos) de estos datos de gran ángulo indica la existencia de dos niveles distintos para la base de la corteza (Moho). El más profundo es un "Moho ibérico", detectado bajo el segmento terrestre muestreado y presentando un fuerte buzamiento hacia el norte hasta la línea de costa, donde se sitúa a unos 60 km de profundidad. A lo largo del segmento marino se pone de relieve un "Moho cantábrico" mucho más superficial, a profundidades que varían entre 30 km bajo la costa y 22 km en el talud continental. La localización y extensión de este segundo Moho queda confirmada en una sección ("stack") de gran apertura, obtenida mediante un procesado multicanal de las reflexiones de gran ángulo. En cambio, la geometría de registro no permite controlar con esta técnica el Moho más profundo en tierra. Finalmente, se ha elaborado una sección sísmica completa combinando las diferentes imágenes proporcionadas por los datos ESCI-N de reflexión vertical y de gran ángulo. Esta transecta N-S sugiere una subducción cortical hacia el norte, con una imagen de imbricación en forma de cuña similar a la obtenida en el perfil ECORS Pirineos.

Palabras clave: perfiles ESCI, transición cordillera Cantábrica-margen Cantábrico, sísmica de gran ángulo, procesado multicanal, sección sísmica unificada, raíz cortical.

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The ESCI-North project (ESCI-N) involved the acquisition of a number of vertical reflection deep seismic profiles on land and at sea (Fig. 1). These profiles document the main crustal features of relevant tectonic domains in the NW Iberian Peninsula, concerning the Cantabrian Mountains and its margins. The 140 km-long E-

W land profile ESCI-N1 was implemented in the external zones of the Variscan orogenic belt in NW Spain (Pérez-Estaún *et al.*, 1994). The hinterland areas of this orogen were sampled by the marine profile ESCI-N3 that consisted of 3 segments totalling 380 km off the north coast of Galicia and Asturias (Álvarez-Marrón *et al.*, in

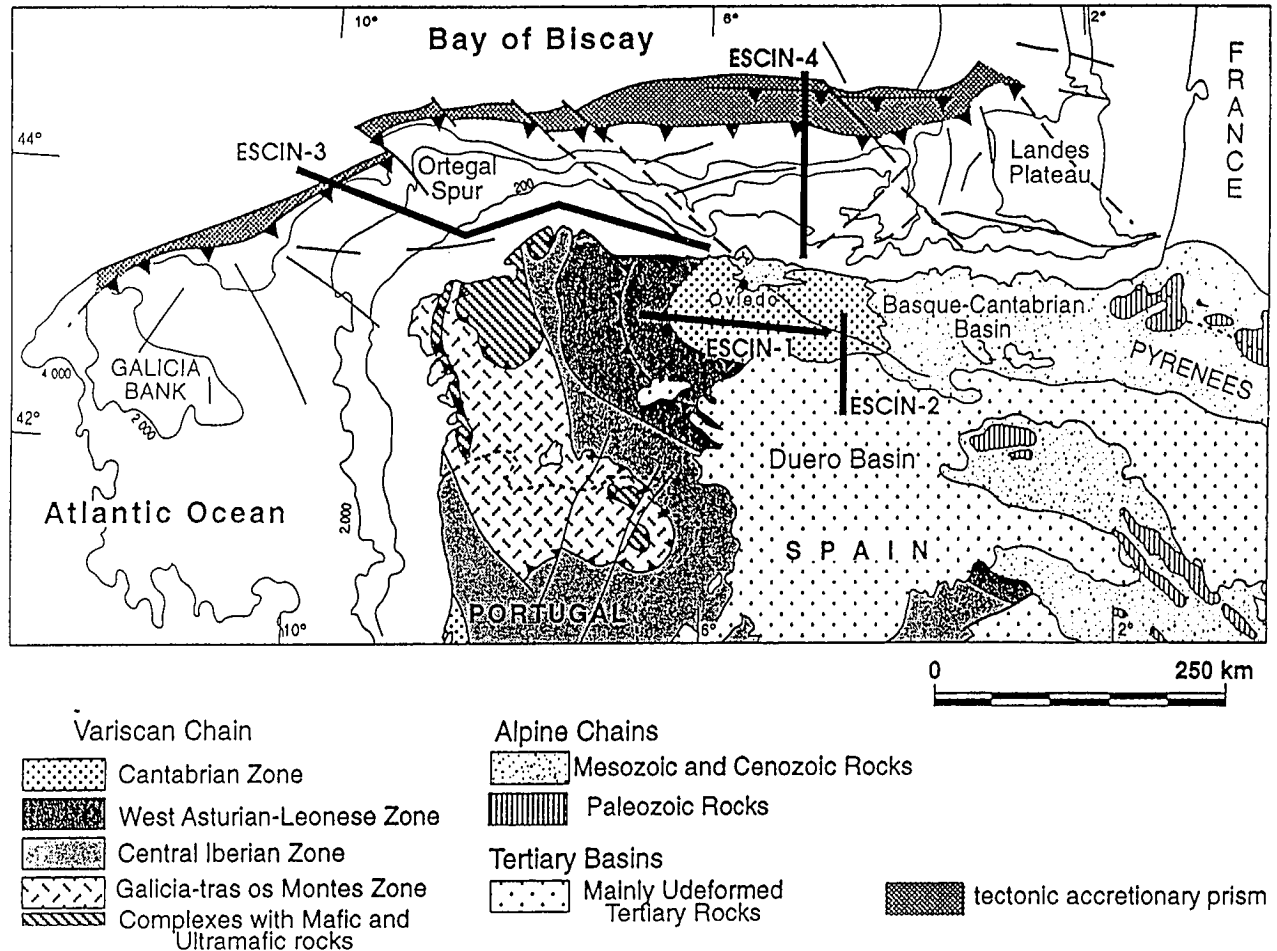


Figure 1.- Geological scheme of the northwestern Iberian Peninsula and continental margin showing the deep vertical reflection profiles recorded in the ESCI-N project.

press). The deep structure of the transition between the Duero basin and the Cantabrian Mountains was imaged by the 65 km-long N-S profile ESCI-N2. Finally, the structural features related to the ocean-continent transition in the southern part of the Bay of Biscay were investigated by the 145 km-long N-S profile ESCI-N4 offshore Asturias (Álvarez-Marrón *et al.*, this vol.). The geological framework and tectonic evolution of the areas related to the ESCI-N profiles are discussed in the different papers of this volume dealing with those profiles (Pérez-Estaún *et al.*, this vol.; Álvarez-Marrón *et al.*, this vol.; Martínez-Catalán *et al.*, this vol.), and will not be detailed here.

The profiles ESCI-N2 and ESCI-N4 were intended to delineate a N-S lithospheric transect across the Cantabrian Mountains and their northern and southern margins, in the area where the Alpine tectonics had produced the main surface uplifts in the Variscan crust. However, the geometry and lateral evolution of the deep structure from the Cantabrian Mountains to the North Iberian margin are not well constrained by the available near-vertical reflection data. The seismic images provided by the two profiles suffer from: i) a lateral shift of about 40 km between both lines, ii) a 35 km-long N-S gap in the seismic sampling, and iii) a significant lack of continuity of the main features observed at depth in both profiles. On

land, the Moho at the northern end of profile ESCI-N2, about 30 km away from the shoreline, can be defined on the stacked section at 15 s TWT, and all the lower crustal reflectivity exhibits a general deepening northwards. At sea, evidences of a Moho around 10 s TWT can be found in the ESCI-N4 profile along a 20 km-short segment, and the deep reflectivity vanishes towards the continental slope.

In this context, the structural constraints that could be further provided by large-aperture recording devices appear as of most relevance, and are investigated in this paper.

Wide-angle data

Two sets of wide-angle seismic data can be considered to constrain a N-S crustal transect across the Cantabrian Mountains and their margins (Fig. 2). On one hand, the vertical profile ESCI-N2 is approximately coincident with a segment of a 200 km-long reversed refraction profile performed in a complementary project focused in providing regional information on velocity-depth distribution along the Cantabrian Mountains and Duero foreland basin (Gallart *et al.*, 1994). Moreover, the air-gun shots along the marine profile ESCI-N4 had also been recorded at wide-angle distances in land, by means of 7

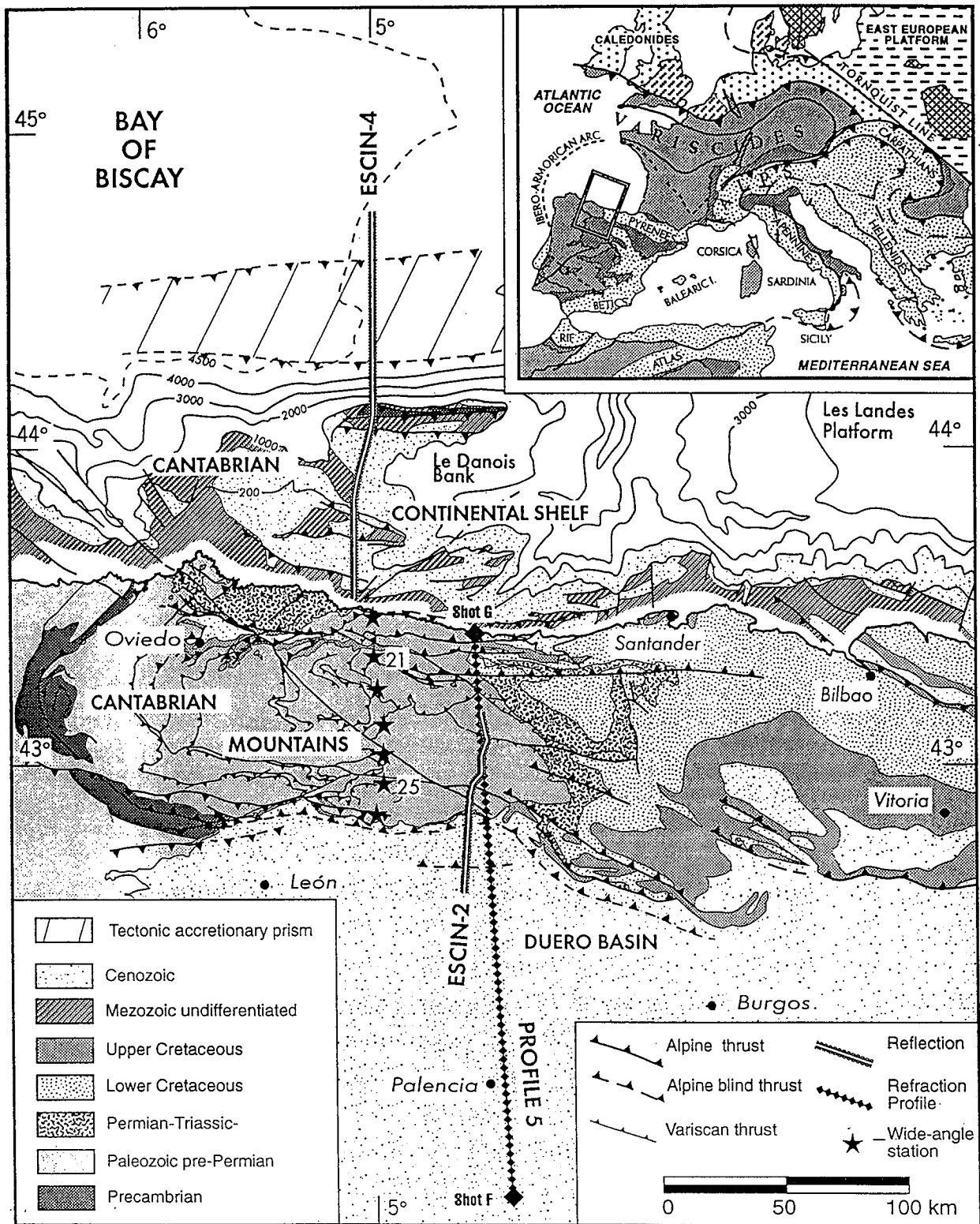


Figure 2.- Large-aperture seismic data used in this work: refraction profile 5 (shots F and G) and piggy-back recording on land (stations 20 to 26) the air-gun shots of profile ESCIN-4.

portable stations deployed in a N-S line at a 10 km station spacing.

The wide-angle data provided by the ESCIN-4 profile have been analysed by two different methodologies: classical velocity-depth forward modelling, and multichannel processing leading to a large-aperture stacked section. In the following, both approaches will be developed, as well as a comparison of the corresponding results with the ne-

ar-vertical images, and a discussion of the overall seismic constraints for the N-S structural transect.

Velocity-depth forward modelling

The N-S refraction profile on land

Within a general reconnaissance by refraction profiling of the external zones of the Variscan chain in NW

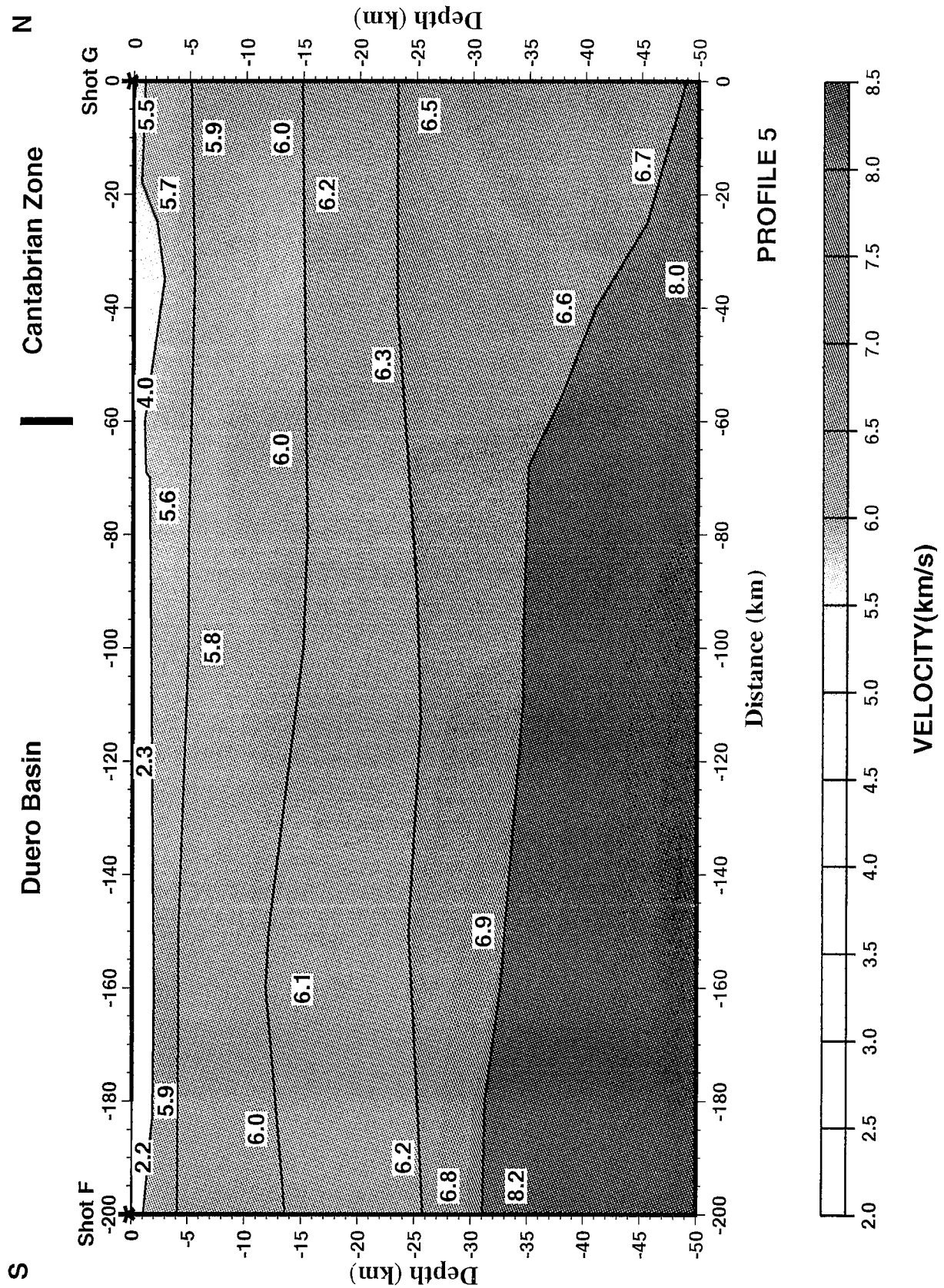


Figure 3.- Velocity-depth model obtained for profile 5, after Pulgar et al. (in press).

Spain, profile 5 was recorded in a N-S direction, parallel to reflection profile ESCI-N2 (Fig. 2) and samples the highest elevations of the Cantabrian Mountains and the transition to the foreland Duero basin. Two shots, named F and G, of 1500 kg dynamite each were fired at both ends of the 200 km-long profile and recorded by 80 portable stations spaced 2.5 km. The main seismic phases observed in the record-sections have been interpreted in a classical forward modelling procedure (Zelt & Smith, 1992) which may include inversion for parts of the model with adequate coverage.

A detailed presentation of the data from shots F and G, as well as correlation and interpretation of phases is given in Pulgar *et al.* (*in press*). The velocity-depth final model obtained for this profile is shown in Fig. 3. The velocity profile corresponds to a Variscan crust characterised by upper, middle and lower levels. The uppermost velocities decrease from more than 5 km/s in the Palaeozoic rocks of the Cantabrian zone down to values of 2.2 km/s in the Tertiary sediments of the Duero basin. The basement and middle crust are characterised along the profile by homogeneous velocities of 5.9-6.0 km/s and 6.2-6.3 km/s respectively. The lower crust presents higher lateral changes in velocity and thickness, and is particularly affected by an important crustal thickening beneath the Cantabrian Mountains. Velocities in the upper mantle seem also to be affected by lateral N-S variations, although direct control from Pn waves is available only for shot F.

At the southern end of the profile the Moho is located at 31 km depth, and shows a moderate deepening along the Duero basin. Depths of 35 km are obtained at the transition to the Cantabrian Mountains, and towards the North the deepening is more acute, but constrained only for a 20 km-long segment. This crust-mantle boundary is consistent with the seismic image provided by the vertical reflection profile ESCI-N2.

The onshore-offshore wide-angle recordings: description and modelling

The piggy-back recording on land stations of the air-gun shots of the ESCI-N4 marine profile provide 7 high-density receiver gathers (trace spacing of 75 m, station spacing 10 km) that sample the transition from the Cantabrian Mountains to the Cantabrian margin at longitude 5° 5' W. All the seismic phases identified in the 7 stations (numbered 20 to 26 from N to S) have been considered and fitted in the forward modelling analysis. Most relevant features of the data can be illustrated in the record-sections of stations 21 and 25 (Figs. 4 and 5). One trace out of three is shown for display purposes. Correlation of seismic phases and travel-time picking has been performed on large-scale full traces record-sections corrected for bathymetry, to minimise perturbations related to strong time-delays and diffractions at the hinge of the continental slope (the water layer increases from 900 m to 4600 m in 15 km distance). However, the final velocity-depth model and the fitting with the observations (see Figs. 4, 5, 7 and 8) will be shown considering the presence of the water layer.

Correlation of first arrivals up to offsets of 30 km in station 21 results in different branches interpreted as refracted within Mesozoic and Cenozoic sedimentary basins located at the Cantabrian platform, the velocity of which range from 4.5 to 5.7 km/s. Arrivals from shots located at offsets beyond 45 km in station 21 show, for all stations, increasing delays up to 1 s, attributed to sedimentary basins of 5-6 km thickness and 3.0 km/s velocity, located beyond 20 km seawards. Beyond the continental slope, a sedimentary sequence down to 10 km depth has been included according to results of ESCI-N4 profile (Álvarez-Marrón *et al.*, this vol.).

The basement, at about 5 km depth, is characterised by a velocity of 6.0 km/s. Although the correlation of Pg refracted phases is perturbed by the lateral variation of the uppermost layers up to the continental slope, the upper crustal features of the model have been constrained also by inversion, as this is the most densely sampled part of the profile.

Reflected energy arrivals are observed in all the record sections. However, the ringing character of the signal difficults the identification of successive arrivals, and local amplitude variations observed systematically in some traces may be due to differences in energy transmission across the sea-bottom. In practice, two intracrustal reflected phases PiP and PcP, delineating the middle and lower crust, and the most energetic PmP Moho-reflection have been identified in the first half of the record-sections. The middle crust is characterised in the model by velocities of 6.2-6.3 km/s, is located at 15 km depth in the South and shallows up to 7-8 km depth in the slope. Beyond this, crustal materials with high velocities about 7.2-7.3 km/s directly underlay the sediments in the model. The top of the lower crust is located at 23 km depth in the southern end of the model, and shallows continuously northwards up to the slope, in correspondence with a velocity increase from 6.4 to 6.9 km/s.

In the second half of the record-sections, for the shots northwards of the continental slope, one single energetic reflected phase is correlated in stations 20 to 23, corresponding to the crust-mantle boundary along the Cantabrian margin. The geometry of the Moho indicates a progressive crustal thinning northwards, from 30 km beneath the shoreline to 22 km depth at the northern side of the slope. Continuity of this horizon is assumed in the model and results in a crustal thickness of about 17 km at the northern end of the ESCI-N4 profile. Upper mantle velocities are not resolved in the absence of Pn data, but velocity contrasts needed for PmP critical distances indicate that low sub-Moho values of 7.8 km/s are compatible with the observations. Beyond the continental slope, different crustal features suggested in the model may characterise a transitional or oceanic-type crust, although they are not constrained in the absence of OBS data.

The reflective pattern changes drastically in the southernmost recordings. For stations 25 and 26, the PmP phase (reflections from a Moho level that produces arrival times consistent with those observed for stations 20 to 24) appears with weaker amplitudes, and is followed

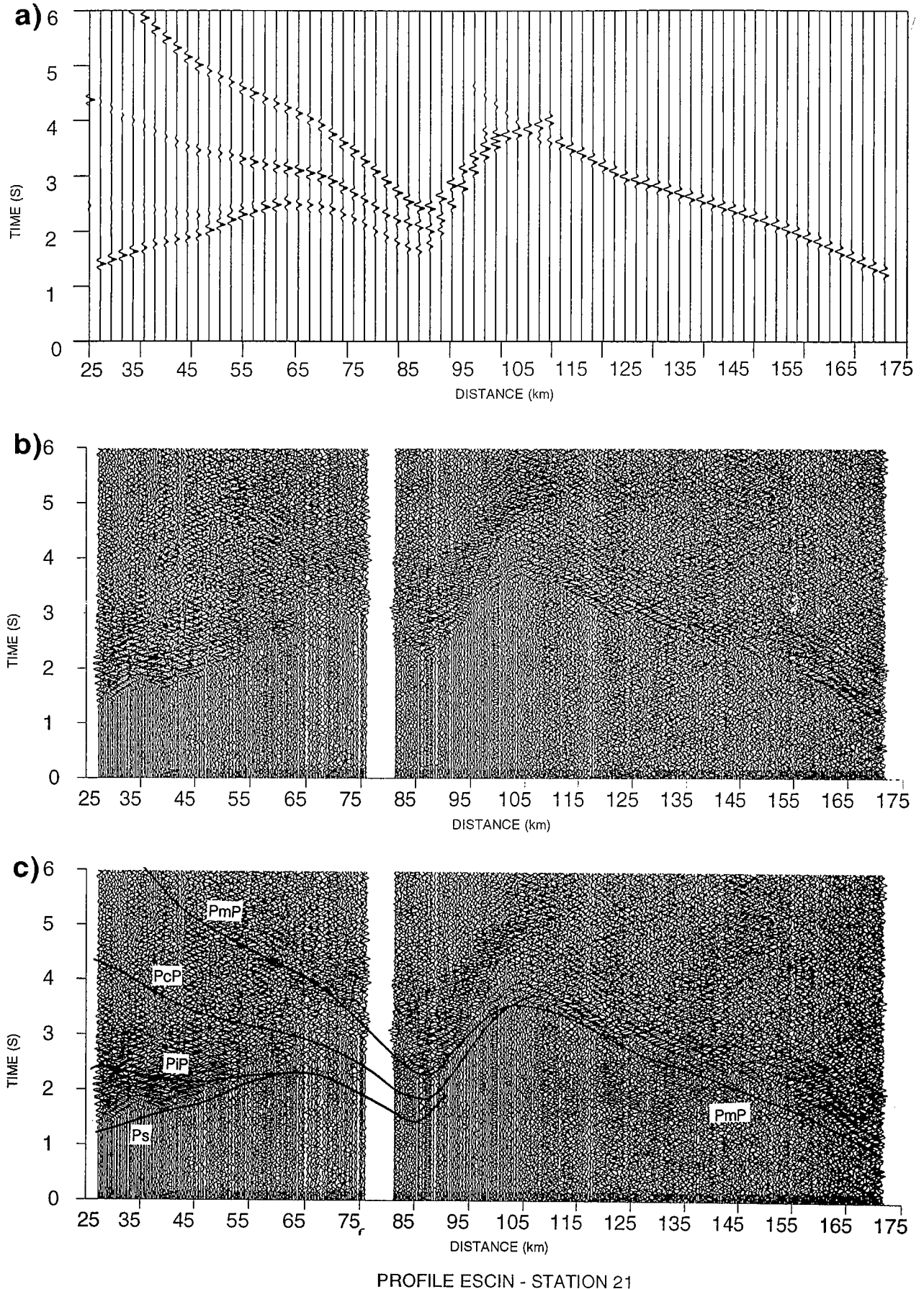
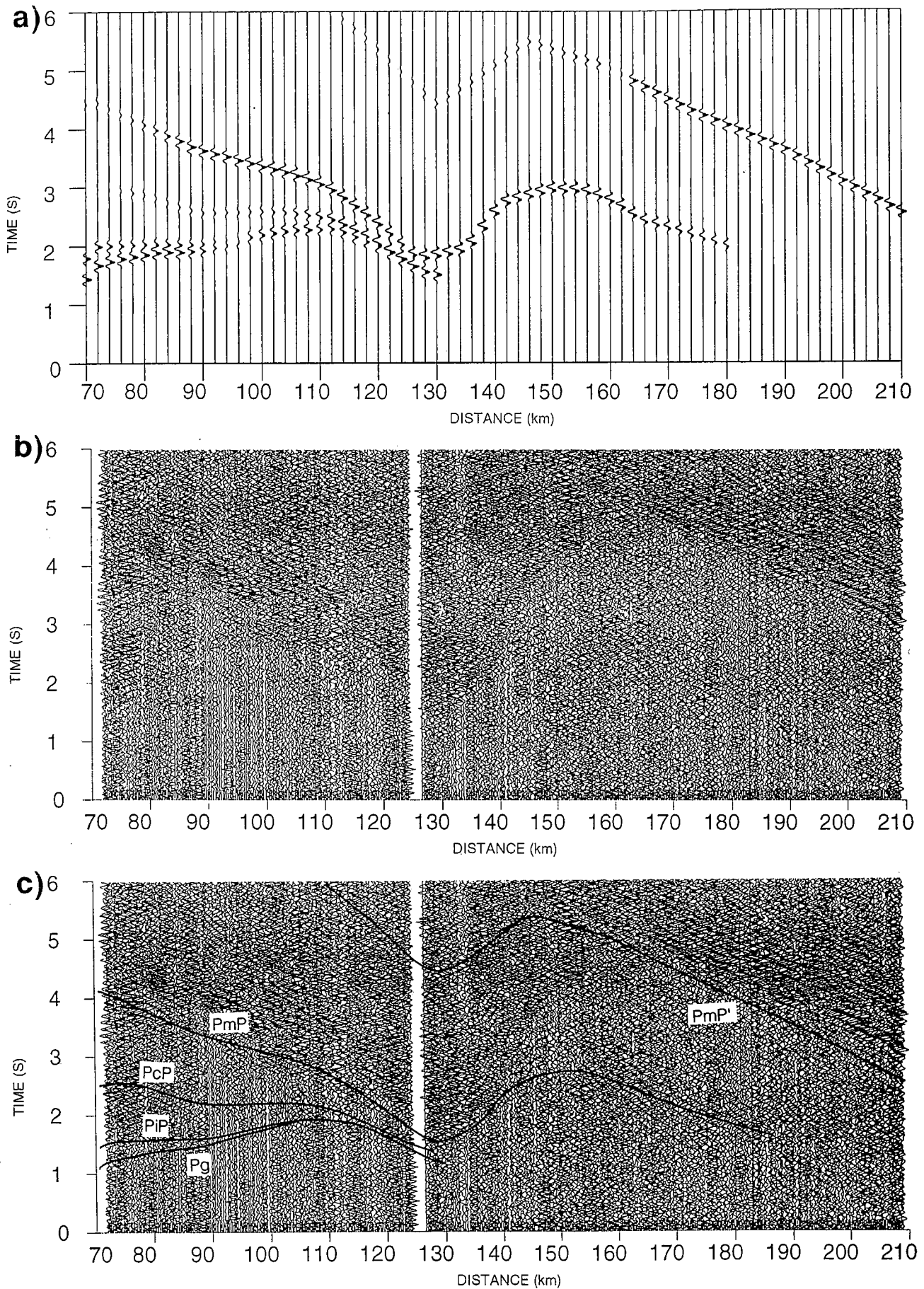


Figure 4.- Data and interpretation of air-gun shots (profile ESCI-N4) recorded in land station 21 (see Fig.2 for location). (4a): synthetics from model of Fig. 7. (4b) record-section reduced by 6 km/s, band-pass filtered (6-12 Hz) and trace-normalised amplitude. Only one trace out of three is displayed for clarity purposes. (4c): travel-time fitting of the main seismic phases, from model of Fig. 7. Distances indicated correspond to offsets between shotpoints and station 21.



PROFILE ESCIN - STATION 25

Figure 5.- Data and interpretation of air-gun shots recorded in station 25. Same distribution and parameters as in Fig. 4.

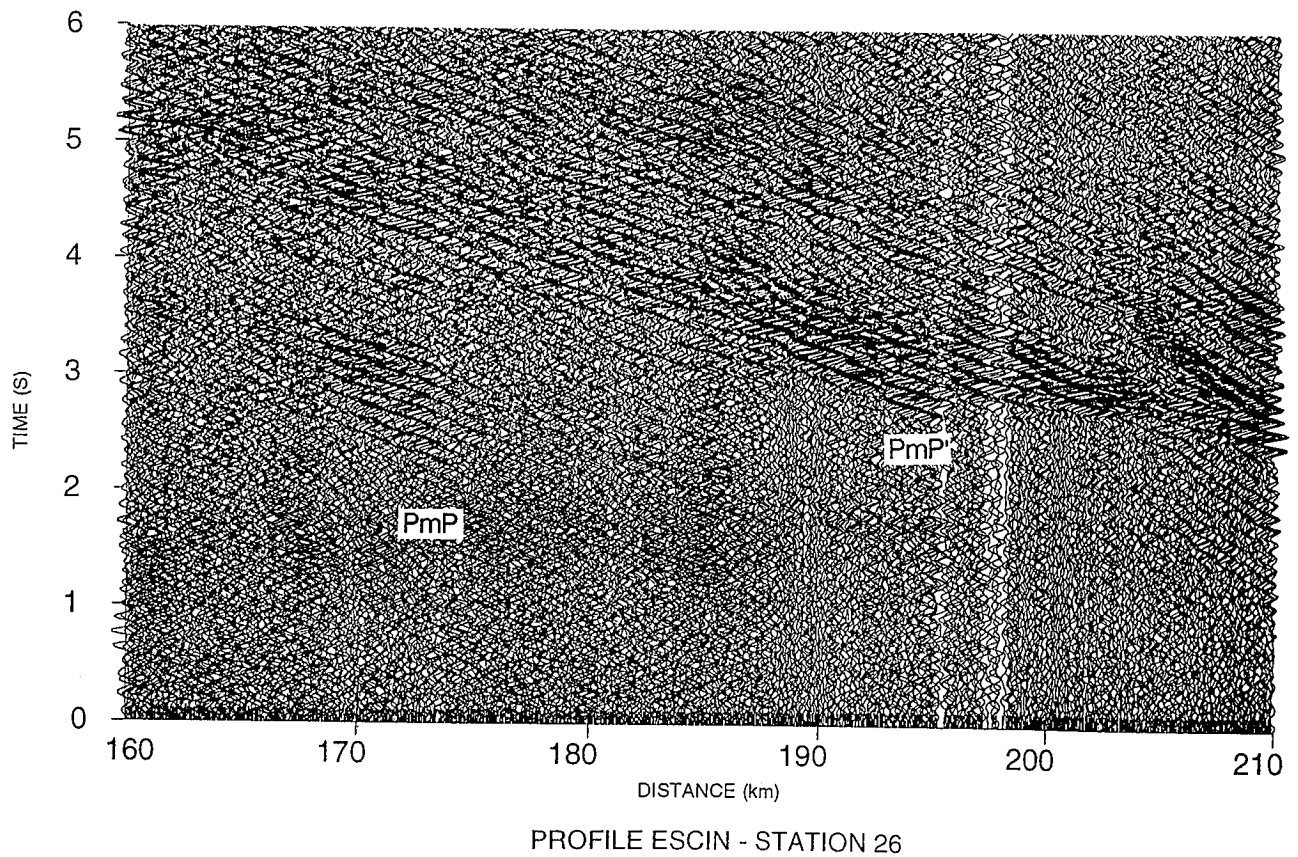
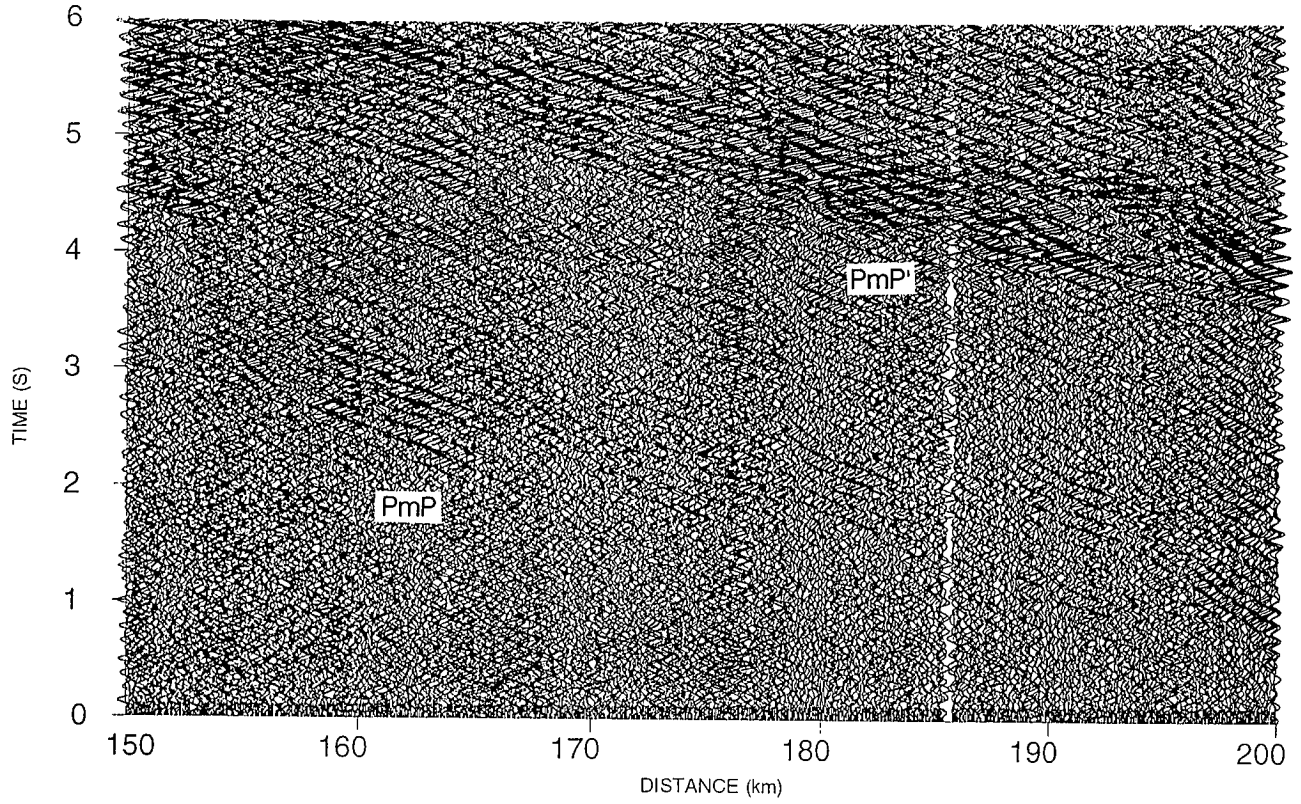


Figure 6.- Blow up of record-sections for stations 25 and 26 showing the distance range where the two reflected phases PmP and PmP' are simultaneously recorded. The two sections display the same shots. Technical parameters as in Fig. 4.

by a more energetic reflected phase at 2-3 s later on, labelled PmP' in Fig. 5.

First, we investigated whether this PmP' phase could correspond to a multiple or peg-leg reflection. Fig. 6 displays the recorded seismograms of the shots which provide arrivals of both reflected phases, i.e., the shots located at distances between 150-200 km from station 25 or 160-210 km from station 26. If PmP' was a multiple phase generated on the source side, the time delay between PmP and PmP' arrivals for a same shot recorded at the two stations should be the same. However, the observed delays in the two record-sections differ by more than 1 s. Moreover, the multiple reflection more likely to be observed is the one associated with the water layer. For the shots involved, the water column is 4500 m, which would imply a delay of 6 s for that multiple, i.e., much later on than the PmP' arrivals. Therefore, the PmP' phase must be attributed to a real reflection at some deep crustal or mantle level.

Several attempts have been made to explain the amplitude and arrival times of this PmP' reflection, together with the PmP phase observed in all the stations. An appropriate fitting could only be achieved by considering that the "Cantabrian margin Moho" extends southward up to the coast, and assuming that a much deeper reflector, the "Iberian Moho", is present further inland and strongly deepens northward up to the shoreline (Fig. 7).

This Iberian Moho is the most striking feature in the velocity-depth model (Fig. 8). It is located at 37 km depth beneath station 26, and reaches about 60 km beneath the shoreline. It could not be modelled further north, as reflections were not observed in stations near the coast. In turn, the shallower Moho of the Cantabrian margin can go beyond the shoreline, but only up to 10 km inland, where it is located at 33 km depth.

Wide-angle multichannel analysis: processing and stacked section

Customarily, refraction/wide angle reflection seismic data are processed and interpreted considering specific methodologies (correlation of main seismic phases and fitting them by forward modelling) which are independent from those dealing with near-vertical reflection data (based on multifold analysis).

Results coming from both types of reflection data are regarded as complementary, but attempts to use them together to constrain a seismic model of the crustal structure are perturbed by a number of uncertainties inherent to each method (phase correlation on the forward modelling, velocity control on the vertical sections, etc.). More conclusive results are foreseen if an unified analysis of the two reflection data sets could be developed.

In this sense, recording on land the ESCI-N4 air-gun shots, in 7 stations in-line with the marine profile, has provided a large-aperture multicoverage around the onshore-offshore transition, and a multichannel wide-angle analysis can be envisaged. By developing a large-aperture processing sequence analogous to the conventional

one for near-vertical reflection data, the corresponding stacked sections can be readily compared and merged into a single crustal image (Gallart *et al.*, 1995; Vidal *et al.*, 1995; Vidal *et al.*, this vol.).

In our profile, due to the large spacing between the recording stations the wide-angle multichannel analysis should be focused on the Moho reflected phases, which are observed in each receiver-gather for tens of kilometres. Fig. 9 shows the area, extending about 15 km inland and 70 seawards, where large-offset multicoverage is achieved. Main steps of the processing sequence applied to the wide-angle ESCI-N4 data can be summarised as follows:

The data were first organised into receiver gathers in SEG-Y format. Geometry and bin width (a value of 500 m is adopted) are essential parameters to establish for pre-processing of data, due to the variability of the distances range. Editing of traces, muting, energy equalisation, band-pass filtering and predictive deconvolution were applied to the receiver gathers. The refracted energy (Pg phases) was eliminated by direct muting, and the CMP gathers formed afterwards. Static and dynamic corrections are to be applied to the CMP gathers prior to the building up of a wide-angle stacked section. Topographic corrections should account for station elevations and water-depth beneath the shots. The Normal Moveout (NMO) correction is essential in this case, as very different large offsets are involved in a single CMP. The NMO is also very dependent on the average velocity considered, which can be constrained up to 0.1 km/s. In practice, NMO velocities for the ESCI-N4 wide-angle CMPs oscillate around 6.2 km/s. After the NMO correction, mute must be applied for some far-offset traces with important stretching.

On the other hand, the limitations of the NMO technique in case of large offsets (Vidal *et al.*, 1995) implicate that processing of PmP reflections using standard reflection packages is feasible for a single reflector, under the assumption of an average velocity above it. Therefore, the distinct deep crustal reflections observed in our profile on the receiver-gathers of the southernmost stations (Figs. 5 and 6) and associated to two different Moho levels in the forward modelling (Figs. 7 and 8) could not be analysed altogether. The stacked section has been built up considering the most energetic Moho reflections beneath the Cantabrian continental margin, which are visible in all the land stations. The features in the stacked section of the second Moho defined in the forward model beneath the Cantabrian Mountains and the problems associated to large-aperture processing of very deep, inclined reflectors will be discussed in the next section.

The wide-angle stacked section obtained after this processing is shown in Fig. 10. The datum plane was situated at sea level, and a datum velocity of 4.5 km/s was considered. A clear reflectivity from the bottom of the crust is imaged along the Cantabrian continental margin. The Moho reflectivity shows a moderate, steady thinning northwards, from around 10 s TWT beneath the shoreline to 7-8 s at 70 km seawards, beneath the continental slope. No wide-angle multicoverage is achieved further

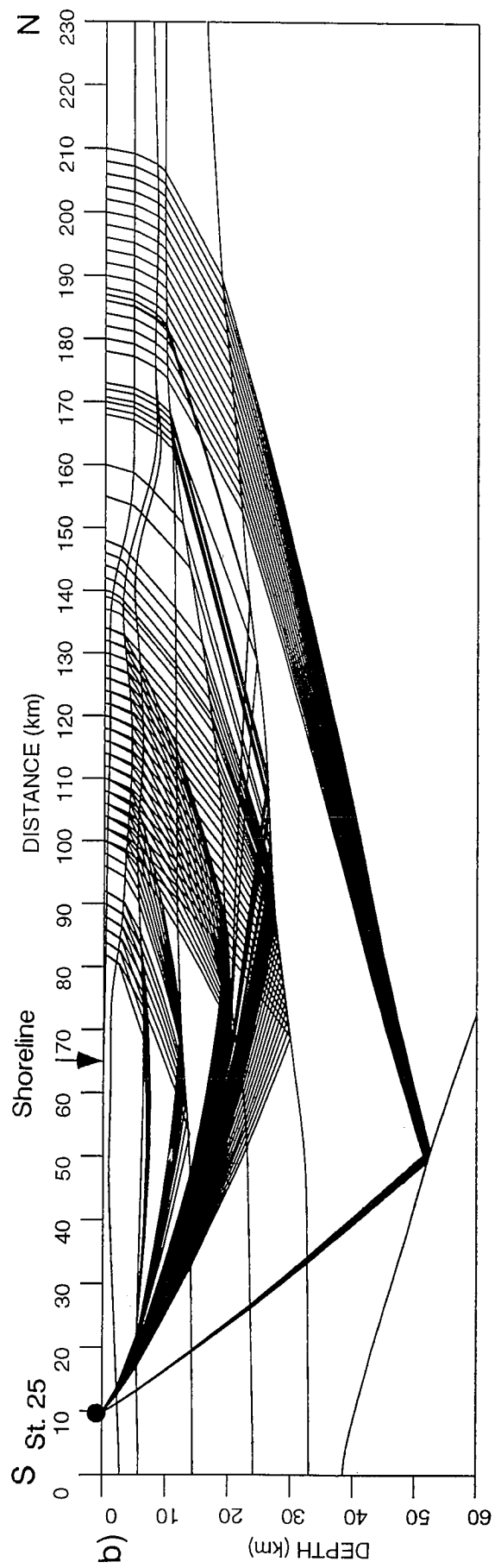
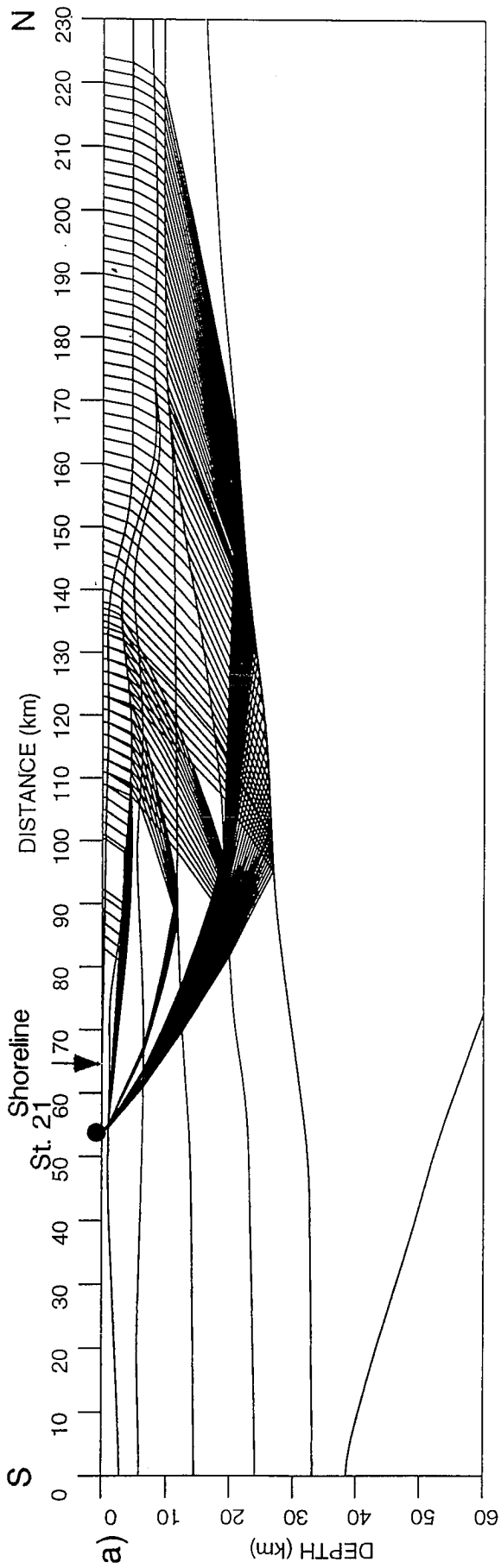


Figure 7.- Ray-tracing modelling for profile ESCI-N4 recorded in stations 21 and 25 (see Fig. 4 and 5). Velocity values detailed in Fig. 8. Distances in the model referred to the southernmost land station 26.

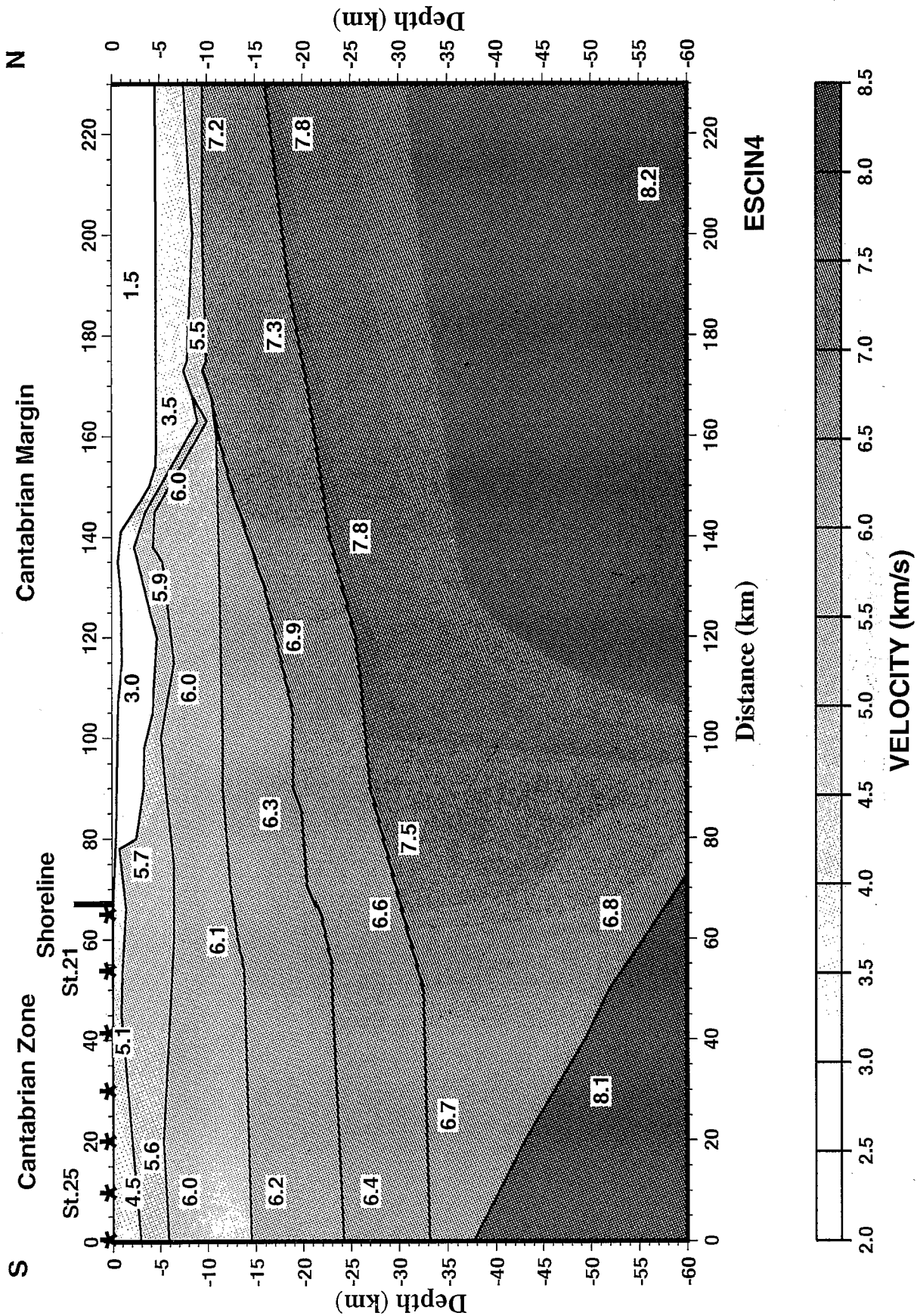


Figure 8.- Velocity-depth distribution along the N-S section using data from all land stations 20 to 26.

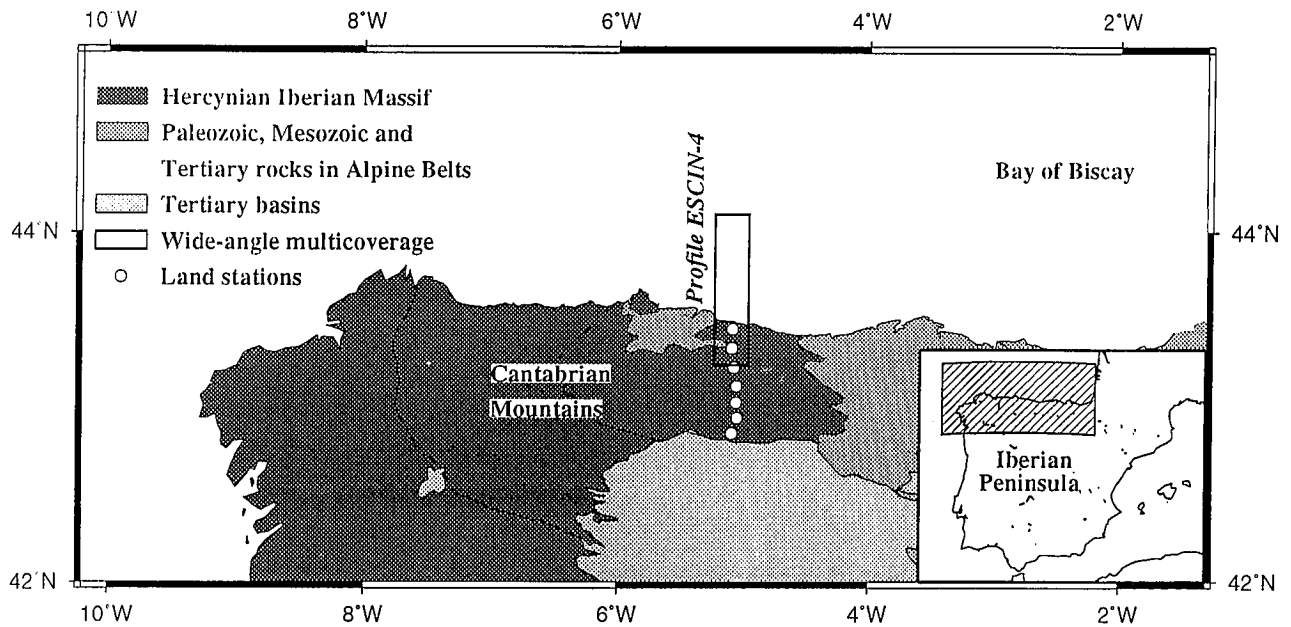


Figure 9.- Area where large-offset multicoverage is achieved.

north, at the abyssal plain. In the southernmost part of the section, the reflective level is continued in the 15 km sampled inland, around 10-12 s TWT.

This wide-angle stacked image is consistent with the velocity-depth model obtained in the forward analysis (Fig. 8). In that model, the Moho beneath the Cantabrian margin is located at 30 km depth beneath the shoreline, continues onshore for some kilometres, and thins northwards up to 23 km depth beneath the continental slope.

The problem of imaging very deep, inclined reflectors in a wide-angle stack

The forward interpretation of the seismic data has shown that along the velocity-depth model two Mohos

coexist at different levels and zones. The structural image suggest the imbrication by shortening of two crusts of different depths, and has similarities to the image obtained in the ECORS-Pyrenees deep reflection profiling. In this sense, it is of interest to investigate how these late energies are imaged in the wide-angle stacked section.

A major problem raised in the previous section is to adapt the vertical reflection processing techniques to large-offset data. Particularly, the NMO correction is feasible for a single reflector with an average velocity above it. Hence, the multichannel processing of the two reflective levels observed in the data should be carried out in two successive, independent steps, one for each reflector. The processing and final stacked image for the first (shallower) reflector, the "continental margin Moho", have

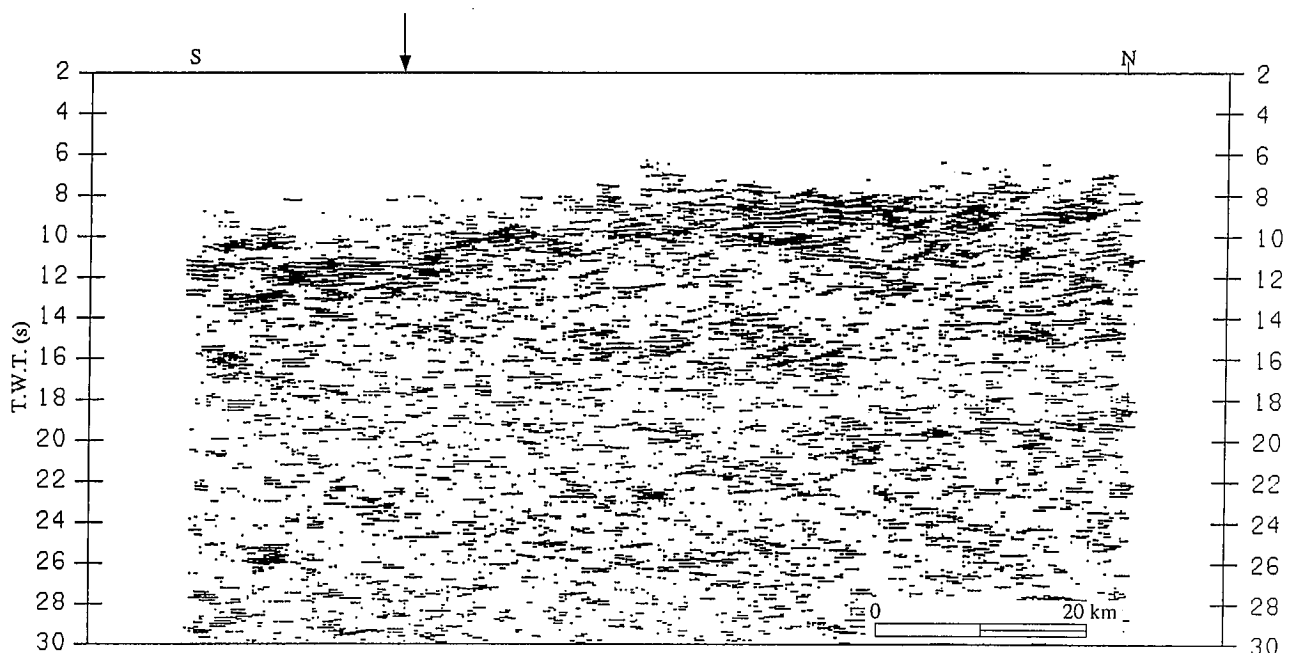


Figure 10.- Final stacked section obtained by adapting the conventional reflection procedure to large offsets. Reflections from the Moho at the continental margin are observed throughout the section, ranging from 10-12 s TWT in the few km inland imaged, to 7-8 s TWT beneath the continental slope.

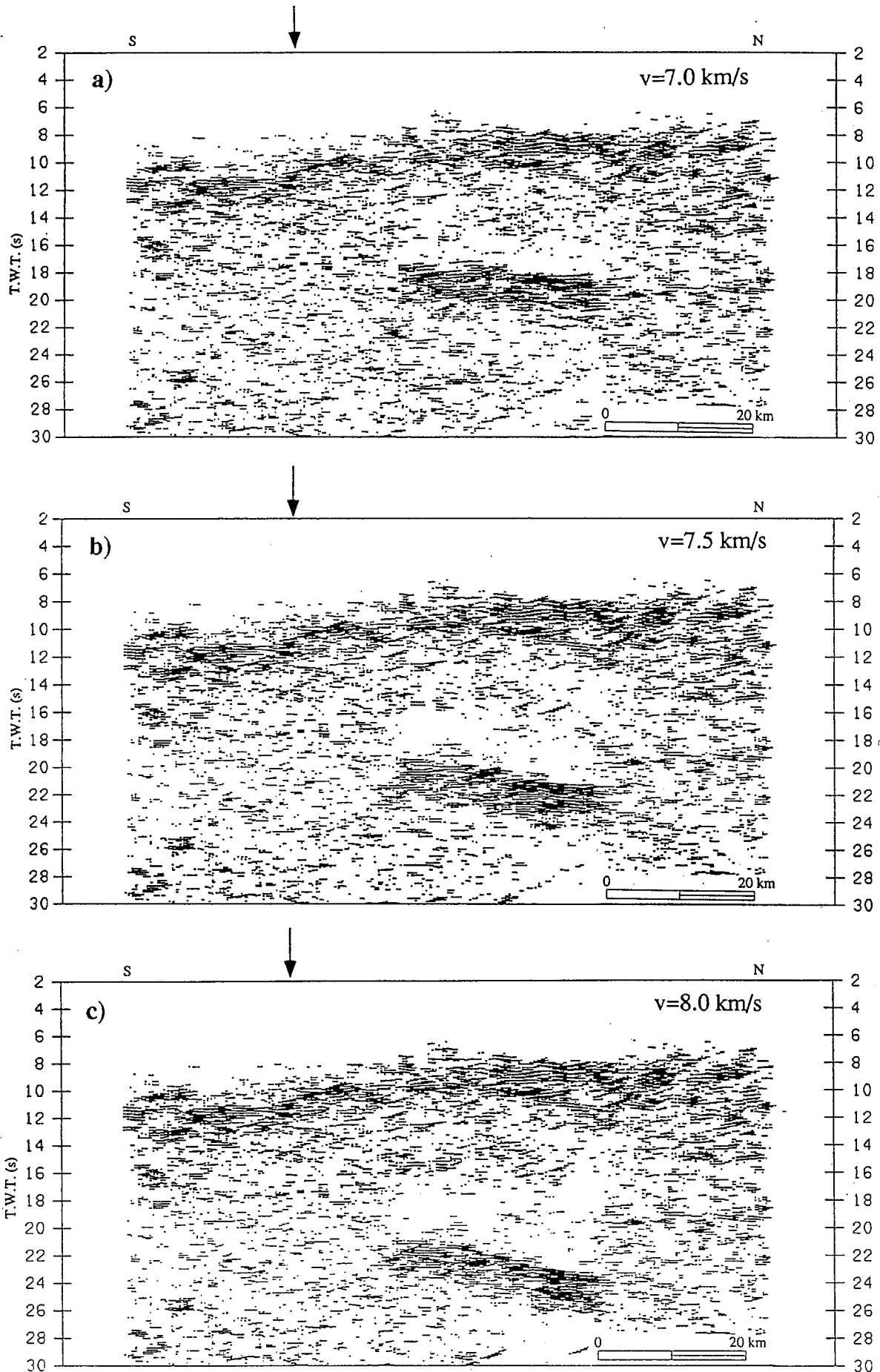


Figure 11.— Three examples of a stack that merges the reflections of the two Mohos, processed separately, depending on the average velocity considered for the deeper, Iberian Moho. Values ranging between 7, 7.5 and 8 km/s (from top to bottom panels) result in similar reflective images, but shifted several seconds.

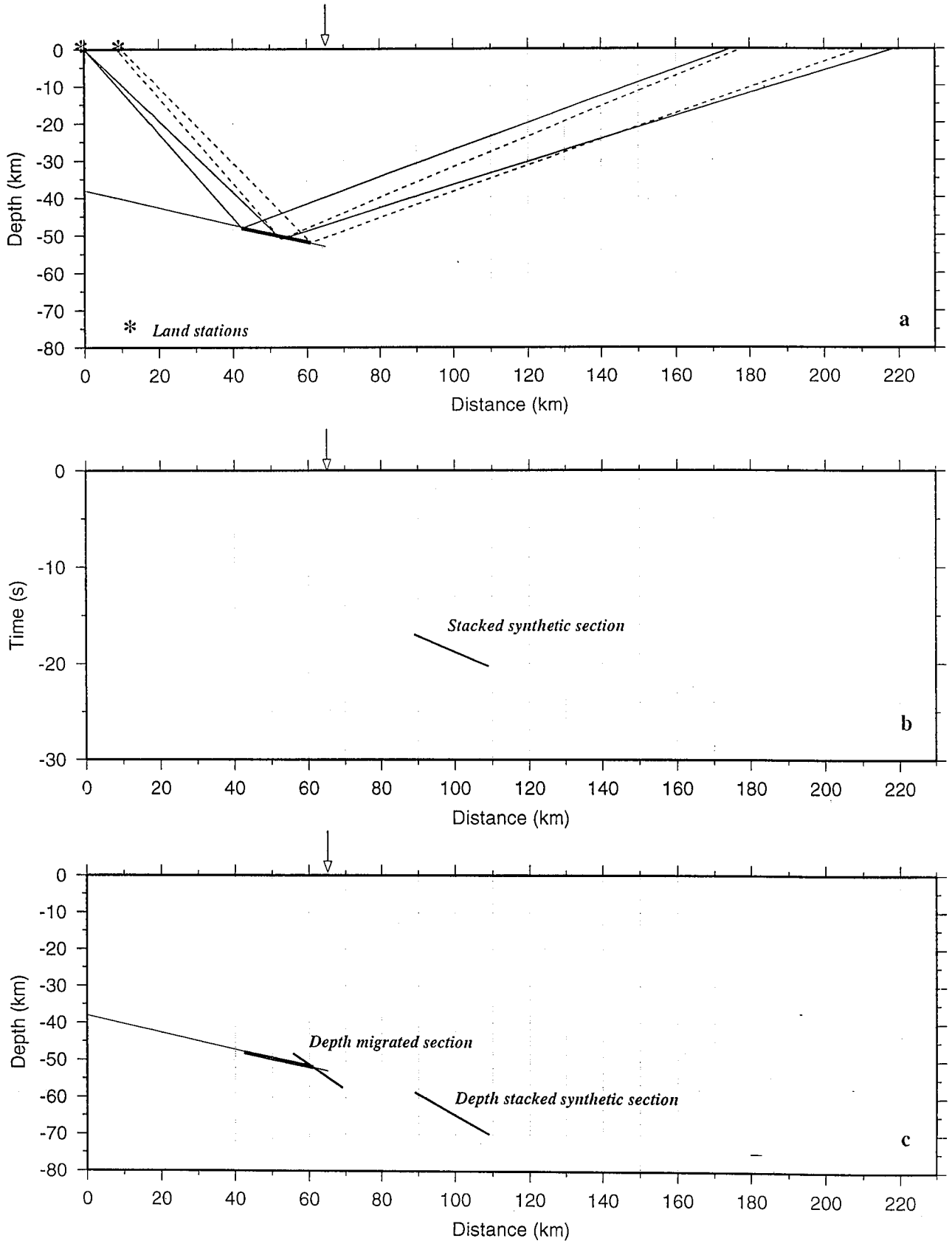


Figure 12.- Example illustrating the problem of multifold processing in case of a deep, inclined reflector sampled at wide-angle offsets. (12a): synthetic data on two stations that record the reflections on such a horizon from shots at large offsets. Features of the model (geometry, average velocity,...) are similar to the real case considered. (12b): image of this reflector (line-drawing) on the stacked synthetic section. In this case the accuracy in NMO velocities is better than 0.2 km/s. (12c): depth location of the reflector before and after migration, using a velocity of 6.9 km/s. The multifold procedure does not restore the reflective segment to its original location. The fitting is even poorer if different migration velocities are considered.

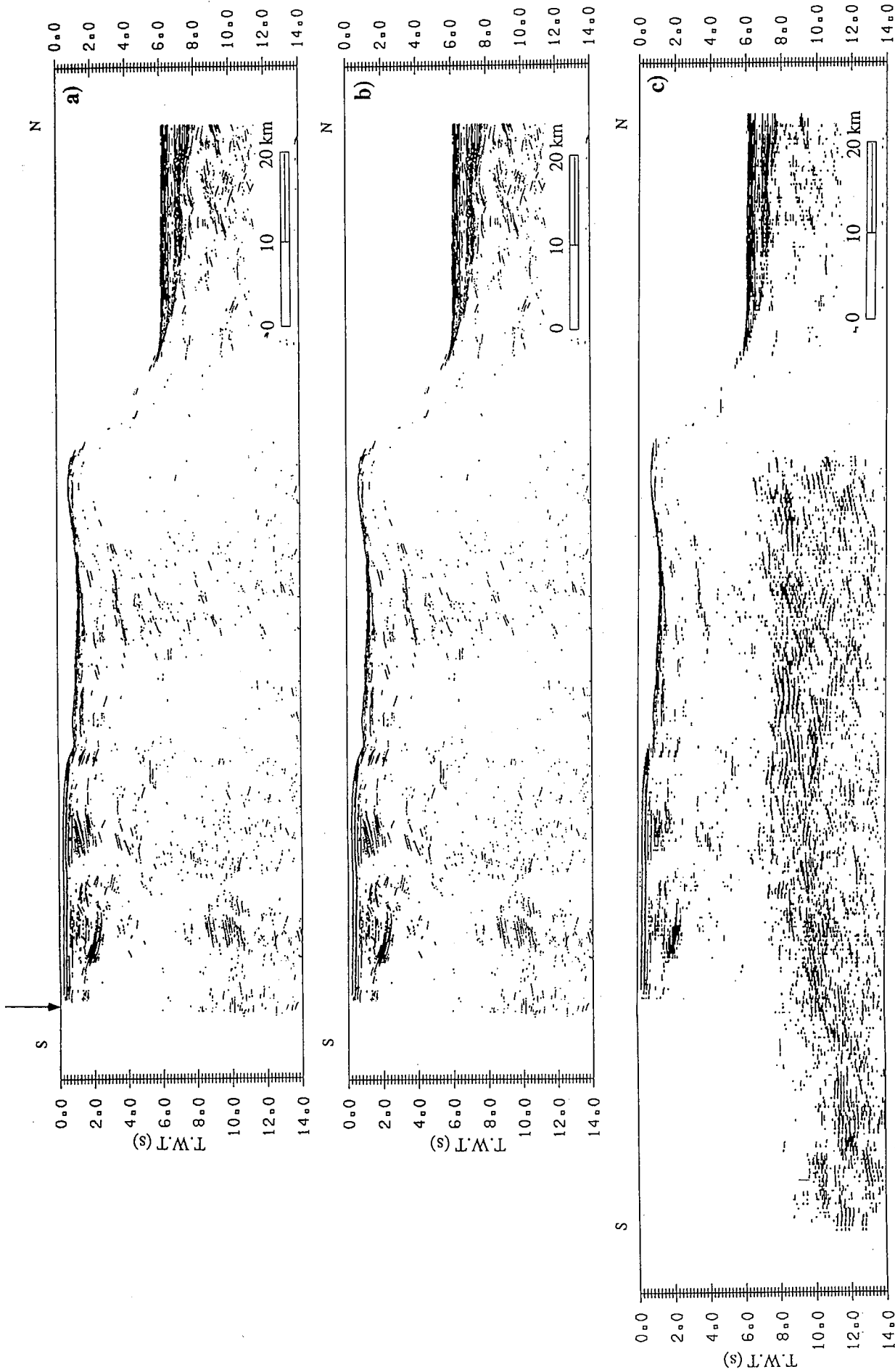


Figure 13.- Final N-S stacked section combining the near-vertical and the wide-angle ESCI-N data. (13a): stack of the near-vertical data of profile ESCI-N4. (13b): same data, decimated to a common CMP spacing (500 m) as for the wide-angle data. (13c): full image after merging the two reflective stacks (Figs. 13b and 10).

already been reported (see Fig. 10). Best-fitting NMO velocities are difficult to establish regarding the deeper reflector (the "Cantabrian Moho"). The corresponding CMPs are made up by traces coming from two stations at most (only one in several cases); the energy onsets are rather diffuse, and similar acceptable alignments can be obtained with very different values of NMO average velocities.

Fig. 11 shows three examples of the stacked sections that result from processing the deep reflector with NMO velocities of 7.0, 7.5 and 8.0 km/s respectively. The final images have been obtained by merging those built up independently for each reflector. Application of time-variant scaling (AGC) was necessary for display purposes. The resolution of the deep reflector is similar in the three cases, although its location at depth varies significantly: from 16-18 s to 22-24 s according to the velocities considered. On the other hand, the real spatial location of this reflector may be far away from that assigned by the CMP procedure, specially if strong dips are involved, as suggested in the forward modelling. Hence, migration should be considered carefully, although the corresponding algorithms are far from being adapted to the depths and offsets involved, and constraints on migration velocities are rather poor.

With these difficulties in mind, prior to undertake a detailed, time-consuming migration analysis on our deep data, we have made some simple tests on the reliability of migration algorithms in case of very deep inclined reflectors and large-offset multicoverage. Fig. 12 illustrates these tests. Starting from a simple one layer crust and a dipping Moho, we calculated the synthetic data on two stations at large offsets, in a geometry similar to that of ESCI-N4 profile. After building up the CMP gathers, and applying static and dynamic corrections, we came up with the synthetic stack. In this case, resolution in NMO

velocities, and hence in the stack, is better than 0.2 km/s. Therefore, we considered a simple segment (the line-drawing of the reflector imaged in the stack) and applied the migration procedure (Chun & Jacewitz, 1981) to relocate this segment. Despite the wide range of migration velocities considered, it has been impossible to place that reflector back to its original position in the synthetic model (see Fig. 12c).

This simple exercise indicates us that migration techniques are not conclusive in case of very deep, inclined reflectors, specially if the only reflection data available came from few stations at very large offsets, as is the case in the ESCI-N4 profile. Therefore, we did not develop any further the multichannel analysis to precise the existence of a deep reflector in the southern part of the section, but focused on the much more reliable image of the Moho at the Cantabrian margin.

Discussion: combining results from small and large-aperture seismic reflection data

Multicoverage sampling around the onshore/offshore transition at the northern margin of the Iberian Peninsula has been achieved by piggy-back recording the ESCI-N4 marine profile in portable stations on land.

Strong reflections at the Moho beneath the Cantabrian continental margin are present along the whole 85 km-long wide-angle stacked section (Fig. 10). This contrasts with the image of the conventional section from the ESCI-N4 profile (Álvarez-Marrón *et al.*, this vol.), where almost no evidences of near-vertical reflected energy are found at deep crustal levels.

Comparison of both stacked sections illustrates the advantage of considering large-aperture geometries which may avoid uppermost heterogeneities disturbing the vertical penetration of energy by undershooting the

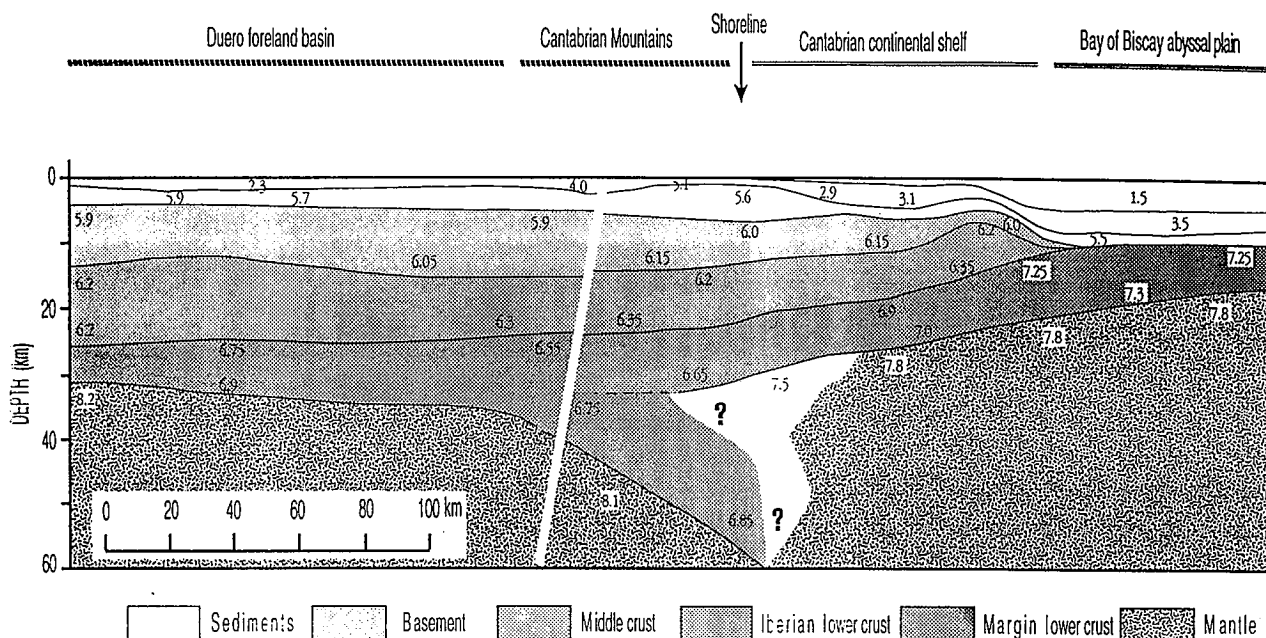


Figure 14.- Schematic crustal section integrating the seismic data sets investigated here. The white line marks the connection (shifting of 40 km) between the refraction and the wide-angle velocity models.

structure of interest at overcritical distances. Moreover, a remarkable consistency in arrival times (10 s TWT) is to be pointed out for the deep reflectivity observed in both sections, located in a short area 20 km offshore.

A full-aperture seismic section can be obtained by merging the two geometrically coincident near-vertical and wide-angle stacks, as shown in Fig. 13. This composite section provides the most complete crustal image of the Cantabrian margin, from the coast to the continental slope.

The wide-angle multicoverage cannot reveal the features at depth of the continent-ocean transition. The area seawards of the slope, where is located the accretionary prism related to the southward subduction of the Bay of Biscay oceanic crust (Álvarez-Marrón *et al.*, this vol.) is not sampled from the land recordings, and OBSs could not be available in that experiment. On the other hand, it is difficult to continue inland the N-S crustal transect provided by stacked sections. The seismic energy from the bottom of the crust beneath the northern flank of the Cantabrian Mountains cannot be imaged properly in the multichannel wide-angle processing, and the vertical profile ESCI-N2 on land is shifted 40 km eastwards and 35 km southwards of the marine line. However, the features of a N-S transect can still be discussed on the basis of the wide-angle forward modelling.

Conclusions: wide-angle seismic constraints to the ESCI-N profiles

A N-S crustal transect of the Cantabrian continental margin can be completed by integrating to the seismic images of the vertical reflection ESCI-N profiles the results of the large-aperture reflection experiments related to that project.

The vertical sections lack continuity and resolution concerning deep crustal images. The ESCI-N2 profile shows several reflective levels deepening northwards up to the end of the profile, 35 km onshore, where the lowermost reflector is located at 15 s. Along the Cantabrian margin, the marine profile ESCI-N4 displays almost no reflected energy beneath the sedimentary sequence, apart from some reflections at 10 s TWT in a short segment 20 km offshore (Álvarez-Marrón *et al.*, this vol.).

In the southern part of the transect, involving the transition from the Duero basin to the Cantabrian Mountains, the refraction profile 5 constrains the seismic velocities of the different crustal levels imaged on the ESCI-N2 line, and confirms a Variscan-type crust beneath the Duero basin. This crust has been completely reworked beneath the Cantabrian Mountains, probably in relation with the Alpine tectonics, resulting in a significant crustal thickening northwards. The amount and extend of this thickening cannot be controlled by the profiles on land (for that purpose, they should have been recorded by devices at sea).

However, the piggy-back recording of the marine ESCI-N4 shots on 7 land stations, aligned from the coast

to 60 km inland, provides an additional high-quality wide-angle data set that constrains the deep crust at the transition from the Cantabrian Mountains to the continental margin along a transect shifted 40 km to the west of the southern segment. The dense-spaced receiver gathers display reflected energy from deep crustal levels that have been attributed in the forward modelling to two different Moho levels. The deeper one is located on the southern part of the sampled area, up to the shoreline where it reaches 60 km depth, and correspond to the northward continuation of the dipping "Iberian Moho" imaged in the land profiling. Between the coast and the continental slope, a much shallower "Cantabrian margin Moho" is well constrained by the velocity-depth model as well as by the wide-angle stacked section. It is located at 30 km depth beneath the shoreline, and shows a progressive crustal thinning along the continental platform, up to 22 km depth at the continental slope. Further North, higher crustal velocities suggest the presence of a transitional or oceanic-type crust, but in that area the model resolution is low, in the absence of OBS data, and there is no wide-angle multicoverage data.

The N-S seismic transect completed by combining small and large-aperture reflection data sets is summarised in Fig. 14 and shows a relevant crustal thickening beneath the Cantabrian Mountains and an abrupt transition towards the continental margin. The structural image indicates the imbrication of two crusts of very different thickness, with a wedge-type pattern of crustal subduction northwards. This image is similar to the Pyrenean one from the ECORS profile, and reveals the importance of the Alpine tectonics at the western end of the Pyrenees.

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