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The ESCI-N Project after a decade: a synthesis of the results and open questions

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Abstract: A synthesis of the results and conclusions from the data corresponding to the ESCI-N project is presented. The ESCI-N project developed in the early 90's providing the first set of deep reflection and refraction data for the Cantabrian Mountains and adjacent areas. The discovery of a crustal root beneath the highest picks of the Cordillera marked a hit point on the studies and the relationship between the Cantabrian Cordillera and the Pyrenees became clear after the ESCI-N project. The study and interpretation of these data produced important findings and new constraints greatly improving the geodynamical and evolutional models of the area.

Key words: ESCI-N project. Reflection and refraction seismics, gravity, crustal root, Variscan orogeny, alpine orogeny.

Resumen: En este artículo se presenta una síntesis de los datos y resultados obtenidos a partir del proyecto ESCI-N, desarrollado en la década de los 90 y que proporcionó las primeras secciones sísmicas de la cordillera y margen Cantábricos. El descubrimiento de una raíz cortical bajo las principales alturas de la cordillera marcó un antes y un después en los estudios y la relación entre la Cordillera Cantábrica y los Pirineos se hizo más clara después del proyecto ESCI-N. El estudio e interpretación de estos datos hizo evolucionar espectacularmente el conocimiento profundo de la corteza terrestre en estas áreas aportando nuevas ideas y modelos sobre la evolución geodinámica del Noroeste Peninsular.

Palabras clave: Proyecto ESCI-N, sísmica de reflexión y refracción, gravedad, raíz cortical, orogenia varisca, orogenia alpina.

The ESCI-N project in North-western Spain was a subprogram of the ESCI Program (Estudios Sísmicos de la Corteza Ibérica), funded by the Spanish administration in the framework of the 1987-1991 National Plan of Research and Technology Development.

Prior to the ESCI-N project and experiments, information about the structure, velocities or even approximate thickness of the crust and nature of the crust-mantle boundary, was non existent for the Cantabrian Cordillera and sparse for surrounding areas. Refraction experiments in the 80's to the West of the ESCI-N project in Galicia, showed a typical Variscan crust with an average thickness of 30 km. (Córdoba et al., 1987; Téllez et al., 1993), similar to other Variscan massifs in Europe (e.g. Prodehl and Aichroth, 1992; Matte and Hirn, 1988; Meissner et al., 1987). The Cantabrian margin at sea had been explored, mainly by French scientists in the 70's (e.g., Boillot et al., 1979; Sibuet and Le Pichon, 1971; Malod et al., 1982) and commercial reflection lines for exploration of oil and gas provided images of the platform (Soler et al., 1981). However, lithospheric structure was unknown until ESCI-N results came out.

The ESCI-N program boosted the geophysical knowledge in the area and provided new and crucial information for the evolution hypotheses of the Cantabrian Cordillera and the North Iberian Margin, emphasizing the relationship between the Pyrenees and Cantabrian realms as parts of a bigger geotectonic picture.

The ESCI-N project focused on four near-vertical deep seismic reflection transects complemented by other geophysical methods such as refraction/wide-angle seismic reflection and gravity and by geological studies based on surface and industrial subsurface data. The survey was originally designed to provide a crustal cross-section of the Variscan orogenic belt in NW Spain as well as the North Iberian Margin to the N and the Duero Basin to the S (Figure 1).

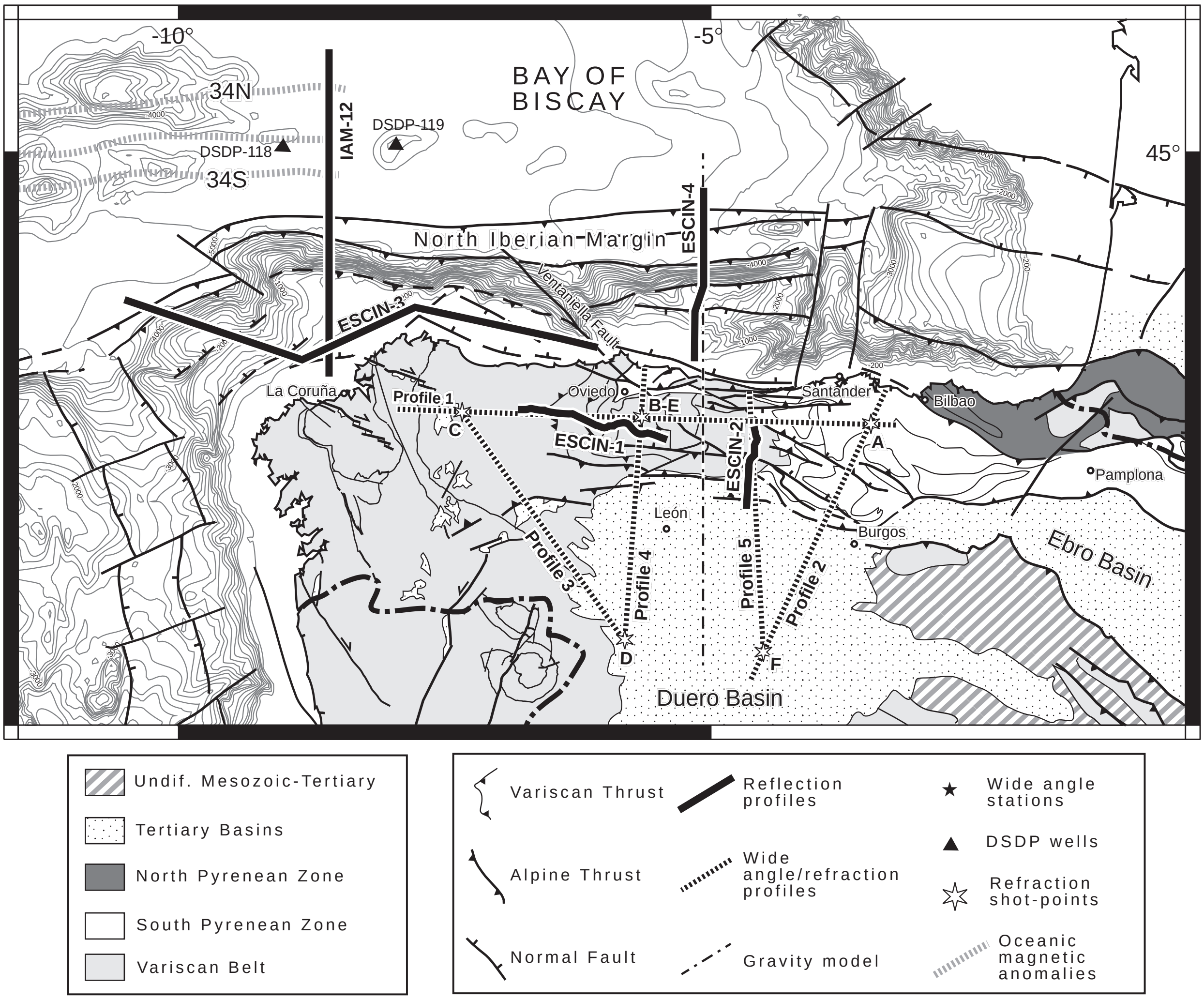

Figure 1. Simplified tectonic setting of the ESCI-N Project in North-western Iberia. Offshore geology indicates the location of the buried accretionary deformation prism and the NW-SE trending major strike-slip faults in the continental margin. Onshore geology indicates major Alpine structures and Variscan basement zones. The lines indicate the ESCIN seismic profiles.

In order to gain insight into the Variscan structures, the reflection profiles ESCIN-1 on land and ESCIN-3 at sea, were sub perpendicular to these structures, running East-West. ESCIN-3 also targeted the younger Mesozoic and Cenozoic structures of the continental platform North of Galicia. Profiles ESCIN-2 on land and ESCIN-4 in the Cantabrian Sea were perpendicular to the Alpine structures, running approximately North-South. ESCIN-2 focused on the deep structure of the transition between the Tertiary Duero basin and the Cantabrian Mountains and ESCIN-4 imaged the crustal structure of the North Iberian Margin.

A series of deep refraction/wide angle reflection profiles were acquired on land together with the deep seismic lines to provide information about velocities and crustal thickness in the area (Profiles 1 to 5 in figure 1). In addition, stations onshore recorded the deep reflection marine profiles ESCIN-3 and ESCIN-4 providing wide angle coverage from the transition between the continental and oceanic domains.

The ESCI-N experiment. Data.

The first deep seismic reflection profile on land in the Cantabrian Cordillera, and by extension in the Northwest of the Iberian Peninsula, was ESCIN-1, recorded in 1991 by the company CGG (Compagnie Generale de Geophysique). The profile was 140 km long, oriented at high angle to the trend of the Variscan structures. The other land profile ESCIN-2, with 65 km length, was recorded through the area of higher topography in the mountains, and aiming primarily to image the Alpine structures, in the North-South direction (Figure 1). The seismic lines were processed by the contracted company and some problems arose during the recording due to the rugged topography and to the high ambient noise in the valleys. Detailed description on acquisition and processing of the ESCIN-1 and ESCIN-2 land profiles can be found in Pérez-Estaún et al., (1994) and Pulgar et al., (1996), respectively.

The ESCI-N deep seismic marine survey included ESCIN-3, divided in three segments with a total length of 380 km, and ESCIN-4, 144.75 km long (Figure 1). The transects were recorded during February 1993 by the MarineVessel SeisQuest. Acquisition and processing were done commercially by Schlumberger GECO–PRAKLA and the details are described in Álvarez-Marrón et al., (1996) and Martínez-Catalán et al., (1997).

The refraction/wide angle reflection profiles 1 to 5 were acquired on land with dynamite charges on shot points A to F, being quasi-coincident with the deep seismic lines ESCIN-1 and ESCIN-2 in the case of Profiles 1 and 5 respectively (Figure 1). The refraction/wide angle reflection profiles ESCIN-3 and ESCIN-4 were acquired using the airgun shots of the reflection vessel as source and recording continuously while the ship made the reflection line at sea. These profiles provide information about the transitional area between the land and the deep sea, with the limitation of lacking the reversed profiles. Details about acquisition, processing and 2-D modelling of the data can be found in Ayarza, (1995), Fernández Viejo, (1997) and Fernández Viejo et al., (1998; 2000).

Gravimetric models along the North-South ESCI-N transects were done (Fernández Viejo et al 1998; Gallastegui, 2000) based on a gravimetric map compiled from sea data (Sandwell and Smith, 1997) and land data provided by the BGI (Bureau Gravimetrique International), complemented by new data acquired along ESCIN-1 profile (Aller, 1993) and selected parts of the studied area (Gallastegui 2000).

The ESCI-N geology: From Variscan belt to the opening of the Bay of Biscay and the Alpine orogeny. A short synthesis of a long story.

The portion of the Variscan belt that crops out in NW Spain corresponds to one of the continental margins involved in the Variscan collision, and constitutes one of the best sections of the Variscan belt in Europe outcropping along 300 km of coastline that runs E-W perpendicular to the strike of the orogen (Matte, 1991). The foreland thrust and fold belt of the Variscan orogen, named Cantabrian Zone, contains east-directed thrust units emplaced during Carboniferous times showing a tight arcuate trend (Pérez-Estaún et al., 1991). The tectonic style is interpreted as thin-skinned with a main detachment located near the Precambrian-Cambrian boundary. To the West, the Cantabrian Zone is separated from the hinterland areas of the orogen by the Narcea antiform, a thrust sheet stacking with Precambrian rocks exposed in its core, the so-called Narcea Antiform. The belt underwent Alpine tectonism especially in the East, forming the actual reliefs of the Cantabrian Mountains that constitute the western extension of the Pyrenees. The Palaeozoic and Precambrian rocks cropping out in the Cantabrian Zone where the seismic study was achieved, form the core of a basement uplift formed during Tertiary times (Alonso et al., 1996).

By the end of the Carboniferous the crust of the continental shelf in north-western Iberia was made up of deeply rooted structures related to the Variscan collision. From Permian to Triassic times the tectonic setting changed and the northern Iberian continental margin underwent approximately N-S rifting during Late Jurassic-Early Cretaceous times. The relative movements between the North American, European and Iberian plates during Early Cretaceous time induced the formation of the Bay of Biscay, contemporaneously with the opening of the North Atlantic Ocean, dividing the European Variscan belt. The absence of magnetic Chron M0 and the age of the synrift sediments drilled on the North Biscay margin mark the beginning of rifting during the Early Cretaceous (Montadert et al., 1979) and the beginning of the oceanic accretion in Late Aptian-earliest Albian time. Prerift sediments consist of Jurassic platform carbonates. As Chron 33 (80 Ma) has not been clearly recognized, the oceanic accretion of the Bay of Biscay ceased after Chron 34 (Williams, 1975). The later post-rift structural evolution of the Bay is strongly linked to the Pyrenean orogenic phases induced by the Campanian –Oligocene (80-35 Ma) convergence of the Iberian Peninsula towards Europe. This approximately N-S convergent movement led to the partial closure of the Bay of Biscay and major deformation of the North Iberian margin.

With this extended history of orogenesis, rifting, ocean formation and collision, the ESCIN project was the beginning of a long time overdue task to image the deep structure and lithospheric characteristics in the area and to unravel the evolution of the Cantabrian Mountains and adjacent margin.

The ESCI-N project and the Variscan features.

The very first image of the Cantabrian zone at depth was imaged in the E-W ESCIN-1 deep seismic profile and showed strong inclined reflections correlatable with Palaeozoic rocks at the surface deformed by thrusting

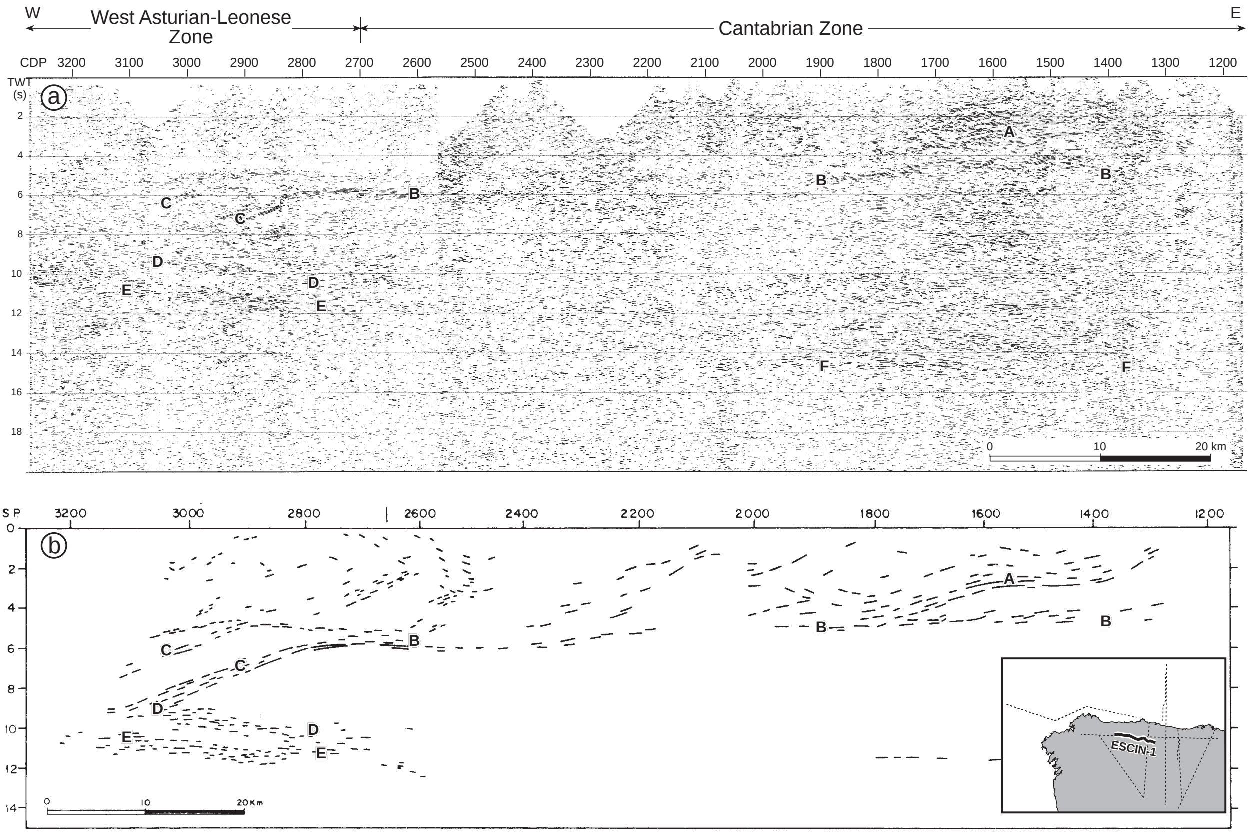

Figure 2. Seismic reflection profile ESCIN-1 in the external parts of the Variscan Orogen in NW Spain. a) Stack section with the interpretation of the main reflections. b) Line drawing of the ESCIN-1 profile from Pérez-Estaún et al., (1994).

and folding during the Carboniferous (A in figure 2). Some of the major thrust fault imaged a ramp-flat geometry merging into a highly reflective band at 5-6 s TWT interpreted as the so-called Cantabrian Zone detachment (Pérez-Estaún et al., 1994) (B in figure 2). The Precambrian basement showed to be seismically transparent in this area, and Moho was interpreted at the base of a few sub-horizontal reflectors at 11 s TWT (E in figure 2).

At the transition to the Variscan hinterland, short inclined reflections were interpreted as corresponding to the Narcea Antiform, placed above a crustal ramp imaged by strong west dipping reflections between 6 and 9 s TWT (C in figure 2). These reflections merge towards the Cantabrian Zone detachment at 6 s and downwards into a reflective lower crust between 9 and 12 s (D in figure 2). These intracrustal reflectors were interpreted as the major Variscan shear zone that marks the transition between the thin-skinned tectonics of the external areas and the thick-skinned tectonics of the hinterland areas. The different signature of the lower crust in the external and hinterland zones suggested that Variscan tectonics affected deep crustal levels in the hinterland areas whereas remained relatively undeformed beneath the foreland. However, the interpretation of the eastern side was further modified by Gallastegui et al (1997) based on a 2-D normal incidence ray tracing modelling constructed from geophysical and geological surface data, proposing a duplication of the Cantabrian Zone basal detachment by a south oriented Alpine thrust that affected the basement (Figure 3). The Moho was also relocated beneath the Cantabrian Zone at 15 s (F in figure 2) where reflectivity suddenly decreases. This hypothesis was developed after interpreting the North-South oriented land profile ESCIN-2 (Pulgar et al., 1996) and related to geological studies in the area (Alonso et al., 1996). It also provided the explanation for the differences in seismic character of the lower crust at the Eastern and Western parts of ESCIN-1.

The Variscan crust was also imaged and quantified based on the results of the refraction /wide angle reflection profile 1 parallel to ESCIN-1 (Fernández Viejo 1997, Fernández Viejo et al., 2000). The crust was divided in three levels: The upper crust, until 12 km depth, with average seismic P-wave velocities of 5.6-6 km /s. The middle crust, showing average velocities of about 6.2-6.4 km/s and a thickness of 10-15 km. The lower crust was represented most of the time by a thin layer of about 10 km, with velocities between 6.7 and

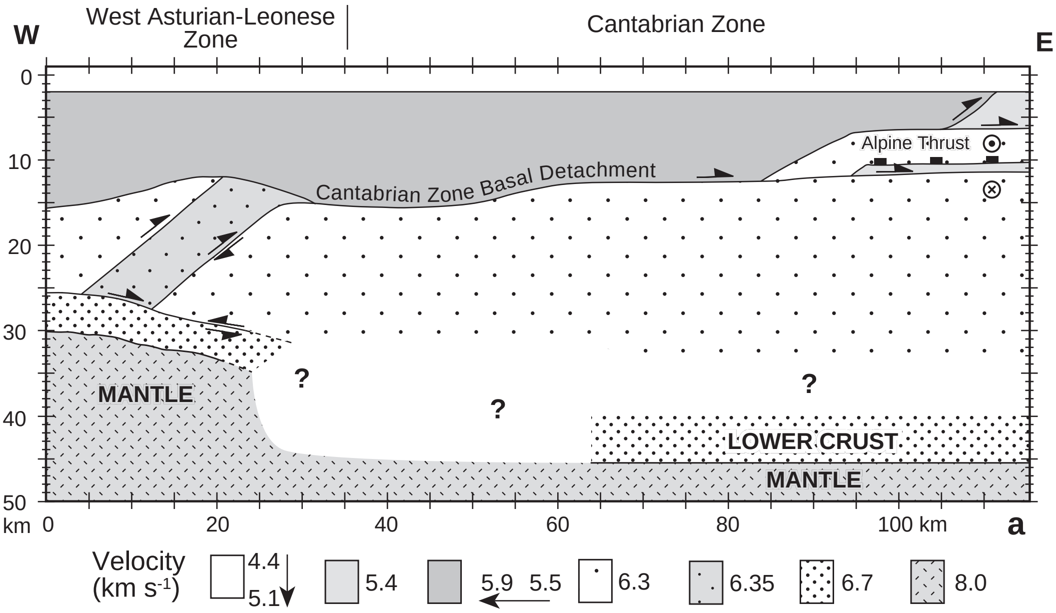

Figure 3. Final model obtained after seismic modelling by Gallastegui et al., (1997) of profile ESCIN-1. The hanging wall of the Alpine thrust moves to the South. Velocities used in the model (km/s) are derived from different sources.

6.9 km/s. The Moho was a first order discontinuity at a depth of around 30-32 km characterized by a jump in velocities to 8.0 km/s, characteristic of mantle rocks. These results were confirmed in a following refraction experiment that repeated and extended eastwards this profile in 1997 (Pedreira et al., 2003; Pedreira, 2004).

At sea, the marine ESCIN-3 near vertical reflection seismic profile was divided in three segments that cross the entire continental margin off north-western Galicia. The platform sampled in profile ESCIN-3 also revealed Variscan crustal structures (Figure 4). ESCIN-3.2 and ESCIN-3.3 show sub-horizontal and dipping reflections at mid-crustal levels that have been related to Variscan compressional structures on land (Ayarza et al., 1998). They also show a very reflective lower crust, whose age is controversial (Álvarez-Marrón et al., 1996). Duplication of the reflective lower crust in segment ESCIN-3.3 (K, L in figure 4) has been the matter of three hypotheses: a preserved crustal-scale Variscan underthrusting, an arrested delamination affecting a thick Variscan crust, or an alpine imbrication (Ayarza et al., 1998). Velocity/depth models of the profile from the refraction/wide angle reflection data proved again a Variscan type of crust in the platform north and West of Galicia (Ayarza, 1995; Fernández Viejo, 1997; Ayarza et al., 1998), similar to the one encountered on land to the West in the 80's (Córdoba et al., 1987). Moho depth is located at around 28 km with gentle variations along the platform (Ayarza, 1995). To the West, in the ESCIN-3.1 segment the transition to the oceanic crust occurs from about 28 km thickness on land to about 11 km in the open sea. (Fernández Viejo, 1997).

The alpine imprint: the crustal root of the Cantabrian Mountains.

The E-W verging Variscan features dominating the ESCIN-1 and ESCIN-3 profiles to the West, along with the refraction profiles, loose their character in the crust towards the oriental domains of the Cantabrian Zone, where the N-S Alpine features dominate.

The first and surprising hint about the presence of a thickened crust beneath the highest picks of the Cantabrian Mountains came from the refraction/wide angle reflection profiles (Pulgar et al., 1996; Fernández Viejo et al., 1998). In profile 1, (Figure 5) the wide angle reflection coming from the crust-mantle boundary displayed very different times at the west and east of the profile. The interpretation of the data, based on inversion of travel times, provided the velocity model for the crust beneath the Cantabrian Zone, and evidenced a big crustal thickness difference between the eastern Cantabrian Zone, reworked in Alpine times at depth and the typical Variscan domains in the west. Moho deepened from about 32 km in the west to more than 45 km depth in the eastern side of the profile, beneath the highest summits of the Cantabrian Mountains.

The most outstanding feature in the N-S deep seismic profile ESCIN-2 (Figure 6) is that beneath the well-imaged Duero Basin the base of the reflective lower crust is subhorizontal at 12 s (33 km) but it bends and deepens northwards until it reaches more than 14 s in the northern end of the profile beneath the Cantabrian Mountains (approximately 47 km). This fact

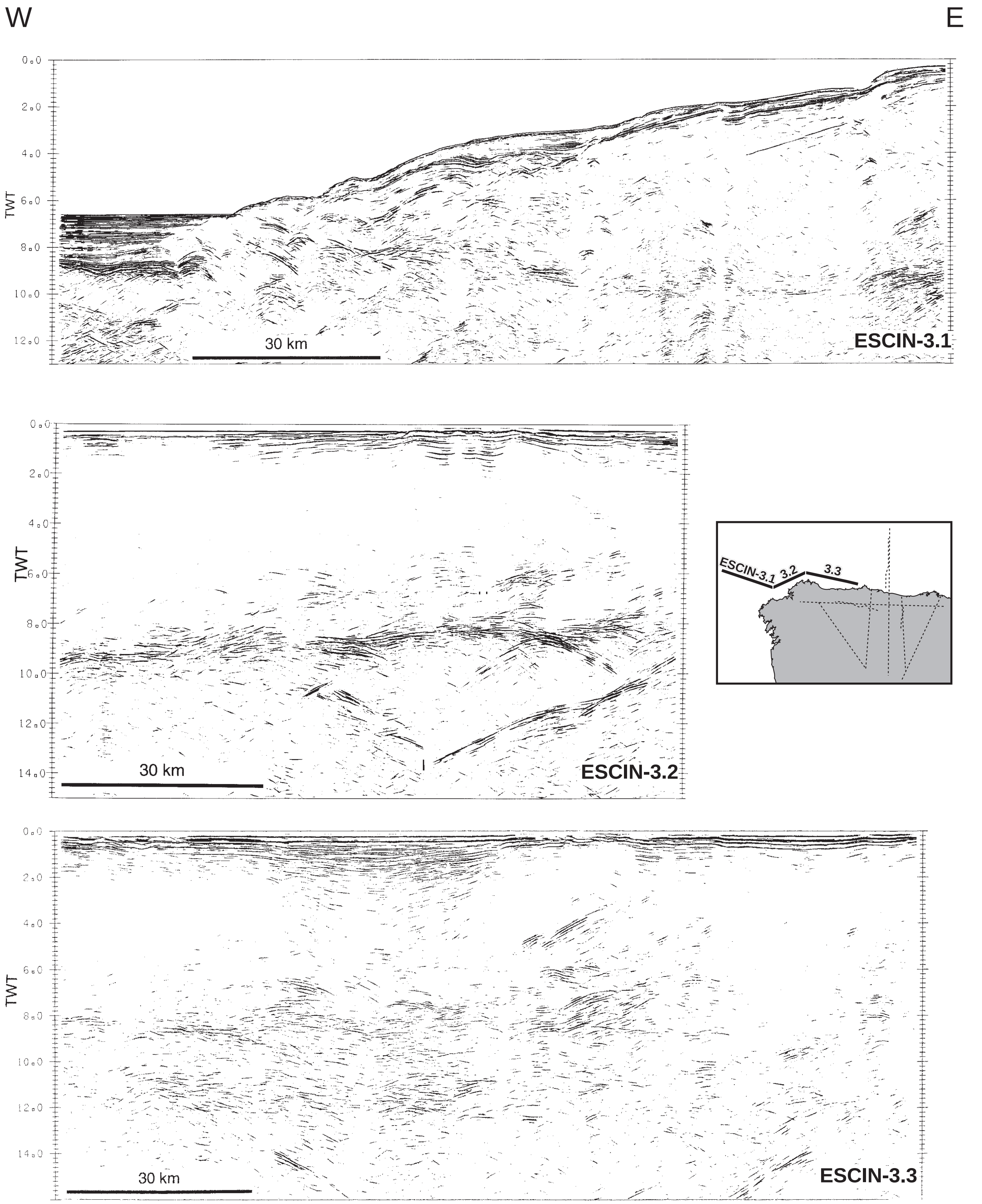

Figure 4. The three segments that compose profile ESCIN-3. Stack coherence filtered sections from Álvarez-Marrón et al., (1996).

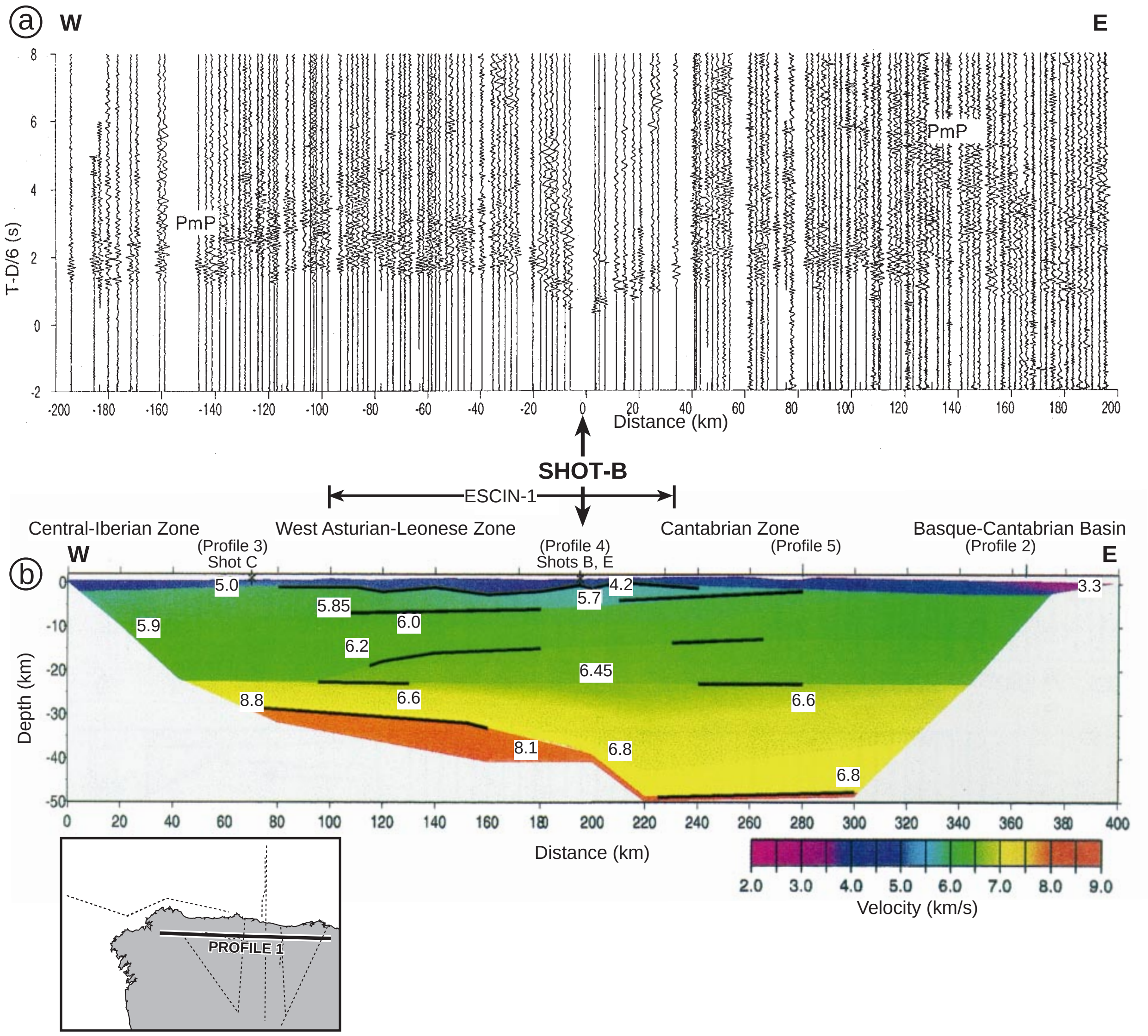

Figure 5. a) Record section of wide angle refraction data from shot point B in Profile 1. Note the difference in times for both PmP at west and East of the shot point. b) Velocity-depth model derived for the E-W profile 1 of refraction/wide angle reflection data from Fernández Viejo et al., (2000). Numbers indicate some representative velocities in km/s. Intersection with other N-S profiles are indicated at the top, as well as the area covered by deep seismic profiles ESCIN-1. The areas beneath the profile (edges and deepest parts) unconstrained by the data are not shown in the model. The layer segments directly sampled by ray paths of the refracted and reflected phases are indicated in black bold lines.

corroborated the interpretation of the refraction profiles and implied not only the thickening of the crust, but a bending of the Iberian lower crust imaged by the N dipping lower crust reflective lamellas (Pulgar et al., 1996; 1997). A magnetotelluric profile coincident with ESCIN-2 also shows the deepening of the crust-mantle boundary to the North (Pous et al., 2001).

In the upper crust, the Alpine imprint is exemplified by discontinuous north dipping reflections in ESCIN-2 interpreted as belonging to the Alpine thrusts merging at 6 s TWT as mid-crustal detachments (Gallastegui, 2000). The southwards thrusting of several crustal slices along these features gave rise to the uplift of the Cordillera in the area (Alonso et al., 1996). The erosion of these reliefs provided the detritus that filled the Duero foreland basin in the South and the basins in the Cantabrian margin to the North. In the interior of the uplifted basement block the alpine deformation was solved basically through the reactivation of former Variscan thrusts and the inversion of Mesozoic normal faults. The amount of shortening of the Variscan basement in the Cantabrian Cordillera has been estimated in about 20%, and a further consequence of the alpine deformation is the steepening of the Variscan thrusts (Pulgar et al., 1999).

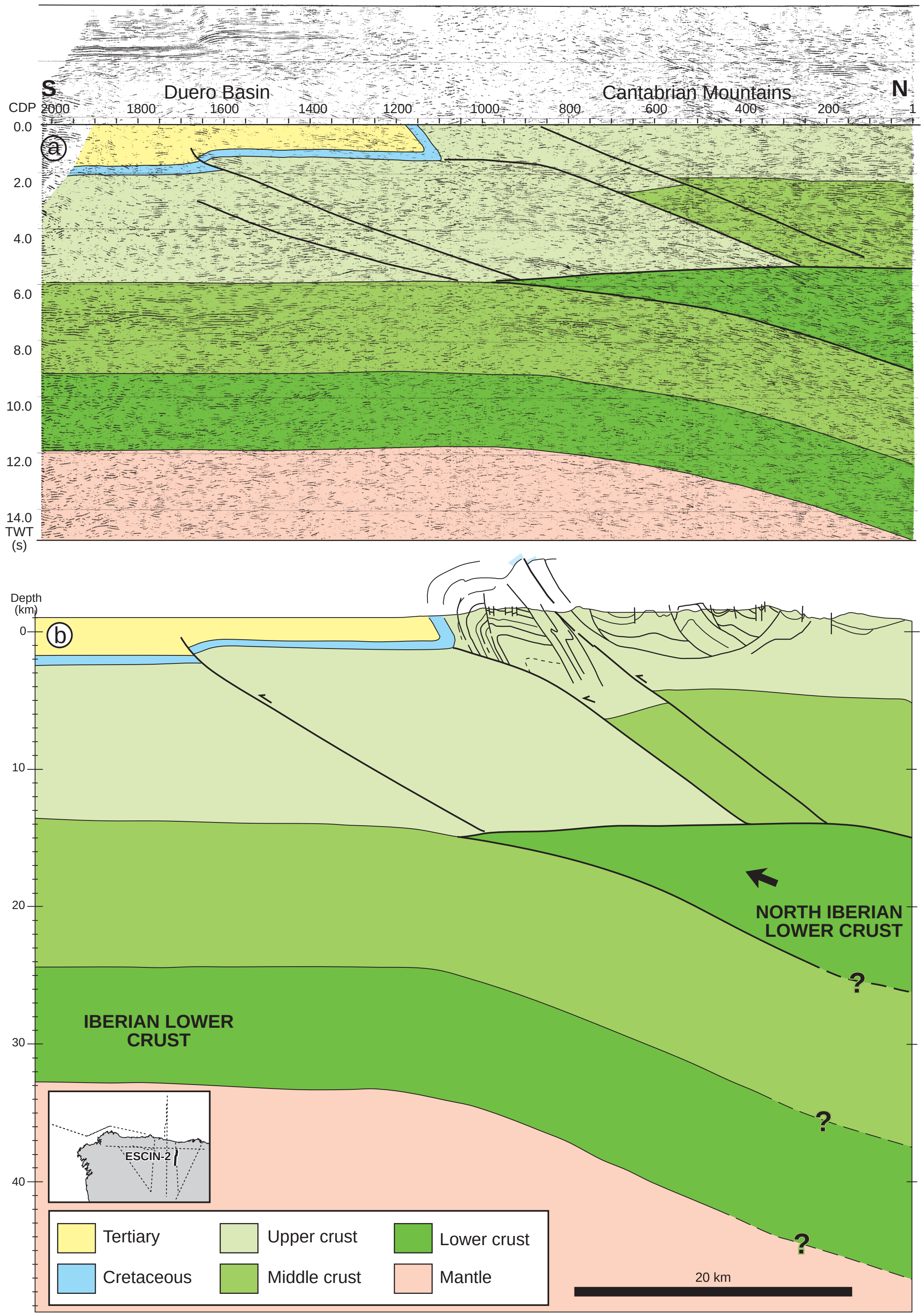

Figure 6. Deep seismic reflection profile ESCIN-2. a) Unmigrated, coherency filtered stack showing the main reflections interpreted in the text (Pulgar et al., 1996). b) Geological model and interpretation of the profile (Gallastegui, 2000).

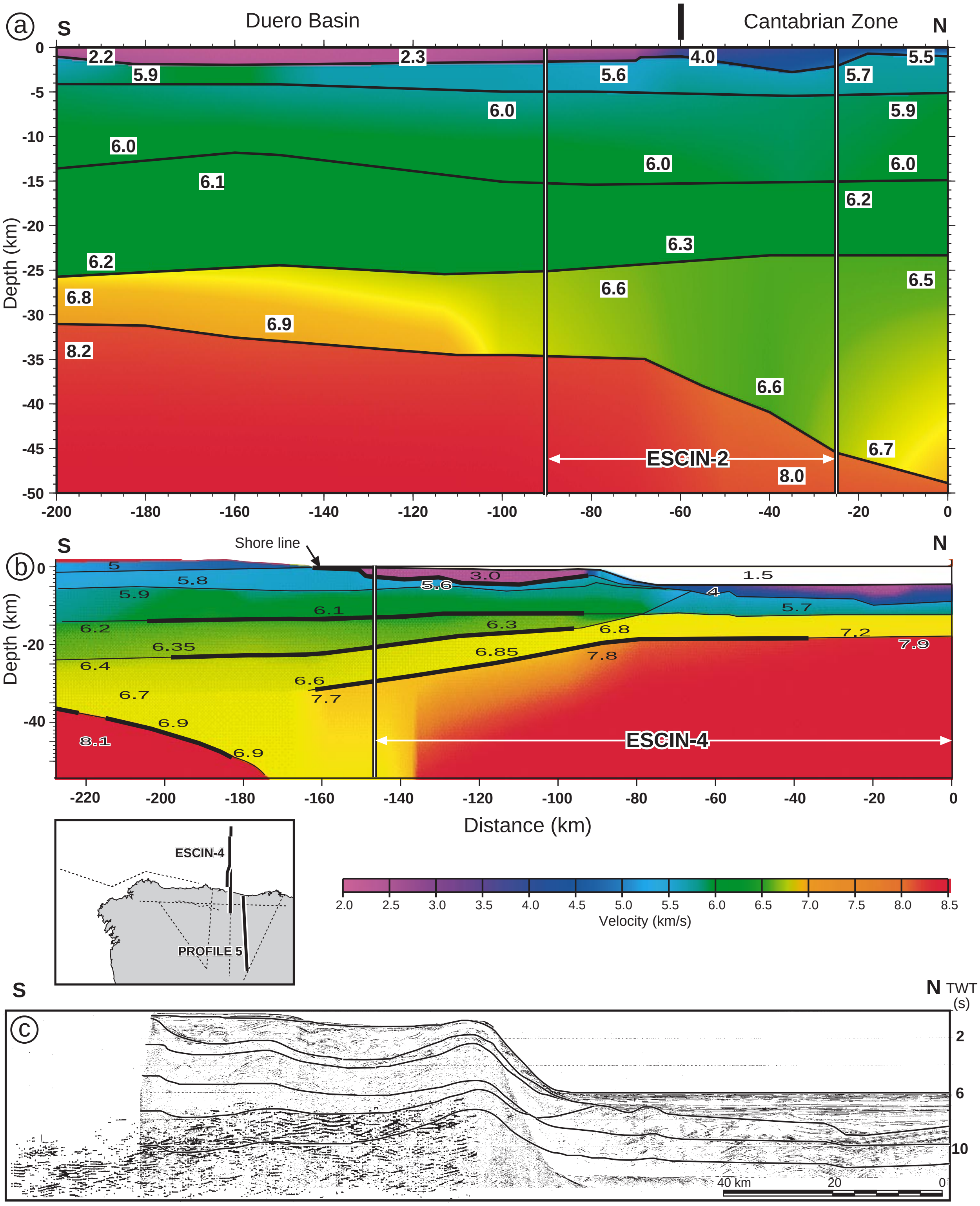

Figure 7. a) P-wave velocity model for profile 5 (Fernández Viejo et al., 1998) showing the coincidence with the near-vertical profile ESCIN-2. b) P-wave velocity model from profile ESCIN-4 (Fernández Viejo et al 2000). Thick black lines show the constrained horizons by ray-tracing. c) Stack coherency filtered section of deep seismic profile ESCIN-4 and overprinted the final N-S stacked section combining the near-vertical and wide angle data from ESCIN-4 profile (from Gallart et al., 1997).

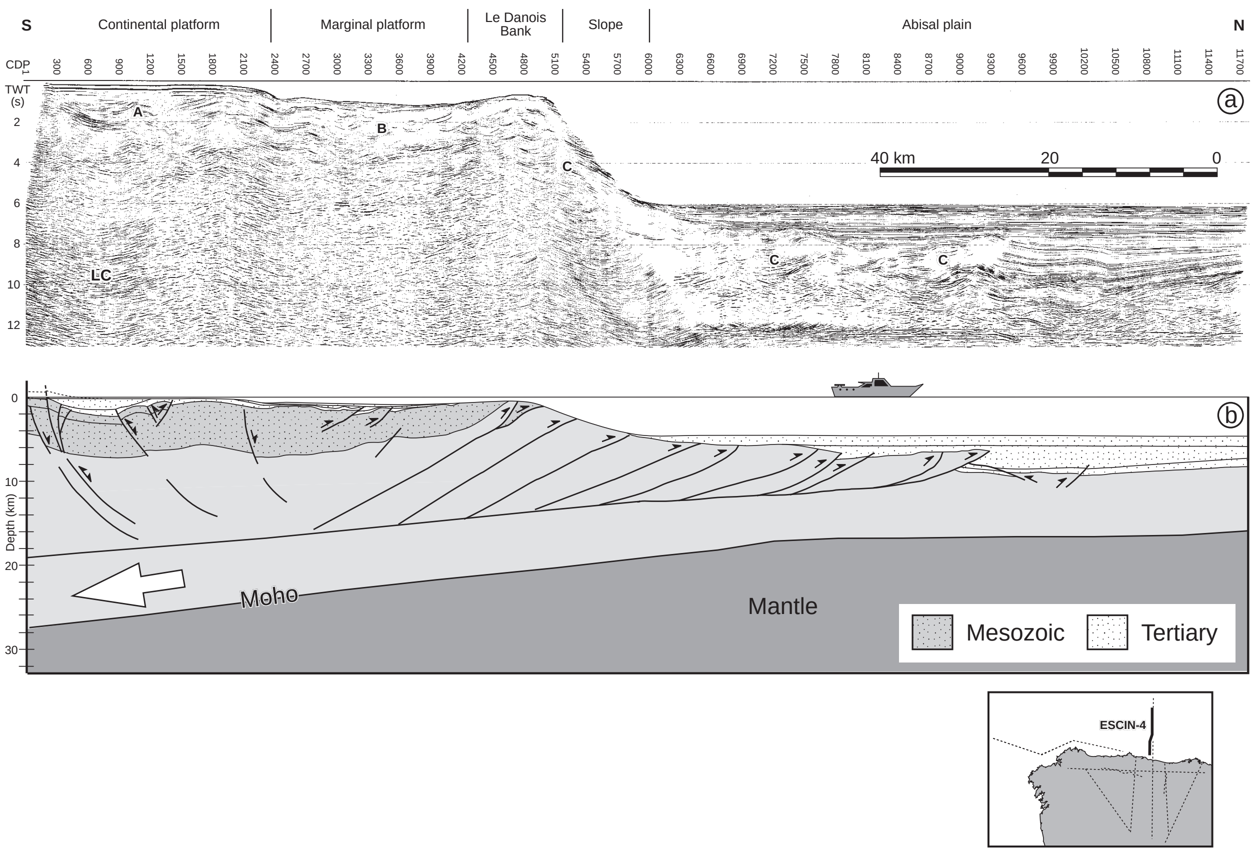

Figure 8. Deep seismic reflection profile ESCIN-4 and geological interpretation (Gallastegui et al., 2002).

Following the crustal root to the North. The plate boundary and the North Iberian margin.

Once the crustal root had been imaged in the refraction and reflection data, the immediate task was to investigate its extent and continuity to the North where the continental margin precluded the continuation of the root structure as such. To the West its absence was confirmed by the deep seismic reflection and refraction data and to the East it was confirmed *a posteriori* by later refraction experiments in 1997 (Pedreira et al., 2003). Another question that arose related to the existence of the crustal root was the way in which compensation of such a deep root was achieved by today's average 2000 m heights in the Cordillera.

The main source of data to study this subject came from the ESCIN-4 deep seismic profile and especially from the refraction profiles in the N-S direction, profile 5 on land (Figure 7a) and profile ESCIN-4 offshore that imaged the transition between the continental and oceanic domains (Figure 7b and 7c). Seven autonomous three-component land stations recorded the marine deep profile providing wide angle sampling of the margin coincident with ESCIN-4 but extended 70 km onshore. This data set was analyzed using two different methodologies: classical velocity depth forward modelling (Fernández Viejo, 1997) and multichannel processing of Moho reflections (Gallart et al., 1997) (Figure 7c).

The methodology relies upon redundancy of ray paths similar to standard multichannel reflection data processing methods, (produced by high density air gun shots and a number of receivers onshore) and the larger amplitude reflections as predicted by ray theory at wide angles as the critical angle of incidence is approached or exceeded. This provided a large-aperture stacked section that could be superposed on the conventional ESCIN-4 to enhance the signature of the crust-mantle boundary beneath the continental platform, which in the deep seismic profile was almost absent. The result showed that the lower crust was a continuous level beneath the platform that extended southwards under the Cantabrian Mountains.

The refraction data showed two different Moho PmP reflections (Fernández Viejo et al., 1998), one at the continent tying with the Moho observed at ESCIN-2 profile on land and refraction profiles 5 and 1; another Moho corresponding to the margin was modelled based on another big amplitude PmP wide angle reflection from the ESCIN-4 refraction data (Fig. 7b). The wide-

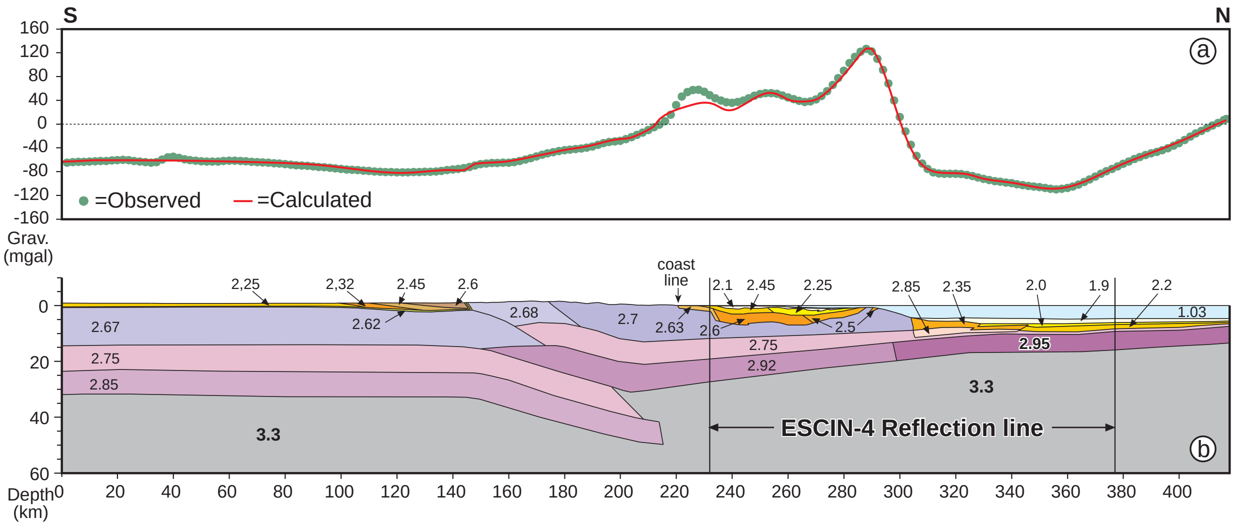

Figure 9. Gravimetric transect from the center of the Bay of Biscay to the Duero Basin in the S coincident with the ESCIN-4 profile (Gallastegui, 2000).

angle multichannel analysis and stacking of the PmP phases confirmed the geometry of the Moho beneath the margin shallowing to the North and the presence of a deeper very steep Moho in the southern part along some kms. (Gallart et al., 1997). The depth of the Moho beneath the margin coincides at 10 s TWT with the only deep reflections encountered in the ESCIN-4 deep reflection profile (LC in figure 8).

The final velocity model (Figure 7b) showed geometry where the lower crust was considerably thickened in land with a steeply dipping Moho to the North beneath the shoreline. This land structure was relayed towards the ocean by a Moho beneath the margin that shallows gradually from 31 to 18 km depth in the abyssal plain. The upper mantle had anomalously low Vp velocities beneath this marginal Moho. The detailed geometry of the two Mohos beneath the coast was enigmatic, due to the absence of a reversed profile. However, a gravity model translating the seismic velocities into densities was done to infer a geometry for the two Moho interfaces (Figure 9). The solution was to interpret wedge-type geometry with an imbrication of the Biscay thinned crust in Iberia where the lower crust had been detached and subducted to the North as also interpreted in the northern end of ESCIN-2. The image closely resembled the one obtained to the East in the Pyrenees, for the European crust and the Iberian plate in the ECORS profile (ECORS Pyrenees Team, 1988). The low velocities in the mantle are probably related to partial melting of the Iberian lower crust, as it has been suggested based on the presence in this area of a conductivity anomaly at depth (Pous et al., 2001).

The upper structure of the crust and sedimentary sequences of the platform is better solved in the near-vertical reflection profile, where the Mesozoic basins were tectonically inverted during the Tertiary. Gallastegui, (2000) and Gallastegui et al., (2002), interpreted in detail these upper sedimentary packages and structure including information from commercial lines and wells from the North Iberian platform. The structures interpreted include inverted Mesozoic normal faults and associated folds near the shore (A in figure 8) and N verging Tertiary thrusts that developed several Tertiary basins in the transition to Le Danois Bank in the N (B in figure 8) (Gallastegui et al., 2002). Most of the deformation concentrated in the imbricate of thrusts that developed along the steep continental slope and its foot, where a thick sedimentary package between 6 and 9-5 s TWT includes a 50 km long north tapered wedge of mainly south dipping reflections corresponding to disturbed sediments within an alpine accretionary prism (C in figure 8). An upper sedimentary package onlaps onto the prism suggesting the cessation of the tectonic activity in the prism that has been dated Late Oligocene. Below this sedimentary package, no other information can be inferred with a degree of certainty about the basement or crustal structure. (Figure 10).

The western side of the North Iberian margin.

The marine ESCIN-3 near vertical reflection seismic profile provides images of the structure beneath the continental shelf and the transition to the Bay of Biscay oceanic crust (Figure 4). In contrast with ESCIN-4, the westernmost segment ESCIN3-1 shows a gentle topographic profile of the continental slope and very different geometrical patterns in the reflectivity. Horizontal reflections from 6.5 to 8.6 s TWT correspond

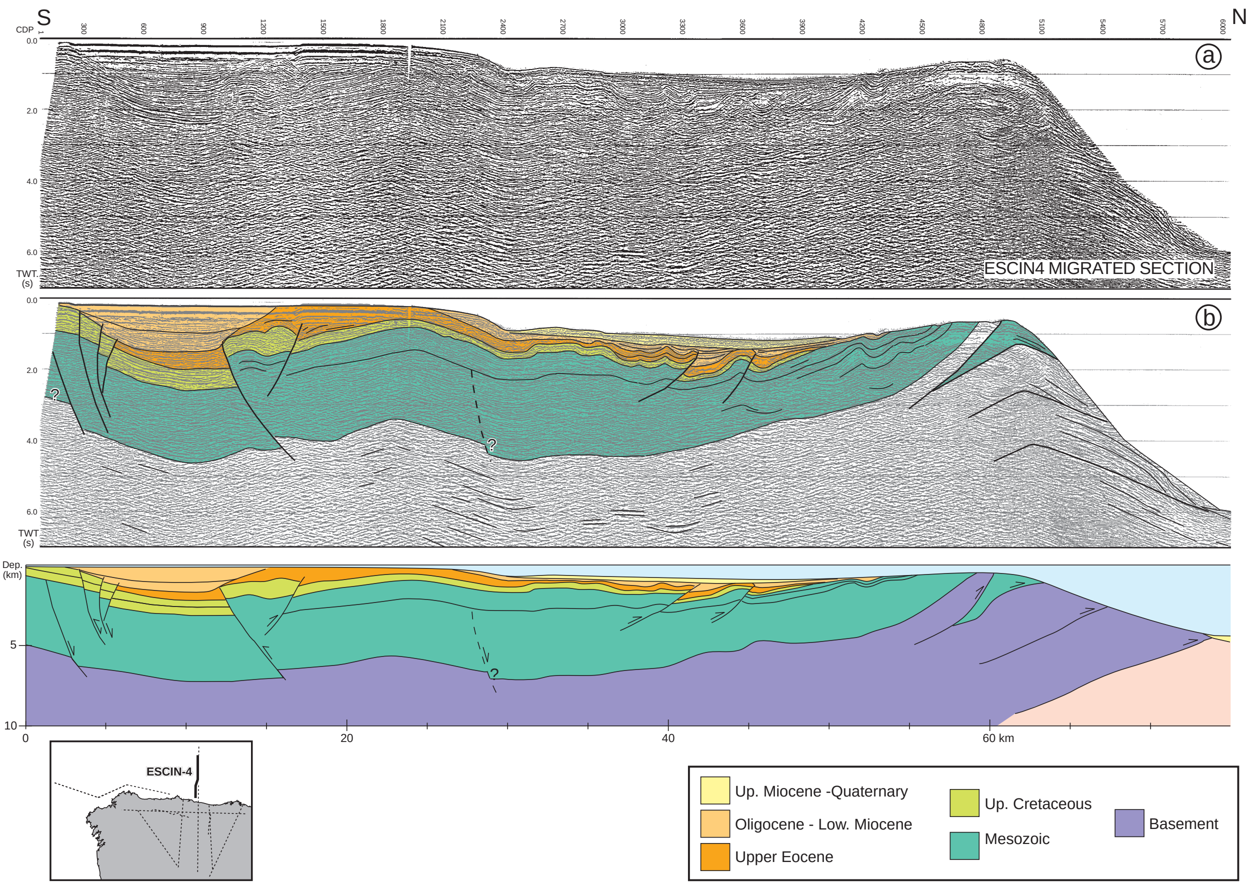

Figure 10. Detailed structure of ESCIN-4 profile along the Cantabrian platform showing the inversion o Mesozoic structures and development of Tertiary thrusts (Gallastegui et al., 2002).

to an undisturbed package of sediments lying above and oceanic-type basement, whereas in ESCIN-4 this type of basement was absent. The oceanic Moho can be tentatively correlated with reflections at 11.2 s TWT (F in figure 4) (Álvarez-Marrón et al., 1996; 1997b). The velocity depth model obtained from the wide angle recordings of this profile showed a good correspondence with Moho discontinuity at around 28 km depth in the continental platform shallowing to 20 km in the oceanic domains to the West, which implies a thickness for the oceanic crust in the area of about 6 km (Fernández Viejo, 1997). Sub-Moho velocities are typical for mantle rocks, in contrast with the anomalously low Vp velocities observed beneath ESCIN-4. A tectonic accretionary prism, seen at the ocean-continent transition, and a band of reflections dipping gently towards the south-east from the base of the continental slope are the other structures related to the convergence of the European and Iberian plates. A major thrust separates the shortened and deformed sediments in the accretionary prism next to the undisturbed previously extended continental shelf (Álvarez-Marrón et al., 1996).

Dipping, mid-crustal reflections in segment ESCIN-3.2 that image the inner parts of the continental platform are interpreted as Variscan features. Younger features imaged mainly near the surface are interpreted as recent slope-drape and sag basins in ESCIN-3.3 and ESCIN-3.2 respectively (Ayarza, 1995). Lower crustal reflectivity in the continental margin is well imaged in both profiles and can be followed until the ocean-continent transition in ESCIN-3.1. The layered lower crust may represent shear zones related to ductile crustal stretching during the Mesozoic that has produced the thinning of the continental crust to the formation of the Bay of Biscay. It could also be a remnant after extension of an originally thicker reflective lower crust. Sub-Moho dipping events appear below the reflective lower crust in ESCIN-3.2 and ESCIN-3.3 segments between 11 and 17 s TWT and might bear upon Alpine subduction zones (Martínez-Catalán et al., 1997) (Figure 4). Recent analysis of these events, in particular the western dipping event inclined to the ESE in ESCIN-3.3 and the WSW dipping event in ESCIN-3.2, suggests that these reflections may represent apparent dips of an inclined surface roughly oriented E-W and dipping to the South, possibly the subducted oceanic crust of the Bay of Biscay (Ayarza et al., 2004). However, the sub-Moho west-dipping event in ESCIN-3.3 is not considered in this interpretation. The refraction/wide angle reflection data also show deep arrivals that could correlate with these features.

Subduction, delamination and crustal root buoyancy.

From the modelling and interpretation of the ESCI-N deep reflection and refraction profiles it can be concluded that the alpine imprint in the crust and mantle of the Cantabrian Zone of the Variscan Massif is much more important than previously thought. The profiles situated to the W and S of the Cantabrian Zone show 30-32 km thick crust on land, similar to most of the Variscan crust in both sides of the Atlantic (Meissner et al., 1987) and reflections can be roughly correlated with the Palaeozoic geology at the surface, including reflections at the continental platform. However in the Cantabrian Zone, the alpine imprint on land has modified the whole crust, with thrusts in the brittle upper parts that provided the ramps to elevate the basement and a deep crustal root in the lower crust beneath the heights of the Cordillera. The N-S Alpine compression developed South verging structures on land in the transition to the Duero Basin, North verging structures in the continental slope and approximately vertical structures in between (Figure 11d).

The buoyancy of the crustal root. Crustal roots in recent orogens are directly related to the process of continental collision and have been observed in all deep seismic lines across them, e.g. Alps (Mueller, 1990); Pyrenees (Choukroune et al., 1989) or Himalayas (Hirn et al., 1984) are good examples of orogens with deep crustal roots. The Cantabrian Mountains are no exception, with the particularity that the continent-continent collision stage has not been achieved. The buoyancy of the deep crustal roots relative to the surrounding mantle is thought to contribute to the support of topography. In old collisional mountain belts, surface relief relative to the magnitude of the underlying crustal root is observed to be smaller than in young mountains due to an increase in crustal root density with greater thermo-tectonic age. The continental lithosphere remains weak enough to permit exhumation of crustal roots in response to erosion of surface topography for hundreds of millions of years. However, the amount of such uplift appears to be significantly reduced by progressive loss of root buoyancy (Fischer, 2004). Based on isostatic considerations, and for a calculated lithospheric thickness of 90 km (Cabal, 1993) the elevation expected for the Cantabrian Mountains in the area of the 45 km crustal thickness would be of around 2 km, (Morgan and Burke, 1985), which is an average of the heights encountered in the Cordillera. Uplift should be still taking place in the area to balance the crustal masses, and it has its expression at the so-called “rasas”, or coastal cliffs that have been uplifted continuously since the Oligocene-Miocene (Flor, 1983), coinciding with the cessation of the subduction at the margin (Le Pichon et al., 1971; Álvarez-Marrón et al., 1997). Compressional deformation continued after subduction until the Neogene, as indicated by structures and inverted basins in the platform (Álvarez-Marrón et al., 1996; Gallastegui et al., 2002), contributing to the uplift on land.

The presence of the crustal root is masked in the gravimetric maps by the long wavelength gradient due to the thinning of the crust towards the sea and the fact that the expected gravimetric minima are normally displaced to the hinterland of the orogens (Meissner et al., 1990). However, it was through gravimetric modelling that the geometry of the crustal root as the result of an indentation was resolved (figure 9) (Fernández Viejo et al., 1998; Gallastegui, 2000).

The ocean-continent transition. Subduction or underthrusting. The lateral variations in the crustal structure are definitely marked in the North Iberian Margin. Such variations affect the type of transition from continental to oceanic domains. In the western side, illustrated by segment ESCIN-3.1 and another North South deep seismic profile from IAM project (Fernández Viejo et al., 1998), the transition between continental and oceanic crust is abrupt, taking place beneath the continental slope and Moho is sub horizontal in the continental shelf. Sub-Moho velocities are typical of mantelic rocks. However, along the ESCIN-4 transect in the E, the transition is smoother, Moho deepens gradually southwards from 18 to 30 km depth near the coastline. Beneath the coast the imbrication of two crustal blocks led to the thickening of the crust, and typical oceanic crust is not evidenced by the ESCI-N data.

Deregnaoucourt and Boillot, (1982), based on the pattern and disappearance of magnetic anomalies in the eastern side of the Bay proposed the presence of thinned continental crust in this area. Early gravimetric studies showed a negative anomaly at the foot of the continental slope coincident with a long deformation structure along the margin. Sibuet and Le Pichon, (1971) interpreted the anomaly as a marginal trough associated to the Eocene subduction. The amount of subducted crust was estimated later by several authors ranging between 40 km (Srivastava et al., 1990) and 120 km (Grimaud et al.,

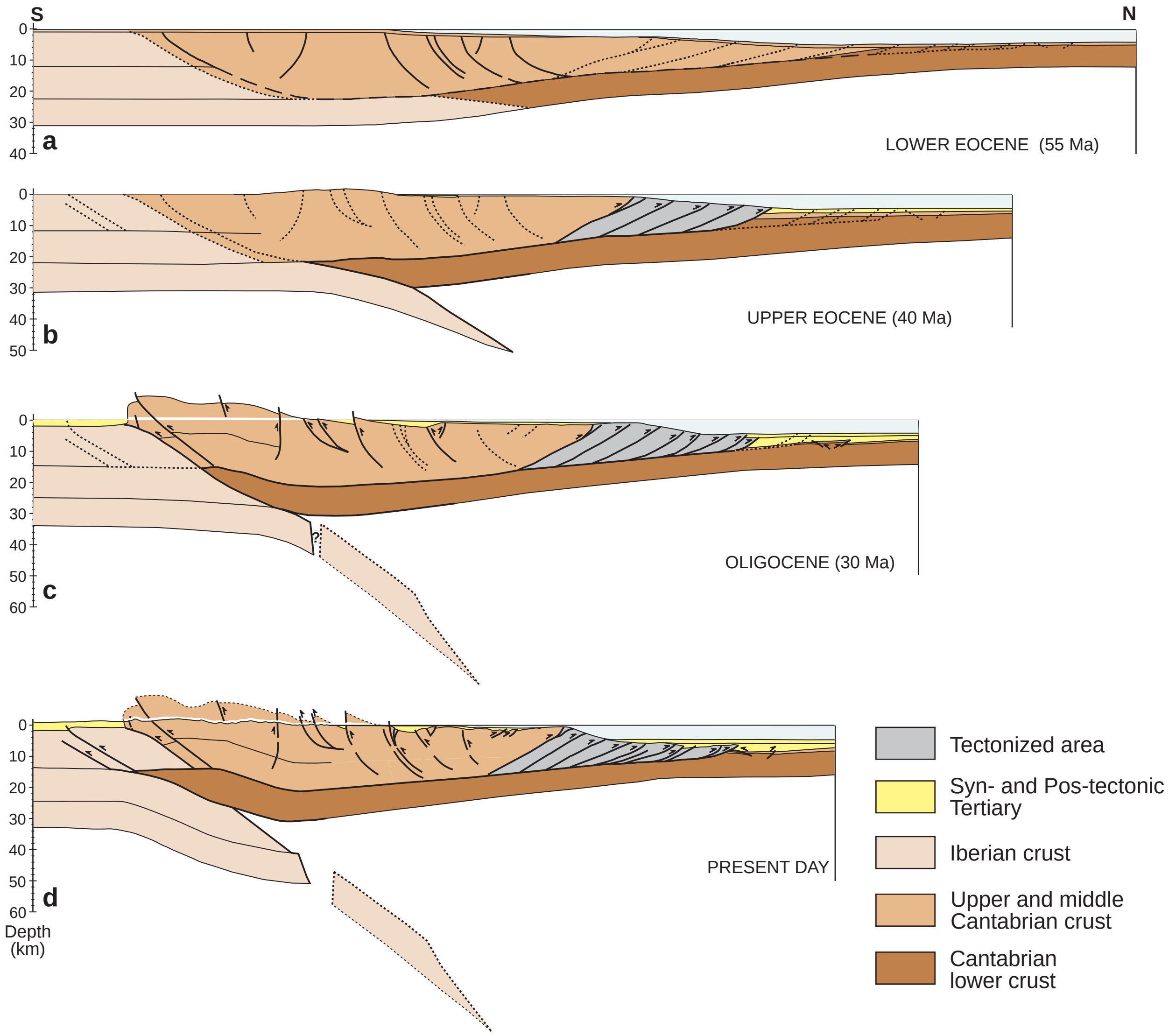

Figure 11. Final model of evolution for the Cantabrian Cordillera and margin during the Tertiary showing a final structure similar to the one interpreted further East in the Pyrenees (Gallastegui, 2000).

1982). The subduction would explain the asymmetry of the magnetic anomalies between the northern and southern continental margins of the Bay of Biscay in the west. The ESCIN-4 transect runs along the proposed transitional area so the nature of the crust in this part of the Bay would have been more likely thinned continental crust by rifting than young oceanic crust resulting of the sea-floor spreading stage. In any case, the mechanical and geophysical characteristics of both crustal types are similar and the result would not be oceanic subduction "sensu stricto". The oceanic crust, if existent, must have been hot and buoyant, hampering a real subduction and finding difficulties to slide beneath the thinned continental crust from the Iberian margin. Moreover, no volcanism or magmatism has been observed in the continent to favour the sinking and melting of an oceanic slab into the mantle. It has been demonstrated that oceanic crusts younger than 70 Ma, as in this case, have problems to sink into the mantle and end up causing buoyant subduction (Sacks, 1983). The slab is then underthrusted beneath the continental margin giving rise to anomalous velocities beneath. The low Vp velocities modelled in the refraction profile ESCIN-4 would relate to partial melt of the Iberian lower crust, in contrast to a dewatering of a hypothetic subducted oceanic slab. This is supported by the magnetotelluric data (Pous et al., 2001). Towards mainland, the slab of thinned crust indented the Iberian crust in a tectonic interwedging that promotes a detachment of the Iberian upper crust and a related underthrusting of the Iberian lower crust below the margin's crust, resulting in the thickening and uplift of the Cantabrian Mountains (Pulgar et al., 1996; Gallastegui, 2000) (Figure 11). The image is then continuous with the deep structural relationship between Iberian and European plates that was imaged in the Pyrenees (Choukroune et al., 1989); (Daignieres et al., 1989).

A possible delamination of the Iberian crust has been suggested in the evolutional models (Gallastegui, 2000) to account for the discrepancy between upper and lower crust length in the balanced sections. In contrast to the stratigraphic delamination of smaller wedge structures, crustal and lithospheric scale delamination is controlled by the distribution of buoyant mass combined with a pattern of mechanical layering. Syncollisional delamination most likely occurs in response to negative buoyancy in contrast to the wedging of a strong indenter into a weaker mass. (Moore and Wiltschko, 2004). When the tectonic stress reaches a critical level during collision, deformation may preferentially begin near the potential delamination horizon due to the stress produced by net negatively buoyant mass below the horizon, in this case, the mafic lower crust. With shallow subduction angles transformation to mafic eclogite may allow delamination to initiate and propagate above the Moho. The delamination site will propagate as long as the tectonic stresses are sufficiently high and net negatively buoyant mass exists in the lower lithosphere and delaminated slab. The seismic velocities of around 7.8 km/s in the wedge may support the eclogitization of the Iberian lower crust and its delamination process, belonging this area then to the mafic lower crust of Iberia.

The initiation of the interwedging and crustal thickening beneath the Cordillera is closely related to the crustal image of the Pyrenees. The lateral transference of tectonic stresses from the Pyrenees towards the West, would force the underthrusting of the Iberian crust beneath the Biscay thinned crust following the trend already stablished in the East (Gallastegui, 2000). It also coincides with the area of major thinning during the Mesozoic, which indicates thermally immature crust, prone to deformation.

It is still a matter of discussion how the interwedging develops to the West giving place to an apparent polarity reversal in the subduction, although the presence of real oceanic crust and the less acute deformation westwards may have allowed the limited subduction of oceanic crust beneath the stronger Iberian crust in the Galicia area where Mesozoic rifting had been also less severe. However, no volcanism has been observed to deduce a significant subduction of oceanic crust. The slab in any case would have not reached more than 60 km depth as magmatic arcs are associated with subduction zones beneath them at a depth of 65-130 km (England et al., 2004).

Recent studies of global subduction zones favour induced nucleation of subduction zones in contrast to simple models of passive margin failure, which despite their popularity, cannot be quantitatively substantiated and are not evident in the geologic record (Mueller and Phillips, 1991). Stern (2004) explains that induced nucleation of the subduction zone is the response to continuous plate convergence following jamming of a subduction zone by buoyant crust. These results in regional compression uplift and underthrusting that may yield a new subduction zone. Transference induced nucleation moves the new subduction zone outboard of the failed one. Polarity reversal induced nucleation also follows collision, but continued convergence in this case results in a new subduction zone forming behind the magmatic arc. In our case, lateral transference of stress to accommodate for the convergence of the two plates created underthrusting at the margin where both plates had thinned continental crust with the same polarity as further East. At the point where we find oceanic crust and stronger continental crust to the West the solution to accommodate the convergence would be to subduct the oceanic crust, causing the polarity reversal.

The limit between these two types of convergence in the North Iberian margin would be located at about 6 degrees longitude, but the geometry and mode of transition is a matter of future investigations. It is tempting to suggest that Ventaniella Fault (Figure 1), a crustal scale fault running NNW-.SSE and other large scale faults in the area may be a consequence of accommodating this transition.

Conclusions. And now what?

It has been explained here the major contributions of the ESCI-N Project to the lithospheric knowledge of the Cantabrian Cordillera and margin, as the western extension of the Pyrenean orogen. The main results of the project include the discovery of the alpine crustal thickening beneath the highest summits on land and the interwedging of two plates at the margin, being the Iberian crust the one that sinks towards the North and the European Biscay crust the one to interwedge at above-Moho level. The area provides a transition from continent-continent collision in the Pyrenees to oceanic subduction in the western side of the Bay of Biscay with an apparent polarity reversal in subducted plate due to pre and syncollisional thermomecanical properties of the plates. It is, thus, a remarkable and unique place to study all the geodynamical processes involved in convergence of plates, especially for immature and incipient subduction zones and for the behaviour of transitional thinned continental crust in compressional regimes. More investigations are needed at the light of the results to clarify the transition of the interwedging to the West or the evolution of the uplift of crustal masses on land to better explain the geological evolution of North Iberia.

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