

# The ESCI-N2 deep seismic reflection profile: a traverse across the Cantabrian Mountains and adjacent Duero basin

J. A. PULGAR<sup>a</sup>, A. PÉREZ-ESTAÚN<sup>b</sup>, J. GALLART<sup>b</sup>, J. ÁLVAREZ-MARRÓN<sup>b</sup>, J. GALLASTEGUI<sup>c</sup>,  
J. L. ALONSO<sup>a</sup> and ESCIN Group<sup>c</sup>

<sup>a</sup> Departamento de Geología, Universidad de Oviedo, Oviedo, Spain

<sup>b</sup> Instituto de Ciencias de la Tierra "Jaume Almera", CSIC, Barcelona, Spain

<sup>c</sup> A. Marcos, F. Bastida, J. Aller, P. Farias, J. Marín and R. García-Espina (Universidad de Oviedo), J.R. Martínez-Catalán (Universidad de Salamanca), E. Banda, J.J. Dañobeitia and G. Fernández-Viejo (Instituto de Ciencias de la Tierra "Jaume Almera", CSIC Barcelona), D. Córdoba (Departamento de Geofísica, Universidad Complutense de Madrid), M.C. Comas (Instituto Andaluz de Geología Mediterránea, CSIC Granada), N. Heredia and R. Rodríguez (Instituto Tecnológico Geominero de España, Madrid).

**Abstract:** The ESCI-N2 deep seismic reflection profile images the crustal structure of the transition between the Cantabrian Mountains and the Duero foreland basin. It was traced perpendicular to the Alpine structural directions to investigate the role of the Alpine deformation in the tectonic evolution of the northern margin of the Iberian Peninsula. Besides the very well imaged sedimentary cover of the Duero basin, the first outstanding feature of the profile is the change in the intensity and character of the reflectivity between shallower and deeper levels of the crust. The reflectivity is weaker in the upper 6 s (TWT), whereas it increases its intensity abruptly below this level. The most remarkable feature observed in the upper crust is represented by discontinuous but line-up, north-dipping reflections interpreted as Alpine thrusts. These thrusts merge into the 6 s level, that can be interpreted as a mid-crustal detachment. The southwards thrusting of several crustal slices along this thrusts gave rise to the tectonic uplift of the Cantabrian Mountains. A reflective lower crust with a band of high reflectivity at its base was imaged in ESCI-N2 profile. The Moho is situated at the base of this reflective zone, that changes its attitude from horizontal beneath the Duero basin to north-dipping beyond the mountain front, with the reflection Moho deepening from 12 to 16 s (TWT). The topography of the Moho implies a downward bending of the "Iberian" lower crust that is interpreted as induced by the indentation of a wedge of the "Cantabrian Margin" lower crust in the middle of the "Iberian" crust. This results in a delamination mechanism that splits the Iberian crust apart with the lower crust subducting northward and the upper crust detaching and uplifting to build up the Cantabrian Mountains.

**Keywords:** Deep seismic, crustal structure, Cantabrian margin, Iberian Variscan Belt, Alpine orogeny, Cantabrian Mountains uplift, crustal delamination, continental crust subduction

**Resumen:** El perfil sísmico ESCI-N2 muestra la primera imagen de la estructura cortical de la transición entre la Cordillera Cantábrica y la cuenca del Duero. El perfil fué trazado perpendicularmente a las direcciones estructurales Alpinas para investigar el papel de la deformación Alpina en la evolución tectónica del margen septentrional de la Península Ibérica. Dejando aparte la buena imagen sísmica obtenida de la cobertera sedimentaria de la cuenca del Duero, la primera característica destacable del perfil es el cambio en la intensidad y carácter de la reflectividad entre los niveles corticales superficiales y profundos. La reflectividad es más baja en los 6 s (TWT) superiores, mientras que incrementa su intensidad abruptamente por debajo de este nivel. El rasgo más destacado observado en la corteza superior es la presencia de una serie de reflexiones discontinuas, alineadas e inclinadas al N que se han interpretado como cabalgamientos Alpinos. Estos cabalgamientos se unen al nivel de 6 s que puede ser interpretado como un despegue en la corteza media. El desplazamiento hacia el S de varias láminas corticales a lo largo de estos cabalgamientos dió lugar al levantamiento tectónico de la Cordillera Cantábrica. El perfil ESCI-N2 muestra una corteza inferior reflectiva con una banda de alta reflectividad en su base. La Moho se sitúa en la base de esta banda reflectiva, que pasa de disponerse horizontal bajo la cuenca del Duero a inclinarse al N una vez traspasado el frente de la cordillera, con una Moho que se hunde desde 12 hasta 16 s (TWT). La topografía de la Moho implica una flexión hacia abajo de la corteza inferior "Ibérica" que se interpreta como inducida por la indentación de una cuña de la corteza inferior del "Márgen Cantábrico" en la parte media de la corteza "Ibérica". Ello implica un mecanismo de delaminación que separa la corteza inferior "Ibérica", que subduce hacia el N, de la corteza superior, que despega y se acorta dando lugar al levantamiento tectónico que originó la Cordillera Cantábrica.

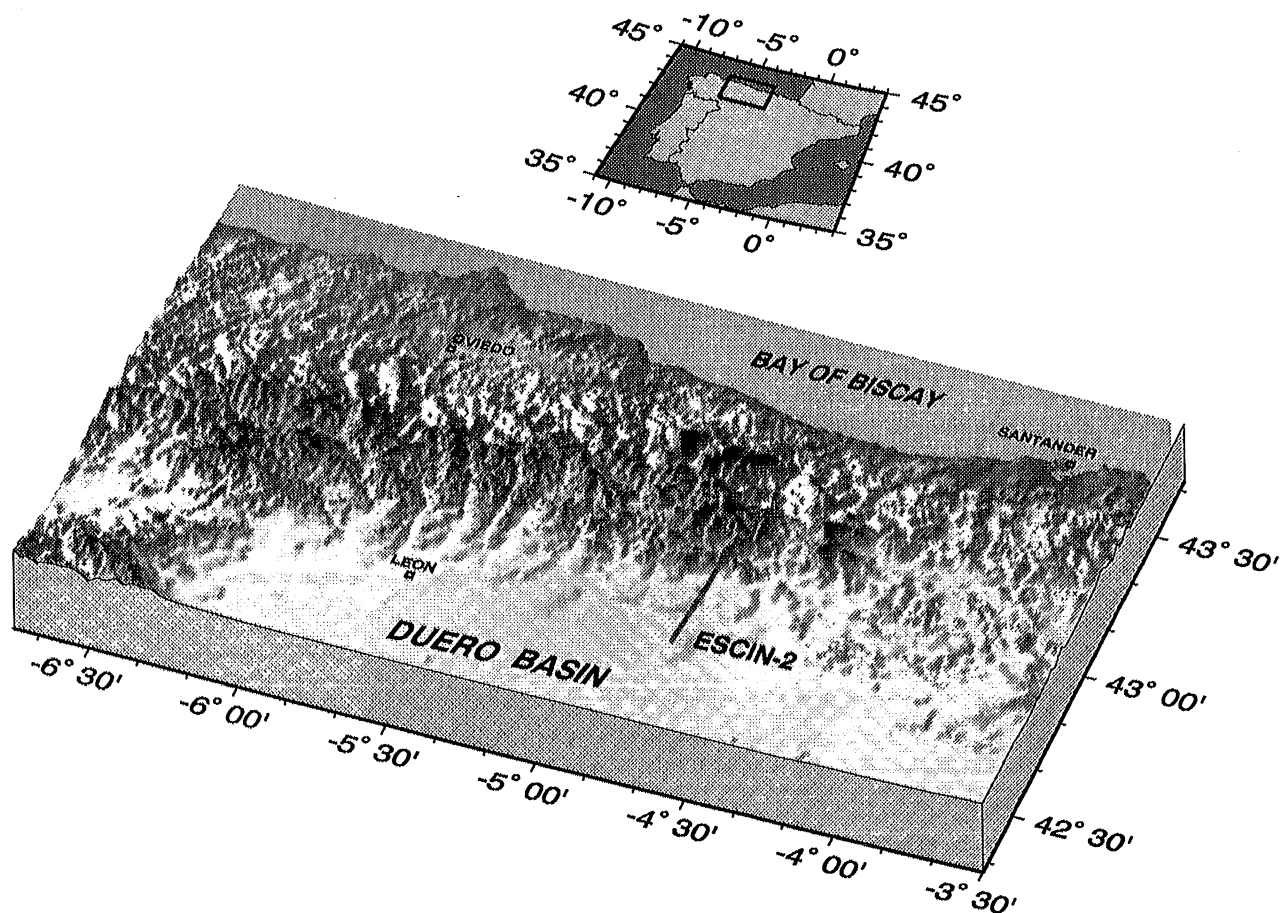
**Palabras clave:** Sísmica profunda, estructura cortical, márgen continental Cantábrico, Cadena Varisca, orogenia Alpina, delaminación cortical, subducción continental.

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## Introduction

The Cantabrian Mountains extend more than 250 km along the northern border of the Iberian Peninsula, with elevations up to 2.5 km, and constitutes the western extension of the Pyrenees. Geologically, the Cantabrian Mountains represent a Paleozoic basement block uplifted

during the Alpine orogeny. The range is flanked on the South by the Duero basin, a foreland basin formed ahead of the southern tectonic front and infilled with up to 2,500 m of continental Tertiary sediments. To the North of the range lies the northern Iberian continental margin and the Bay of Biscay abyssal plain (Fig. 1).



**Figure 1.** 3D topographic diagram block with the location of ESCI-N2 deep seismic reflection profile in the transition between the Cantabrian Mountains and the Duero Basin.

The ESCI-N2 deep seismic reflection profile was traced along a N-S line running across the southern slope of the Cantabrian Mountains (Fig. 1). The profile shows the seismic structure of the continental crust beneath the Cantabrian Mountains and the transition to the Duero foreland basin (Fig. 2). The profile was planned as a traverse across the southern tectonic front of the range to investigate the role of the Alpine deformation in the tectonic evolution of the northern margin of the Iberian Peninsula.

This profile is a part of the ESCIN (Estudio Sísmico de la Corteza Ibérica Norte) project. From 1991 to 1994, this and other related projects collected a variety of geophysical and geological data to study the crustal structure and the tectonic evolution of the northern margin of the Iberian Peninsula. These projects include the acquisition of two deep seismic reflection profiles inland (ESCI-N1 and ESCI-N2 profiles), another two offshore (ESCI-N3 and ESCI-N4 lines) and several refraction/wide angle reflection profiles (Pérez-Estaún *et al.*, 1994; Alvarez-Marrón *et al.*, in press; Pulgar *et al.*, in press; Gallastegui *et al.*, in press; see also this volume).

First results of the E-W deep reflection ESCI-N1 profiles on-land (Pérez-Estaún *et al.*, 1994; Gallastegui *et al.*, in press; Pérez-Estaún *et al.*, this volume) provide a seismic image of the deep crustal structure in the external part of the Variscan belt (Cantabrian Zone).

Significant lateral variations in the seismic image show that Variscan tectonics strongly affected middle and lower levels in the hinterland areas to the West, whereas they remained essentially undeformed beneath the foreland areas to the East. The offshore western continuation of this transect was imaged in the ESCI-N3 profile that was planned to investigate the deep structure of the hinterland area of the Variscan orogen (Álvarez-Marrón *et al.*, 1997a; Martínez-Catalán *et al.*, 1997).

The aim of the ESCI-N2 profile was to image the deep structure of the Cantabrian Mountains and to evaluate the effect of the recent Alpine tectonics on the Variscan crust. So, it is traced perpendicular to the principal structural directions and subparallel to the inferred shortening direction associated with the Alpine orogeny. At the same time, other complementary seismic data sets were acquired to obtain a complete image of the crustal structure of this part of the northern Iberian margin (Pulgar *et al.*, in press; Alvarez-Marrón *et al.*, in press; Alvarez-Marrón *et al.*, this 1997b; Gallart *et al.*, 1997). They include: (1) a 145 km-long multichannel deep seismic profile (ESCI-N4) crossing the platform margin offshore Asturias, (2) a 200 km-long reversed refraction profile from explosive sources at both ends (profile 5) and (3) a large-aperture recording on land of marine ESCI-N4 profile (Fig. 2).

This paper presents the major features imaged in the ESCI-N2 profile and their geological interpretation.

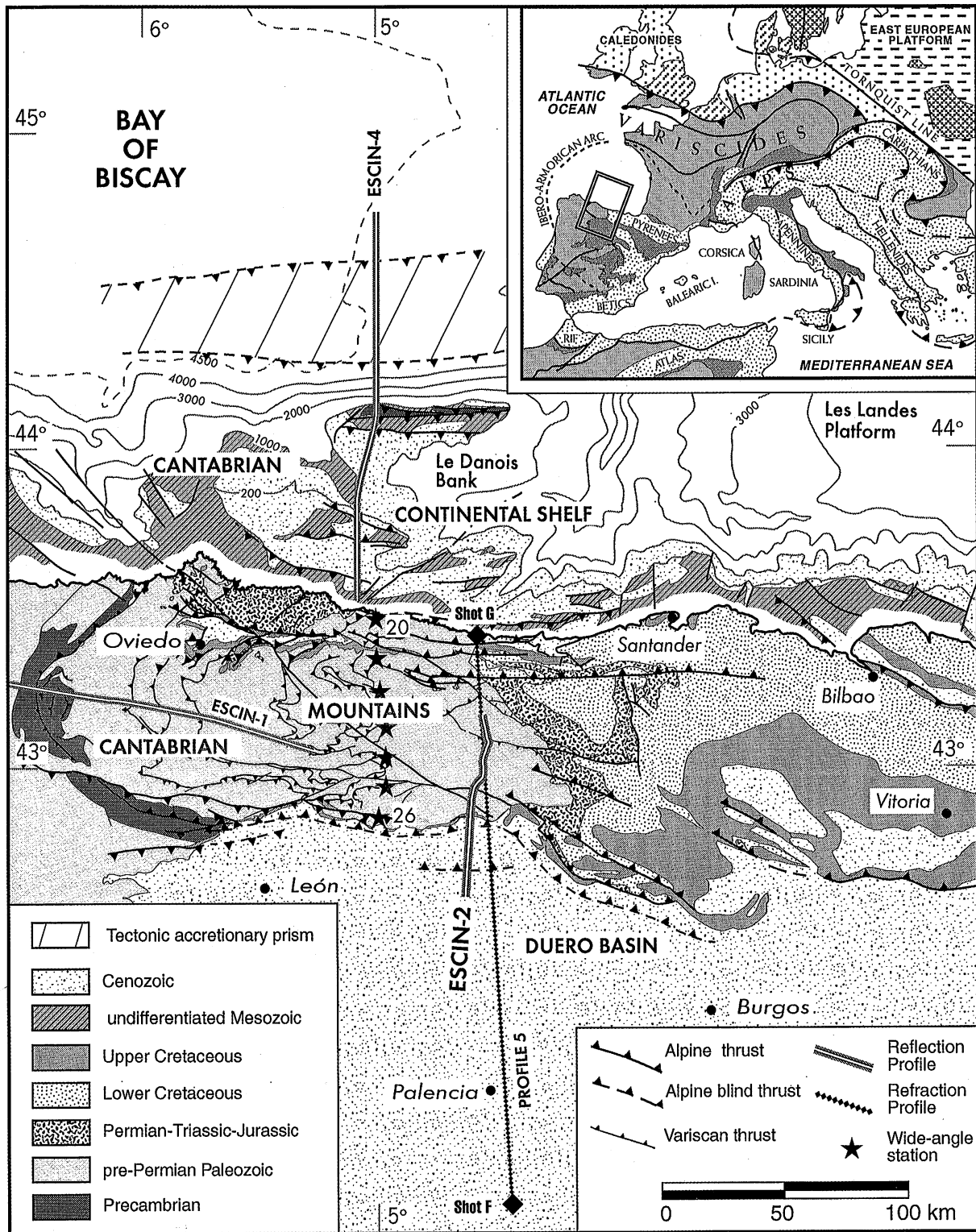


Figure 2.- Geological sketch map of the northern border of the Iberian Peninsula with the location of ESCI-N2 and other seismic data collected under the ESCIN and other related projects.

**Geological setting**

The Cantabrian Mountains is a region with a complex geological history resulting from several tectonic events occurred in Paleozoic, Mesozoic and Cenozoic times. During the Paleozoic, the NW Iberian Peninsula was a part of a continental margin involved in the Variscan collision between Laurentia and Gondwana (Matte,

1991; Pérez-Estaún *et al.*, 1991). Paleozoic and Upper Proterozoic rocks crop out describing a very pronounced bend, named Ibero-Armorican Arc (Fig. 2). The core of this arc is occupied by the most external zone of this Variscan belt, the so-named Cantabrian Zone, that represents a thin-skinned foreland and thrust fold belt (Juli-vert, 1971; Pérez-Estaún *et al.*, 1988; Pérez-Estaún *et al.*,

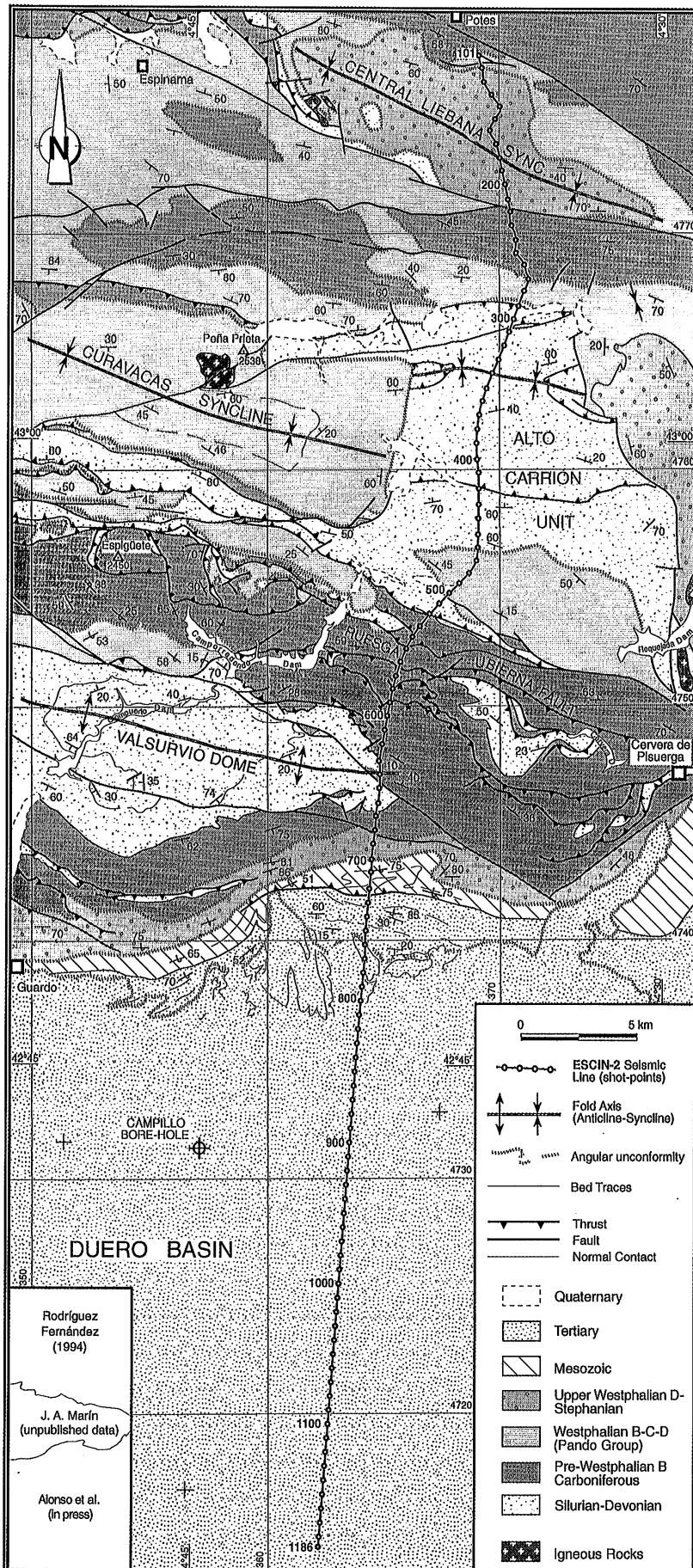


Figure 3.- Geological map of the area surveyed by profile ESCI-N2.

1994). It contains several thrust sheets of Palaeozoic rocks emplaced during carboniferous times (Fig. 2). Metamorphism and cleavage are scarce.

The post-Variscan tectonic history of the area began with a rifting episode giving rise to a Permo-Triassic basin (Martínez García *et al.*, 1983; Lepvrier and Martínez García, 1990; Espina, 1992). A later extensional event, related to the beginning of the opening of the Atlantic Ocean and the Bay of Biscay, ensued during Late Jurassic and Early Cretaceous times (Le Pichon *et al.*, 1971; Williams, 1975; García-Mondejar, 1989; Verhoef and Srivastava, 1989). From Albian times onwards, the newly formed basins remained stable, coinciding with the sea-floor spreading phase of the Bay of Biscay, until tectonic inversion occurred during the Tertiary.

The Variscan basement and an undetached Mesozoic cover were uplifted during the Alpine (Pyrenean) orogeny in Cenozoic times to build up the Cantabrian Mountains. In a N-S cross-section, the overall structure of this area consists of a wide regional monoclinal flexure that can be explained as result of a major fault-bend fold related to a large basement-thrust ramp (Alonso *et al.*, in press). This N-dipping basement-thrust is completely buried and, at the surface, its displacement is accommodated by a fault propagation fold causing the overturning of the Mesozoic-Cenozoic cover in the southern border of the mountain range (Fig. 2). The estimated displacement along this basement-involved thrust is about 25 km (Alonso *et al.*, in press).

#### *Surface geology along the profile.*

The ESCI-N2 profile transects the South-eastern part of the Cantabrian Zone, crossing several Variscan units and the northern border of the Duero basin. The most prominent geological features of the zone traversed in the profile are showed in the Figure 3.

The major and most outstanding structure in the southern front of the Cantabrian Mountains is the Valsurvio Dome (Koopmans, 1962; Marín *et al.*, 1995). Its southern limb is overturned and involves Palaeozoic, Mesozoic and Tertiary rocks (Fig. 3). A small reverse fault and several minor folds occur associated with the overturned limb. The progressive rotation of this limb during Alpine deformation is recorded by a syntectonic unconformity developed in the Tertiary sediments along the northern margin of the Duero Basin (García Ramos *et al.*, 1982; Alonso *et al.*, in press). The Tertiary succession is a coarsening-upward sequence up to 2500 m thick, consisting of sandstones, polymictic and siliceous conglomerates, deposited by alluvial fans with radii up to 25 km. Stratigraphic profiles can be obtained at the basin margin, where beds change southwards from overturned to subvertical attitude and then become progressively more gentle as a result of synsedimentary deformation. The succession becomes eventually horizontal towards the foreland and only the uppermost 100 m of the sequence outcrop.

As regards the Variscan basement, the Valsurvio Dome involves Devonian to Upper Carboniferous rocks. A

Variscan imbricate thrust system, mainly developed into Lower Carboniferous rocks, was folded by the Valsurvio Dome. Other minor folds are located to the northeast of the Dome, in the Cervera de Pisuerga area, which also folded the same thrust system (Pulgar, 1973) (Fig. 3).

The northern limit of the Valsurvio Dome is the Ruesga Fault (Fig. 3), named Ubierna Fault to the Southeast, where it involves Mesozoic rocks. This fault played as a normal fault during Mesozoic times and then was inverted as reverse fault during the Alpine Orogeny (Espina *et al.*, in press).

To the north of the Ruesga Fault, allochthonous units carrying Silurian to Lower Carboniferous age formations occur in the Alto-Carrión Unit. The Silurian-Devonian rocks display deeper facies than those the rest of the Cantabrian Zone (Brouwer's Palentian facies, Brouwer and van Grinkel, 1964). These units overlie turbiditic and olistostromic sequences of Namurian to Westphalian A ages. This allochthonous units have been regarded as rooted in this zone (Ambrose, 1974) or interpreted as large exolistholits originated from the south of the Valsurvio Dome (Frankenfeld, 1983). Siliceous conglomerates and a turbiditic graywacke-shale sequence of Westphalian age cover unconformably thrusts and related folds. However, allochthonous units and unconformable rocks are subsequently folded together, giving rise to a large upright synform (Curavacas syncline) (Rodríguez Fernández, 1994). To the north, the most important structure is the Central Liébana Syncline, that only involves Carboniferous synorogenic rocks (Fig. 3).

#### **Data acquisition and processing**

The ESCIN-2 deep seismic reflection profile was recorded in July 1993. The profile consists of a 65 km-long line oriented N-S, running subperpendicularly across the transition between the Cantabrian Mountains and the Duero foreland basin (Fig. 2). The profile starts, in the North, close to Potes (Cantabria), near the southern border of the Picos de Europa and it crosses the mountain range along the Carrión river valley to penetrate into the Duero basin in the North of the Palencia Province.

The data were acquired with a 240-channel geophone spread (14,5 km length) using 60 m geophone group spacing and laid out as a symmetrical split-spread with roll-on. A total of 212 shots were recorded that consisted in single-hole 10-25 kg dynamite source. The record length was 25 s, with a mean 30-fold coverage. The field recording of the profile was realized by the Spanish Branch of the 'Compagnie Générale Géophysique' (CGG), under contract and supervision of the Geology Department of the University of Oviedo. The Data acquisition parameters are displayed in Table 1. The abrupt topography in the northern part of the profile, with elevation change of up 0.9 km, created some difficulties in the field acquisition that in some places affected the quality of the data, specially in the Valsurvio Dome area (Fig. 2).

The first processing of the field data was realized by CGG-London following the sequence showed in Table 2.



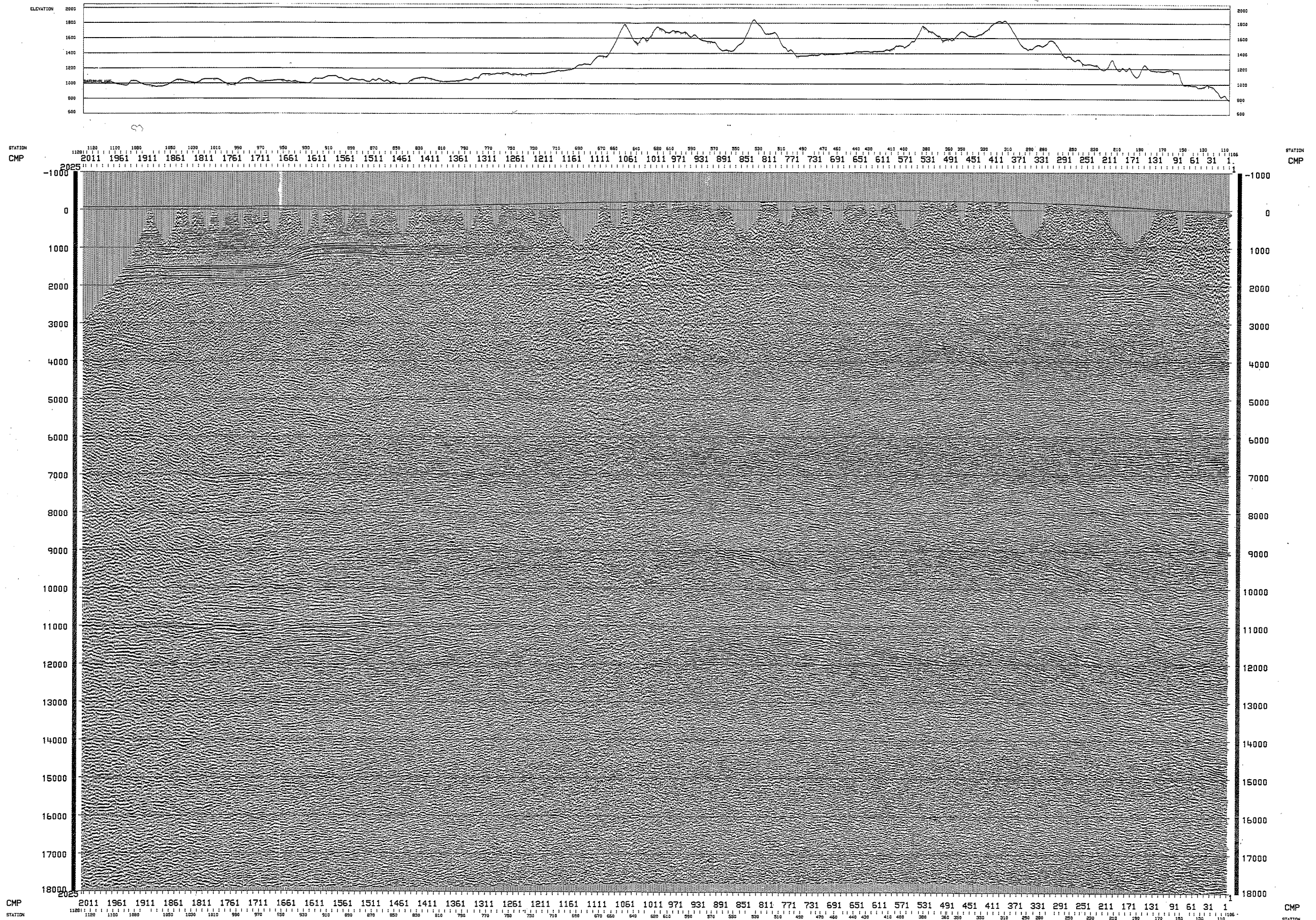


Figure 4.- Stack section of ESCIN-2 profile processed with the parameters shown in Table 2.

**Table 1.-** Data acquisition parameters of the ESCIN-2 deep seismic reflection profile.

Energy Source	Dynamite - single-hole
Hole depth	24 m
Charge	20 kg
Geophone Type	GSC 20D
Number of traces	240
Interval between traces	60 m
Geophone array	linear
N.° geophones per group	18
Interval between geophones	3.33 m
Total length geophone group	60 m
Spread configuration	Symmetrical split-spread
Coverage	3000%
Recording instrument	SERCEL SN 348
Record length	25 s
Sample interval	4 ms
Filters	Low cut: out High cut: 62.5 Hz @ 72 dB/oct
Tape format/density	SEG-B/6250 BPI

The unmigrated section obtained is shown in the Figure 4. A lateral coherency filtering was later applied in the Geology Department of the University of Oviedo to Figure 5.

### Seismic data description

Despite the general character of the reflectivity in the upper part, where short and discontinuous reflections are predominant, the southernmost part of the profile (cdp's 1200-2010) shows very strong flat reflectivity in the upper 2 seconds TWT, that image the mostly undeformed Mesozoic-Tertiary sedimentary succession that infills the Duero basin. The most striking characteristic of this part is the presence of strong and highly continuous reflections between 1 and 2 seconds that are slightly sifted upwards to the North of CDP 1650 (A in Fig. 5). Above this reflections, the seismic image is characterized by more sparse and discontinuous flat reflections (B in Fig. 5).

The reflectivity under the Cantabrian Mountains is poorer and characterized by short and near-horizontal or moderate dipping reflections. Two types of remarkable features can be observed:

(a) The first kind of events is very apparent in the northernmost part of the line where a sub-horizontal band of strong and continuous reflections is observed at a depth of about 2 s (C in Fig. 5). Shorter and sub-horizontal or moderately dipping reflections also appear in other parts of this uppermost crust.

(b) The second kind of events is represented by weak, rather discontinuous but lined up, north-dipping reflections that can be followed crossing all the upper crust. They are imaged along two bands that extend from 5-6 s upwards, either reaching the surface (D-D' and E-E' in Fig. 5) or dying in the Mesozoic-Tertiary cover of the Duero basin (F-F' and G-G' in Fig. 5). In this case,

the F band of discontinuous north-dipping reflectors can be correlated with the discontinuity where the strong subhorizontal reflections that image the bottom of sedimentary succession of the Duero basin are shifted upwards.

Reflections in the lower portion of the crust, below 6 s, are rather conspicuous, defining a general high reflectivity pattern. In the southern part of the profile, a consistent seismic fabric of horizontal, short and discontinuous reflections can be observed between 6 and 10 s, approximately. A band of strong, horizontal and more continuous reflections appears between 10 and 12 s. This band can be followed to the northern half of the line, where it deepens from 12 to 16 s (H in Fig. 5). A rather strong reflectivity, with dominating north-dipping reflections, characterizes the seismic image of this part of the crust between 6 and 16 s (Fig. 5). In the northern end of the profile, a zone with prominent horizontal reflections, that wedges southwards, can be observed between 6 and 9 s, approximately (I in Fig. 5).

### Geologic interpretation

Besides the very well imaged sedimentary cover of the Duero basin, one of the most outstanding features of the profile is the change in the intensity and character of the reflectivity between shallower and deeper levels of the crust. The reflectivity is weaker in the upper 6 s

**Table 2.-** General processing sequence of the ESCIN-2 deep seismic reflection profile.

#### PROCESSING SEQUENCE:

Processing record length: 25 s  
Processing sample interval: 8 ms  
Survey datum plane: mean sea level +1000m

#### A. PRE-STACK SEQUENCE:

1. Demultiplexing
2. Amplitude recovery
3. Dynamic trace equalization: Window: 0s-25s - Operator length: 5000ms
4. Bad trace edition
5. Slalom line CMP gather to 25s, CMP interval 30m nominal
6. Anti-alias filter and resample to 8 ms
7. Elevation replacement static correction to near-surface floating datum plane (FDP) (survey datum +1000 above sea level)
8. Spatially variant mute
9. NMO correction
0. Surface consistent residual statics
11. Stack 3000% coverage nominal

#### B. POST-STACK SEQUENCE:

12. Time variant trace mix
13. Time variant bandpass filter
14. F/X domain random noise attenuation
15. Dynamic trace equalization
16. Static correction from FDP to survey datum of +1000m above sea level.

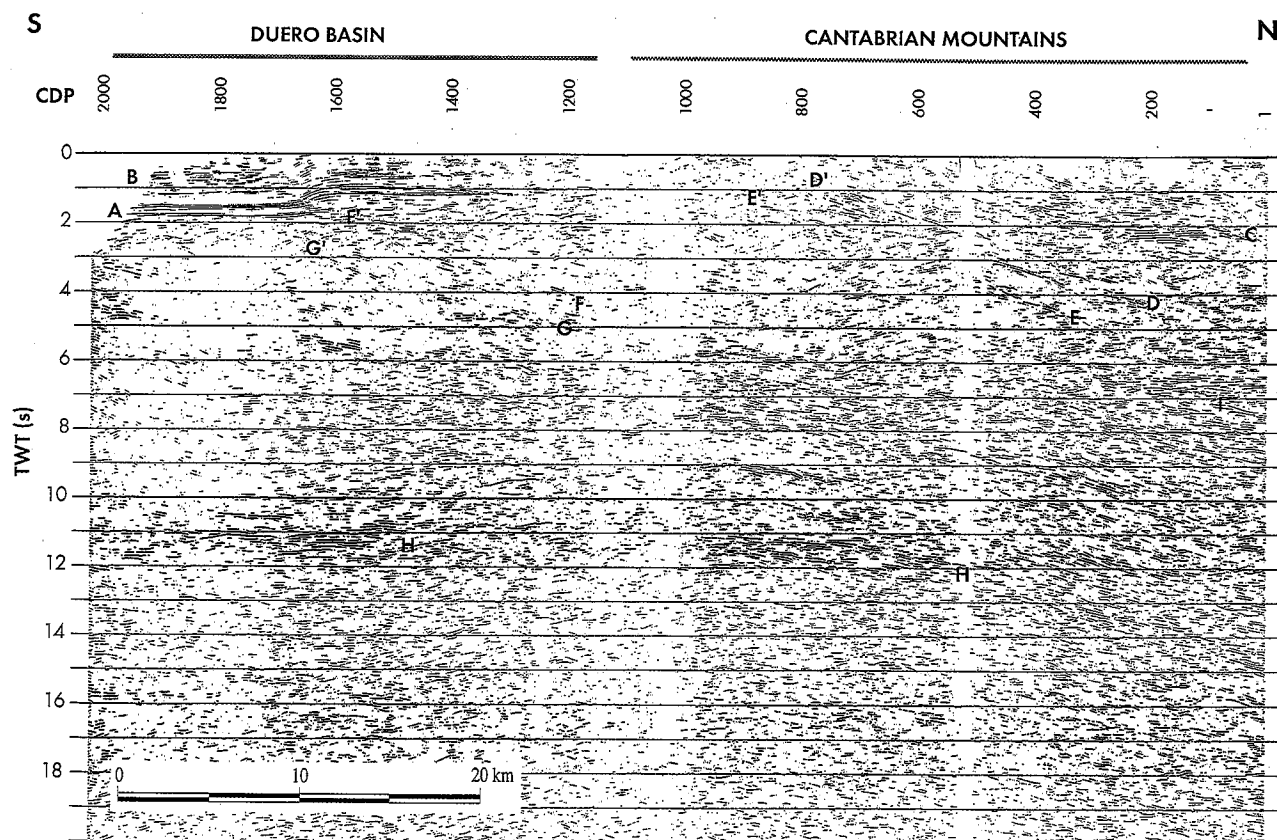


Figure 5.- Unmigrated ESCI-N2 profile with a lateral coherency filter showing the main reflections described in the text. Note the flat reflections correlated with Cretaceous (A) and Tertiary rocks (B) from the Duero Basin, the N-dipping reflectors in the upper 6 s (D, E, F, G) interpreted as Alpine thrust and the high reflectivity band at the base of the lower crust (H), with the Moho deepening from 12 s beneath the Duero basin to 16 s beneath the Cantabrian Mountains.

TWT, whereas it increases its intensity abruptly below this boundary. This zone of stronger reflectivity extends from 6 to 12 s TWT, with the highest reflectivity at its base.

#### Near-surface structure

The sedimentary cover of the Duero basin is very well imaged in the southern part of the profile (Fig. 6). The sparse discontinuous flat reflections in the uppermost part image the Tertiary sediments, whereas the Cretaceous rocks at the bottom of the basin are responsible for the strong and highly continuous reflections between 1.5 and 2 s TWT, that are sifted upwards 0.5 s approximately, to the North of CDP 1650 (Fig. 6). This interpretation is well constrained by surface geology and data from a very close oil exploration bore-hole. The sifting observed in those reflections is produced by a north-dipping reverse fault cutting across the Mesozoic succession that appears folded and uplifted in the hanging-wall. This fault fades out upwards in the Tertiary where only a drape fold with a syntectonic unconformity is observed. This fault can be traced downwards following the band of north-dipping discontinuous reflections that reaches almost 6 s depth (Fig. 5), where it seems to merge into a thin band of sub-horizontal reflections between cdp's 850-1050. Another band of similar north dipping reflections (G in Fig. 5) can be in-

terpreted as another basement fault that, however, does not affect the sedimentary cover.

Similar features displayed in this upper part of the crust can also be interpreted as Alpine faults cutting deep across the basement. One of these faults can be recognized in the northern border of the Tertiary sedimentary basin (E-E' in Fig. 5) and followed downward until a band of horizontal reflections located at 5-6 s (cdp 276). This agrees with the interpretation proposed by Alonso *et al.* (in press) on the basis of surface geology data, that explains the overall structure of the Cantabrian Mountains as an Alpine uplift produced by southward displacement along a basement-involved thrust. At the surface, the displacement along this fault give rises to a big monoclinical fold overturning the Palaeozoic, Mesozoic and Tertiary rocks (Fig. 6). A small reverse fault and minor folds associated with the overturned limb do occur. A Tertiary continental succession showing a remarkable syntectonic unconformity evidence the Alpine age of this structures (Alonso *et al.*, in press).

All these basement-faults merge to the 6 s level, that can be interpreted as a mid-crustal detachment. The shortening of the upper crust above this level induced the southward thrusting of several crustal slices responsible of the uplift of the Cantabrian Mountains.

Other features displayed in the upper crust can be related with Variscan structures. The most prominent feature is the subhorizontal band of strong and rather conti-



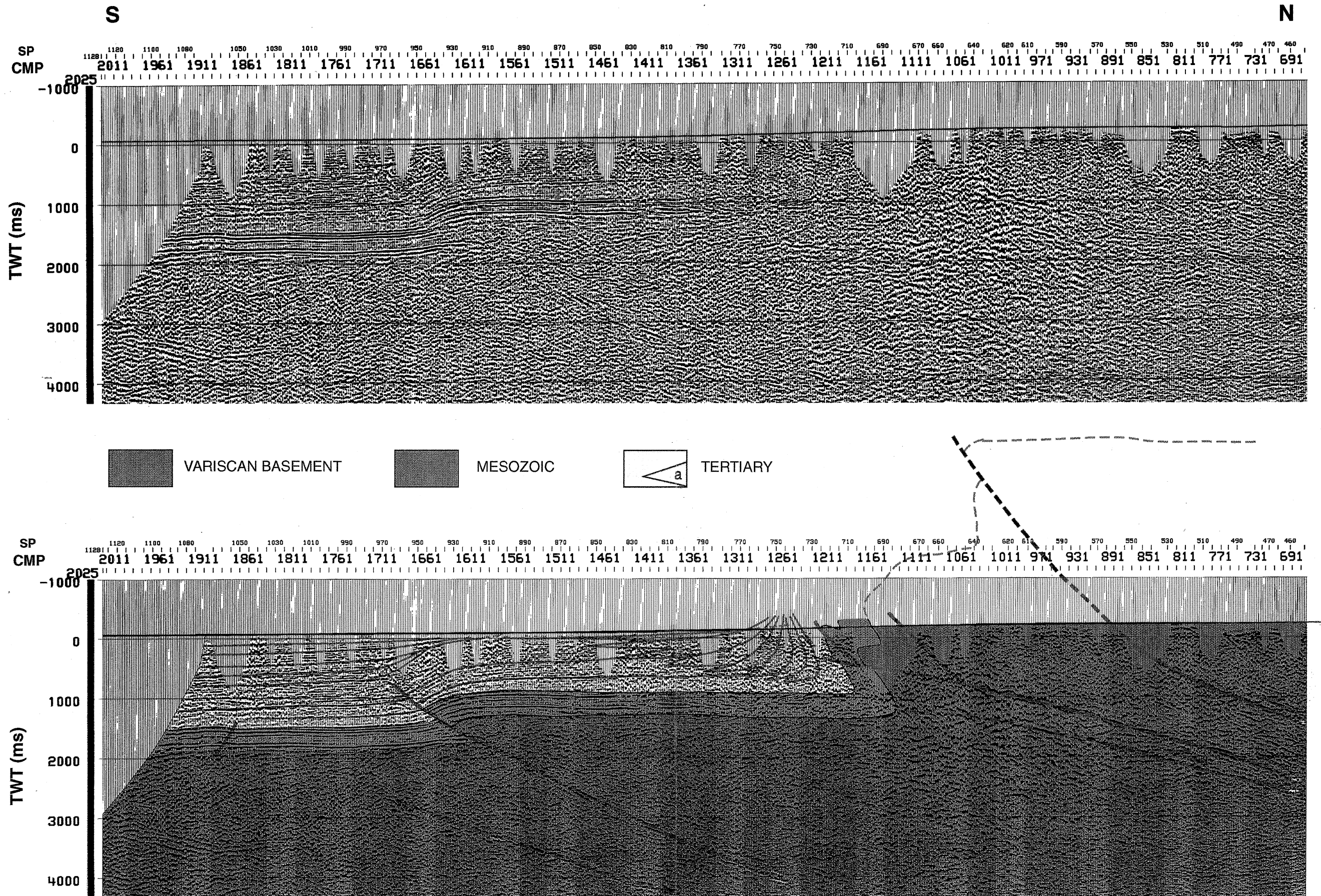


Figure 6.- Window of the southern part of the stack section of ESCI-N2 profile and interpretation showing the reflections from the Duero foreland basin and the transition to the Cantabrian Mountains. Note the N-dipping Alpine faults responsible for the inversion of the Mesozoic and Tertiary synorogenic sequence and the uplift of the Cantabrian Mountains to the N of CDP 1160.

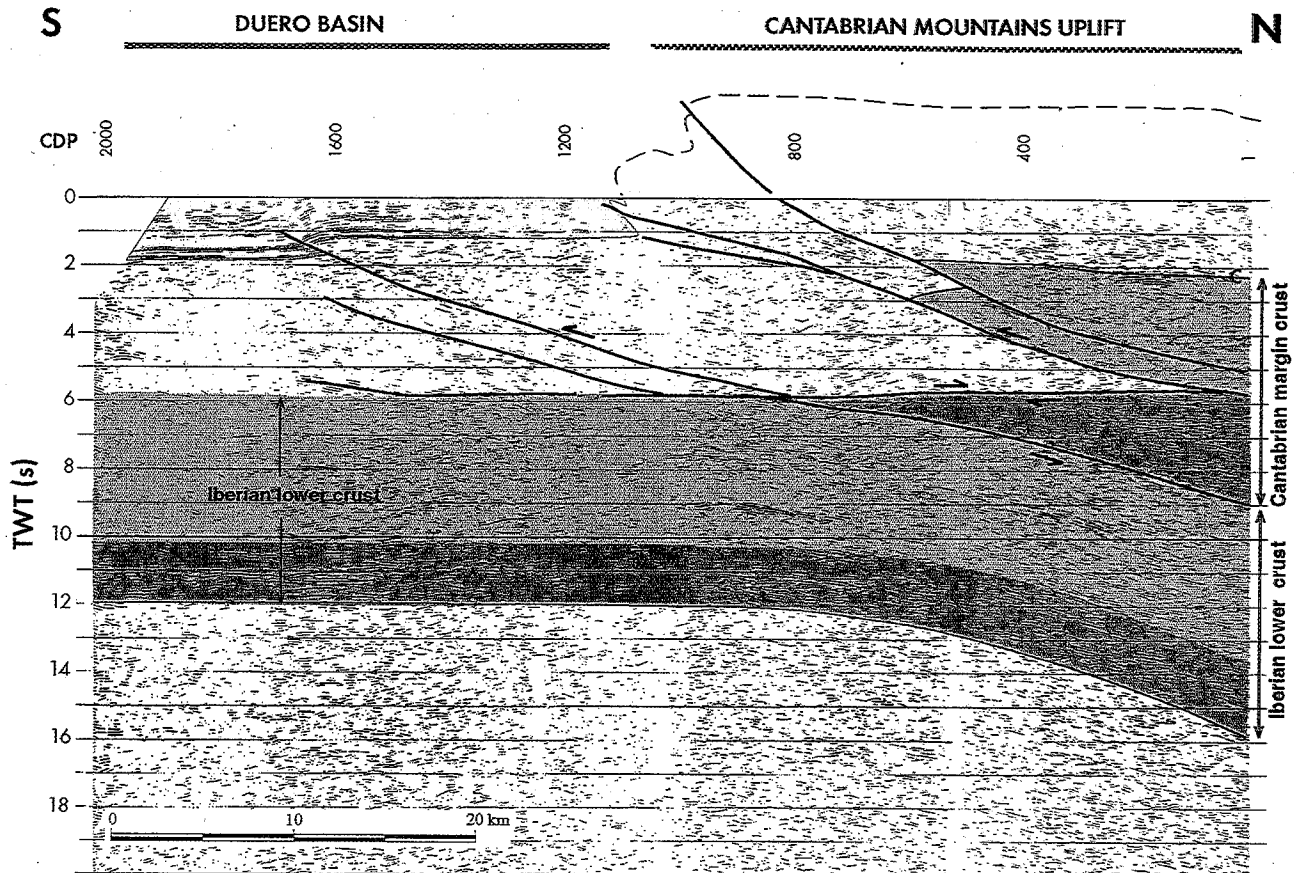


Figure 7.- Interpreted coherency filtered section of unmigrated ESCI-N2 showing the Alpine duplication of the lower crust under the Cantabrian Mountains and the northward subduction of the Iberian lower crust under the Cantabrian margin crust.

nuous reflections at 2 s, in the northern part of the profile (C in Fig. 5). It can be interpreted as the base of the Palaeozoic sedimentary sequence in this zone. This structure has been well imaged and modeled in the E-W reflection profile ESCI-N1 (Pérez-Estaún *et al.*, 1994; Gallastegui *et al.*, in press) and is considered to be the boundary between the pre-Variscan basement and the Palaeozoic succession thrust and folded during the Variscan orogeny.

#### Deep structure

Beneath the Duero basin, a band of strong, horizontal and quite continuous reflections appears underneath a rather homogeneous seismic fabric of horizontal, short and discontinuous reflections (Fig. 5). The base of this reflective zone is interpreted as the base of the crust, i.e., the Moho discontinuity (Fig 7). This interpretation is based in the seismic character, depth position and dip of this strong reflective band. This Moho position can be correlated with a velocity jump from 6.9 km/s to 8.2 km/s in a near coincident reversed refraction profile (Pulgar *et al.*, in press)

The strong reflectivity of the lower crust immediately above the Moho can be interpreted as the seismic expression of a laminated lower crust (Fig 7). This high reflectivity zone above Moho is characteristic of the Alps, Pyrenees and others areas in Phanerozoic Europe (Bois *et al.*, 1988; Pffiffner *et al.*, 1990; Bois and ECORS Scienti-

fic Parties, 1991; Valasek *et al.*, 1991). The thickness of the laminated lower crust in ESCI-N2 profile is similar to the one of the Alps or the Pyrenees. The zone of erratic line-up of short reflections extends up to 6 s level, that is interpreted as the upper-lower crust boundary (Fig. 7).

Beneath the Cantabrian Mountains, the high reflective band of the lower crust is dipping northwards, with the reflection Moho deepening from 12 to 16 s, at the northern end of the profile. The topography of the Moho implies a downward bending of the Iberian lower crust that deepens into the upper mantle beneath the main elevations of the Cantabrian Mountains. The zone of prominent subhorizontal reflections situated immediately above in the northern end of the profile can be interpreted as a lower crust wedge protruding and thickening the Iberian lower crust (Fig. 7).

The structural disharmony between the upper and lower crust implies an intracrustal decoupling mechanism beneath the Cantabrian Mountains. The decoupling horizon must be situated at the 6 s level, in the upper-lower crust boundary. Above this detachment horizon a North-dipping thrust ramp cutting across the upper crust and an uppermost part of the lower crust can be related to the uplift of the range. The detachment and uplifting of the crust can be interpreted as inducted by the indentation of a wedge of the "Cantabrian margin lower crust" in the

middle of the "Iberian crust". This southwards indentation of the "Cantabrian margin lower crust" splits the "Iberian crust" apart, giving rise to the northwards subduction of the Iberian lower crust.

### Discussion and conclusions

The ESCI-N2 deep-seismic reflection data evidence a very important Alpine reworking and thickening of the Variscan crust under the Cantabrian Mountains that is also supported by wide-angle reflection and refraction data (Gallart *et al.*, 1997; Pulgar *et al.* in press). Two sets of wide-angle seismic data can be considered to constraint the ESCI-N2 reflection data and to obtain a complete transect from the Cantabrian Mountains to the Cantabrian margin. On one hand, a nearly coincident 200 km-long reversed refraction profile (profile 5, Fig. 2). This profile shows a Moho located at 31 km at its southern end, that deepens moderately along the Duero basin until it reaches 35 km in the mountain front. Beneath the Cantabrian Mountains the Moho deepening is more acute confirming the interpretation of ESCI-N2 data. The refraction data is in agreement with a Variscan-type crust beneath the Duero basin that was completely reworked beneath the Cantabrian Mountains.

On the other hand, the piggy-back recording on 7 land stations of the air-gun shots of the ESCI-N4 offshore profile (Fig. 2) provides a high-quality wide-angle data set that images the deep crust at the transition from the Cantabrian Mountains to the continental margin (Gallart *et al.*, 1997; Pulgar *et al.* in press). This wide-angle data also supports a thickening of the lower crust below the main elevation of the range, that abruptly disappears to the North. The Iberian Moho is located at 37 km depth beneath the mountain front (St. 26, fig. 2) and reaches about 60 km beneath the shoreline, about 70 km to the North. A much shallower "Cantabrian margin Moho" is well constrained beyond the shoreline only up to 10 km inland, where it is located at 33 km depth, as far as the continental slope. The geometry of this Cantabrian margin Moho indicates a progressive crustal thinning northwards, from 30 km beneath the shoreline to 22 km depth at the northern side of the slope and 17 km at the northern end of the ESCI-N4 profile (Gallart *et al.*, 1997).

The most significant features in the crustal structure of this traverse across the Cantabrian Mountains is the asymmetric thickening of the crust beneath the Cantabrian Mountains, which is interpreted as a consequence of the underthrusting of the "Iberian lower crust" beneath the "Cantabrian margin lower crust" and subsequent subduction into the continental margin mantle. These results are a strong support for a delamination mechanism at a mid-crustal level by the indentation of a "Cantabrian margin lower crust" wedge that splits the "Iberian crust" apart, thereby subducting the lower crust of the Iberian plate to greater depth, and detaching and uplifting the upper crust of the Iberian crust to build up the Cantabrian Mountains.

The deep seismic signature of the crust in the Cantabrian Mountains shows a strong parallelism with those

observed across the Pyrenees along the ECORS seismic profile (ECORS Pyrenean Team, 1988; Choukroune & ECORS Team, 1989; Roure *et al.*, 1989; Daignières *et al.*, 1989; Muñoz, 1992). In both cases, the crustal structure deduced from the seismic data is characterized by a detachment and delamination of the upper crust related with the northward underthrusting of the southern lower crust below the northern one. Very similar features are also observed in the Alps where the crustal structure in the collision zone between the European and African plates is characterized by a vertical Moho offset with an asymmetric thickening of the crust, which is interpreted as an underthrusting of the European lower crust beneath the Adriatic lower crust (Frei *et al.*, 1989; Mueller, 1990; Pfiffner *et al.*, 1990; Valasek *et al.*, 1991; Hitz & Pfiffner, 1994).

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