Results from the ESCI-N3.1 and ESCI-N3.2 marine deep seismic profiles in the northwestern Galicia Margin

J. ÁLVAREZ-MARRÓN[1], A. PÉREZ-ESTAÚN[1], J. J. DAÑOBEITIA[1], J. A. PULGAR[2],
J. R. MARTÍNEZ CATALÁN[3], A. MARCOS[2], F. BASTIDA[2], J. ALLER[2],
P. AYARZA ARRIBAS[3], J. GALLART[1], F. GONZÁLEZ-LODEIRO[4], E. BANDA[1],
M. C. COMAS[5] and D. CÓRDOBA[6]

[1] *Instituto de Ciencias de la Tierra, Jaume Almera, CSIC, 08028 Barcelona, Spain.*
[2] *Departamento de Geología, Universidad de Oviedo, 33005 Oviedo.*
[3] *Departamento de Geología, Universidad de Salamanca, 37008 Salamanca.*
[4] *Departamento de Geodinámica, Universidad de Granada, 18002 Granada.*
[5] *Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada, 18002 Granada.*
[6] *Departamento de Geofísica, Universidad Complutense, 28040 Madrid.*

Abstract: The ESCI-N3 marine profile recorded 20 s of near vertical reflection seismic data offshore Northwest Galicia. This paper deals with two segments of the profile; ESCI-N3.1 which crosscuts the continental slope and a short part of the deep sea areas, and ESCI-N3.2 which images a section of the continental platform. In the ESCI-N3.1 profile, horizontal reflections from 6.5 to 8.8 s (TWT) correspond to an undisturbed package of sediments lying above an oceanic-type basement. A few kilometres long, strong horizontal reflection at 11.2 s may represent an oceanic Moho reflection. A tectonic accretionary prism is seen at the ocean-continent transition, and a band of reflections dips gently towards the south-east, from the base of the gently dipping continental slope. The ESCI-N3.2 profile, is characterised by bright, continuous lower crustal reflections from 8 to 10 s. A band of strong sub-Moho reflections dips gently towards the south-west from 10 to 13.5 s. The reflective features imaged in these profiles are correlated with major structures that evidence the various tectonic events comprising the geological history of the area. This history includes at least three main tectonic events, the Variscan collision during Palaeozoic times, a subsequent rifting with formation of the Bay of Biscay basin during the Mesozoic, and a compressional event in the Cenozoic.

Keywords: Deep reflection seismics, North Iberian Margin, crustal structure.

Resumen: El perfil marino ESCI-N3 registra 20 s de datos de sísmica de reflexión vertical en el noroeste de Galicia. En este trabajo se analizan dos segmentos del perfil, que incluyen la llanura abisal, pasando por el talud continental (ESCI-N3.1) hasta la plataforma continental (ESCI-N3.2). En el perfil ESCI-N3.1 las reflexiones horizontales entre 6.5 y 8.8 s corresponden a sedimentos marinos depositados sobre un basamento oceánico. Un horizonte fuertemente reflectivo de varios kilómetros de longitud, situado a 11, 2 s se interpreta como la Moho oceánica. En la transición océano continente se observa un pequeño prisma de acrección y una banda de reflexiones inclinadas hacia el sureste que alcanza la base del talud continental. El perfil ESCI-N3.2 se caracteriza por la existencia de alta reflectividad en la corteza inferior (entre 8 y 10 s) y por una banda fuertemente reflectiva por debajo de la Moho que se inclina suavemente hacia el suroeste desde 10 hasta 13,5 s. Los horizontes reflectivos se correlacionan con estructuras mayores relacionadas con los diversos episodios tectónicos registrados en la historia geológica del margen Nord-Ibérico. Esta historia geológica incluye al menos tres episodios tectónicos principales: la colisión varisca en el Paleozoico, la extensión mesozoica que generó el Golfo de Vizcaya y la compresión cenozoica que afectó el norte de la península.

Palabras clave: Sísmica de reflexión profunda, margen Nord-Ibérico, estructura cortical.

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The Iberian continental margin in northwestern Galicia trends slightly south-westwards from the Ortegal Spur to join the Iberian Atlantic Margin in the Galicia Bank (Fig. 1). This area, has been largely investigated by French researchers who acquired geological and geophysical data, including reflection seismic, magnetic and gravity data of the whole North Iberian Margin (see compilation by Debysier *et al.*, 1971).

The ESCI-North survey (ESCI-N) included the acquisition of four deep seismic profiles; two onland (Pé-

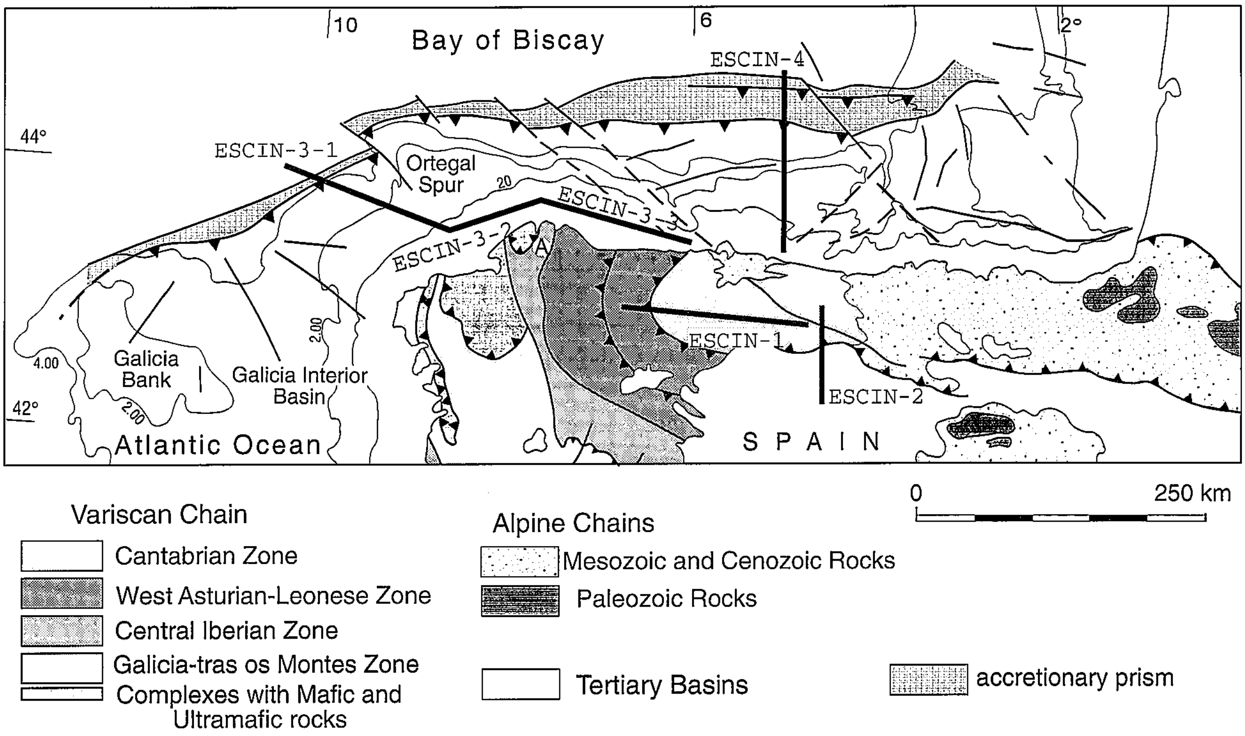

Figure 1.- Geological map of northwestern Iberia with geological zones (Julivert *et al.*, 1972, Farias *et al.*, 1987). Offshore geology is adapted from Boillot & Malod (1988). Thick black lines are the ESCI-N seismic profiles. A, location of the Ollo de Sapo antiform in the Central Iberian Zone.

rez-Estaún *et al.*, 1994, Pulgar *et al.*, 1996), and two offshore (Álvarez-Marrón *et al.*, 1996) (Fig. 1). The marine profiles were designed to study the crustal structure of the northern Iberian Margin and the nature of the ocean-continent transition in the southern part of the Bay of Biscay. This paper deals with the two western segments of profile ESCI-N.3; ESCI-N3.1 and ESCI-N3.2. The aim is to describe the main features imaged in these two marine profiles and suggest their correlation with major structures related to the various tectonic events comprising the geological history of the margin. The results from the eastern ESCI-N3.3 profile are in Martínez-Catalán *et al.* (this vol.).

Tectonic evolution of the northwestern Iberian Margin

The section of the Variscan orogen that crops out onland nearest to the ESCI-N3.1 and 3.2 seismic profiles corresponds to the hinterland areas of the Northwest Iberian Variscides (Fig. 1), and consists mostly of allochthonous and parautochthonous rocks grouped in the Central Iberian Zone and the Galicia-Tras-os-Montes Zone (Farias *et al.*, 1987). Most of the Central Iberian Zone in this area is constituted by intrusive rocks (Martínez *et al.*, 1990). Moreover, within the Ollo de Sapo antiformal structure, there are Lower Ordovician sediments which lie unconformably on probable Late Proterozoic to Early Cambrian age subvolcanic to volcaniclastic rocks (Parga Pondal *et al.*, 1964). These deformed and metamorphosed rocks, belong to the Lower Palaeozoic continental margin of Godwana, involved in the Variscan collision (Pérez-Estaún *et al.*, 1991). The Galicia-Tras-os-Montes Zone is comprised of a large stack of allochthonous units thrust onto the Central Iberian Zone. They include several terranes of unknown provenance and origin with the upper units constituted by ophiolitic and highly metamorphosed rocks (complexes with mafic and ultramafic rocks in Fig. 1) that represent the Variscan suture (Pérez-Estaún *et al.*, 1991).

The North Iberian continental margin formed during Late Jurassic-Early Cretaceous times by a rifting process during the break-up between Eurasia and North America (Le Pichon *et al.*, 1971, Verhoef & Srivastava, 1989), sea-floor spreading continued in the Bay of Biscay until the Late Cretaceous (Williams, 1975). The initiation of sea floor spreading is marked by an Aptian-Albian age break-up unconformity on the platform (Le Pichon *et al.*, 1971, Montadert *et al.*, 1979).

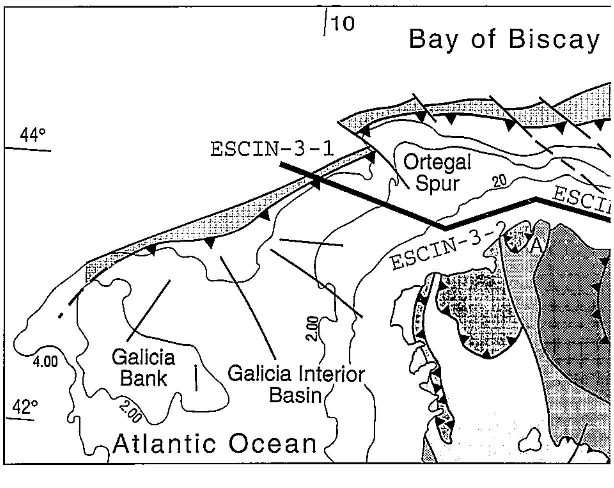

Figure 2.- Map of offshore gravity anomalies redrafted from Lalaut *et al.* (1981).

Tertiary convergence of Iberia and Eurasia activated the continental margin, and a marginal trench developed (Sibuet & Le Pichon, 1971, Sibuet *et al.*, 1971, Boillot *et al.*, 1979; Grimaud *et al.*, 1982). This trench is characterised by a belt of negative gravity anomalies (Fig. 2, Lalaut *et al.*, 1981). The Cenozoic structures on the north Iberian margin (Fig. 1) offshore Northwest Galiçia include an accretionary prism (Derégnaucourt & Boillot, 1982) that is interpreted to be related to the subduction of the Bay of Biscay ocean floor under the Iberian margin during Palaeocene-Eocene times (Boillot *et al.*, 1979, Boillot and Malod, 1988). This subduction may have started in the Late Cretaceous and probably continued episodically until after Eocene times, possibly during Oligocene and even during the Neogene. The timing of subduction is based on seismic correlation with holes DSDP 118 and 119 by Laughton *et al.* (1972).

Seismic data acquisition and processing

The ESCI-N deep seismic marine survey was acquired during February 1993 by the MV SeisQuest. Acquisition and processing were done commercially by Schlumberger GECO-PRAKLA. Profile ESCI-N.3 is composed of three segments of different azimuths. The ESCI-N3.1 is the western-most segment, and has a length of 141 km. It crosses the continental slope from 44°N, 10°30' W to 43°35.57' N, 8°50.25' W. The ESCI-N3.2 central segment is 98 km long, and runs near the coast from 43°35.98' N, 8°51.99' W to 43°57"N, 7°45' W. The ESCI-N3.3 is the eastern-most segment, with a length of 141 km from 43°36.99' N, 7°47'W to 43°40.73' N, 6°4.27'W (Fig. 1).

The acquisition configuration is displayed in Fig. 3. The vessel towed a 4500 m long analog streamer at a mean depth of 12 m, that included 360 groups of hydrophones with a group interval of 12.5 m. To avoid cavitation noise from the ship an offset of 240 m was used. The shooting was performed with a wide tuned array (80 m) configured in 6 strings of 17.5 m long each in order to reduce out-of-plane energy (Hobbs & Snyder, 1992). A mixed configuration of sleeve and g.i. guns increases the nominal power up to 25% more than the classical standard array. The data were shot at 75 m pop-rate using this large array of 5490 in^3 (90 l) at 2000 psi (13.8 MPa) nominal pressure with a record length of 20.48 s (two-way-travel-time) and a sampling interval of 4 ms, nominal coverage of 30 fold. The recording system included the following filtering, a low-cut filter of 3 Hz/6dB and a high-cut filter of 250 Hz/72dB.

The processing sequence for the ESCI-N marine data is presented on Table I. The data were resampled at 8 ms. Although the sequence is conventional, some of the parameters used were only chosen after extensive testing primarily directed to obtain a good image at great depths. Testing was also required because the lines cross diverse geological provinces and therefore optimum processing parameters for any one zone can vary dramatically along one line. To enhance the signal to noise ratio we have applied a lateral coherent operator, semblance based, in the time domain (Milkreit & Spencer, 1989). Thus, the phase coherent signal can be separated from background noise on the basis of coherency estimates, a) background noise has no spatial coherency, and b) coherent noise can

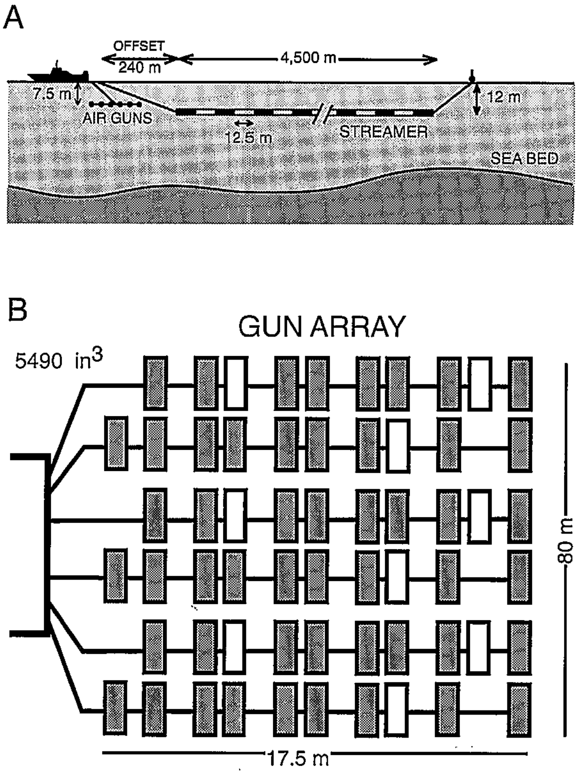

Figure 3.- Acquisition configuration. A: Configuration in section view. B: Airgun array configuration in plan view. A total of 60 guns where under the water, shaded blocks correspond to the active guns totalling 51, white blocks correspond to spare guns.

Table I.- Processing sequence.

1. RESAMPLE (8 ms)
2. ADJACENT TRACE SUMMATION
3. SPHERICAL DIVERGENCE COMPENSATION
4. COMMON MIDPOINT GATHER (30 fold, 12,5 m interval)
5. PRESTACK DECONVOLUTION (operator length 200 ms predictive gap 32 ms)
6. FK DEMULTIPLE (Fk 12 ms/ tr)
7. VELOCITY ANALYSIS (every 3 km)
8. NMO CORRECTION
9. PRE STACK INNER AND OUTER MUTES
10. STACK
11. NOISE ATTENUATION FILTER
12. POST STACK DECONVOLUTION (operator length 300 ms predictive gap 60 ms)
13. TIME VARIANT FILTER 0 - 2 s 4 - 50 Hz
    2 - 6 s 4 - 40 Hz
    6 -10 s 4 - 30 Hz
    10 -16 s 4 - 20 Hz
14. GUN AND STREAMER STATIC CORRECTION (+ 15 ms)

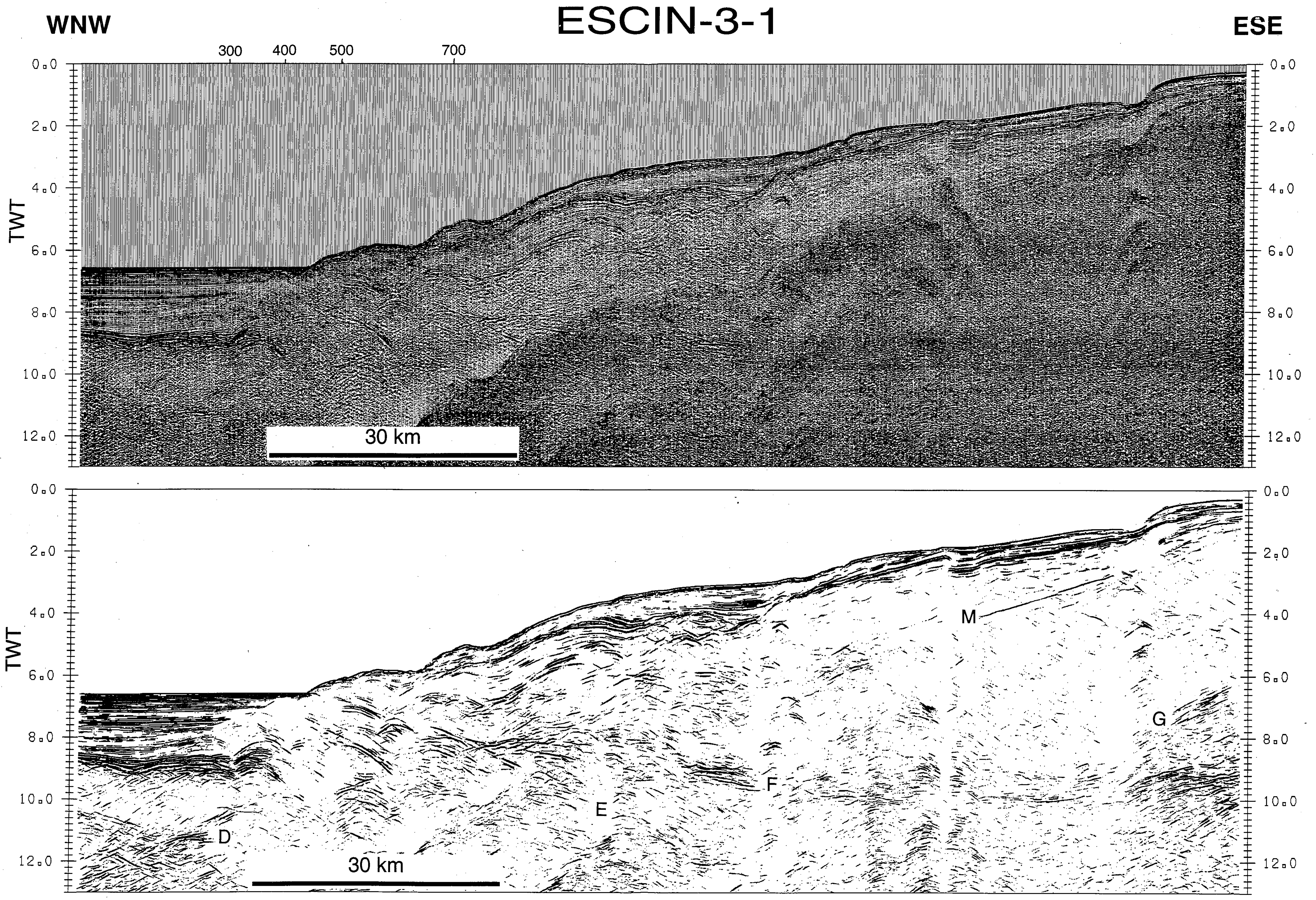

Figure 4.- A: Stack section of profile ESCI-N3.1 (upper image). B: Coherence filtered section with a -0.2 to 0.2 s km^{-1} slowness bandpass filter applied at a window length of 1000 m (lower image), capital letters are the features described in the text. M, multiple.

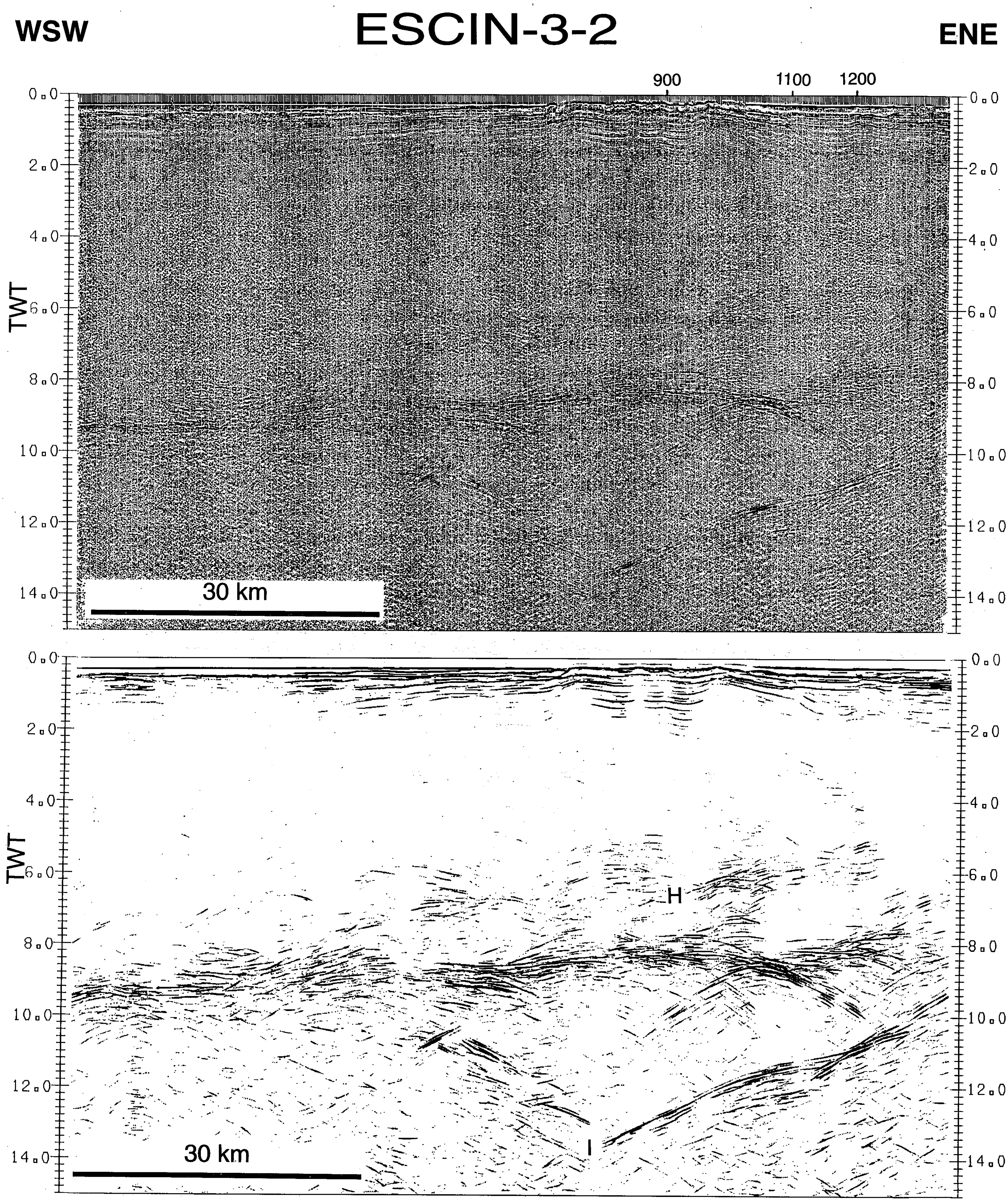

Figure 5.- A: Stack section of profile ESCI-N3.2 (upper image). B: Coherence filtered section with a-0.2 to 0.2 s km^{-1} slowness bandpass filter applied at a window length of 1500 m (lower image), capital letters are the features described in the text.

be separated from the signal depending on the different dips (slowness) (Neidell & Taner, 1971). We have used a filter that band passes most of the velocity ranges with window lengths varying between 750 m to 1750 m depending on the profile.

Reflectivity patterns of ESCI-N3.1 and ESCI-N3.2 profiles

Profile ESCI-N3.1

This profile images a continental slope with a gentle slope (about 2°) starting from 200 m depth and with no sharp shelf break, reaching depths of more than 4500 m at the north-western end of the profile (Fig. 4).

In the north-western end of the profile, in the open sea area (west of SP 300, Fig. 4B), two reflection fabrics are distinguished. An upper panel of horizontal reflections from 6.5 to 8.8 s and a lower panel with mainly out-of-plane diffractions. These two panels are separated by a strong reflection at about 8.8 s that can be followed from the edge of the section until shotpoint 400. A few kilometres long, bright, horizontal reflection at 11.2 s can also be seen (D in Fig. 4B). The upper panel of horizontal reflections terminate laterally in the area of the transition to the continental slope against a small wedge of disturbed reflections, commonly with diffractions that are seen between SPs 300 and 500, above the strong reflection at 8.8-9 s. A band of reflections (E in Fig. 4B) dipping towards the south-east from the foot of the continental slope can be followed until depths equivalent to 13 s.

Primary reflections are clear in a thin band (c.a. 1 s) in the upper part of the crust, in the continental slope. These reflections frequently terminate laterally by truncation, and by onlap and downlap relationships. In deeper parts of the profile, a band of layered, bright reflections that deepens gently eastwards is present at about 8 s to 9 s (F in Fig. 4B). This band of reflections joins reflection E near SP 700 that merges from the base of the continental slope. On the right part of the profile, a band of WNW dipping reflections are present at mid crustal levels, between 6 and 8 s (G in Fig. 4B).

Profile ESCI-N3.2

This profile images a section of the continental platform in a profile close to the coastline and at shallow water depths (less than 200 m). Subhorizontal and quite continuous reflections are seen in the upper 1 s of the profile that, in some cases, terminate laterally into areas of little reflectivity (Fig. 5). A thick transparent zone in upper-middle crustal levels is present above 5 s, and primary reflections can be distinguished down to 14 s (Fig. 5). This deep highly coherent reflectivity includes bright, layered continuous reflections from 8 to 10 s across the whole line, and diffractions below SP 1100 at about 9 s. Above the band of layered reflections, some inclined reflections dipping in both directions are also imaged. The most continuous and largest, located between SPs 900 and 1100 (H in Fig. 5B), dips gently towards the southwest from 5 to 7 s. Below the sub-horizontal layered band of reflections, some dipping reflections are imaged. A band dipping to the WSW from 9 s can be followed until 14 s (I in Fig. 5B and 6). This band contains bright continuous reflections with a clear bend around shot point 1200, changing from a steeper to a gentler dip downslope.

Data interpretation and discussion

Profile ESCI-N3.1

A striking feature of this profile is the gentle topographic profile of the continental slope in contrast to that of ESCIN-4 (Álvarez-Marrón *et al.*, this volume), even taking into account the slight obliquity of profile ESCIN-3-1 with respect to the dip slope direction.

The thin reflective band along the upper part of the crust in the continental slope (Fig. 4) may be related to recent slope-drape and slope basin sediments. Data from dredges of the Cybere Campaign (Malod *et al.*, 1984) in the Ortegal Spur continental slope give a Late Eocene-Neogene age to sediments with similar disposition, located above a Middle Eocene unconformity (Temine, 1984). In the north-western slope of the Galicia Bank, the slope drape sediments are of Oligocene to recent age (acoustic unit 1 of Mauffret & Montadert, 1988). Below the slope basin sediments in the ESCI-N3.1 profile, the oldest sediments could correspond to Upper Cretaceous syn-rift sequences, although the contact between the Variscan basement and the Mesozoic cover can not be clearly determined from this profile. In the Ortegal Spur area, syn-rift sediments of Cretaceous age have been found by the submersible Cybere (Malod *et al.*, 1984). In addition, Hauterivian to Late Aptian age sediments have been described above the basement in the north-western slope of the Galicia Bank (acoustic unit 4 of Mauffret & Montadert, 1988).

Sibuet *et al.* (1987) have interpreted the structure below the continental shelf off the west coast of Galicia (Galicia Interior Basin, Fig. 1) as tilted, fault-bounded basement blocks that progressively thinned the continental crust towards the ocean-continent boundary. However, in the north-western slope of the Galicia Bank, Mesozoic extensional basement faults were reactivated during the convergent motion between Iberia and Eurasia in the Cenozoic (Malod *et al.*, 1993). Serpentinised peridotites form part of the basement in the lower slope, nearest to the ocean-continent boundary (Malod *et al.*, 1993).

The structure at mid crustal levels is not clearly delineated in ESCI-N3.1 profile, although the existence of extensional faults deforming the basement in the upper slope can be inferred from the configuration of upper crustal sediments that display abrupt lateral terminations.

Based on onshore refraction data in the Galicia area, Córdoba *et al.* (1987) postulate the seaward shallowing of the Moho discontinuity from 32 km onland to 29 km in the northern coast. According to this interpretation, the set of reflections F are situated at Moho depths and probably corresponds to the layered lower crust of the continental crust stretched during the Mesozoic. In this profile, the continental crust thins progressively seawards and probably ends near SP 700, where the layered lower crust intercepts reflection E at a travel time of 8 s (Fig. 4B).

At the western end of this profile an oceanic-type crust is imaged and D reflection (Fig. 4B) probably corresponds to the oceanic Moho. The oceanic basement is here exceptionally deep, below 8.2 s and has an approximate thickness of 6 km (assuming a constant velocity of 6 km/s). This oceanic crust is covered by sub-horizontal undeformed sediments in the NW end of the profile.

With respect to the ocean-continent transition in this profile, the seismic image can be interpreted as that of a compressional ocean-continent boundary. However, accretion of ocean sediments in this section seems to have been much less important than in ESCI-N4 (Álvarez-Marrón *et al.*, this volume). The wedge-shaped package of reflections between shot points 300 and 500 may correspond to deformed sediments in a small (less than 20 km long) accretionary prism at the foot of the continental slope (Fig. 4B). The strong reflective band of reflections at 8.8 s is beneath the accretionary prism and probably corresponds to the top of the oceanic basement that is subducted under the continental margin. Reflection E may correspond to a major landward-dipping thrust that separates the accretionary prism from a landward dipping backstop formed by the thinned continental crust (Fig. 4B).

Judging from the overall architecture of upper crustal basins, and the extensional structures of the thinned continental crust in the area of the continental shelf crosscut by ESCI-N3.1 profile, this western end of the North Iberian margin does not seem to have been inverted or affected by compressional deformation above the landward dipping thrust E. This is in contrast with what has been found to the East of the margin, in ESCI-N4 profile where the Mesozoic basins in the continental platform appear inverted and deformed by probably Tertiary folds and thrusts (Álvarez-Marrón *et al.*, this volume).

Profile ESCIN-3-2

This profile runs almost parallel to the continental margin and is sub-perpendicular to the onland strike of Variscan structures. In the upper part of the crust, primary reflectivity is related to the sedimentary infill of probably recent sag basins. The configuration of the basins appears undisturbed and seems not to have been affected by any compressional tectonism (Figs. 5B).

At mid crustal levels, above 8 s, there are dipping events that may correspond to Variscan features that correlate with N-S trending structures onshore (i.e. reflection H in Fig. 5B).

The lower crust is highly reflective and the reflection Moho is interpreted to be located at the base of the layered lower crust. This layered lower crust shallows gently towards the ENE and the reflectivity can be related to shear structures developed during the Mesozoic extensional phase of formation of the margin. It could also be the remnant, after extension, of an originally thicker reflective lower crust. This latest interpretation has been suggested for the Goban Spur area in the southwestern continental margin of Britain (Peddy *et al.*, 1989) which has also been formed from stretching of a previous Va-

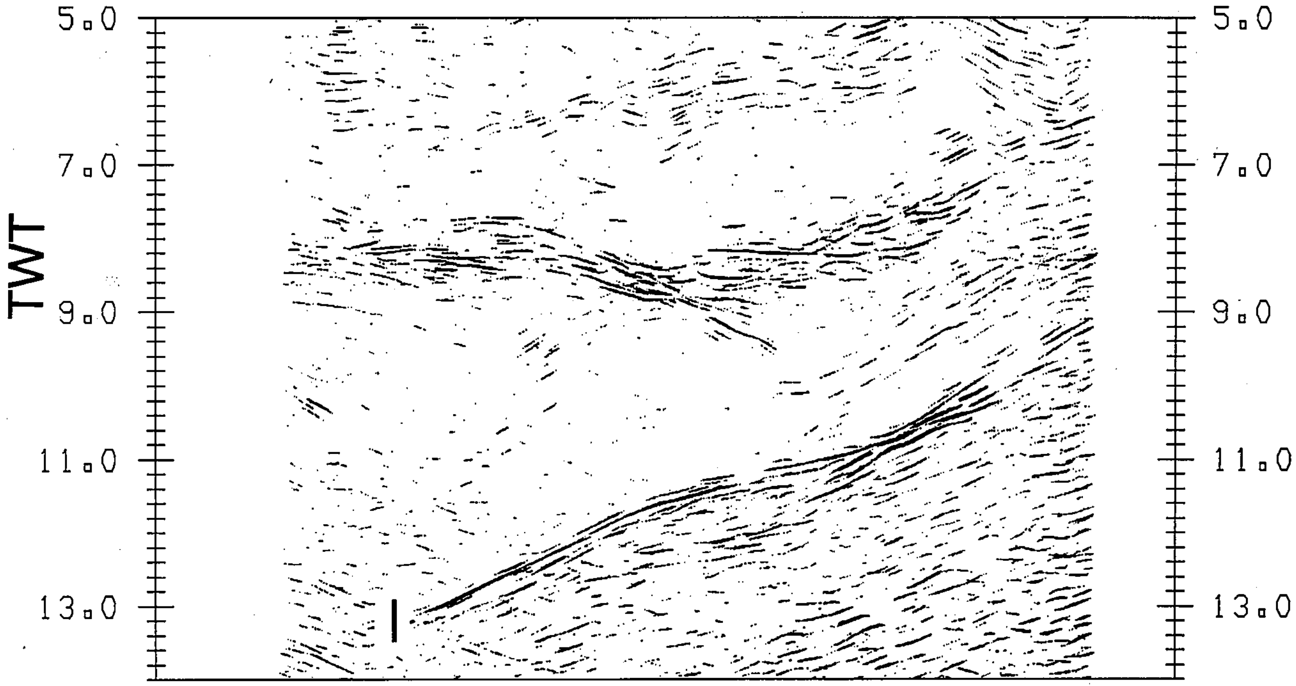

Figure 6.- Window of migrated profile ESCI-N3.2 coherence filtered section with a -0.4 to 0.4 s km^{-1} slowness bandpass filter applied at a window length of 875 m. The layered lower crust shows a gentle topography with broad curvature in this part of the profile between 7 and 9 s. Below the reflective Moho, at the base of the layered lower crust, a bright reflection shows a smooth staircase geometry reaching traveltimes of 13 s.

riscan crust. The same interpretation has also been applied to the València Trough area (Watts *et al.*, 1990).

Below the Moho, dipping reflections are present (Figs. 5 and 6). Their nature and origin is for the moment unclear. Further interpretation of the data and correlation with other ongoing geophysical analysis are needed. However, it may be speculated that they are related to subduction processes and could be produced by the remnants of a downgoing, possibly oceanic slab.

Conclusions

The marine ESCI-N3.1 and ESCI-N3.2 near vertical reflection seismic profiles cross the entire continental margin off northwestern Galicia and provide images of the structure beneath the continental shelf and the transition to the Bay of Biscay oceanic crust. The reflectivity in these profiles is seen at upper, mid and lower crustal levels, and also in the upper mantle.

Dipping, mid-crustal reflections in profile ESCI-N3.2 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 profiles ESCI-N3.1 and ESCI-N3.2, respectively.

Lower crustal reflectivity in the continental margin is well-imaged in both profiles. This lower crustal reflectivity can be followed until the ocean-continent transition in profile ESCI-N3.1. The layered lower crust reflectivity may image 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 the remnant, after extension, of an originally thicker reflective lower crust.

Well imaged, sub-Moho reflections are seen in the continental shelf in profile ESCI-N3.2, and are probably related to the Cenozoic subduction processes. Other structures related to the convergence of European and Iberian plates are at the ocean-continent transition in profile ESCI-N3.1 and include a tectonic accretionary prism and a major thrust that separates the shortened and deformed sediments in the accretionary prism next to the undisturbed, previously extended continental shelf.

The oceanic crust of the Bay of Biscay is also imaged at the western end of profile ESCI-N3.1 where a series of continuous, subhorizontal reflections of about 1.5 km thick lie on top of a 6 km thick oceanic basement. The oceanic Moho boundary can be tentatively correlated with the highly energetic reflection at 11.2 s.

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