Results from the ESCI-N4 marine deep seismic profile in the northern Iberian Margin

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Abstract: The ESCI-N4 deep marine seismic profile is 145 km long and crosses the North Iberian continental margin in a N-S direction offshore Asturias. It records 20 s of near vertical seismic data that images the crustal structure of the continental platform and the transition to the deep sea areas of the southern Bay of Biscay. The reflectivity of the upper crust in the continental platform images the Mesozoic Le Danois and Ribadesella basins that include inverted structures developed during Tertiary times. These structures are north-verging blind thrusts and associated growth folds developed above a south dipping detachment interpreted to be located near the basement-cover contact. To the North of the steep continental slope a thick sedimentary package is imaged between 6 and 9.5 s (TWT) which includes a 50 km long, north-tapered wedge of mainly south dipping reflections corresponding to disturbed sediments within an Alpine-age accretionary prism. The oceanic-type basement dips gently landwards towards the deformation front beneath the prism, and an upper sedimentary package onlaps onto the prism suggesting the cessation of the tectonic activity in the prism that has been dated as Late Oligocene.

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

Resumen: El perfil ESCI-N4 tiene una longitud de 145 km y cruza en dirección N-S el margen continental nordibérico al norte de Asturias. Este perfil registra 20 s de datos de sísmica de reflexión vertical que muestran la estructura cortical de la plataforma continental y la transición hacia aguas profundas de la parte sur del Golfo de Vizcaya. La parte superior del perfil, en la plataforma continental, muestra las cuencas mesozoicas de Ribadesella y Le Danois que incluyen estructuras invertidas durante el Terciario. Estas estructuras incluyen cabalgamientos ciegos vergentes al norte con pliegues asociados, desarrollados por encima de un cabalgamiento basal inclinado al sur que se localiza cerca del contacto basamento-cobertera. Hacia el norte del talud continetal se observa una cubierta sedimentaria muy gruesa, entre 6 y 9.5 s (TWT), que incluye un conjunto en forma de cuña de 50 km de largo, de reflexiones inclinadas principalmente hacia el sur. Esta cuña es interpretada como un prisma de acreción tectónica desarrollado en tiempos alpinos. El basamento, posiblemente oceánico, buza suavemente hacia el sur bajo la cubierta sedimentaria hasta alcanzar el frente de deformación del prisma. Los sedimentos subhorizontales que cubren totalmente el prisma de forma transgresiva hacia el sur indican el cese de la actividad tectónica en el mismo. El cese de la acreción se ha datado como Oligoceno tardío.

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

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The northern continental margin of Spain trends mostly E-W and constitutes the southern border of the Bay of Biscay. Up until the beginning of the 1970's this margin was largely investigated by French researchers (see compilation by Debysier *et al.,* 1971), who acquired geological and geophysical data, including reflection seismic, magnetic and gravity data. Much of this research has focused towards elucidating the relative movements of the Iberian plate with respect to Europe during the Mesozoic, and several hypothesis for the opening of the Bay of Biscay have been proposed (synthesised in Sibuet, 1989).

The ESCI-North survey (ESCI-N) included the acquisition of four deep seismic profiles, two onland (Pérez-Estaún *et al.*, 1994, Pulgar *et al.*, 1996) and two offshore (Álvarez-Marrón *et al.*, 1996) (Fig. 1). The marine profiles total about 500 km and 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 ESCI-N4 profile that crosses the continental margin in a N-S direction across the Le Danois Bank (Fig. 1). The paper describes the major features imaged in this profile and suggests their correlation with major

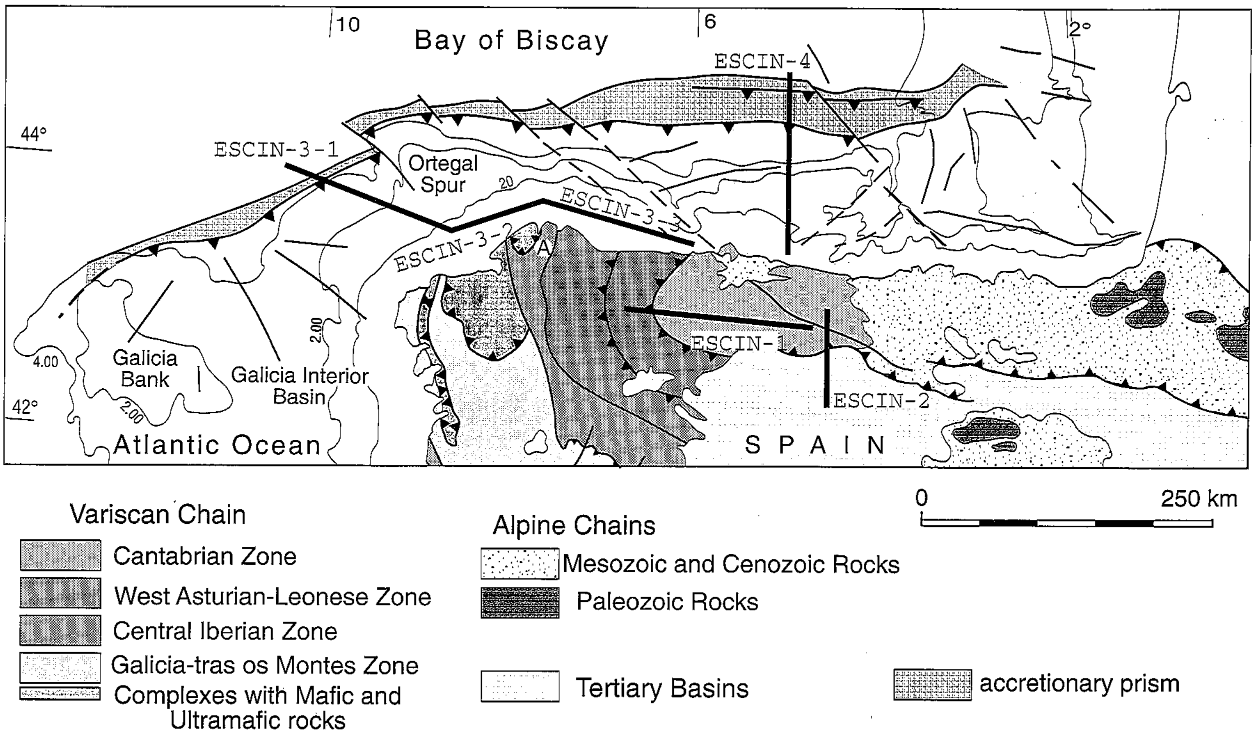


Figure 1.- Geological map of north-western Iberia with geological zones (Lotze, 1945; Julivert *et al.*, 1972). Offshore geology is adapted from Boillot & Malod (1988). Thick black lines are the ESCI-N seismic profiles.

structures related to the Mesozoic-Cenozoic evolution of the margin.

Geological framework and tectonic evolution of the North Iberian Margin

Deep rooted Variscan structures of the hinterland areas and the upper crustal level structures of the foreland thrust and fold belt developed in the north-western Iberian crust before extensional tectonics began in Permian and Triassic times. Onland Permo-Triassic extensional activity resulted in the formation of minor fault bounded basins and related alkaline volcanism (Martínez-García, 1983; Martínez-García & Tejerina, 1985, García-Mondéjar *et al.*, 1986, Suárez-Rodríguez, 1988). The onshore sedimentary record consists mainly of continental facies rocks of varied thickness, typified by frequent red beds.

The Bay of Biscay basin initiated as a subsidiary rifted arm of the north Atlantic ocean during the break-up between Europe and North America in the Mesozoic (Le Pichon *et al.*, 1971, Verhoef & Srivastava, 1989). Synrift sequences, related to pull-apart basins, are found in the Basque-Cantabrian Basin onshore (García-Mondéjar, 1989). The initiation of sea floor spreading confirmed by the identified magnetic chron 34 (Williams, 1975, Srivastava *et al.*, 1990) in the Bay of Biscay is marked by an Aptian-Albian age break-up unconformity on the platform (Le Pichon *et al.*, 1971, Montadert *et al.*, 1979). Sea-floor spreading in the Bay of Biscay continued up until the Late Cretaceous (Williams, 1975) related to the oblique separation of Iberia from Eurasia that included an anti-clockwise rotation of the Iberian plate relative to stable Europe (Van der Voo, 1969; Sibuet, 1989). The Mesozoic sedimentary cover on the platform margin is thin, ranging from 100 to 1500 m (Malod & Boillot, 1980, Malod *et al.*, 1984).

During the Tertiary, the convergence between Iberia and Eurasia activated the continental margin and resulted in the formation of a marginal trench (Sibuet & Le Pichon, 1971, Sibuet *et al.* 1971, Boillot *et al.*, 1979; Grimaud *et al.*, 1982). The trench is characterised by a belt of negative gravity anomalies that follows the E-W trend of the margin from the Galicia Bank to the N-S French continental margin, where it splits into two branches bounding the northern and the southern sides of the Landes plateau (Fig. 2). The Tertiary activation of the North Iberian Margin produced inversion of Mesozoic extensional basins, both in the continental shelf and onland (Boillot *et al.*, 1971, García-Mondéjar, 1989), and reactivated extensional faults as reverse faults (Temine, 1984). The offshore structures 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 continental margin of Iberia during Palaeocene-Eocene times (Boillot *et al.*, 1979, Boillot & 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 (Laughton *et al.*, 1972).

The latest deformation during the Tertiary is reflected onshore in uplift of the Variscan basement (Pulgar *et al.*, 1996), in the reactivation of previous extensional faults

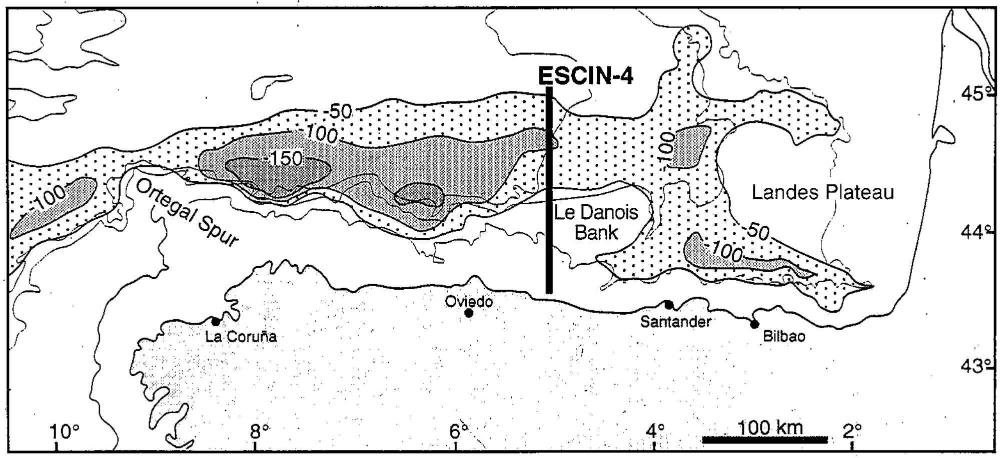


Figure 2.- Map of offshore gravity anomalies (redrafted from Lalaut *et al.*, 1981). Contours are in milliGals.

and in shortening along a gentle north-dipping, major reverse fault located at the northern edge of the Duero basin (Alonso *et al.*, 1996).

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-N4, which has a total length of 145 km, started near the coast line at 43°35'N, 5°10'W and finished in the inner Bay of Biscay at 44°53'N, 5°4.96" W (Fig. 1).

We mention here briefly the acquisition configuration parameters (Fig. 3). The vessel towed a cable of 4500 m length with 360 channels. To avoid cavitation noise from the ship an offset of 240 m was used. The shooting was performed with a tuned airgun array of 80 m width to reduce out-of-plane energy (Parkes *et al.*, 1984, Hobbs & Snyder, 1992). The data were shot at 75 m pop-rate using an array of 5490 in3 (90 l) at 2000 psi (13.8 MPa) nominal pressure with a record length of 20.48 s (two-way-travel-time), a sampling interval of 4 ms and a 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.

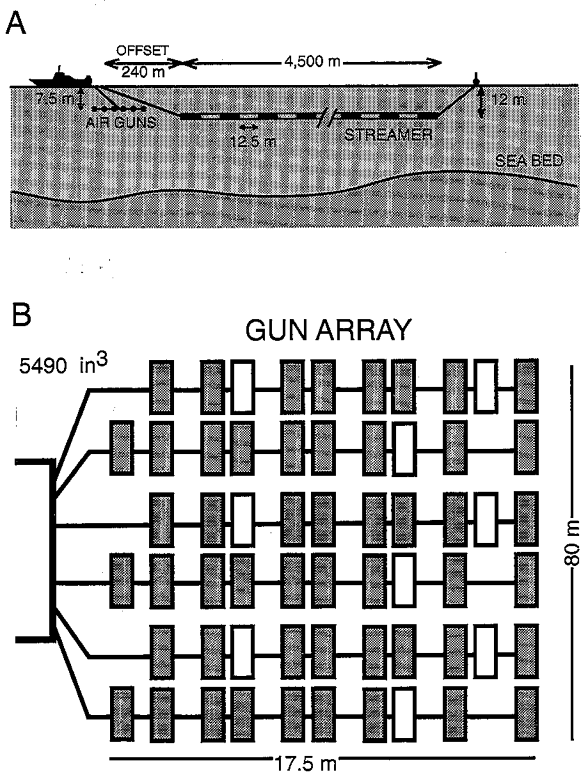


Figure 3.- Acquisition configuration. A: Configuration in section view. B: Airgun array configuration in plan view. A total of 60 guns where under the water, shaded blocks correspond to the active guns totalling 51, white blocks correspond to spare guns.

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)

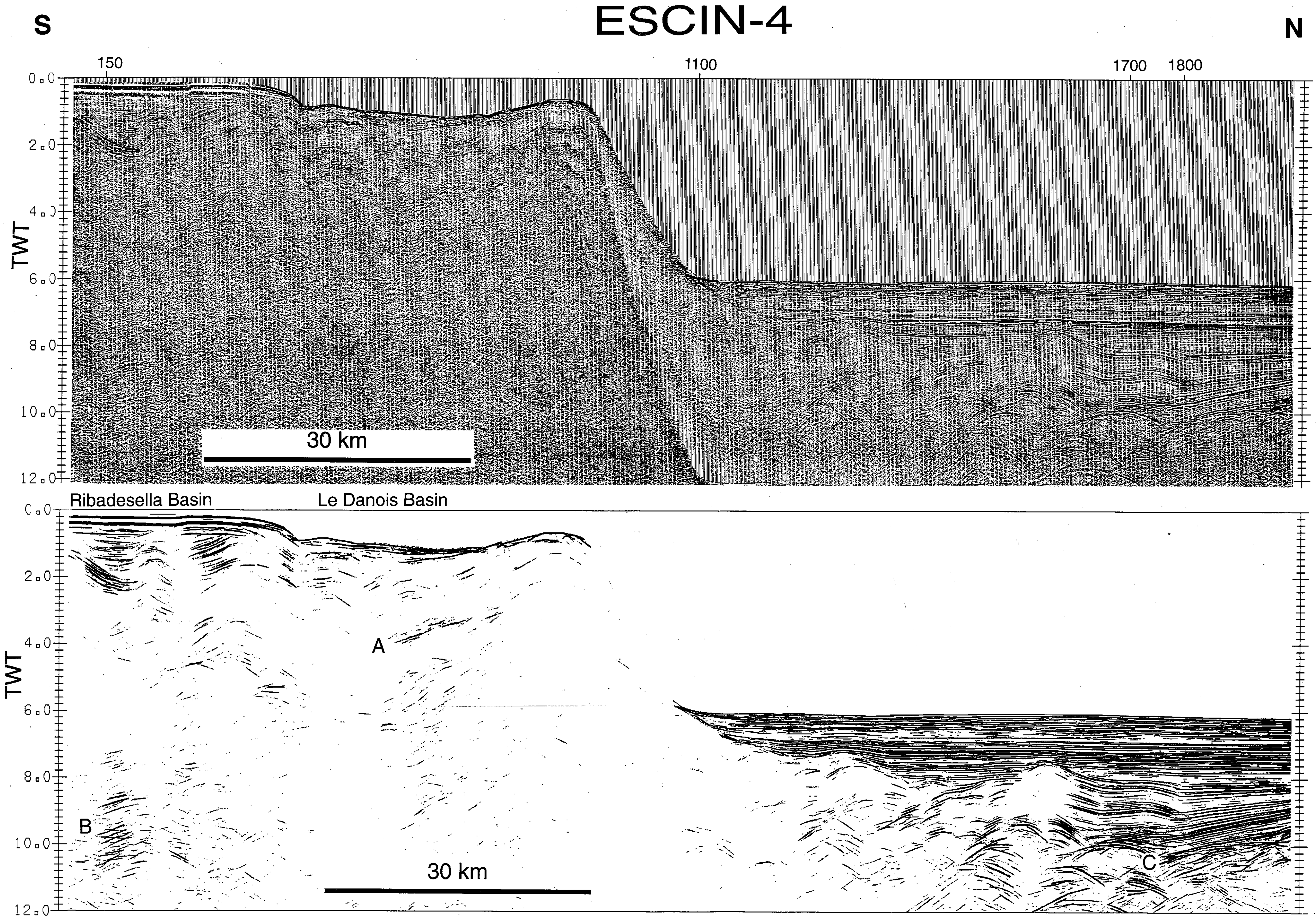


Figure 4.- A: Stack section of Profile ESCI-N4 (upper image). B: Coherence filtered section with a -0.2 to 0.2 s km-1 slowness bandpass with a 1750 m window length (lower image), capital letters are the features described in the text.

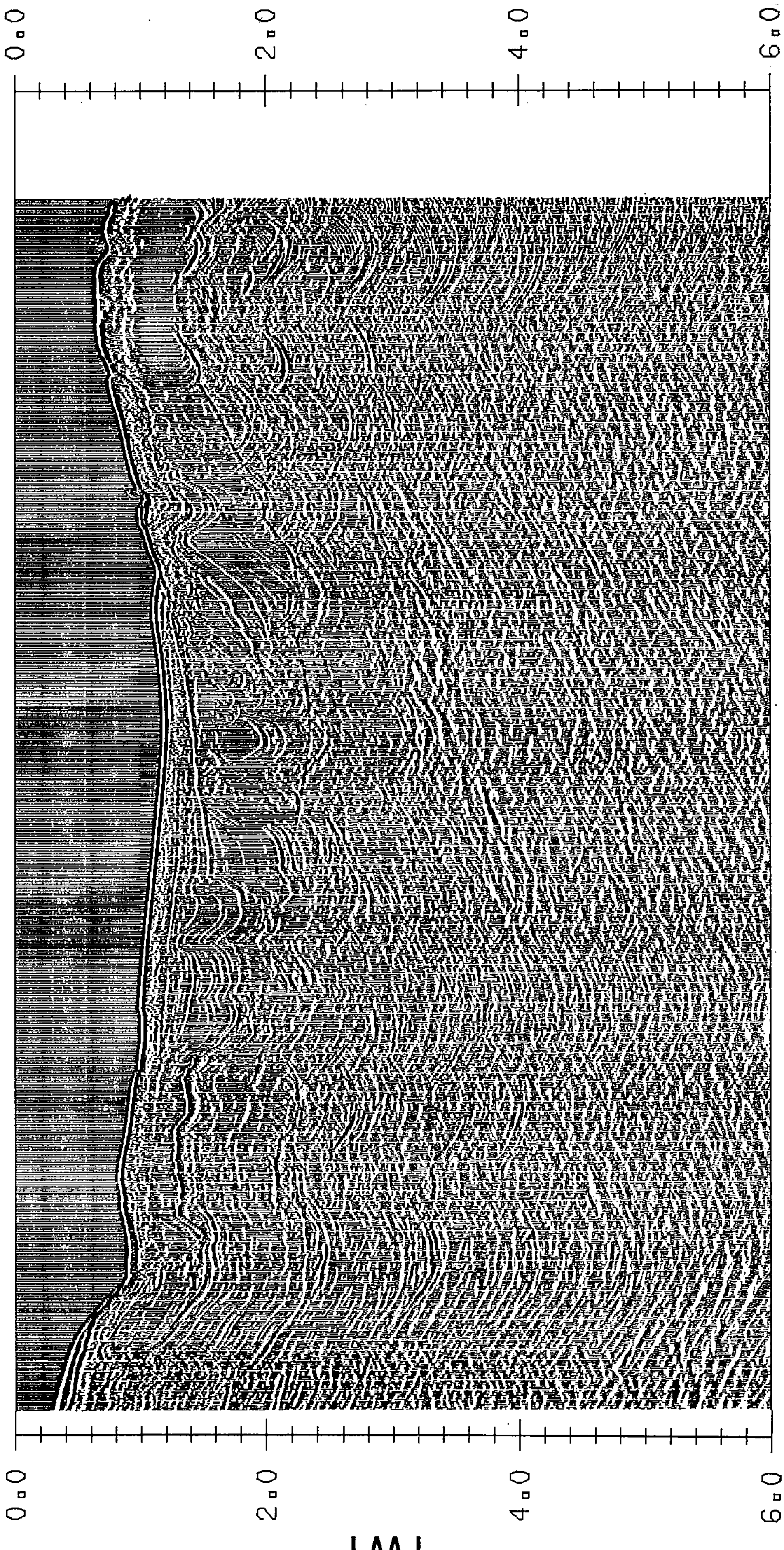


Figure 5.- Window of ESCI-N4 migrated section in the area of Le Danois basin, showing the inverted nature of the basin, see text for discussion.

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, 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 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-N4 marine profile

The southern part of this profile images the continental shelf with water depths ranging from less than 200 m up to 1500 m in the area of the Le Danois basin (Fig. 4). The continental break is marked by the Le Danois Bank bathimetric high with depths of c.a. 1000 m, and a steep continental slope (more than 13°) marks the transition to open sea. The deep sea area in the North of the section shows a flat sea bed at 4500 m depth.

The region of the continental platform shows relatively higher and coherent reflectivity in the upper 4 s particularly in the areas of the Ribadesella and Le Danois basins (Figs. 4a and b). A package of south and north-dipping sub-parallel reflections with a central antiformal feature can be seen down to about 4 s in the area of the Ribadesella basin. A thin band of strong reflections dip gently towards the south beneath the mainly curved reflections of the Le Danois basin (A in Fig. 4b). Below 4 s the coherent reflectivity diminishes, probably due to interference with multiple arrivals. Short and discontinuous, layered reflections might correspond to primary energy at a depth equivalent to 9 s beneath shot point 150 (B in Fig. 4b).

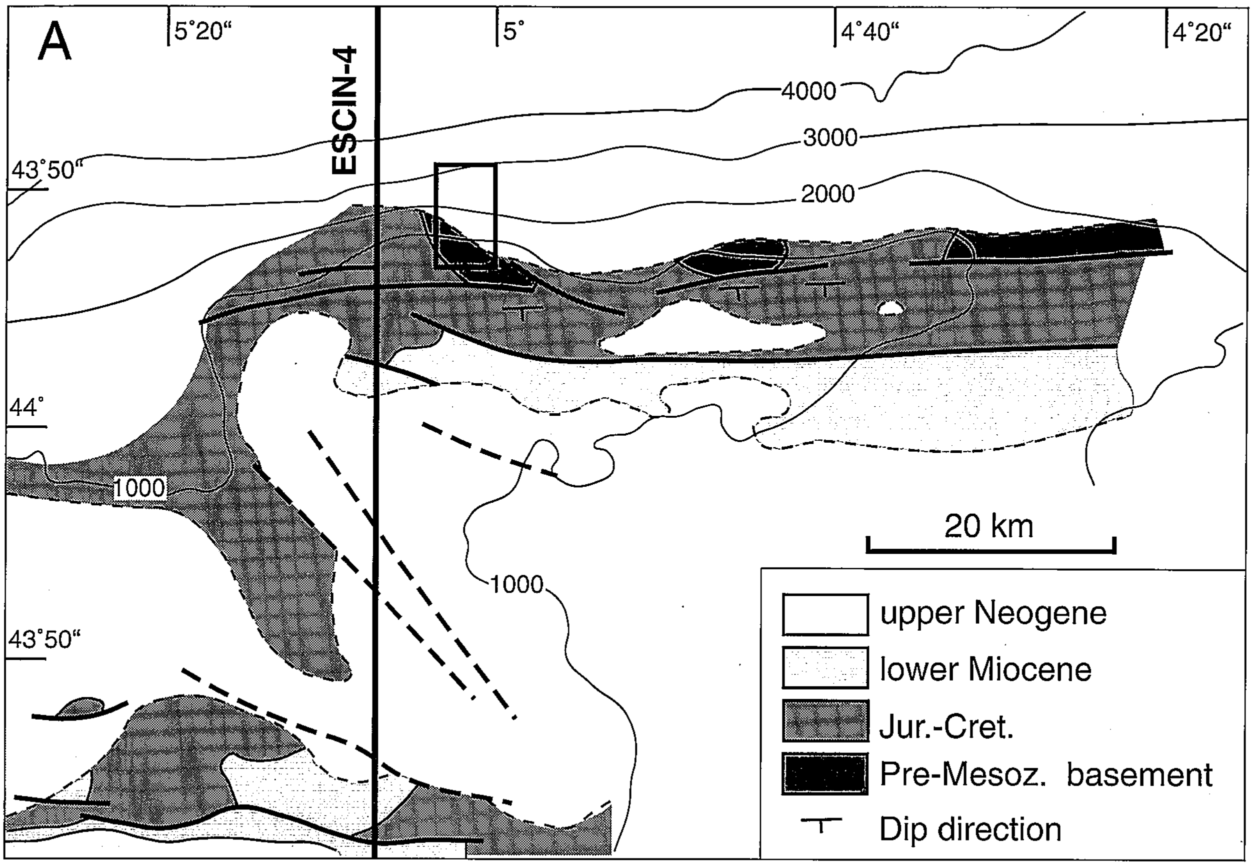
To the North of the steep continental slope, the sea floor is reached at 6 s and deepens slightly towards the north (less that 1° slope). The seismic image is of very good quality until 12 s, where the image is hampered beneath this travel time by the arrival of the first water bottom multiple. Three packages of different reflection fabrics can be distinguished in the oceanic part of the profile. A more than 50 km long, north tapered, wedge-shaped package of reflections with frequent diffractions can be seen from 6 to 11.5 s in the South (shot point 1100) and from 8 to 9 s in the North (shot point 1800). The main attitude of these reflections is south-dipping with, also, disrupted inclined reflections. Above it, an upper package of well-layered, sub-horizontal reflections varies from thin in the South (from 6 to 6.5 s, shot point 1100), to thicker (from 6 to 9.2 s) at the northern end of the profile. In this northern part, the lowest reflections of this package are gently inclined to the South and directly overly the third and lowest package. This deepest package of reflections is composed mainly of out-of-plane diffractions and disrupted reflections below the gently southward dipping reflections at 9 to 10 s (C in Fig. 4b) that can be followed southward until shot point 1700.

Data interpretation and discussion

The reflectivity in the Le Danois basin (Fig. 5) delineates the sedimentary succession of this Mesozoic basin that has been inverted during the Eocene, with reactivation of previous basement involved extensional faults (Boillot *et al.*, 1979, Temine, 1984). The basin is the site of active recent sedimentation (Fig. 6A), the uppermost wedge shaped sedimentary sequence onlaps onto the gentle southern slope of the Le Danois Bank (Fig. 5) and has been attributed to Upper Neogene age sediments by Malod & Boillot (1980). Pre-Mesozoic basement rocks are thought to crop out on the Le Danois Bank (Boillot *et al.*, 1979). Anticlinal folds with north-verging thrusts in their cores form growth anticlines with syn-tectonic, probably Tertiary sedimentation in their limbs (Fig. 5). The syn-tectonic sediments are imaged by the fan-like geometry of reflections in the synformal areas. Reflections with a similar disposition have been attributed to a possible Palaeocene age in interpretations of shallow Sparker seismic profiles nearby (Boillot *et al.*, 1979). Reflection terminations include onlap onto the limbs of the growing anticlines. The basin has not been totally inverted judging from the southwards inclination of the interpreted top basement reflections (A in Fig. 4b). However, the sedimentary pile appears to be detached over the basement with probably listric, north verging thrusts in the cores of associated growth folds (Fig. 5). Cross-sections constructed from dredge and dive sampling of the Le Danois northern slope indicate the existence of outcrops of Palaeozoic basement rocks and north verging thrusts (Malod & Boillot, 1980, Fig. 6).

The Cenozoic overprinting of the previous structure of the basin has not been very important and therefore the Mesozoic configuration may still be deduced. From the present architecture it can be inferred that the basin was probably asymmetric, with thicker sedimentary fill to the South (Fig. 4b) above reflection A (Fig. 4b). The deeper parts of the continental crust are not so well imaged, and the few landward dipping reflections seen (B in 4b) could correspond to the layered lower crust (LLC).

To the North of the continental slope, the ocean-continent transition is marked by an accretionary prism that is at least 50 km long in this section. Reflection C, beneath a very thick sedimentary cover, may be interpreted as the top of the Bay of Biscay oceanic basement (Fig. 4b). The seismic character is similar to other images of known oceanic crust in the Atlantic (i.e. in ESCI-N3.1 profile, Álvarez-Marrón *et al.*, this vol.). However, available geophysical data are not conclusive on the nature of the basement in these inner areas of the Bay of Biscay. At the northern end of the profile, the thickness of the sediments may reach 3.5 km (assuming a constant velocity of 2 km/s). The interpreted top of the oceanic



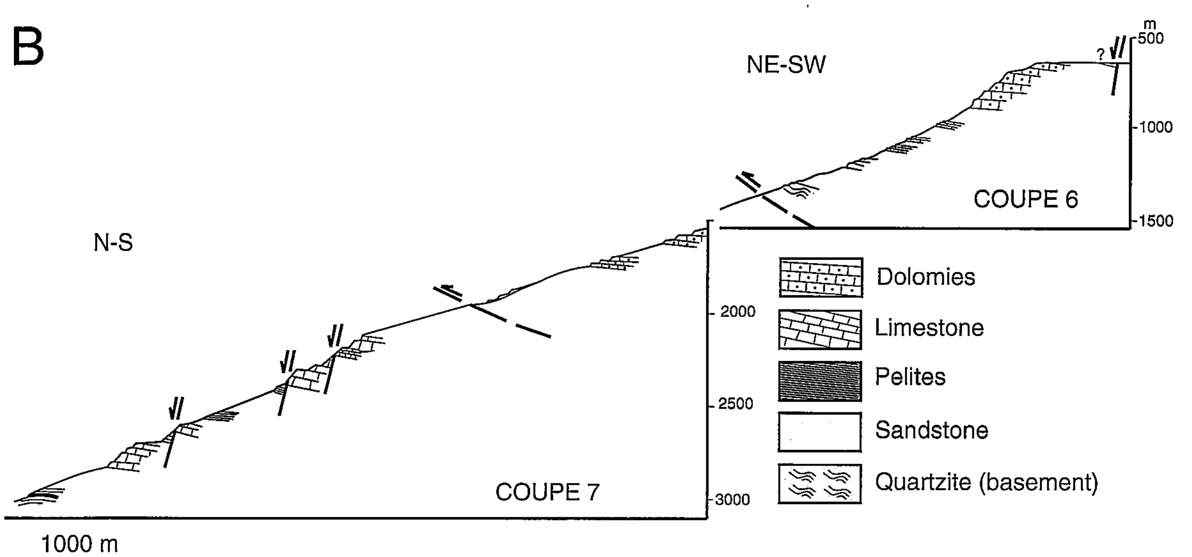


Figure 6.- A: Geological map of the Le Danois basin area (redrafted from Boillot *et al.*, 1979) with location of ESCI-N4 profile. Thick box is the location of cross-sections in B. B: Cross section of the Le Danois Bank northern slope (location, thick box in A) constructed from dredge and dive data (redrafted from Malod & Boillot, 1980). Notice that vertical scale is exaggerated.

basement dips gently landwards towards the deformation front with a corresponding thickening of the incoming sediment section. The southward onlap of the sedimentary package above the accretionary prism suggests the cessation of the tectonic activity in the prism. Based on seismic correlation with DSDP holes 118 and 119 (Laughton *et al.*, 1972) that gives the ages of the sediments at the northern slope of the North Spanish Trough, it has been proposed that subduction stopped by Late Eocene times (Deréngnaucourt & Boillot, 1982). These holes were drilled near the Cantabria Sea Mount in the central western end of the Bay of Biscay, about 300 km to the west of ESCI-N4 profile. If relative variations in the timing of subduction along the North Spanish Margin have occurred, the age for the cessation of subduction in the inner Bay of Biscay may be still an open question.

Conclusions

The N-S trending marine ESCI-N4 near vertical reflection profile crosses the entire continental margin of northern Spain and provides seismic images of the structure beneath the continental shelf and the transition to the Bay of Biscay oceanic crust.

Younger features imaged mainly near the surface in the platform include the Le Danois and Ribadesella Mesozoic extensional basins inverted during the Cenozoic. Other structures related to the convergence of the European and Iberian plates are at the ocean-continent transition and include a tectonic accretionary prism that separates the shortened and deformed sediments in the accretionary prism next to the inverted, previously extended continental shelf.

The oceanic basement of the Bay of Biscay is also imaged in profile ESCI-N4. A very thick undisturbed sedimentary package of about 3.5 km thick is seen above the oceanic type basement. The contact between the sediments and the oceanic basement deepens gently towards the South with a corresponding thickening of the incoming sediment section of the accretionary prism. A package of subhorizontal sediments onlapping southwards onto the accretionary prism suggest the cessation of the tectonic activity in the prism.

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