Structure of the Internal-External Transition Zone in the northern Iberian Massif: implications for the interpretation of deep crustal seismic profiles

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Abstract: In the northern Iberian Massif, the Narcea antiform is an extensive outcrop of Precambrian rocks that bounds two distinct areas with important palaeogeographic, structural and metamorphic differences: the internal Westasturian-Leonese Zone and the external Cantabrian Zone. Beneath the Narcea antiform, the ESCI-N1.2 seismic profile depicts a crustal-scale, west-dipping reflector between 6 and 10 seconds TWT below the surface. This reflector has been interpreted as a major Variscan shear zone. Recent surface investigations of the structural geology of the region raise doubts about this interpretation. The exposed shear zones do not appear to correspond with the inclined reflector interpreted as the "Narcea thrust" in the ESCI-N1.2 profile for several reasons. For example, the published, non-migrated data implies that the "Narcea thrust" requires a large culmination at present surface levels, but such a culmination does not exist. In addition, reflections situated above this reflector are nearly horizontal. Migration of the section would only steepen the "Narcea thrust", which would change its geometry and interpretation. Another regional constraint is the absence of the allochthonous ramp of the "Narcea thrust" in the Cantabrian Zone, which would have to exist if this reflector continued into the Cantabrian Zone detachment. The "Narcea thrust" reflector must therefore be either (a) a pre-Variscan feature, cross-cut by a Variscan detachment, (b) a Variscan ramp not related to the Narcea antiform, but rather to a deeper and older structure, or (c) a Late Variscan - Alpine feature. In all cases, it should not be interpreted as being directly related to the geological structures found at the surface.

Keywords: Variscan Belt, Iberian Massif, Narcea antiform, shear zones, crustal structure.

Resumen: El perfil sísmico de reflexión ESCI-N1.2 muestra, debajo del antiforme del Narcea, un reflector entre 6 y 10 s. TWT, inclinado hacia el Oeste. Este reflector ha sido interpretado como una importante zona de cizalla varisca. La interpretación de los datos de superficie cuestiona esta interpretación. Las zonas de cizalla de Trones y del Narcea son las estructuras más importantes existentes en el antiforme del Narcea, extendiéndose más de 70 km a lo largo del antiforme. Estas zonas de cizalla, no parece que puedan corresponderse con el reflector inclinado interpretado como el "cabalgamiento del Narcea" en el perfil ESCIN-1.2 por varias razones. Por ejemplo, a partir de los datos publicados, no migrados, el "cabalgamiento del Narcea" requeriría una culminación apreciable en superficie mucho mayor que la culminación visible actualmente en el antifotme del Narcea. Además, las reflexiones que se sitúan sobre este reflector son subhorizontales. La migración de estos reflectores aumentaría la pendiente del "cabalgamiento del Narcea" permitiendo otro tipo de interpretación. Además de lo expuesto, y desde un punto de vista regional, otro límite a esta interpretación lo constituye la ausencia de la rampa alóctona del "cabalgamiento del Narcea" en la Zona Cantábrica, que debería de existir en el caso de que este reflector se continuase en la Zona Cantábrica. El "cabalgamiento del Narcea" debe de ser, por tanto (a) un accidente prevarisco cortado por un despegue varisco; (b) una rampa de un cabalgamiento varisco no relacionado con el antiforme del Narcea sino con con otra estructura más profunda y antigua o; (c) una estructura tardivarisca o alpina. En todos los casos no se debería interpretar como directamente relacionada con las estructuras situadas inmediatamente por encima y que se reconocen actualmente en superficie.

Palabras clave: Cadena Varísca, Macizo Ibérico, antiforme del Narcea, zonas de cizalla, estructura cortical.

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External to internal zones transition in most orogenic belts share common features that can be grouped into two categories: palaeogeographic changes and structural-metamorphic changes. Palaeogeographic change coincides with this boundary as it limits deeper sediments of the deformed sedimentary wedge to the internal zone, with shallower continental shelf-type sediments restricted to the external one. From a structural-metamorphic point of view: (1) The external-internal zone limit bounds different structural styles and metamorphic conditions. Recumbent folding, ductile shear zone development and widespread cleavage characterise the structural architecture of internal zones. In external zones brittle thrusts and related culmination folds depict the main structural framework. (2) Metamorphism in the internal zones is of a barrowian type, ranging from low to high grade.

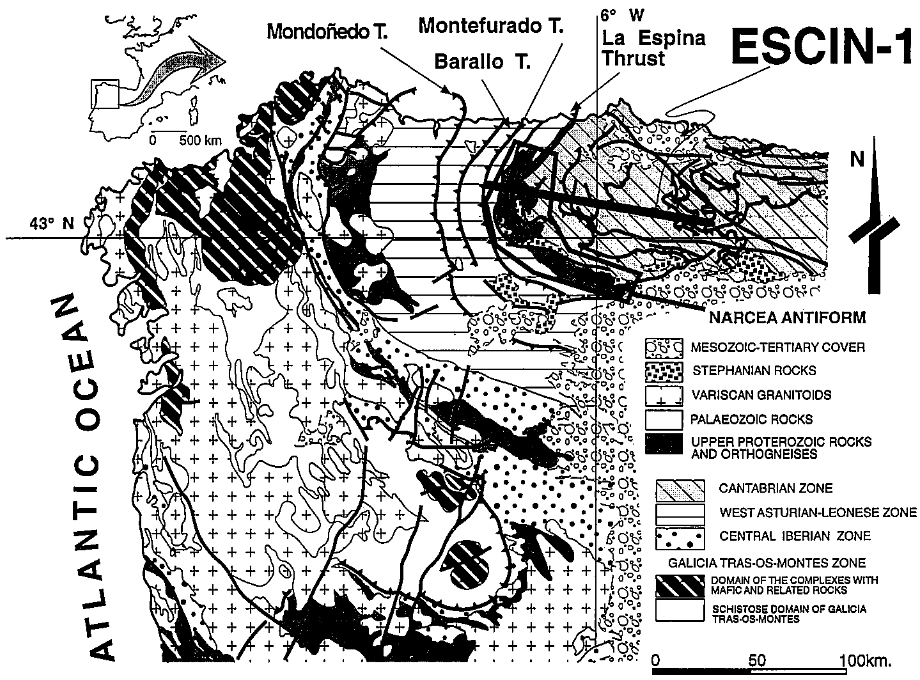

Figure 1.- Geological sketch map of northwestern Spain with location of major palaeogeographic units and the study area. After Lotze (1954), Julivert *et al.* (1972) and Farias *et al.* (1987).

However, in the external zones no barrowian gradient can be perceived, and only diagenetic and anchizonal transformations take place in these rocks. (3) The limit between the internal and the external zones itself is always a thrust with substantial displacement, usually thrusting basement rocks from the hinterland over the thin-skinned deformed foreland fold and thrust belt in the external zones. In some instances this boundary may have been later reactivated with a normal fault component, as may be the case in the Alps (Avigad *et al.*, 1993; Seward and Mancktelow, 1994) or the Betics (García Dueñas *et al.,* 1992). In addition, in the Betic Chain, other authors report thrusts of the external zones over the internal ones (Lonergan *et al.*, 1994).

In the northern Iberian Massif (Fig. 1), the limit between the internal Westasturian-Leonese Zone and the external Cantabrian Zone crops out at La Espina thrust, located in the Narcea antiform (Fig. 2). The characteristics described previously for the internal to external zones transition match the observations done at the Narcea antiform, an extensive outcrop of Precambrian age (Upper Proterozoic) rocks. Nevertheless, the lack of "true" basement rocks overthrusting the Cantabrian Zone makes this limit somewhat unusual.

All the features described for external to internal zones of transition are found in most collisional orogenic belts, as can be seen in the examples depicted in Fig. 3. Another feature widely recognised at the external-internal zones limit is the presence of broad culminations, situated above large ramps of thrusts involving the basement.

The recent crustal seismic reflection profile across the Cantabrian Zone and the Narcea antiform (Fig. 2), the ESCI-N1.2 seismic profile (Pérez-Estaún *et al.* 1994), provides new insight into the description of the internal to external transition in this particular orogenic belt.

The presence of steeply inclined reflectors below the Narcea antiform (Fig. 4) extending down into the lower crust, referred to as the Narcea thrust by Pérez-Estaún *et al.* (1994), raises the question of whether the internal to external limit in the Variscan belt of NW Iberia is a crustal scale feature, or whether the prominent reflector represents another event unrelated to the development of the internal-external zone limit. The above-mentioned authors interpret the west-dipping reflectors below the Narcea antiform as a Variscan ductile shear zone deforming basement rocks at the roots of Cantabrian Zone thrusts. However, the lack of direct correlation between surface geology and these seismic reflectors at the Narcea antiform widens the range of possible interpretations, as will be described in this paper.

The purpose of this paper is to describe the structure of the external to internal boundary zone and to establish the relationship, or lack of it, between the geometry observed in the actual cross-section and the deep reflection observed below the Narcea antiform. The different possible interpretations of the so called "Narcea thrust", mainly its age and amount of displacement, are presented. For each case the related features that may befound at the present surface are described.

Geological setting: the structure of the Narcea antiform

The Narcea antiform is a prevalent arcuate structure that runs more than 70 km along the limit between the Westasturian-Leonese Zone and the Cantabrian Zone (Figs. 1 and 2). The palaeogeographic features, the general structure and the metamorphism of the Westasturian-Leonese Zone to the West and the Cantabrian Zone to the East are widely described in Martínez Catalán *et al.* (1990), Pérez-Estaún *et al.* (1988, 1990, 1994), Suárez *et al.* (1990) and references therein. The foreland or exter-

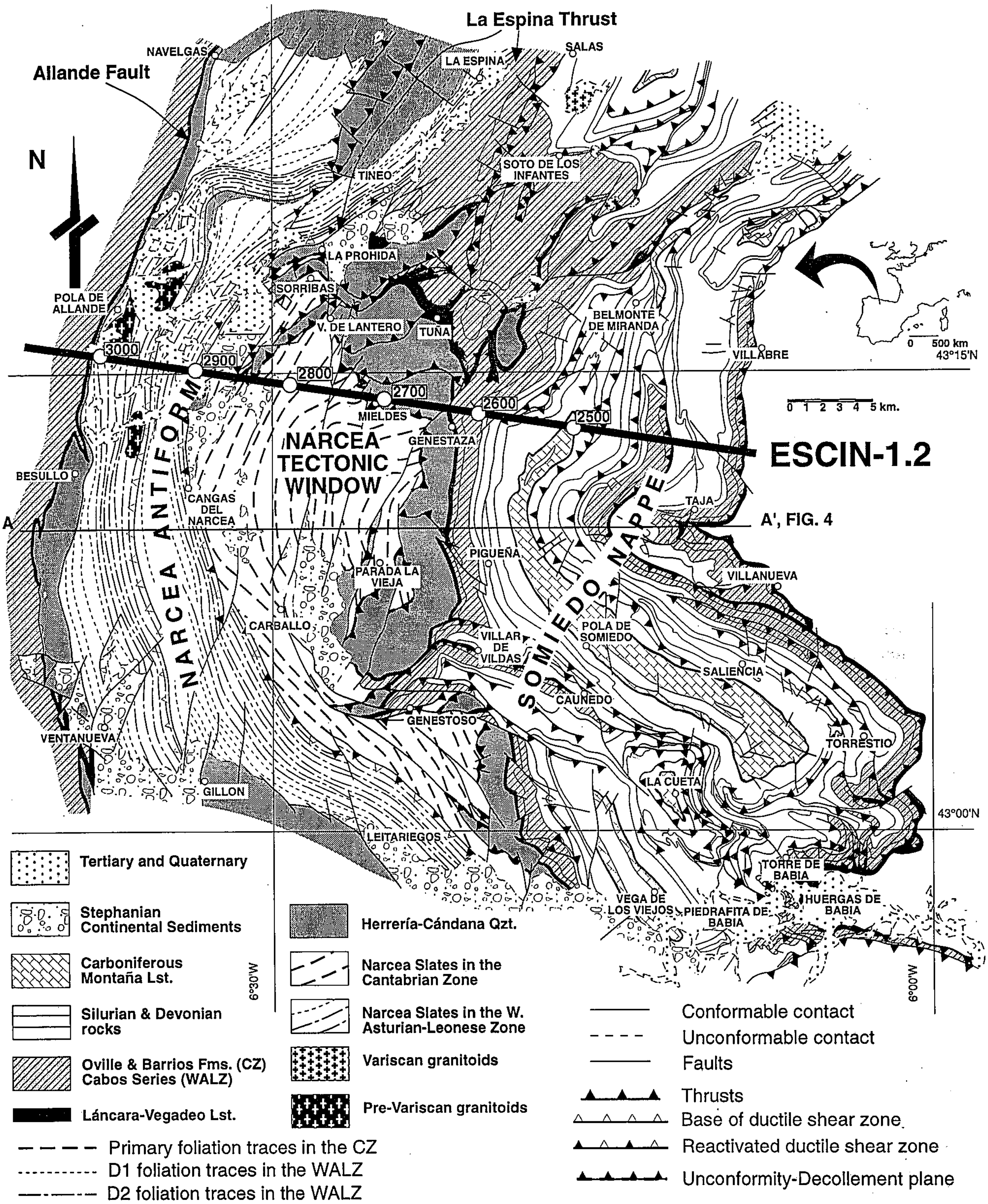

Figure 2.- Geological map of the Narcea antiform and the Somiedo unit; and trace of the ESCI-N2.1 seismic profile (numbers indicate shot points). Based on own data and Julivert *et al.*, 1968; 1977 a; 1977 b; Marcos, 1973; Martínez Álvarez *et al.*, 1975; Pello, 1976; Bastida *et al.*, 1980, 1984; Marcos *et al.*, 1980; Marcos & Pulgar, 1980; Crespo Zamorano, 1982; Truyols *et al.*, 1982; Matas *et al.*, 1982; Navarro, 1982; Heredia, 1984; Gutiérrez-Alonso, 1987; Bastida & Castro, 1988; Gutiérrez-Alonso & Villar, 1989; Alonso *et al.*, 1989; Bastida & Gutiérrez-Alonso (1989), Gutiérrez-Alonso *et al.*, 1990; Suárez *et al.*, 1990; Gutiérrez-Alonso, 1992.

nal zone, the eastern flank of the Narcea antiform, is the Cantabrian Zone, a typical thrust belt with an unmetamorphosed sedimentary, pre-Carboniferous Palaeozoic sequence composed of up to 7000 m of mostly stable marine platform sediments. These sediments thin to the East and are covered by a Carboniferous syn-orogenic sequence of variable thickness (Marcos & Pulgar, 1982). The western flank of the Narcea antiform is part of the hinterland or internal zone, called the Westasturian-Leonese Zone. This zone is composed of a thick lower Pala-

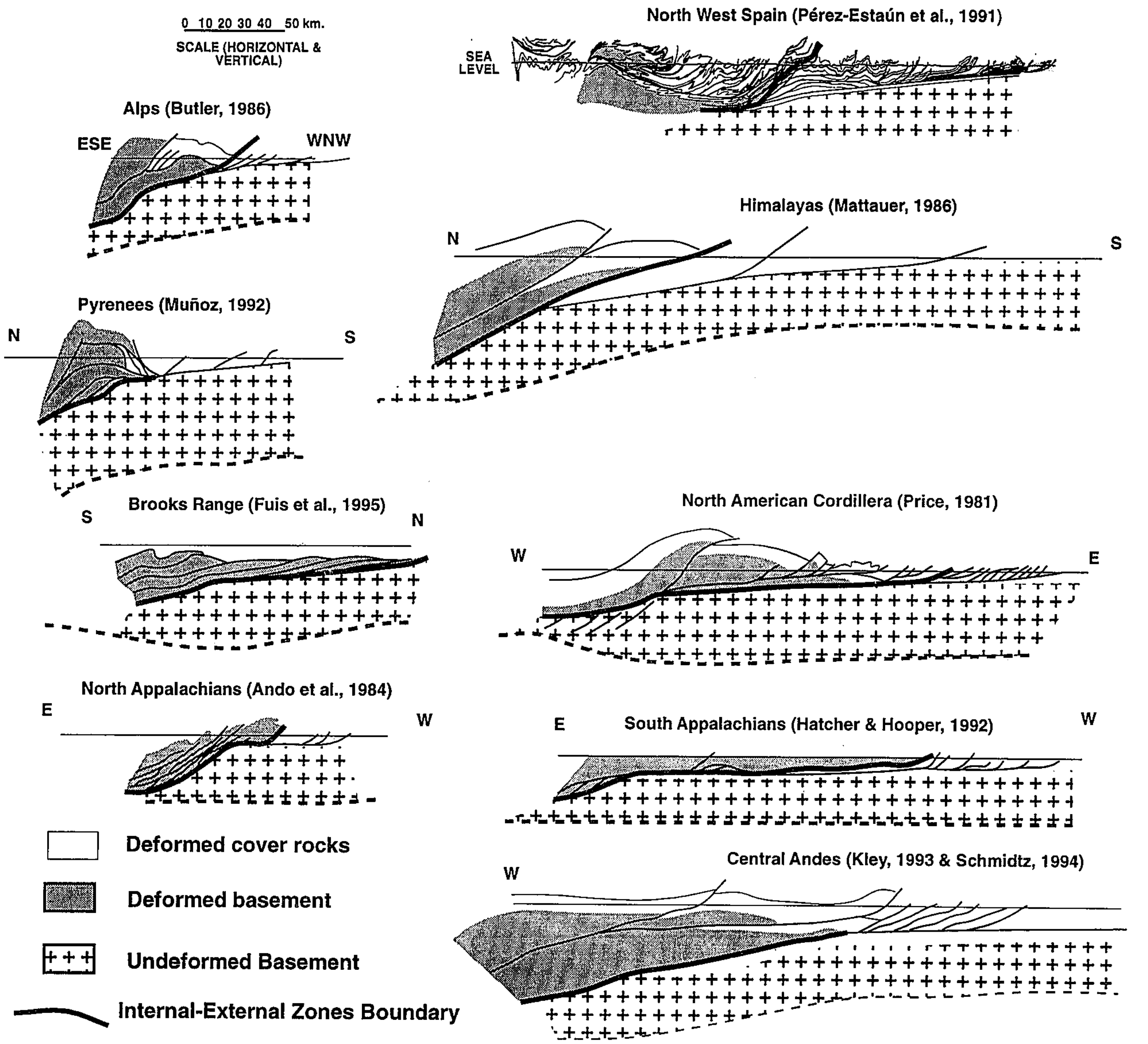

Figure 3.- Schematic cross-sections of different orogens showing the common features found in the external to internal zone limits. Rocky Mountains (Price, 1981); Himalayas (Mattauer, 1986); Alps (Butler *et al.*, 1986), Central Andes (Kley, 1993; Schimidtz, 1994); Northern Appalachians (Ando *et al.*, 1984); Southern Appalachian (Hatcher & Hooper, 1992); Pyrenees (Muñoz, 1992); Brook Ranges (Fuis *et al.*, 1995); Variscan of NW Iberia (Pérez-Estaún *et al.*, 1991)

eozoic sequence (>7000 m for the Cambro-Ordovician sequence only) affected by conspicuous internal deformation and greenschists metamorphism (Marcos, 1973; Pérez-Estaún *et al.*, 1990). In both zones, below the Palaeozoic sequence and separated from it by an angular unconformity, the Upper Proterozoic Narcea slates of undetermined thickness are exposed. The Narcea slates crop out in the core of the Narcea antiform and are composed mainly of slates and greywackes consisting mainly of greenish to black shale and sandstone with turbiditic facies and containing prevalent clasts of plagioclase and volcanic shaped quartz. In the western sector of the Narcea antiform it is common to find interbedded volcanoclastic rocks, and there are two deformed granitoid bodies of uncertain age. The Narcea slates are considered basement rocks of the Variscan orogen in this sector and, despite its low metamorphic grade that makes it different from most other orogens where the basement is usually constituted by high grade metamorphic rocks, it can be considered as true basement in the sense of Coward (1983). Similar basement rocks crop out again further West at the Lugo antiform (Fig. 1), though they are of higher metamorphic grade than in the Narcea antiform.

The general structure of the area is an asymmetrical antiform with a highly strained western backlimb that has undergone polyphase deformation, and a little strained eastern forelimb characterised by thin-skinned deformation (Figs. 2 and 5). This divides the Narcea antiform into two sectors: the Cantabrian Zone (the easternmost) and the Westasturian-Leonese Zone (the western sector), representing the autochthonous and allochthonous blocks of the La Espina thrust, respectively (Gutiérrez-Alonso, 1992).

The Narcea slates are affected by several deformation events. On one side there is a pre-Variscan (Vendian) deformation post-dated by the angular unconformity at the

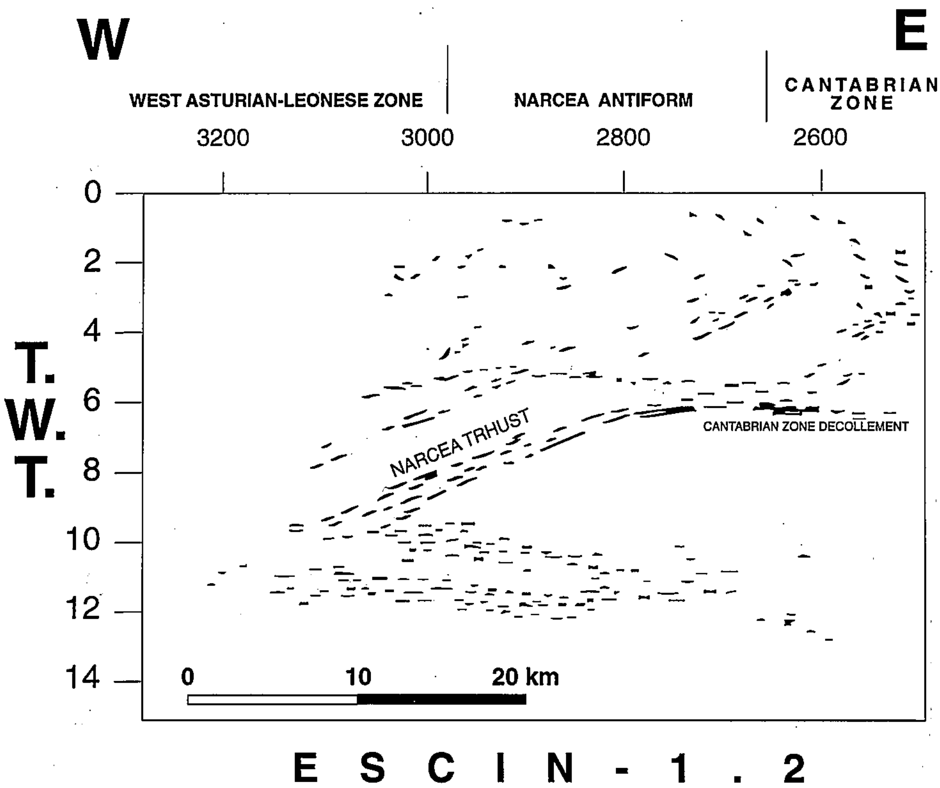

Figure 4.- Line drawing of profile ESCI-N1.2 (Pérez-Estaún *et al.*, 1994), where the most important reflections can be observed.

base of the Cándana-Herreria quartzite. This deformation did not give rise to structures recognisable in the field.

During the Variscan orogeny, deformation in the Palaeozoic rocks of the Westasturian-Leonese Zone was characterised by east-vergent recumbent folds with N-S hinges and west dipping axial planes, along with widespread primary axial plane foliation (D1). In the Narcea Slates Formation. no large folds related to this event are recognised due to the lack of appropriate markers, but the foliation is parallel to that found in the Palaeozoic rocks and the intersection lineation S_0/S_1 is vertical, parallel to outcrop scale fold hinges. There are folds related to D1 deformation in the North of this area in Lower Palaeozoic rocks with approximate N-S horizontal axes and vertical axial planes. These folds are subangular with interlimb angles ranging from 40° to 80° (Aller. *et al.*, 1989). The D1 cleavage recognised in the Narcea slates is a penetrative planar fabric, that is axial planar to the aforementioned outcrop scale folds. This foliation never crenulates a previous one related to the pre-Variscan deformation. Its field appearance is a penetrative cleavage in pelitic rocks and a more spaced cleavage in sandstone. Foliation refraction is very common. Under the microscope there is a rough cleavage in the sandstone and a rough slaty cleavage in the pelitic rocks. A well-developed slaty cleavage is found only locally.

The most relevant feature found in the Westasturian-Leonese Zone is the existence of thrusts developed after

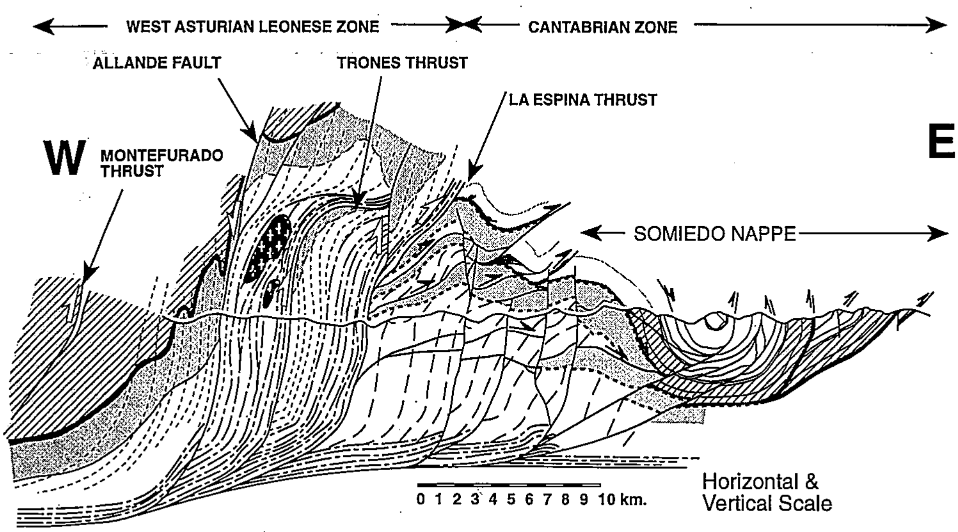

Figure 5.- Geological cross-section of the Narcea antiform. Location is A-A' in Fig. 2. Legend as in Fig.2.

the D1 folding phase. This thrusting event is known as second phase (D2). The most important thrusts in this zone, from West to East, are Mondoñedo, Barayo, Montefurado, Trones and La Espina (Marcos 1973; Bastida and Pulgar, 1978; Martínez-Catalán, 1985; Aller *et al.*, 1987; Martínez-Catalán *et al.*, 1991; Gutiérrez-Alonso, 1992 and Aller & Bastida, 1993) (Fig. 1). All these thrusts developed under low-grade metamorphic conditions diminishing in intensity from West to East, from garnet bearing conditions at the western limit of the basal Mondoñedo thrust to chlorite in the eastern thrusts. All these thrusts developed shear zones of different widths and characteristics.

The La Espina and Trones thrusts (Figs. 2 and 5) developed at the western limb of the Narcea antiform a continuous arcuate outcrop only interrupted by low displacement late faults. These thrusts can be followed for tens of km in the study area. They are lost below unconformable Stephanian rocks and appear again in the southern branch of the Asturian arc. These thrusts are thought to have tens of km of displacement (Alonso *et al.*, 1990; Gutiérrez-Alonso, 1992). They are easily detected when they superimpose the Narcea slates over the Palaeozoic rocks, but are not so easily observed when the Narcea slates are duplicated. In the latter case they can be detected by mapping related D2 shear zones found in the hangingwall. These thrusts havet a vertical or slightly reversed attitude now, due to passive rotation produced by the thin-skinned style imbrication of the Cantabrian Zone units to the East (Fig. 5). The Trones Thrust duplicates the Narcea Slates Formation. and locally thrust them over the Cándana-Herreria quartzites. The La Espina thrust is the true limit between the Cantabrian and the Westasturian-Leonese Zones and thrusts the Narcea slates over rocks of the Cantabrian Zone ranging in age from Upper Proterozoic (Vendian) to Late Carboniferous (Stephanian). Both thrusts develop large shear zones in the hangingwall, with widths up to 2 km. The shear zones develop a wide range of structures related to simple shear: crenulation cleavages, tectonic banding, phyllonitic and mylonitic foliations with σ and δ type porphyroclasts, a well developed stretching lineation, and occasional S-C and ECC foliations. The age of D2 foliation related to shear development has been determined by Martínez-Catalán *et al.* (1993), who obtained a plateau age of 321 ± 1 Ma by means of whole rock ^{39}Ar - ^{40}Ar. The width and intensity of these two shear zones related to the thrusts, contrasting with the deformation in the surrounding rocks, indicate that they may correspond to the major thrusts found in most internal to external transition zones.

East of La Espina thrust, the Cantabrian Zone sector of the Narcea antiform crops out in the Narcea tectonic window as the footwall of the Somiedo nappe (Fig. 2). The Narcea tectonic window is exposed due to erosion of a thrust culmination at the boundary between the hinterland and the foreland fold and thrust belt (Figs. 2 and 5). The present geometry of the culmination is the result of duplex formation and late out-of-sequence thrusting involving rocks of the Somiedo nappe footwall crosscutting the former main sole decollement. Subsequent antiform re-folding and faulting did not substantially modify the geometry of the main structure and the relationships between the different rock units involved. Late deformation resulted mostly in fracturing and the steepening of the thrust planes. The main structural features of this area can be seen on the geological map (Fig. 2) and have been described in detail elsewhere (Julivert & Marcos, 1973; Marcos, 1973; Bastida *et al.*, 1984; Heredia, 1984; Gutiérrez-Alonso, 1987, 1992, *in press*; Pérez-Estaún & Bastida, 1990; and Pérez-Estaún *et al.*, 1988, 1994).

The Narcea tectonic window and the Somiedo unit are characterised by the thin-skinned style of deformation, with scarce development of foliation, which only appears in the Narcea slates. Due to late Variscan deformation and possibly some Alpine overprint, these thrusts underwent minor movements that gave rise to crenula-

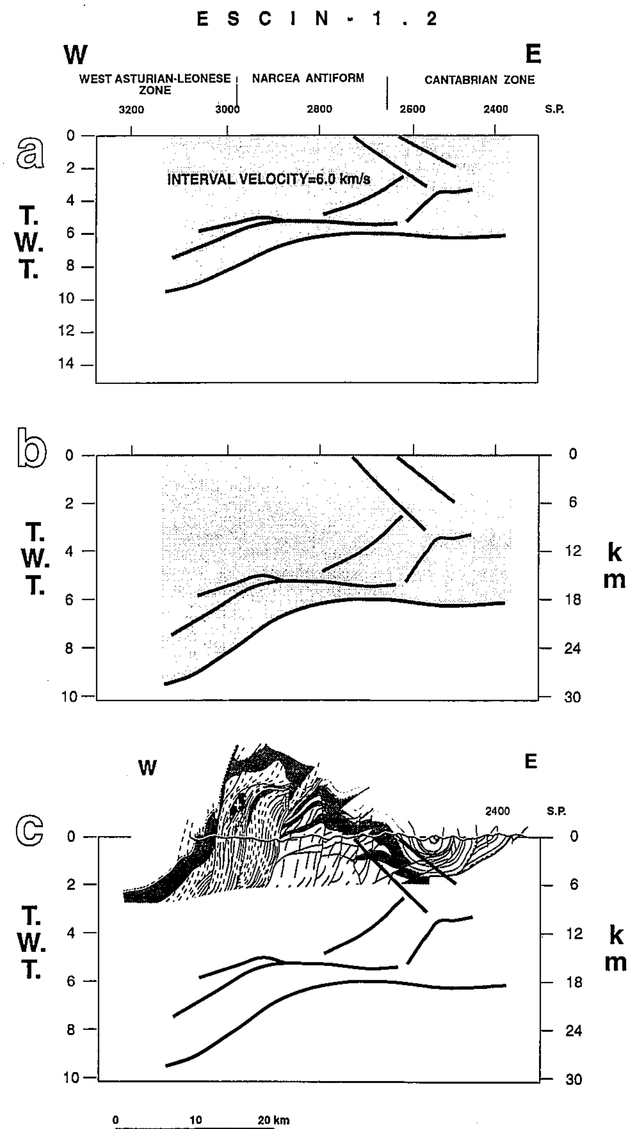

Figure 6.- a.- Main reflectors of ESCI-N1.2 seismic profile (From Pérez-Estaún *et al.*, 1994). b.- Migrated reflectors. c.- Geological cross-section plotted onto the migrated reflectors. Explanation in the text.

tion cleavages with vertical axes and right lateral asymmetry, perhaps due to right lateral movements and kink-band folding near the thrust plane. These minor movements locally thrust Narcea slates over the late Stephanian late orogenic continental coal-bearing rocks.

The overall metamorphism at the Narcea antiform is very low to low-grade, with some increase in grade to the West as described by Gutiérrez-Alonso & Nieto (1996). The anchizone to epizone boundary is located approximately in the middle of the Narcea tectonic window and is related to the increase of finite strain in the rocks as well as increasing fabric penetration.

The Narcea antiform at depth: discussion

Fig. 5 depicts the cross-section of the Narcea antiform and the Somiedo unit, the westernmost nappe of the Cantabrian Zone, showing an interpretation of its structure at depth. Note the contrasting deformation styles in both flanks of the Narcea antiform representing styles typical of the external and internal zones. The interpretation at depth presented in this work suggests the presence of an almost flat surface acting as a ductile decollement below the Westasturian-Leonese Zone, which continues into the Cantabrian Zone. From this decollement several imbrications propagated upwards, thrusting the Westasturian-Leonese Zone over the Cantabrian Zone. This interpretation contrasts with that of a steep crustal scale shear zone cropping out at the Westasturian-Leonese Zone - Cantabrian Zone boundary, which is substantiated neither by the small metamorphic variation in both flanks of the Narcea antiform, nor the geometry that would result from that kind of shear zone, which would require a much broader culmination than the one observed today.

The features observed in the ESCI-N1.2 deep seismic profile support the interpretation of an almost flat decollement, as postulated by Pérez-Estaún *et al.* (1991), and explain the nature of the deep reflections observed below the basal decollement.

In order to establish the relationship between the geological cross-section and the main reflections observed in the seismic profile ESCI-N1.2 that crosses the whole Narcea antiform, the main reflectors observed in the seismic profile (Figs. 4 and 6a) were converted to depth using an event migration, with a constant reduction velocity of 6.0 km·s^{-1}, according to preliminary velocity analysis made by Martínez-Catalán & Ayarza, (pers.

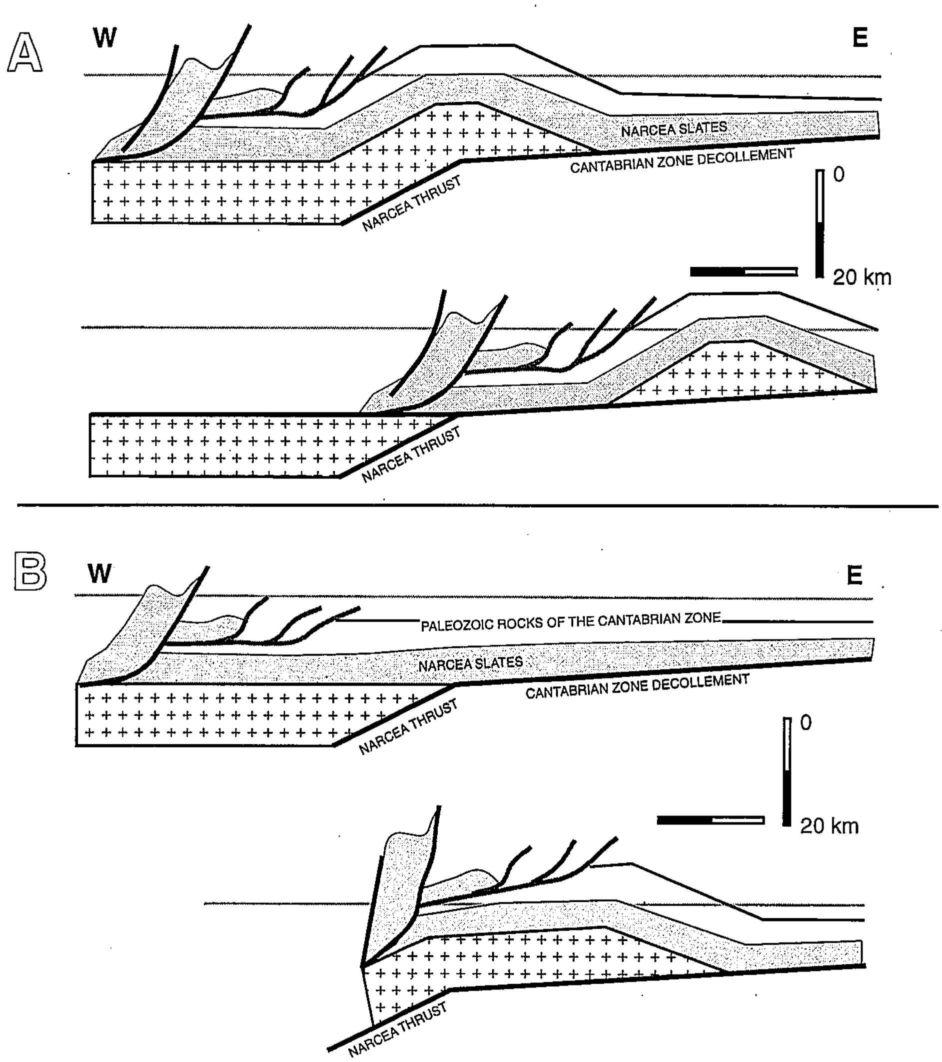

Figure 7.- Two models of interpreting the "Narcea thrust" as a major ramp. Note the large culminations generated in both cases. Explanation in the text.

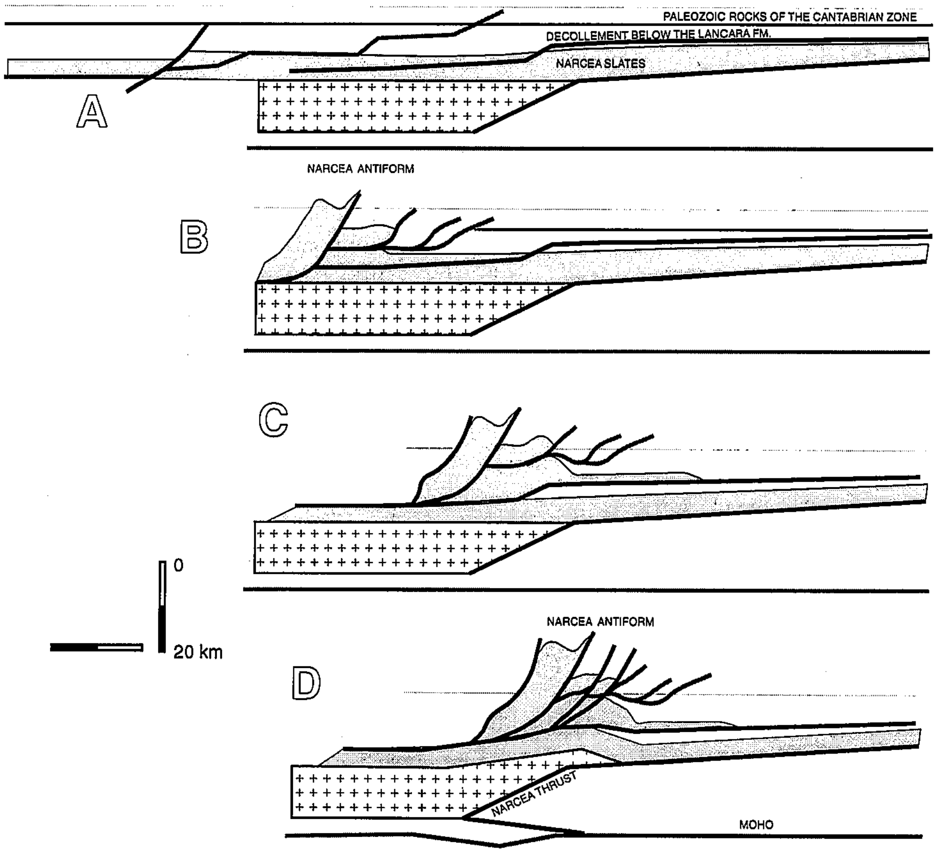

Figure 8.- Proposed model of evolution of the Internal-External transition zone and its relation with the "Narcea thrust". Light grey Precambrian rocks. A- Initial configuration and trajectories of future thrusts. B.- First stage of thrusting. C.- Second stage of thrusting. D.- Late Variscan evolution and Narcea antiform re-folding.

com.) (Fig. 6b). The migration is very simple and more precise migration methods would lead to more accurate results. Nevertheless, the purpose of this migration was only to obtain (1) a rough idea of reflector geometry in order to facilitate comparison with the structure, and (2) a more realistic idea of the actual slopes of the reflectors, which is of critical importance for geological interpretation. The resulting migration and the interpreted geological cross-section are shown in Fig. 6c.

The uppermost reflectors found in this sector are in the Cantabrian Zone and can be correlated with lithological stratigraphic contacts or with faults (mostly thrusts), which are the most important structures found in the Cantabrian Zone. It is surprising that the shear zones related to the La Espina and Trones thrusts do not appear in this profile, although important shear zones in other orogens are usually well imaged by this technique.

It can be seen how the uppermost east-dipping reflectors from 0 to 4 s (Fig. 4) coincide with the eastern flank of the Narcea antiform. One of these reflectors is probably the Barrios Formation, a very competent Ordovician quartzitic unit. The other reflector found in the upper part of the profile may be correlated with the unconformity between the Narcea slates and the Herrería quartzite. The higher west dipping reflectors may be interpreted as out-of-sequence thrust faults, widely described in this area (Bastida *et al.*, 1984; Heredia, 1984; Gutiérrez-Alonso, 1987).

The interpretation of the reflectors located below 5 s (Fig. 4) is more speculative. The subhorizontal ones present in the eastern part of the profile are interpreted as the basal decollement of the Cantabrian Zone, as they have very good continuity with the ESCI-N1.1 and good correlation with the surface geology. The west-dipping ones, on the other hand, may be interpreted in several different ways, that will be discussed subsequently.

Correlation of the main reflectors with the major ductile thrusts and associated shear zones of the Narcea antiform (i.e., La Espina and Trones thrusts) is not possible as they are located West of the main reflector (Fig. 6c), described by Pérez-Estaún *et al.* (1994) as the "Narcea thrust" (Fig. 4). Another possibility is that this reflector, or group of reflectors, represents the ramp into which the basal decollement of the Cantabrian Zone roots to the West. As there are two different stages of thrusting in the Cantabrian Zone (Pérez-Estaún *et al.*, 1991), the possible role of this ramp has to be investigated for both stages.

Fig. 7 shows two possible mechanismsfor carrying the Narcea antiform over the so called "Narcea thrust". In the first case (Fig. 7A) the "Narcea thrust" would have moved during the first stage, generating a major culmination over it that would have been cut by the second thrusting event and carried to the East. Such a culmination does not exist in the Cantabrian Zone; therefore the "Narcea thrust" is not likely to have originated during the first thrusting stage of the Cantabrian Zone. In the second case (Fig. 7B) the "Narcea thrust" would have been carried passively over the ramp during the second thrusting stage. This would have led to a much broader culmination which again is not found in the Cantabrian Zone.

As explained above, the so-called "Narcea thrust" is difficult to interpret as a Variscan thrust related to the rooting of most of the eastward displacement that took place in the Cantabrian Zone. Additional data supporting this hypothesis are provided by the interpretation of the ESCI-N3.3 profile (Ayarza, 1995; Martínez-Catalán *et al.*, this vol.). In profile ESCI-N3.3 the main decollement below the Westasturian-Leonese Zone is located at approximately the same depth as the upper part of the "Narcea thrust", continuing the shallow dipping to the West of the basal decollement of the Cantabrian Zone. If this interpretation is correct, the view that a major ramp links the basal decollement of the Westasturian-Leonese Zone to the Cantabrian Zone, where the latter would have rooted, has to be revised.

In light of the facts and interpretations mentioned above, an alternative interpretation of the zone's general evolution can be presented (Fig. 8). In this model the deep west-dipping reflectors of the ESCI-N1.2 profile are interpreted as pre-Variscan features, probably dikes of mafic rocks intruded during the Lower Palaeozoic rifting process proposed by Aller (1994), that may crop out locally (Gutiérrez-Alonso & Villar, 1990). The general evolution of the present structure seen at surface levels comprised a two-stage thrusting sequence above a flat decollement, according to the model by Pérez-Estaún *et al.* (1991). Thrusting placed the Narcea antiform above the pre-Variscan mafic intrusions imaged in ESCI-N1.2. During the latest stages of Variscan evolution of the external to internal boundary zone, or even during Alpine times, the surfaces defined by the mafic rocks acted as thrust planes of relatively small displacement, causing the re-folding and fracturing of the structures above it, creating the Narcea antiform and duplicating lower crust below it, so giving rise to the crocodile-like pattern imaged in the ESCI-N1.2 profile. This interpretation leads to the conclusion that the "Narcea thrust" is probably not a major feature in the Variscan evolution of this sector of the Variscan belt of NW Spain and, therefore, that the internal-external transition zone in the northern Iberian Massif at the Narcea antiform is not a crustal scale feature, but rather a structure carried above this notable reflector. Therefore, this reflector was originally far East of the internal-external zone structural and palaeogeographic transition.

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References

Aller, J. (1994): A 2 1/2D interpretation of the Cantabrian Zone magnetic anomaly using geological and geophysical constraints: structural implications. *Rev. Soc. Geol. España*, 7 (3-4): 327-335.

Aller, J., Bastida, F., Cabal, J. and Pérez-Estaún, A. (1989): Geología del sector Cabo Vidio-San Juan de la Arena-Tineo (Zona Asturoccidental Leonesa, NO de España). *Trabajos Geol., Univ. Oviedo*, 18: 95-111.

Aller, J. and Bastida, F. (1993): Anatomy of Mondoñedo Nappe basal shear zone (NW Spain). *Jour. Struct. Geol.*, 15: 1405-1419.

Alonso, J.L., Aller, J., Bastida, F., Marcos, A., Marquinez, J., Pérez-Estaún, A. and Pulgar, J.A. (1990): *Mapa geológico de España, 1:200000, Hoja n.° 2 (Avilés)*, Instituto Tecnológico Geominero de España, Madrid.

Ando, C.J., Czuchra, B.L., Kempeler, S.L., Brown, L.D., Cheadle, M.J., Cook, F.A., Oliver, J.E., KauFormationan, S., Walsh, T., Thompson, J.B., Lyons, J.B. and Rosenfeld, J.L. (1984): Crustal profile of mountain belt: COCORP deep seismic profiling in New England Appalchians and implications for architecture of convergent mountain chains. *Amer. Assoc. Petrol. Geol. Bull.*, 68: 819-837.

Avigad, D., Chopin, C., Goffé, B. and Michard, A. (1993): Tectonic model for the evolution of the western Alps. *Geology*, 21: 659-662.

Ayarza, P. (1995): *Procesado, interpretación y modelado del perfil de reflexión profunda ESCIN-3.3 (Zonas Asturoccidental-Leonesa y Centro Ibérica)*. Tesis Doctoral. Universidad de Salamanca.

Bastida, F. and Gutiérrez-Alonso, G. (1989): Síntesis cartográfica de las unidades occidentales de la Zona Cantábrica.*Trabajos Geol. Univ., Oviedo,* 18: 117-125.

Bastida, F., Marcos, A., Pérez-Estaún A., Pulgar, J.A., Galan, J. and Vargas, I. (1980): *Mapa Geológico de España, 1:50000, 2.ª Serie. Hoja n.° 75 (Naviego).* Instituto Geologico y Minero de España, Madrid.

Bastida, F., Marcos, A., Pérez-Estaún A. and Pulgar, J.A. (1984): Geometría y evolución estructural del Manto de Somiedo (Zona Cantábrica, NO de España). *Bol. Inst. Geol. Min. España*, 95: 517-539.

Bastida, F. and Pulgar, J.A. (1978): La estructura del Manto de Mondoñedo entre Burela y Tapia de Casariego (Costa Cantábrica, NW de España). *Trabajos Geol. Univ. Oviedo*, 10, 75-124.

Butler, R.W.H., Matthews, S.J. and Parish, M. (1986): The NW External Alpine Thrust Belt and its implications for the geometry of the Western Alpine Orogen. In:*Collision tectonics* (M.P.Coward and A.C. Ries, Eds.), *Geol. Soc. London, Spec. Pub.*, 19: 37-50

Coward, M.P. (1983): Thrust tectonics, thin skinned or thick skinned and the continuation of thrusts to deep in the crust. *Jour. Struct. Geol.*, 5: 13-23.

Crespo Zamorano, A. (1982): *Mapa Geológico de España, 1:50000, 2.ª Serie. Hoja n.° 76 (Pola de Somiedo)* , Instituto Geológico y Minero de España, Madrid.

Fuis, G.S., Levander, A.R., Lutter, W.J., Wissinger, E.S., Moore, T.E. and Christensen, N.I. (1995): Seismic images of the Brooks Range, Arctic Alaska, reveal crustal-scale duplexing. *Geology*, 23: 65-68.

García-Dueñas, V., Balanyá, J.C. and Martínez-Martínez, J.M. (1992): Miocene extensional detachements in the outcropping basement of the Northern Alboran Basin (Betics) and their Tectonic implications. *Geo-Mar. Lett.*, 12: 88-95.

Gutiérrez-Alonso, G. (1987): *La estructura de la parte Norte de la Ventana Tectónica del Narcea*, Seminario de Investigación, Inédito, Universidad de Oviedo.

Gutiérrez-Alonso, G. (1992): *El Antiforme del Narcea y su relación con los mantos occidentales de la Zona Cantábrica*. PhD Thesis, Univ. Oviedo, Oviedo, 318 p. (unpubl.).

Gutiérrez-Alonso, G. (*in press*): Strain partitioning in the footwall of the Somiedo Nappe: structural evolution of the Narcea Tectonic Window. *Jour. Struct. Geol.*

Gutiérrez-Alonso, G. and Nieto, F. (1996): White mica "crystallinity", finite strain and cleavage development across a large structure (Narcea Antiform, Variscan Belt of NW Spain). *Jour. Geol. Soc. (London)*, 153: 287-299.

Gutiérrez-Alonso, G.and Villar, P. (1989): *El Precámbrico del Antiforme del Narcea.* Unpublished report, Instituto Tecnológico Geominero de España, Madrid.

Gutiérrez-Alonso, G., Villar, P. and Martín-Parra, L.M. (1990): La estructura del Antiforme del Narcea. *Cuad.Lab. Xeol. Laxe*, 15: 271-279.

Hatcher, R.D. Jr and Hooper, R.J. (1992): Evolution of crystalline thrust sheets in the internal parts of mountain chains. In: *Thrust tectonics*: (K.R. McClay, Ed.): 217-233, Chapman & Hall, London.

Heredia, N. (1984): La estructura de la escama de Villar de Vildas

(Manto de Somiedo, Zona Cantábrica). *Trabajos Geol., Univ. Oviedo*, 14: 65-78.

Julivert, M., Marcos, A. and Pulgar J.A. (1977a):. *Mapa Geológico de España , 1:50000, 2.ª Serie, Hoja n.º 27 (Tineo).* Instituto Geologico y Minero de España, Madrid.

Julivert, M., Marcos, A. and Pulgar J.A. (1977b): *Mapa Geológico de España, 1:50000, 2.ª Serie, Hoja n.º 51 (Belmonte de Miranda).* Instituto Geologico y Minero de España, Madrid.

Kley, J. (1993): *Der Überang von Subandin zur Ostkordillere in Südbolivien (21°15'-22°S): Geologische Struktur und Kinematik.* Ph.D. Thesis, Freie Univ. Berlin.

Lonergan, L., Platt; J.P. and Gallaher, L. (1994): The Internal-External Zone Boundary in the eastern Betic Cordillera, SE Spain. *Jour. Struct.Geol.,* 16: 175-188.

Marcos, A. (1973): Las series del Paleozoico inferior y la estructura herciniana del occidente de Asturias (NW de España). *Trabajos Geol., Univ. Oviedo*, 6: 3-113.

Marcos, A. and Pulgar, J.A. (1980): *Mapa Geológico de España, 1:50000, 2.ª Serie, Hoja n.º 11 (Luarca).* Instituto Geologico y Minero de España, Madrid..

Marcos, A. and Pulgar, J.A. (1982): An approach to the tectonostratigraphic evolution of the Cantabrian foreland thrust and fold belt, Hercynian Cordillera of NW Spain. *N.Jb. Geol. Paläont. Abh.*, 163: 256-260.

Marcos, A., Martínez, F.J., Julivert, M. and Pulgar, J.A. (1980): *Mapa Geológico de España, 1:50000, 2.ª Serie, Hoja n.º 50 (Cangas del Narcea).* Instituto Geologico y Minero de España, Madrid.

Martínez Catalán, J.R. (1985): Estratigrafía y estructura del Domo de Lugo (Sector Oeste de la Zona Astruroccidental Leonesa). *Corpus Geologicum Gallaeciae*, (Segunda Serie) II, 219 p.

Martínez Catalán, J.R., Pérez Estaún, A., Bastida, F., Pulgar, J.A. and Marcos, A. (1990): West Asturian-Leonese Zone.Structure. In: *Pre-Mesozoic Geology of Iberia.* (R.D Dallmeyer and E. Martínez García, Eds.): 103-104, Springer-Verlag, Berlin.

Martínez Catalán, J.R., Dallmeyer, R.D., Gil Ibarguchi, I., Arenas, R., Gervas, P., Farias, P., Aller, J., Bastida, F. and Gutiérrez Alonso, G. (1993): $^{40}Ar/^{39}Ar$ dating of deformation fabrics in the relative autochthon in NW Spain. *Terra Abstracts.* Terra Nova, 5: 391, Suplement 1.

Martínez Catalán, J.R., Ayarza Arribas, P., Pulgar, J.A., Pérez-Estaún, A., Gallart, J., Marcos, A., Bastida, F., Alvarez-Marrón, J., Gonzalez Lodeiro, F., Aller, J., Dañobeitia, J.J., Banda, E., Cordoba, D. and Comas, M.C. (this vol.): Results from the ESCI-N3.3 marine deep seismic profile along the Cantabrian continental margin. *Rev. Soc. Geol. España.*

Mattauer, M. (1986): Intracontinental subduction, crust mantle decollement and crustal stacking wedge in the Himalayas and other collision belts. In: *Collision tectonics* (M.P. Coward and A.C. Ries, Eds.), *Geol. Soc. London, Spec. Pub.*, 19: 37-50.

Muñoz, J.A. (1992): Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: *Thrust tectonics* (K.R. McClay, Ed.): 235-246, Chapman & Hall, London.

Pérez-Estaún, A., Bastida, F., Alonso, J.L., Marquínez, J., Aller, J. Álvarez Marrón, J., Marcos, A. and Pulgar, J. (1988): A thin skinned model for an arcuate fold and thrust belt: the cantabrian Zone (Variscan Iberoarmorican Arc).*Tectonics* , 7: 517-537.

Pérez-Estaún A. and Bastida, F. (1990): Cantabrian Zone. Structure. In: *Pre-Mesozoic Geology of Iberia.* (R.D. Dallmeyer and E. Martínez-García, Eds.): 55-69, Springer-Verlag, Berlin.

Pérez-Estaún, A., Bastida, F., Martínez Catalán, J.R., Gutiérrez Marco, J.C., Marcos, A. and Pulgar, J.A. (1990): West Asturian-Leonese Zone, Stratigraphy. In: *Pre-Mesozoic Geology of Iberia.*(R.D. Dallmeyer and E. Martínez-García, Eds.): 92-102, Springer-Verlag, Berlin.

Pérez-Estaún, A., Martínez-Catalán, J.R. and Bastida, F. (1991): Crustal thickening and deformation sequence in the footwall to the suture of the Variscan belt of northwest Spain. *Tectonophysics*, 191: 234-253.

Pérez-Estaún, A., Pulgar, J.A., Banda, E., Álvarez-Marrón, J. and ESCI-N Research Group. (1994): Crustal structure of the external variscides in northwest Spain from deep seismic reflection profiling. *Tectonophysics*, 232: 91-118.

Price, R.A. (1981): The Cordilleran freland thrust and fold belt in the southern Canadian Rocky Mountains. In: *Thrust and Nappe Tectonics* (K.R. McClay and N.J. Price, Eds.), *Geol. Soc. London, Spec. Pub.*, 9: 427-448.

Seaward, D. and Macktelow, N.S. (1994): Neogene kinematics of the Central and western Alps: Evidence from fission-track dating. *Geology*, 22: 803-806.

Schmidtz, M., (1994): A balanced model of the southern Central Andes. *Tectonics*, 13: 484-492.

Suárez, O., Corretgé, L.G. and Martínez, F.J. (1990): West Asturian-Leonese Zone. Distribution and Characteristics of the Hercynian Metamorphism. In: *Pre-Mesozoic Geology of Iberia.* (R.D. Dallmeyer and E. Martínez-García, Eds.): 129-133, Springer-Verlag, Berlin.

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