Pergamon

Journal of Structural Geology, Vol. 18, No. 10, pp. 1217 to 1229, 1996
Copyright © 1996 Elsevier Science Ltd
Printed in Great Britain. All rights reserved
0191-8141/96 $15.00+0.00

PII: S0191-8141(96)00034-X

Strain partitioning in the footwall of the Somiedo Nappe: structural evolution of the Narcea Tectonic Window, NW Spain

GABRIEL GUTIÉRREZ-ALONSO

Departamento de Geología, Universidad de Salamanca, 37008 Salamanca, Spain

(*Received* 4 *August* 1995; *accepted in revised form* 29 *April* 1996)

Abstract—The Somiedo Nappe is a major thrust unit in the Cantabrian Zone, the external foreland fold and thrust belt of the North Iberian Variscan orogen. Exposed at the Narcea Tectonic Window are Precambrian rocks below the basal decollement of the Somiedo Nappe, which exhibit a different deformation style than the overlying Paleozoic rocks above the basal decollement. During Variscan deformation, folding and widespread sub-horizontal, bedding-parallel decollements were produced in the hanging wall within the Paleozoic rocks. Vertical folding, with related axial–planar cleavage at a high angle to the decollement planes, developed simultaneously in the upper Proterozoic Narcea Slates of the footwall, below the detachment. The relative magnitude of finite strain, measured in the footwall rocks, diminishes towards the foreland. These observations indicate that (1) significant deformation may occur in the footwall of foreland fold and thrust belts, (2) the shortening mechanism in the footwall may be different from that of the hanging wall, and (3) in this particular case, the partitioning of the deformation implies the existence of a deeper, blind decollement surface contemporaneous with the first stages of the foreland development, that does not crop out in the region. This implies a significant shortening in the footwall, which must be taken into account when restoration and balancing of cross-sections is attempted. A sequential diagram of the evolution of the Narcea Tectonic Window with a minimum shortening of 85 km is proposed, explaining the complete Variscan evolution of the foreland to hinterland transition in the North Iberian Variscan orogen. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Deformation in the footwall below the basal detachment of a foreland fold and thrust belt is generally not expected to occur synchronously with thrust generation, though some localized uplift may occur (i.e. Moxa Arch, Kraig *et al.* 1987). In most models, the footwall is considered to remain undeformed, and shortening is accommodated by detachment and rigid translation, and by faulting and folding in the hanging wall of the basal thrust. One reason for this, perhaps, is that the footwall is rarely accessible to direct observation, unless a tectonic window happens to have developed in the rearmost part of the thrust and fold belt.

Displacement transfer between decollements located at different depths occur at the boundary between the foreland and the hinterland of most orogens. Such displacement transfer takes place in the Variscan belt of NW Spain in a 'slip transfer zone'. Slip transfer zones are characterized by two decollement planes located at different depths with the same displacement direction and sense. Between both decollements, a volume of rocks becomes internally strained in a way similar to the contractional composite structures described by Rykkelid & Fossen (1992), but at a much larger scale.

This paper documents such a structure in the Variscan belt of NW Spain, the Narcea Tectonic Window (Figs. 1 and 2), and demonstrates significant synchronous shortening of the footwall beneath a major thrust unit during the early stages of the thrust belt generation. The shortening is accomplished by folding and internal deformation whose intensity decreases towards the foreland. Assuming no internal deformation in the upper sheets, the diminishing strain gradient in the footwall implies an increasing amount of displacement of the basal detachment towards the foreland, together with a decreasing amount of shortening in the footwall in the same direction. Such deformation has important implications in the construction of geometrical and evolutionary models of the hinterland–foreland limit in this orogen, as can be seen in the sequential diagram presented in this work depicting the different stages of evolution that led to the present configuration of the Narcea Antiform and surrounding units.

GEOLOGICAL SETTING

The example presented is located in the Narcea Antiform (Fig. 1), a broad culmination at the foreland–hinterland transition in the Variscan orogen of north-western Iberia. The foreland, the eastern flank of the Narcea Antiform, is represented by the Cantabrian Zone, a typical thrust belt with an unmetamorphosed sedimentary pre-Carboniferous Paleozoic sequence composed of up to 7000 m of mostly stable marine platform sediments, thinning to the East, covered by a Carboniferous syn-orogenic sequence of variable thickness (Marcos & Pulgar 1982). On the other hand, the western flank of the Narcea Antiform is part of the hinterland, called the West Asturian–Leonese Zone. This zone is composed of a thick lower Paleozoic 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 Paleozoic sequence, and separated from it by an angular unconformity, the upper Proterozoic Narcea Slates, of undetermined thickness, are exposed. The Narcea Slates are composed mainly of slates and greywackes with turbiditic facies with minor vulcanoclastic intercalations more abundant towards the west. The boundary between both zones is sharp, the La Espina Thrust, a major structural limit marked by a thrust with very intense ductile deformation associated (Gutiérrez-Alonso 1992).

Regarding the structural framework, in the foreland of this orogen (the Cantabrian Zone), the most important decollement surface is located at the base of the Lower to Middle Cambrian Láncara Limestone. This surface acted as the basal, or sole thrust of most of the large nappe units constituting the foreland fold and thrust belt (Julivert 1971). At the rearmost part of the foreland, a second, deeper decollement is found close to the base of the Lower Cambrian Herrería Quartzite. This decollement controlled the development of out-of-sequence duplex-type structures that crop out as antiformal stacks (Marcos 1968, Julivert 1971, Pérez-Estaún 1971, Julivert & Marcos 1973, Alonso 1987, Gutiérrez-Alonso 1987, Pérez-Estaún & Bastida 1990). Below two of the antiformal stacks, the Narcea and the Villabandín stacks, the latter out of the study area, the Narcea Slates are exposed in tectonic windows. The Narcea Tectonic Window (Figs. 1 and 2) represents an excellent opportunity to study the processes involved in the synchronous deformation of the footwall of a large thrust unit located at the rearmost part of a foreland fold and thrust belt. In the hinterland of this belt, the West Asturian–Leonese Zone, the basal thrust is located at a deeper level, in the Precambrian rocks of the Narcea and Villalba Series. This change in depth of the basal thrust in adjacent domains implies the existence of a slip transfer zone linking the two basal thrusts. The evolution of this slip transfer zone controls initial footwall deformation below the Somiedo Nappe in the Cantabrian Zone (Fig. 1), which is the main focus of this paper. The subsequent incorporation of the footwall into the foreland thrust wedge during the second deformation stage in the Cantabrian Zone is described in detail by Pérez-Estaún *et al.* (1991).

The most relevant structural feature found in the Narcea Tectonic Window is the distribution of cleavage and its geometric and genetic relations to the folds above and below the Cambrian–Precambrian unconformity that acted as a decollement plane during the early stages of the deformation that gave rise to the Narcea Tectonic Window. Despite the lack of absolute ages proving synchronous cleavage generation above and below the floor thrust, and that structures of different ages can look very much alike (Williams 1985, Tobisch & Paterson 1988, Gray & Mitra 1993), regional geological criteria and detailed structural analysis (Pérez-Estaún 1978, Gutiérrez-Alonso 1992) indicate that the primary foliation observed both above and below the unconformity originated at the same time. In the West Asturian–Leonese Zone, there is evidence of several generations of cleavage, superposed in space and time (Matte 1968, Marcos 1973 etc.), but that superposition does not appear to affect the Cantabrian Zone, including the Narcea Tectonic Window as it does not propagate further than the boundary between the West Asturian–Leonese Zone and the Cantabrian Zone.

The Narcea Antiform may be divided into two areas based on early Paleozoic palaeogeography and characteristics of Variscan deformation and metamorphism. These two areas are (i) the most strained and metamorphosed allochthonous units of La Espina and Trones to the West and (ii) the non-metamorphic Narcea Tectonic Window to the East (Figs. 1–3).

The Somiedo Nappe footwall rocks crop out in the Narcea Tectonic Window due to erosion of a thrust culmination at the boundary between the hinterland and the foreland fold and thrust belt (Figs. 1 and 3). 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 cross-cutting the former main sole decollement. Subsequent antiform generation and faulting did not substantially modify the geometry of the main structure and the relationships between the different rock units involved. Amplification resulted mostly in the steepening of the thrust planes. The main structural features of this area can be seen in the geologic map (Fig. 2) and have been described in detail elsewhere (Julivert & Marcos 1973, Marcos 1973, Bastida *et al.* 1984, Heredia 1984, Gutiérrez-Alonso 1987, Pérez-Estaún *et al.* 1988, 1994, Pérez-Estaún & Bastida 1990.

The floor thrust of the Narcea stack, bounding the Narcea Tectonic Window to the north and east, coincides with a major angular unconformity situated on the base of the Herrería Quartzite and above the underlying Narcea Slates (Lotze 1956, Julivert & Martínez-García 1967, Matte 1968, Bosch 1969, Marcos 1973). The western limit of the Narcea Tectonic Window is the La Espina thrust (Fig. 2), that also represents the boundary between the hinterland (West Asturian–Leonese Zone) and the foreland fold and thrust belt (the Cantabrian Zone).

As a summary of the geological setting, Fig. 3 depicts a cross section of the Narcea Tectonic Window and the surrounding units in which the complex structure of this area is shown. The Narcea Tectonic Window is overlain to the east by the Somiedo Nappe, the westernmost thrust unit of the Cantabrian Zone, and to the west by ductile thrusts developed in the West Asturian–Leonese Zone rocks. This cross-section illustrates well the two contrasting styles of deformation between the foreland and the hinterland, namely fold and thrust belt vs. ductile shear deformation, respectively. It is worth noting the difference in deformation style between the Narcea slates and the Herrería Quartzite in the Narcea Tectonic Window. Note that folds in the Narcea Slates cannot be drawn because the fold axes, subvertical, are parallel to the cross-section plane.

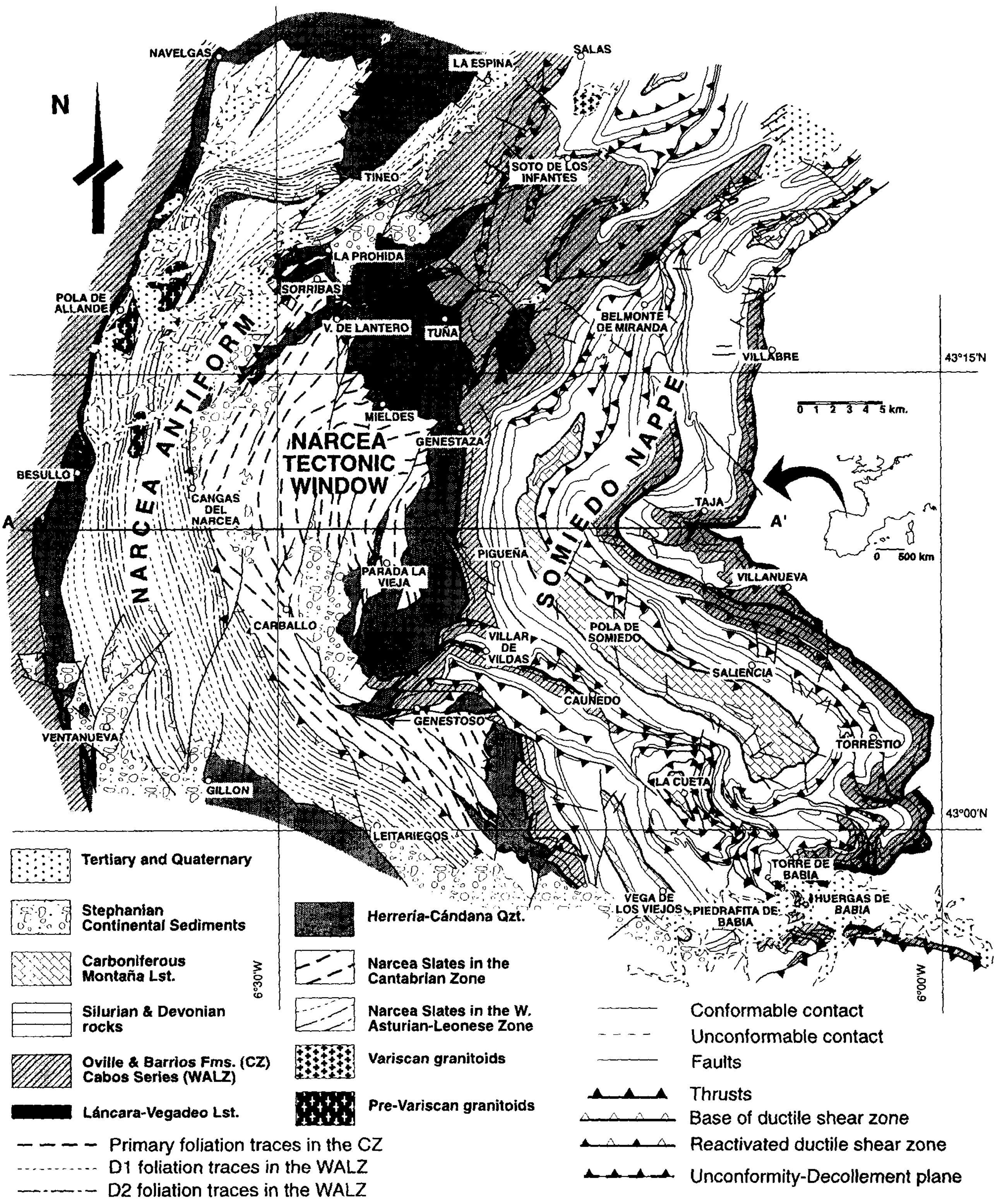

Fig. 1. Location of the study area and geological map of the Narcea Antiform and surrounding units after Marcos (1973), Julivert *et al.* (1977), Crespo Zamorano (1982), Bastida *et al.* (1984), Heredia (1984), Aller *et al.* (1989), Bastida & Castro (1987), Bastida & Gutiérrez-Alonso (1989), Alonso *et al.* (1989, 1990), Gutiérrez-Alonso *et al.* (1990), Suárez *et al.* (1990), Gutiérrez-Alonso (1987, 1992). A–A' trace of cross-section depicted in Fig. 3 (CZ— Cantabrian Zone, WALZ— West Asturian–Leonese Zone).

DEFORMATION IN THE NARCEA TECTONIC WINDOW

The Narcea Tectonic Window lies close to the boundary between the hinterland or 'internal zone' of the Variscan Belt to the west, which is composed of metamorphosed, polyphase-deformed rocks, and deformed sedimentary rocks of the foreland or 'external zones' of the Cantabrian Zone to the east. Geologic investigations have been performed in the Narcea

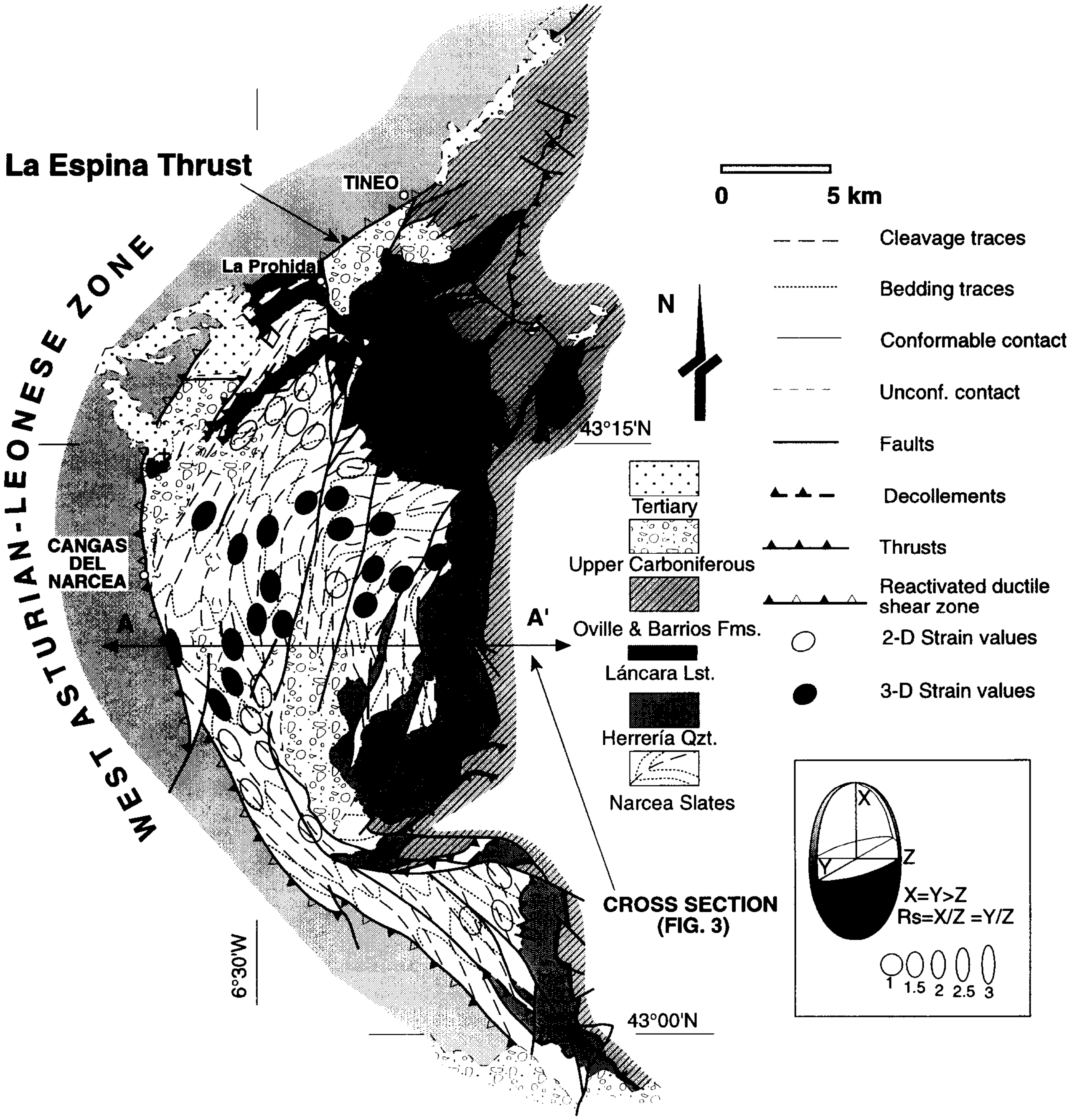

Fig. 2. Geological map of the Narcea Tectonic Window. The map shows the distribution of the Precambrian Narcea Slates and the Paleozoic rocks highlighting important structural elements. Traces of cleavage and bedding in the Narcea slates are constructed from local S_0/S_1 relations across the whole area. Legend as in Fig. 1. *R*s values were obtained by the Fry method from sandstones interbedded in the Narcea Slates. Inset: Legend for the finitre strain values and finite strain ellipse and its relation with the *R*s values measured in the Narcea Slates. The cleavage plane is parallel to *XY* plane.

Tectonic Window for some time (Marcos 1973, Julivert *et al.* 1977, Crespo Zamorano 1982, Bastida *et al.* 1984, Gutiérrez-Alonso 1987, 1992, Bastida & Gutiérrez-Alonso 1989, Gutiérrez-Alonso *et al.* 1990. These investigations demonstrate the origin of the different deformation styles exhibited by the Precambrian Narcea Slates and the Paleozoic Herrería Quartzite (Julivert *et al.* 1968, Pérez-Estaún 1971, Aller *et al.* 1989), and the evolution of an area where the 'cleavage front' has been previously described as occurring in the Narcea Slates, marked by the change from areas of extensive cleavage development (West Asturian–Leonese Zone) to areas without cleavage (Cantabrian Zone). The 'cleavage front' coincides with the increase in metamorphism from anchizone to epizone, as indicated by white mica 'crystallinity' (Gutiérrez-Alonso & Nieto 1996).

In the present study, detailed structural mapping was undertaken to re-evaluate these ideas. The investigation included extensive measurements of the orientation of structural elements that enabled the construction of the bedding and cleavage traces depicted in Fig. 2. Owing to the lack of distinct stratigraphic horizons within the Narcea Slates, this method is the only one suitable to reconstruct the structure inside the Narcea Tectonic

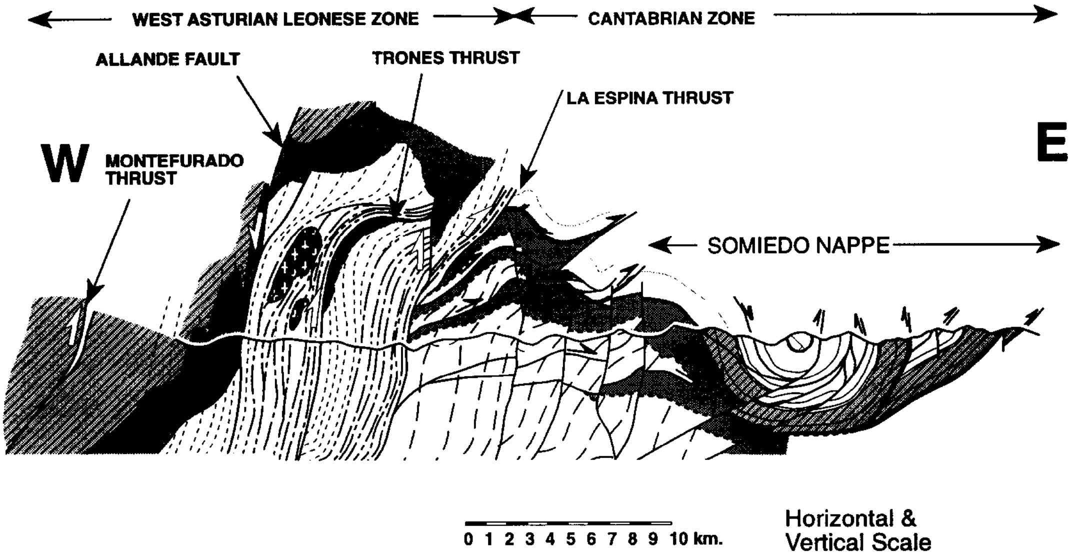

Fig. 3. Cross-section of the Narcea Antiform and adjacent units. The cross-section spans to the units adjacent to the Narcea Tectonic Window, represented in the geological map. Location and legend in Figs. 1 and 2. Note the contrasting deformation styles east and west of the Narcea Tectonic Window.

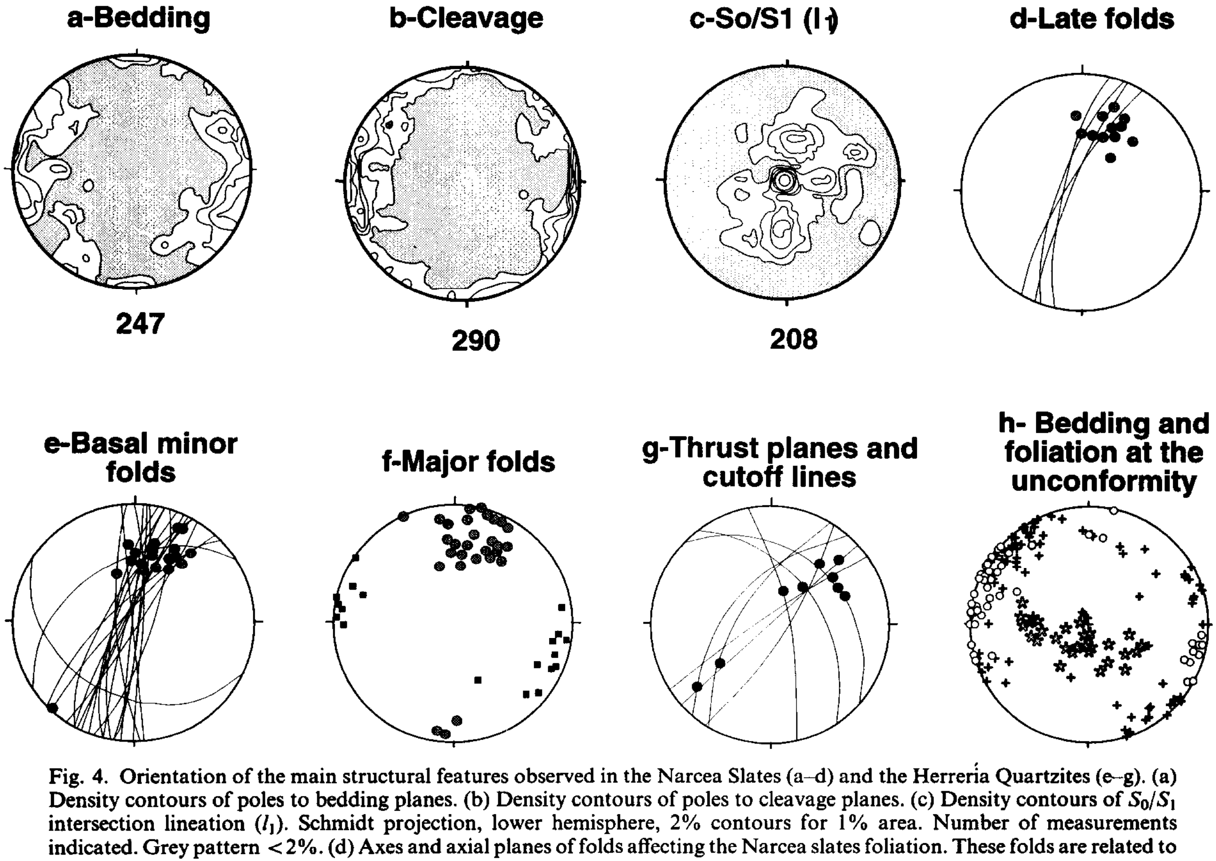

Fig. 4. Orientation of the main structural features observed in the Narcea Slates (a–d) and the Herreria Quartzites (e–g). (a) Density contours of poles to bedding planes. (b) Density contours of poles to cleavage planes. (c) Density contours of S_0/S_1 intersection lineation (l_1). Schmidt projection, lower hemisphere, 2% contours for 1% area. Number of measurements indicated. Grey pattern < 2%. (d) Axes and axial planes of folds affecting the Narcea slates foliation. These folds are related to the late out-of-sequence thrusting. (e) Folds related to minor thrusts, great circles are axial planes and dots are fold axes. (f) Major folds in the Herreria Quartzite, dots are fold axes and squares are poles to axial planes. (g) Thrust planes and cutoff lines developed in the basal beds of the Herreria Quartzites, showing both frontal and lateral features. (h) Bedding of the Narcea Slates (crosses), the Herreria Quartzites (stars) and cleavage in the Narcea Slates (dots) close to the unconformity–decollement plane. Note the vertical attitude of bedding, cleavage and intersection lineation in the Narcea Slates.

Window. The orientation of the main structural features present in the Narcea Slates and the Herrería Quartzites are shown in Figs. 4 (a–h).

Present bedding in the Narcea slates is mostly vertical (Fig. 4a), as is axial planar cleavage (Fig. 4b). Folds have variable interlimb angles, from 50° to 90°, and fold axes, or bedding/cleavage intersection lineations (l_1) are also vertical (Fig. 4c). Cleavage traces (Fig. 2) are arcuate probably due to later oroclinal bending caused by the closing of the Ibero–Armorican Arc (Julivert & Marcos 1973, Julivert & Arboleya 1984, Hirt *et al.* 1992, Parés *et al.* 1994, Stewart 1995 and references therein).

Qualitatively, intensity of the cleavage increases from east to west. At the eastern part of the Narcea Tectonic Window, a rough cleavage is defined by pressure solution seams, but mica growth is not observed. In the western part of the Narcea Tectonic Window, the cleavage becomes a penetrative type 2 cleavage (Durney & Kisch 1994), varying from its incipient form to a fully developed slaty cleavage. Here, both pressure solution seams and white-mica and chlorite growth can be identified.

Cleavage and bedding in the Narcea Slates are at a high angle to the Herrería Quartzite contact (Figs. 1–3). In general, the Herrería Quartzite is not affected by the cleavage, although occasionally the cleavage found in the Narcea Slates continues into the lowermost several meters above the contact with the Narcea Slates. In addition, the primary cleavage in the Narcea Slates exposed in the West Asturian–Leonese Zone, in the western flank of the Narcea Antiform, is continuous with the ubiquitous cleavage present in the overlying Paleozoic rocks. These observations are important and indicate that the cleavage formed after the deposition of the Herrería Quartzites and, therefore, is likely to be of Variscan age (Julivert & Martínez-García 1967, Pérez-Estaún 1978).

Deformation in the Herrería Quartzite is completely different from that in the underlying Narcea Slates. Despite the fact that quartzites are not generally susceptible to cleavage formation, cleavage is developed locally, only in the lowermost few meters (or even decimeters) of the Herrería Quartzites, and is recognized in interbedded pelitic rocks or in the discontinuous basal microconglomerates. The cleavage in these rocks, oblique to the cleavage in the Narcea Slates, is sub-parallel or aligned at a small angle to bedding and to the unconformity plane due to shearing along the latter. Close inspection of the unconformity plane in several outcrops near Villar de Lantero, Parada la Vieja and Sorribas reveals centimeter-scale fault gouges and breccias, indicating that the unconformity plane was activated as a decollement surface. In many outcrops, mostly south of the study area, additional evidence for detachment along the unconformity plane is visible in the form of metre-scale imbricate thrusts duplicating the lowermost beds of the Herrería Quartzite.

It is suggested that the deformation in the Herrería Quartzites is related to thrusting and akin folding. Folds are the most common structures and have axes oriented N–S that plunge 0°–30° (Figs. 4e & f). Thrust faults are also a common feature, as can be seen in the geologic map and cross-section (Figs. 1–3). Some small-scale thrusts, with both frontal and lateral cutoffs, are oriented as shown in Fig. 4(g), indicating movement directions to the ESE, consistent with the general thrust transport directions in this sector of the Cantabrian Zone (Gutiérrez-Alonso 1992). Note that folds affecting the Narcea Slates foliation (Fig. 4d) have the same orientation as the fold axes and thrust cutoff lines in the Herrería Quartzites. This is interpreted as related to folds that originated during the late thrusting events that affected both, the Herería Quartzites and the Narcea Slates, and therefore show the same orientation as those in the overlying rocks.

No attempt has been made previously to elucidate the shortening undergone by the Narcea Slates during the Variscan orogeny. The lack of mappable units in the Narcea slates that allow the characterization of the precise shape of the folds precludes the calculation of the amount of shortening due to folding. Only strain analysis can provide a minimum estimate of the shortening undergone by these rocks during the Variscan orogeny. In addition, the present geometry of the Narcea Slates bedding in the Narcea Tectonic Window is the result of the superposition of important Variscan events (mostly Lower and Middle Carboniferous) over Late Proterozoic deformation, which produced large wavelength folds. These Proterozoic folds probably had E–W axes, vertical axial planes, and steep limbs resulting in a high angle unconformity of the base of the Herrería Quartzites. It should be noted that one important factor controlling the deformation in the Narcea Slates in the Narcea Tectonic Window in relation to the Variscan shortening, is the original oblique orientation (approximately E–W) of bedding in the Narcea Slates, resulting in the aforementioned folding. This initial orientation explains the different plunge of the Variscan fold axes in the Narcea Slates and in the Paleozoic formations (Figs. 4c & 4e–f respectively). A general comparison of the orientation of bedding and cleavage in both the Narcea Slates and the Herrería Quartzite close to the uncomformity plane along the whole Narcea Tectonic Window, is presented in Fig. 4(h). It can be noted that a π-diagram with the bedding data from the Herrería Quartzite at the unconformity would lead to a fold axis close to those found regionally, but a similar diagram constructed for the Narcea Slates bedding data yields vertical fold axes. Note also that cleavage in the Narcea Slates is axial planar to the folds found in the Narcea Slates and in the Herrería Quartzites, indicating a common origin of both sets of folds from initially oblique bedding surfaces.

Variscan deformation of the Narcea Antiform continued subsequent to the aforementioned deformation, and the whole Narcea Antiform, including the Narcea Slates of the Narcea Tectonic Window, was affected by out-of-sequence thrusting. This deformation stage is largely responsible for the features observed in the actual cross-section (Fig. 3). All the thrusts, in this cross-section (Fig. 3), that cross-cut the cleavage affecting the Narcea Slates and the decollement located in the base of the Herrería Quartzites, are related to the late thrusting event, postdating the axial plane cleavage generation and responsible for the present shape of the Narcea Antiform, together with late faulting. Local refolding related to this late thrusting event is recorded by meter-scale folds affecting the axial planar cleavage of the Narcea Slates and therefore, re-folding the earlier folds although no large-scale interference patterns resulted due to the different scale of both sets. These folds are particularly evident close to the village of La Prohida, in the northern part of the Narcea Tectonic Window, where the Narcea Slates are involved in a late imbricate thrust system. The attitude of such folds is shown in Fig. 4(d).

STRAIN MEASUREMENTS IN THE PRECAMBRIAN ROCKS

In order to test and quantify the progressive east to west increase in deformation in the Narcea Slates, that can be noted qualitatively in the penetrativity of the cleavage developed in the slates, samples were collected for finite strain measurements. Samples were always collected in sandstone layers, interbedded with the slates in turbiditic sequences. The samples are located on limbs of symmetric sinusoidal folds to avoid local strain variation that might occur in the hinges. Thin sections were made in slates to observe the nature and characteristics of the cleavage and in sandstones to perform Fry strain analysis (Fry 1979). The Fry method computes the angular and distance relationships between the centers of adjacent grains that are modified according to the aspect ratio and orientation of the finite strain ellipsoid. As all the strain measurements were performed in sandstones they are lithology-specific. The reason for performing the finite strain measurements in the sandstones present in the sequence is that it is only in those rocks that the finite strain can be computed. Therefore, the results obtained are likely to be minima of the whole sequence because the sandstones have deformed less than the slates, as is usually the case with competent/incompetent sequences. The results are interpreted to be representative of the whole sequence as there are sandstone beds in all the exposed Narcea Slates. According to this, the results obtained, some of which can be seen in Fig. 5, should be regarded as more semi-quantitative than truly quantitative, but they allow comparison between samples with the same characteristics (grain-size, matrix-clast ratio, etc.).

The 3D analysis of 18 samples were performed using two perpendicular sections, both cut normal to cleavage, but one normal and the other parallel to the bedding–cleavage intersection lineation (l_1). The results from those samples indicate oblate ('pancake'-shaped) finite strain ellipsoids, where $0 \leq k \leq 1$ (k is the Flinn parameter, Fig. 6a), with the XY plane parallel to the cleavage plane. Sixteen 2D strain analyses were performed normal to cleavage and to l_1, leading to results consistent with the 3D analysis. The use of 2D data assumes a constant oblate shape for the finite strain ellipsoid, a reasonable assumption based on the 3D analysis. The *R*s values obtained are proportional to the finite strain ($Rs = X/Z$ or Y/Z as $X \approx Y > Z$, Fig. 2), thus, higher *R*s values represent more intense deformation. The finite strain ellipsoid shapes are depicted in Fig. 2, which shows that the long axis of the finite strain ellipsoids are aligned parallel to the foliation traces. *R*s values obtained from the analysis range from 1.2 to 3.

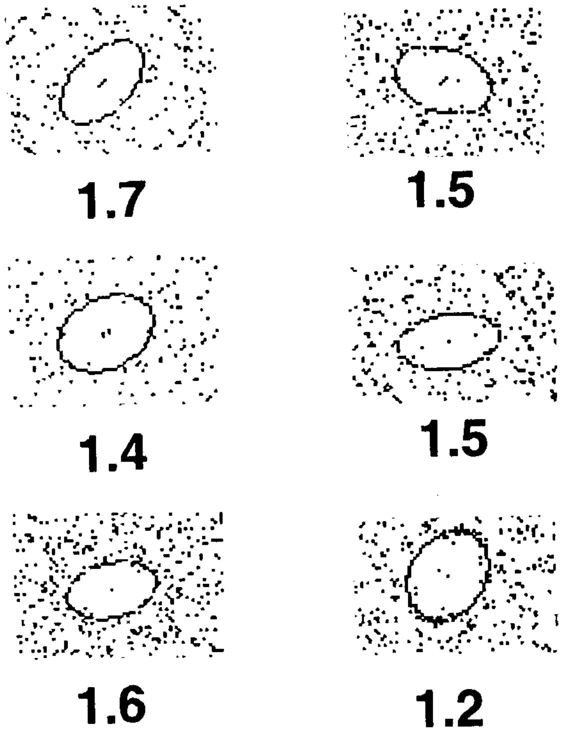

Fig. 5. Some examples of Fry analysis samples used in this work with the *R*s values obtained.

The results of finite strain analysis (Figs. 2 and 6b)

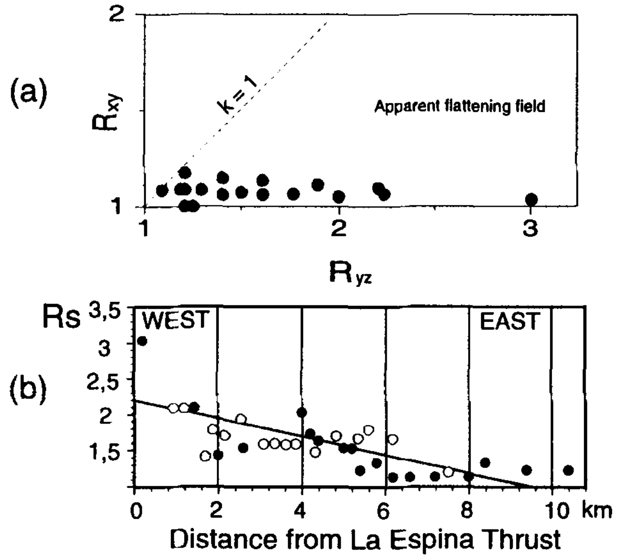

Fig. 6. (a) Flinn plot showing that all the samples analyzed fall into the apparent flattening field. (b) Plot of *R*s values vs distance from La Espina Thrust. Data have been projected along the strike of the structures into the vertical surface of the cross-section in Fig. 3. Best fit line calculated from the 3D ellipsoids (black dots). 2D ellipses are represented by white dots and are less indicative as they are further away from the section trace and, therefore, projection into A–A′ is more speculative.

indicate a steady decrease in finite strain, from west to east in the central part of the Narcea Antiform and from NW to SE in the northern part. The gradual east-southeast decrease in finite strain, along with the absence of local strain gradients imply that cleavage resulted from a regional, homogeneous deformation mechanism (Fig. 6b). It is suggested here that the most likely mechanism responsible for imparting cleavage in this very low-grade metamorphic rock is the shortening resulting in the genesis and amplification of the Variscan folds developed in the Narcea Slates of the Narcea Tectonic Window. Such shortening must have decreased in intensity from west to east as recorded in the sandstones and probably the Precambrian rocks located further east, below the eastern nappes of the Cantabrian Zone, are not deformed during Variscan times.

In addition to the increase in finite strain from east to west an increase in the metamorphic conditions from anchizone to epizone has been described in the Narcea Tectonic Window (Gutiérrez-Alonso & Nieto 1996) based on the 'crystallinity' of the metamorphic white mica.

DISCUSSION

The evidence suggests that deformation of the Narcea Slates originated during Variscan times by shortening accommodated by folding and axial planar cleavage development, with a decrease in strain intensity from west to east, that is, from the hinterland to the foreland. Shortening is interpreted to be accompanied by volume loss as pressure solution processes are important, especially in the western limit. Shortening took place in the same direction as propagation of the thrust units and the decollements in the overlying Herrería Quartzites. The geometry and evolution of the Narcea Tectonic Window is summarized in Fig. 7. Figure 7(a) represents an upward slip transfer zone, similar to those described by Rykkelid & Fossen (1992, fig. 12), but at a much larger scale and affecting rocks which are less metamorphosed. The shaded region is the rock volume susceptible of internal deformation between two decollements at different depths, the decreasing internal deformation in the sense of movement of the decollements of this volume of rock is an effect of the buttressing of the rearmost block (the hinterland, West Asturian–Leonese Zone) against the footwall of the upper decollement (the Somiedo Nappe, Cantabrian Zone). The shaded region represents the Narcea Slates exposed in the Narcea Tectonic Window. In the block diagram (Fig. 7b), the detached and imbricated Paleozoic rocks overlie the Precambrian Narcea Slates. The latter are affected by folds with subvertical axes and axial-planar cleavage striking parallel to the Herrería Quartzites fold axes.

Assuming that the shortening in the Narcea Slates does not propagate downwards, that is to say, into the basement, and therefore the overall deformation style is thin-skinned, this block diagram demonstrates the need for two decollements in the overall structure, the upper one at the unconformity plane separating the Narcea Slates and the Herrería Quartzites, and the other, a blind decollement, at a greater uncertain depth. The existence of two decollements solves the problem of the compatibility between the shortening undergone by the Narcea Slates and the overlying rocks. A second, blind decollement parallel to the exposed one has been inferred in other areas (Engelder & Engelder 1977, Marshak 1986, Geiser 1988, Kulander & Dean 1988, Jordan & Noack 1992). In the present case it can be interpreted that it is a shear zone rather than a fault plane, according to the deformation observed in the Precambrian rocks to the West. Folding and imbrication in the Herrería Quartzites are related to the decollement at the unconformity plane located at its base. Below the blind, lower decollement there might exist either undeformed Narcea Slates or other undeformed basement rocks not exposed in the region, which would represent the true autochthon of the Cantabrian Zone in this sector. It is still unresolved if the postulated lower blind decollement is located at a lithological boundary or found within the Narcea Slates.

The proposed model of strain and deformation partitioning is depicted as a conceptual cartoon in Fig. 7(c). The Herrería Quartzites (horizontal stripes), shorten by thrusting under plane-strain conditions without internal finite strain nor cleavage development, except for the lower part where some shearing takes place. Shortening in the Narcea Slates (represented by reference vertical lines), is accomplished by folding, with the maximum shortening in the horizontal direction. The lack of rotational features related to cleavage development and the lack of vergence depicted by the folds suggest pure shear as the main deformation in the Narcea Slates. Folding and axial planar cleavage development decrease towards the east accompanied by the decrease in the axial ratio values of the finite strain ellipsoid. The net slip on the upper decollement at the unconformity plane increases in displacement toward the east because it progressively accumulates the total shortening undergone by its footwall. In contrast, the inferred lower decollement decreases in displacement to the east according to the strain gradient revealed by the Narcea Slate strain analysis, as illustrated by the progressively larger spacing of the vertical lines to the east. The Paleozoic rocks were deformed without internal strain or cleavage development, undergoing rigid translation above the upper decollement with related folds that do not show major extension parallel to the fold axes. The Precambrian Narcea Slates, however, have experienced shortening by folding and axial cleavage development, probably with volume reduction.

The true cross-section (Fig. 3) shows the same pattern as the model, except that it is complicated by several late-Variscan superposed thrusting events, some of them of the out-of-sequence type and antiform amplification. The depth of the lower detachment is tentative, and is constrained by rocks exposed further west, in the shear zones related to La Espina and Trones thrusts, where this decollement plane is interpreted to crop out due to out-of-sequence thrusting (reactivated ductile shear zone

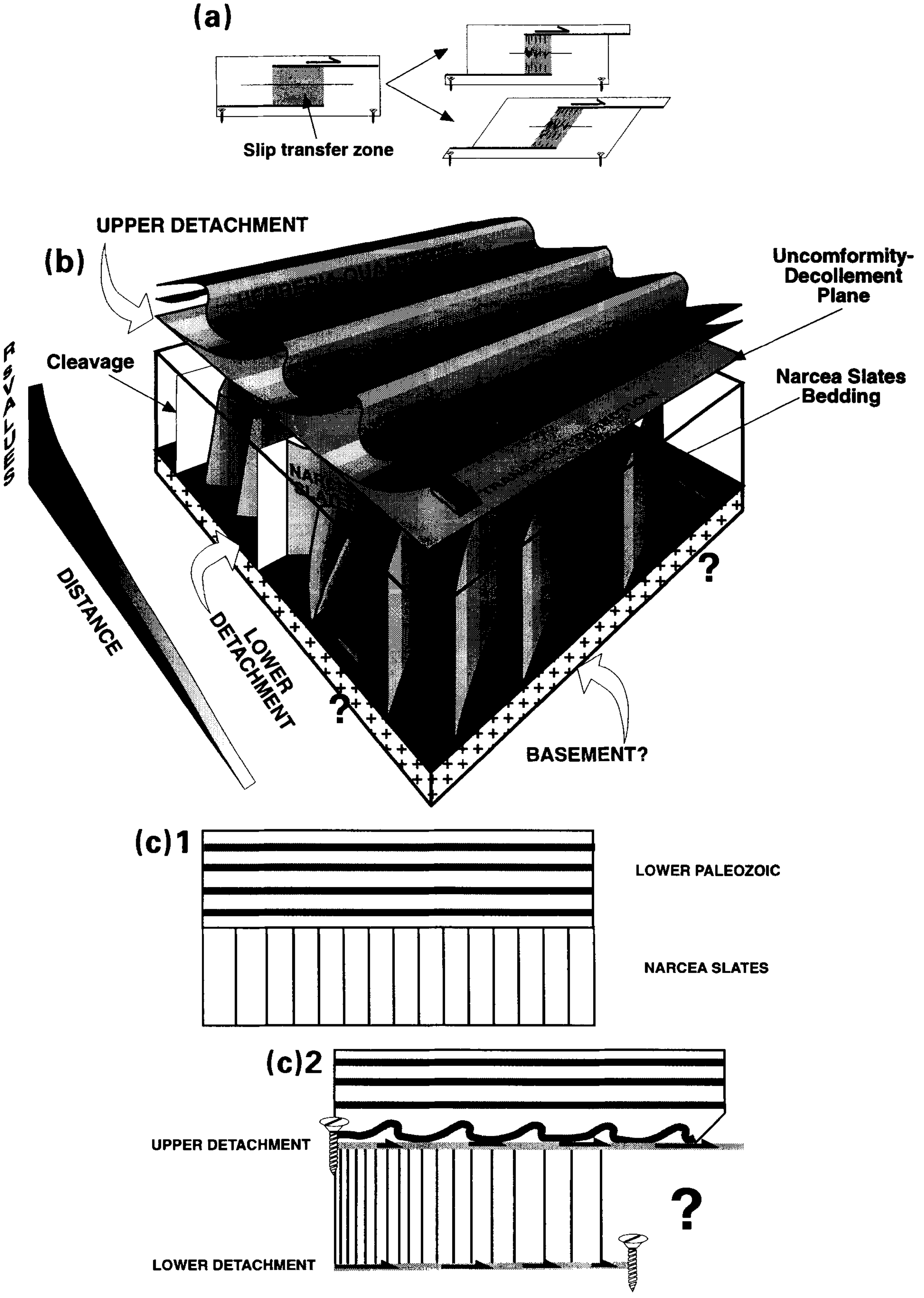

Fig. 7. Interpretative geometrical model of the Narcea Tectonic Window. (a) Compressive 'slip transfer zones' with volume loss according to Rykkelid & Fossen (1992). (b) Schematic block diagram of the structural relations observed between the different deformation styles and mechanisms. (c) Conceptual cross-section. For more information refer to the discussion.

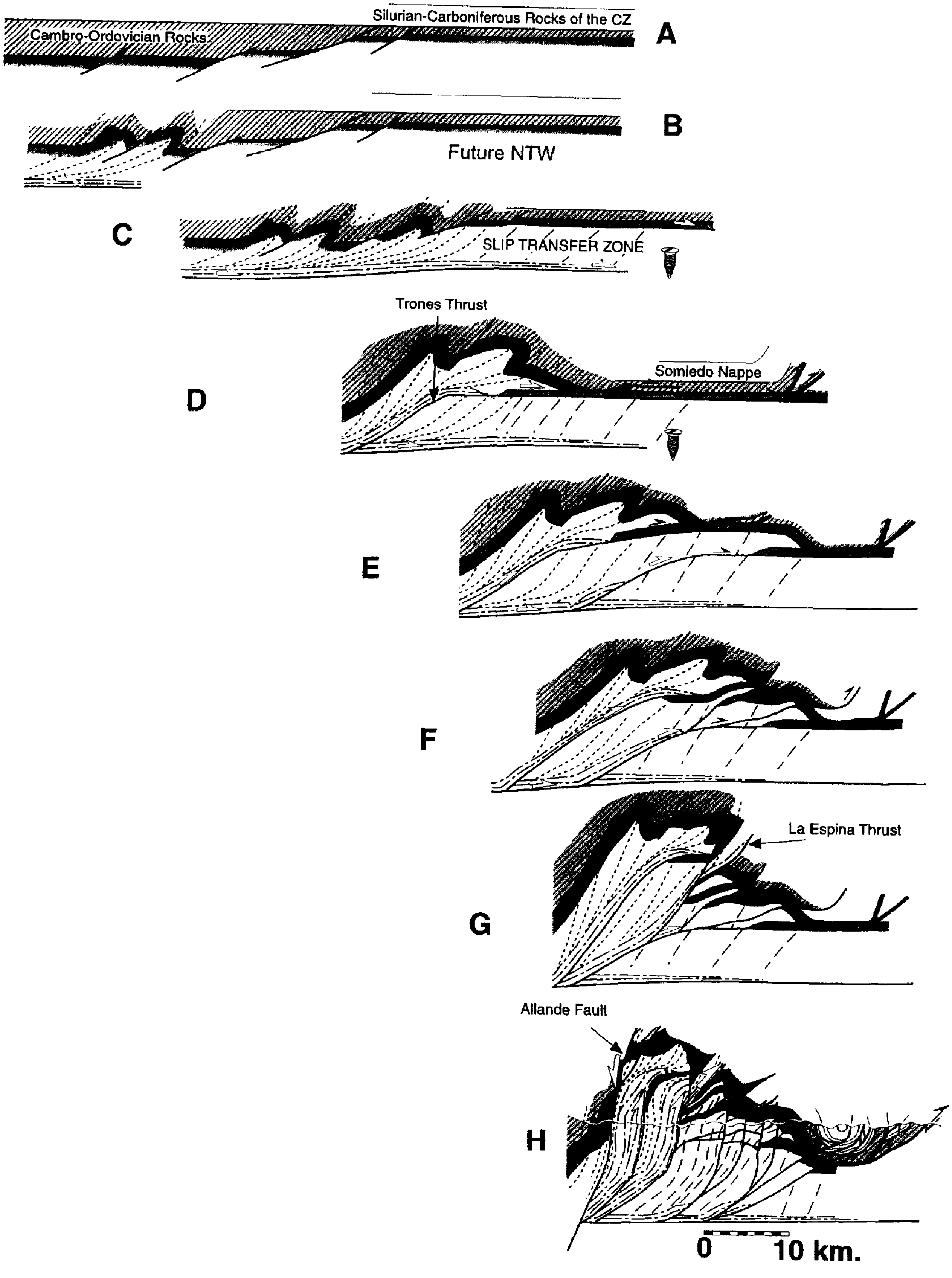

Fig. 8. Sequential diagram showing the kinematic Foreland–Hinterland boundary in the North Iberian Variscan Orogen as deduced from the structure of the Narcea Tectonic Window (NTW) and surrounding areas. See text for explanation of Stages A–H.

symbol in Fig. 1). Thermobaric conditions for the phyllonites developed in these shear zones have been constrained to 340°–400°C and 3–4 kbar (Gutiérrez-Alonso & Nieto 1996). In the out-of-sequence thrusting stage, the lower decollement in the Narcea Slates acts as the sole thrust of the late stages of thrusting. Folds affecting and, therefore, postdating the cleavage of the Narcea Slates are found related to the late thrusting events (Gutiérrez-Alonso 1992). These structures involve the previously strained Narcea Slates, and build up the antiformal stack that allows the exposure of the Narcea Tectonic Window (Pérez-Estaún & Bastida 1990, Pérez-Estaún *et al.* 1991).

A recent seismic survey across the Narcea Tectonic Window (Pérez-Estaún *et al.* 1994) unfortunately does not reveal the shallow structure of this area. The reflectors found in the middle and lower crust below the Narcea Antiform are far too deep to attempt interpretation regarding the deformation that took place under shallow (epizonal) conditions. The only reflector interpreted by these authors as the basal thrust of the Cantabrian Zone is horizontal and located at ca. 5 s (TWTT) and is related to the latest stages of deformation as it is responsible for the emplacement of the easternmost units of the Cantabrian Zone. Nevertheless, this horizontal reflector may have a long and complex history and may have played several roles throughout the course of Variscan history of the Narcea Tectonic Window. It could represent the lower decollement related to the early geologic history of the Narcea Tectonic Window that has been reactivated during subsequent deformation events. This interpretation will be further developed to build the tectonic model presented below.

The geometric and genetic relationships between deformation in the Narcea slates and the overlying Paleozoic sequence are key factors in unravelling the deformational history of the Narcea Tectonic Window, which is located along the foreland–hinterland boundary of the Variscan Belt of NW Spain. This deformational history can be seen in the sequential diagram of Fig. 8. The cross-section of Fig. 3 has been partially restored, as there is a domain without internal deformation (the Paleozoic rocks of the Cantabrian Zone, where accurate restoration is possible) and another two domains where restoration is tentative (the Narcea Tectonic Window and West Asturian–Leonese Zone). The resulting palinspastic restoration is used to illustrate the kinematic development in this area. This restoration assumes a complex piggy back sequence for the Cantabrian Zone based on Pérez-Estaún *et al.* (1991), who describe two superimposed thrusting sequences, and a superposition of structures in the West Asturian–Leonese Zone, as also stated by Marcos (1973). Sequential diagrams have proven very useful in understanding the kinematic evolution of complex fold and thrust belts (e.g. Alonso 1987).

The sequential diagram presented depicts, illustrates and summarizes the complex evolution of the Narcea Tectonic Window and its surrounding units. Stage A shows the initial restored configuration of the involved rocks. During the first stages of deformation in the West Asturian–Leonese Zone (B), the Narcea Slates of the Narcea Tectonic Window remained undisturbed while *D*1 folding and *D*2 ductile deeper shearing took place in the Narcea Slates in the West Asturian–Leonese Zone. Subsequently, the displacement of the West Asturian–Leonese Zone to the east transfers into two main detachment horizons, one located at the base of the Herrería Quartzite and another one deeper inside or below the Narcea slates (Stage C). It is during Stage C when shortening took place in the Narcea Slates by means of folding with vertical axes bounded by the two detachment horizons described, the fold axial plane traces (and therefore the axial cleavage foliation traces) are depicted as lines oblique to both detachments with diminishing spacing to the west, indicating the increase in finite strain towards the west. Note the tip line in the eastern limit of the detachment below the Narcea Slates. The location of this tip line is tentative and can be placed further east, but it serves to indicate that the decollement probably does not climb to upper levels through ramps as suggested by the lack of related culminations in the Cantabrian Zone that would indicate this. During Stage D the Trones thrust developed, transferring its displacement to a detachment below the Láncara Limestone that is responsible for the initial emplacement of the westernmost unit of the Cantabrian Zone, the Somiedo Nappe.

Stages E and F depict two thrusting sequences involving the Narcea Slates and the overlying Paleozoic rocks. While the previous decollement below the Láncara Limestone is re-activated during Stage E to transfer displacement from deeper thrusts, generating a duplex, the thrusts developed in Stage F were out-of-sequence and cut the decollements located at the base of the Láncara Limestone and the Herrería Quartzite with a breached geometry. In Stage G, the development of the La Espina thrust took place cutting all the previous thrust planes and decollements as an important out-of-sequence thrust. Stage H depicts the late faulting that gave rise to the present day configuration, including the formation of the Allande Normal Fault bounding the Narcea Antiform to the west. It is noteworthy that the minimum computed shortening depicted in this sequential diagram is ca. 75 km. (i.e. 62%).

CONCLUSIONS

This paper demonstrates that shortening can take place in the footwall below the sole thrust of a major thrust unit. This deformation takes place in a slip transfer zone, where internal deformation of the rocks is the result of accommodation of the displacements in two decollements located at two different depths. This deformation implies the formation of a deeper subsidiary blind sole thrust in the rearmost part of the foreland fold and thrust belt during its early stages of development. This observation has important implications for the understanding of the geometry and kinematics evolution of the limit between the foreland and the hinterland in the Variscan belt of NW Spain. Balanced cross-sections in areas undergoing thin-skinned deformation often assume that no deformation occurs in rocks beneath the considered sole thrust and may consequently underestimate the total amount of crustal shortening. Such deformation, however, must be taken into account when restoring or balancing cross-sections. The example of the Narcea Tectonic Window illustrates these ideas. The kinematic model presented explains the sequential development of structures found in the Narcea Tectonic Window and constrains the minimum shortening of this structure to 62%.

Acknowledgements—Helpful discussions with the structural geology groups in Oviedo and Salamanca Universities (Spain) and EGEO s.a. are greatly appreciated, especially F. Bastida, A. Pérez-Estaún, D.G.A.M. Aerden, J.R. Martínez-Catalán, L.M. Martín and P.Villar. I wish to thank G. Draper, M. Gross, and J. Longoria of Florida International University who corrected and discussed previous versions of the manuscript. Reviews from G. Axen, and S. Marshak, improved an earlier version of the manuscript. Additional comments by J.B. Silva and two anonymous referees have been of great help. This project was funded by the DGICYT, grants PB-90-0860-C03-02 and PB-93-1149 C03-02. Additional funding was provided by a research grant from the University of Salamanca.

REFERENCES

Alonso, J. L. 1987. Sequences of thrust and displacement transfer in the superposed duplexes of the Esla Nappe Region (Cantabrian Zone, NW Spain). *J. Struct. Geol.* 9, 969–983.

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

Alonso, J. L., Alvarez-Marrón, J. & Pulgar, J. A. 1989. Mapa geológico de la parte sudoccidental de la Zona Cantábrica. *Trabajos de Geología. Universidad de Oviedo* **18**, 127–135.

Aller, J., Bastida, F., Cabal, J. & Pérez-Esta, A. 1989. Geología del sector Cabo Vidio—San Juan de la Arena—Tineo (Zona Asturoccidental Leonesa, NO de España). *Trabajos de Geología. Universidad de Oviedo* **18**, 95–111.

Bastida, F. & Castro, S. 1988. Estructura del sector septentrional de la Escama de Tameza (Zona Cantábrica, NW de España). *Trabajos de Geología. Universidad de Oviedo* **17**, 67–85.

Bastida, F. & Gutiérrez-Alonso, G. 1989. Síntesis cartográfica de las unidades occidentales de la Zona Cantábrica. *Trabajos de Geología. Universidad de Oviedo* **18**, 117–125.

Bastida, F., Marcos, A., Pérez-Esta, A. & Pulgar, J. A. 1984. Geometría y evolución estructural del Manto de Somiedo (Zona Cantábrica, NO de España). *Boletín Instituto Geológico y Minero de España* **95**, 517–539.

Bosch, W. J. van den 1969. Geology of the Luna-Sil Region, Cantabrian Mountains (NW Spain). *Leidse Geologische Mededelingen* **44**, 137–255.

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.*

Durney, D. W. & Kisch, H. J. 1994. A field classification and intensity scale for first generation cleavages. *J. Austr. Geol. & Geophys.* **15**, 257–295.

Engelder, T. & Engelder, R. 1977. Fossil distortion and decollement tectonics of the Appalachian Plateau. *Geology* **5**, 457–460.

Fry, N. 1979. Random point distributions and strain measurements in rocks. *Tectonophysics* **60**, 806–807.

Geiser, A. 1988. The role of kinematics in the construction and analysis of geological cross-sections in deformed terranes. In *Geometries and mechanisms of thrusting with special reference to the Appalachians* (edited by Mitra, G. & Wotjal, S.). *Spec. Pap. geol. Soc. Am.* **222**, 47–76.

Gray, M. B. & Mitra, G. 1993. Migration of deformation fronts during progressive deformation: evidence from detailed structural studies in the Pennsylvania Anthracite region, U.S.A. *J. Struct. Geol.* **15**, 435–449.

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

Gutiérrez-Alonso, G. 1992. *El Antiforme del Narcea y su relación con los mantos occidentales de la Zona Cantábrica.* Unpublished PhD Thesis, University of Oviedo, Oviedo.

Gutiérrez-Alonso, G. & Nieto, F. 1996. White-mica 'crystallinity', finite strain and cleavage development across a large Variscan structure NW Spain. *J. geol. Soc. Lond.* **153**, 287–299.

Gutiérrez-Alonso, G., Villar, P. & Martín Parra, L. M. 1990. La estructura del Antiforme del Narcea. *Cuadernos del Laboratorio Xeoloxico de Laxe* **15**, 271–279.

Heredia, N. 1984. La estructura de la escama de Villar de Vildas (Manto de Somiedo, Zona Cantábrica). *Trabajos de Geología. Universidad de Oviedo* **14**, 65–78.

Hirt, A. M., Lowrie, W., Julivert, M. & Arboleya, M. L. 1992. Paleomagnetic results in support of a model for the origin of the Asturian Arc. *Tectonophysics* **213**, 321–339.

Jordan, P. & Noack, T., 1992. Hangingwall geometry of overthrusts emanating from ductile decollements. In *Thrust Tectonics* (edited by McClay, K. R.) Chapman-Hall, 311–318.

Julivert, M. 1971. Decollement tectonics in the Hercynian Cordillera of NW Spain. *Am. J. Sci.* **270**, 1–29.

Julivert, M. & Arboleya, M. L. 1984. A geometrical and kinematical approach to the nappe structure in an arcuate fold belt: the Cantabrian nappes (Hercynian chain, NW Spain). *J. Struct. Geol.* **6**, 499–519.

Julivert, M. & Arboleya, M. L. 1986. Aereal balancing and estimate of aerial reduction in a thin skinned fold and thrust belt (Cantabrian Zone, NW Spain): constraints on its emplacement mechanisms. *J. Struct. Geol.* **8**, 407–414.

Julivert, M. & Marcos, A. 1973. Superimposed folding under flexural conditions in the Cantabrian zone (Hercynian Cordillera, NW Spain). *Am. J. Sci.* **273**, 353–375.

Julivert, M., Marcos, A. & Pulgar, J. A. 1977. Mapa Geológico de España E 1:50000 2^a Serie, Hoja N° 27 (Belmonte de Miranda). *Instituto Geológico y Minero de España.*

Julivert, M. & Matínez-García, E. 1967. Sobre el contacto entre el Cámbrico y el Precámbrico en la parte meridional de la cordillera Cantábrica y el papel del Precámbrico en la orogénesis Herciniana. *Acta Geol. Hispánica* **2**, 107–110.

Julivert, M., Pello, J. & Fernandez, L. 1968. La estructura del Manto de Somiedo (Cordillera Cantábrica). *Trabajos de Geología. Universidad de Oviedo* **2**, 1–43.

Kraig, D. H., Wiltschko, D. V. & Spang, J. H. 1987. Interaction of basement uplift and thin-skinned thrusting, Moxa Arch and the Western Overthrust Belt, Wyoming: a hypothesis. *Bull. geol. Soc. Am.* **99**, 654–662.

Kulander, B. R. & Dean, S. L. 1988. The North Mountain–Pulaski fault system and related thrust sheet structure. In *Geometries and Mechanics of Thrusting* (edited by Mitra, G. & Wotjal, S.) *Spec. Pap. geol. Soc. Am.* **222**, 107–118.

Lotze, F. 1956, Das Präkambrium Spaniens. *N. Jb. F. Geol. Palläont. Min.* **8**, 377–380.

Marcos, A. 1968. La tectónica de la unidad de La Sobia-Bodón.*Trabajos de Geología. Universidad de Oviedo,* **2**, 59-81.

Marcos, A. 1973. Las series del Paleozoico inferior y la estructura herciniana del occidente de Asturias (NW de España). *Trabajos de Geología. Universidad de Oviedo* **6**, 3–113.

Marcos, A. & Pulgar, J. A. 1982. An approach to the tectonostratigraphic evolution of the Cantabrian foreland thrust and fold belt, Hercynian Cordillera of NW Spain. *Neues Jahrb. Geol. Palaeontol., Abh.* **163**, 256–260.

Marshak, S. 1986. Structure and tectonics of the Hudson Valley fold–thrust belt, eastern New York State. *Bull. geol. Soc. Am.* **97**, 354–368.

Matte, Ph. 1968. La structure de la virgation Hercynienne de Galice (Espagne). *Rev. Geol. Alpine* **44**, 1–128.

Martínez Catalán, J. R. 1985. Estratigrafía y estructura del domo de Lugo (Sector Oeste de la zona Austuroccidental–Peonesa). *Corpus Geologicum Gallaeciae,* **2**, 1–291.

Parés, J. M., Van der Voo, R., Stamatakos, J. & Pérez-Esta, A. 1994. Remagnetization and postfolding oroclinal rotations in the Cantabrian/Asturian arc, Northern Spain. *Tectonics* **13**, 1461–1471.

Pérez-Estaún, A. 1971. La ventana tectónica de Villabandín (Antiforme del Narcea, León). *Breviora Geológica Astúrica,* **XV**, 7–13.

Pérez-Estaún, A. 1978. Estratigrafía y estructura de la rama Sur de la Zona Asturoccidental–Leonesa., *Memorias Instituto Geológico y Minero de España,* 92.

Pérez-Estaún, A. & Bastida, F. 1990. Cantabrian Zone, Structure. In *Pre-Mesozoic Geology of Iberia* (edited by Dallmeyer, R. D. & Martínez-García, E.) Springer-Verlag, Berlin, 55–68.

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

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

Pérez-Estaún, A., Martínez-Catal, J. R. & Bastida, F. 1991. Crustal thickening and deformation sequence in the footwall to the suture of the Variscan belt of northwest Spain. *Tectonophysics* **191**, 243–253.

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

Rykkelyd, E. & Fossen, H. 1992. Composite fabrics in mid-crustal gneisses: observations from the Øygarden Complex, West Norway Caledonides. *J. Struct. Geol.* **14**, 1–9.

Stewart, S. A. 1995. Paleomagnetic analysis of fold kinematics and implications for geological models of the Cantabrian/Asturian arc, North Spain. *J. geophys. Res.* **100**, 20079–20094.

Suárez, A., Heredia, N., López, F., Toyoc, J. M., Rodríguez Fernández, L. R. & Gutiérrez Alonso, G. 1990. Mapa Geológico de España 1:50000, 2ª serie, N° 102 (Barrios de Luna). *Instituto Tecnológico Geominero de España.*

Tobisch, T. T. & Paterson, S. R. 1988. Analysis and interpretation of composite foliations in areas of progressive deformation. *J. Struct. Geol.* **10**, 745–754.

Williams, F. 1985. Multiply deformed terrains—problems of correlation. *J. Struct. Geol.* 7, 269–280.