Journal of the Geological Society, London, Vol. **153**, 1996, pp. 287–299, 8 figs. 1 table. Printed in Northern Ireland

White-mica 'crystallinity', finite strain and cleavage development across a large Variscan structure, NW Spain

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Abstract: X-ray diffraction analyses were performed on white-micas, formed under strain and low-grade metamorphic conditions, from sandstones and siltstones along a transect through the Narcea Antiform, a large structure that separates the external from the internal zones of the Variscan belt of NW Spain. The results indicate a close spatial relationship between the onset of metamorphism and the cleavage front. At the cleavage front, strain is characterized by oblate ellipsoids that have $x = y{:}z$ ratios from 1 to 1.5. The $x = y{:}z$ ratio increases westward (up to 3.0), as does the grade of metamorphism, and is accompanied by an increase in the 'crystallinity' index of the white-mica from very low to low metamorphic grade. This increase corresponds qualitatively to an increase in penetrativeness of the axial planar cleavage. In the western part of the Narcea Antiform, the major deformation event was the development of kilometre-scale, reverse shear zones. Because of polyphase deformation, these rocks are not suitable for quantitative strain analysis, but qualitatively, finite strain can be observed to be prolate and invariably larger in this region than in the eastern sector. The metamorphic grade is higher in the western part of the Narcea Antiform, with local maxima occurring next to the base of the shear zones. The b_0 cell parameter, a semi-quantitative geobarometer measured in the white-mica, is chaotic in the Eastern sector, showing a clear detrital inheritance. In the western sector it is rational due to complete re-equilibration during thermal resetting. The inverse correlation between finite strain and white-mica 'crystallinity' is close, showing that the anchizone-epizone limit can be related to the increase of finite strain above values of $R_s = 1.5$. The close relation between white-mica 'crystallinity' and strain is suitable for tracking strain variations in extensive fine-grained siliciclastic rocks where no appropiate strain markers are found.

Keywords: white-mica, crystallinity, structural geology, strain, cleavage.

One of the most common problems in areas characterized by the onset of metamorphism and finite strain is establishing a direct measurable relation between these two parameters and with features directly observable in the rocks, such as cleavage intensity. The relations between finite strain, metamorphic grade and cleavage development are described in the Narcea antiform, NW Spain, a structure where wide ranges of these parameters can be found.

Most orogens exhibit extensive belts of low-grade metamorphic rocks. These belts are difficult to characterize, because of the major differences that usually occur in metamorphic thermobaric conditions, structural style and deformation mechanisms. Illite or white-mica 'crystallinity' analysis is a powerful and widespread tool for the study of low grade metamorphic belts within orogens in the absence of reliable indicator minerals where no mafic rocks crop out. It is common to find extensive areas where the representative paragenesis is white-mica + chlorite + quartz ± feldspar ± carbonates. This paragenesis covers a wide range of thermobaric conditions within the categories of very low-grade and low grade metamorphism, that is to say from advanced diagenesis to the entry of biotite. The crystallochemical parameters of white-mica have been widely and successfully used to constrain better such pressure and temperature conditions.

Another common feature of low-grade metamorphic belts is an abrupt change in the deformation style and mechanisms associated with extensive basement outcrops. In some of these belts the change from a thin-skinned deformation style, lacking cleavage development, to a syn-metamorphic deformation where cleavage is a widespread pervasive structure, is marked by large overthrusts with dozens of kilometers of displacement accompanied by highly strained rocks. The cleavage front is normally situated in the foreland, where some of the sedimentary rocks have developed a tectonic fabric. Some phyllosilicates will have grown in a preferred orientation, leading to fabrics of progressive penetrativeness.

The relation of white-mica 'crystallinity' with large structures in low grade metamorphic belts has been established in several areas (Venn anticline, Kasig & Späth 1975; Frank & Späth 1991; Central Alps, Frey *et al.* 1980; Moroccan meseta, Piqué 1982; Pennant anticline, Roberts & Merriman 1985; North Hill End Synclinorium, Offeler & Pendergast 1985; Welsh Basin, Bevins & Robinson 1988, Roberts *et al.* 1989; Lesser Himalaya, Johnson & Oliver 1990), but not for such a large-scale orogenic boundary as the foreland-hinterland transition. Donahoe *et al.* (1989) report changes in the metamorphic grade from very low to low in the foreland-hinterland transition in the southern Appalachian chain without precisely defining the nature of these changes.

The very low to low-grade metamorphism transition in the Variscan belt of Northwest Spain is located in the

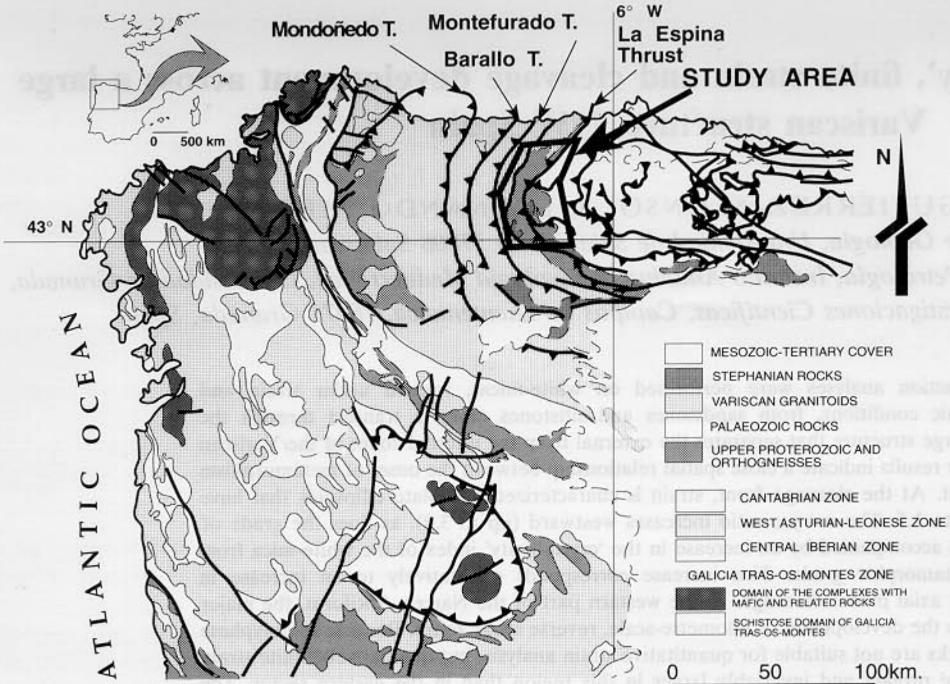

Fig. 1. Geological sketch map of northwestern Spain with location of major paleogeographic units and the study area. T, Thrust. After Lotze (1954), Julivert *et al.* (1972), Martínez-Catalán (1985), Farias *et al.* (1987), Martínez-Catalán *et al.* (1992).

boundary between the foreland, the Cantabrian zone, and the hinterland, the West Asturian–Leonese zone (Fig. 1). The foreland–hinterland transition is marked by the presence of a structurally complex, antiformal stack called the Narcea antiform (Julivert 1971). White-mica 'crystallinity' in the Narcea antiform and its surroundings, was studied in part by Pérez-Estaún (1973, 1978), Martín Parra & Bardají (1989), and Brime & Pérez-Estaún (1980) who studied the southern branch of the Narcea antiform and the Cape Peñas area to the north, respectively searching for metamorphic changes related to the 'cleavage front'. Other publications related to white-mica 'crystallinity' in the Cantabrian zone are those of Aller & Brime (1983), Aller *et al.* (1987), Brime (1981) and Blenkinsop (1987). The paper by Aller *et al.* (1987) is of special interest, as it reuses data from Pérez-Estaún (1973, 1978), Brime & Pérez-Estaún (1980), Brime (1981) and Aller & Brime (1983), to interpret data as a function of cleavage development or burial by thrusting. The only works in the West Asturian–Leonese zone are those of Blenkinsop (1987), Brime (1985) and Yenes *et al.* (1990), the latter assuming the Sierra de la Demanda Precambrian and Palaeozoic outcrops to be part of the West Asturian–Leonese zone.

For the following reasons, the Narcea antiform is a structure suitable for studying the relationships between strain and 'crystallinity' and using the results to constrain the conditions under which the deformation took place.

(1) It constitutes a major structural and palaeogeographic boundary in the Variscan belt of NW Spain (Lotze 1945; Julivert *et al.* 1972).

(2) It consists of a well-known antiformal structure and two large thrust units, composed of a stack of several slices showing variable strain (Julivert & Pello 1967; Matte 1968; Julivert 1971; Marcos 1973, Gutiérrez-Alonso *et al.* 1990; Gutiérrez-Alonso 1992).

(3) Lithologies include laterally persistent, homogeneous siliciclastic rocks, suitable for both strain and white-mica 'crystallinity' determinations.

(4) There are great differences of deformation intensity and deformation superposition along the chosen cross section, providing a wide range of contingencies to test correlations under different conditions.

(5) The amount of strain is well established over much of the area. (Gutiérrez-Alonso 1992.)

The aim of this paper is to report a detailed study of the white-mica 'crystallinity' across a large structure where important structural changes take place, and compare the results with finite strain values and the intensity of cleavage development.

Geological setting

The Narcea antiform crops out in the Cantabrian Mountains, in northwest Spain. It shows an arcuate trend along a more than 70 km long exposure (Fig. 1). It is composed of terrigenous sedimentary rocks with turbiditic facies of the Upper Proterozoic Narcea Slates, unconformably overlain by shallow-water Cambrian deposits comprising the Cándana–Herrería Quartzite and the Láncara–Vegadeo Limestone. Above these formations the Middle Cambrian to Lower Ordovician Oville and Barrios Formations occur in the Cantabrian zone, while the Cabos Series occurs in the West Asturian–Leonese zone (Figs 1 & 2).

For the geological description, two areas have to be clearly differentiated at the Narcea antiform. These two areas are separated by the La Espina thrust (Figs 1 & 2), which superimposes (1) the most strained and metamorphosed West Asturian–Leonese zone (hinterland or internal zones), over (2) the commonly non-metamorphic, thrust-and-fold-belt style, Cantabrian zone (foreland or external zone), from west to east. The basis of the difference between these two zones is the palaeogeography during early Palaeozoic times and the characteristics of the Variscan deformation and metamorphism. Relevant literature on the structure and regional significance of this area can be found in the following papers: Marcos (1973), Bastida *et al.* (1984), Pérez-Estaún & Bastida (1990); Martínez-Catalán *et al.* (1990); Gutiérrez-Alonso (1987, 1992); Aller *et al.* (1989); Gutiérrez-Alonso & Villar (1989) and Gutiérrez-Alonso *et al.* (1990) and Pérez-Estaún *et al.* (1991, 1994).

Metamorphism is low grade, chlorite zone (Martínez-Catalán *et al.* 1990; Alonso *et al.* 1991). In some cases biotite has been recognized, but it is probably related to late Variscan granite intrusions and associated contact metamorphism. The metamorphic conditions during the entire geological history of these rocks never exceeded greenschist facies. The most common parageneses recognized optically are quartz + white-mica + chlorite ± K-feldspar in the West Asturian–Leonese zone and quartz + white-mica + chlorite in the Cantabrian zone.

Materials and methods

The analysis and interpretation of crystallochemical, metamorphic white-mica parameters: 'crystallinity', b_0 cell parameter and basal spacing ($d(002)$)—by means of X-ray diffraction (XRD) allows, under ideal circumstances, the determination of metamorphic grade in low temperature rocks. When applied to the Narcea antiform, in conjuction with data from other methods and sources, the temperatures and pressures which pertained when the major Variscan structures developed may be deduced.

The main factors thought to control variations of the three white-mica crystallochemical parameters are: temperature (Schaer & Persoz 1976; Blenkinsop 1987), lithology (Kubler 1968; Dunoyer de Segonzac 1970; Blenkinsop 1987) and deformation. The relationship between white-mica 'crystallinity' and degree of deformation is clear at a regional scale, particularly in areas where there is the transition from anchizone to epizone and where there is progressive development of cleavage (Teichmüller & Teichmüller 1979; Piqué 1982; Kemp *et al.* 1985; Primmer 1985; Roberts & Merriman 1985; Aller *et al.* 1987). Especially interesting is the extensive review carried out by Kisch (1991*a*), integrating data from a large number of publications and summarizing some relations between parameters in the lower and middle anchizone, and illustrating the need for more studies in areas where the onset of metamorphism and cleavage development takes place. We examined white-mica 'crystallinity' in 26 samples of the Narcea Slates, from both the Cantabrian zone (18 samples) and the West Asturian–Leonese zone (8 samples), and 5 samples from the lower Palaeozoic Candana Quartzite and Los Cabos Series. Samples were chosen on the basis of uniform grain size and composition. All of them were dark greenish gray siltstones or fine grained sandstones, except for some of the phyllonites (mylonitized siliciclastic rocks, with an intense tectonic grainsize reduction, composed mostly of phyllosilicates) sampled in the West Asturian–Leonese zone.

Sampling was carried out as close as possible to a line that transects completely the Narcea antiform, where a representative geological cross-section has been constructed by projecting plunging structures into the cross-section. The sample collection has avoided areas where there is evidence of post-deformational heating. This procedure allows the complete visualization of large structures and the projection of analytical or numerical data in the geological cross section, so facilitating interpretation of the data.

Sample preparation and determination of white-mica 'crystallinity' values were performed as recomended by the IGCP 294 IC working group (Kisch 1991*b*). The XRD analysis of illite 'crystallinity' were made on whole-rock and $<2\,\mu$m oriented aggregates using a Phillips PW 1710 X-ray diffractometer equipped with a graphite monochromator and automatic divergence slit. Cu$K\alpha$ radiation was used. Each sample was step-scanned with measurement of peak widths using computer-stored data. The measured index is the Kubler Index, which is better suited for regional studies than the Weaver Index (Donahoe *et al.* 1989).

Several efforts have been made to standardize and correlate 'crystallinity' indices from different laboratories and to define the anchizone-epizone boundary (Blenkinsop 1988; Kisch 1990, 1991b). The most recent attempt was that of Warr & Rice (1994). These authors recomend the transformation of the data obtained at any laboratory to internationally comparable data (CIS data) by means of an equation obtained using international standards. Our data (y) were transformed to illite 'crystallinity' values (x) using a formula ($y = 0.674x + 0.052$) obtained with the interlaboratory standards provided by the forementioned authors.

The XRD analyses were performed on both whole-rock and $<2\,\mu$m fraction in order to measure the effect of metamorphism on detrital white-mica. The b_0 cell parameter of white-mica and chlorite was measured using a polished slice of rock, cut perpendicular to foliation to avoid interference from peaks other than (060) (Sassi & Scolari 1974; Guidotti & Sassi 1986; Frey 1987). The quartz peak at 59.96°2θ was used as an internal standard. Spacing was measured by difference with the quartz peak using computer stored data obtained at low scan-speed.

The use of finite strain measurement techniques permits a quantitative or semi quantitative approach to the intensity or penetrativeness of cleavage that is related to the finite strain. Cleavage develops perpendicular to the shortest axis (z-direction) of the strain ellipsoid and increases in intensity with the R_{xz} or R_{yz} strain ratio (see Ramsay & Huber 1983, p. 181, for a detailed list of publications).

To avoid the effect of strain variation in the hinges, samples for strain analysis were always collected from fold limbs. The strain measurements were made in samples of sandstones interbedded in the Narcea Slates, with no evidence of superimposed deformation, restricting the measurements to the Cantabrian zone. A total of eighteen samples was measured as close as possible to the cross-section trace, at sample locations indicated in Fig. 2. Two measurements were made at each locality in order to obtain three-dimensional finite strain values. Samples were oriented normal to foliation, one being normal to, and the other parallel to the intersection lineation S_0/S_1. Strain data were compiled from Gutiérrez-Alonso (1992). Axial ratios were determined in three dimensions using the Fry (1979) method on sandstone thin sections. Determinations were done over 90 to 100 centres of grains per section. Three dimensional analysis yielded oblate ellipsoids ($1 > k \geq 0$, Flinn 1965), with the xy plane ($z < y \leq x$), contained in the cleavage plane (i.e. Z normal to the cleavage plane). The R_s obtained is the mean value between R_{xz} and R_{yz} which in most cases are coincident or showing small differences up to 0.1.

XRD Results

The same minerals are present, in varying proportions, in both whole-rock and $<2\,\mu$m fractions. The ubiquitous mineral assemblage is quartz + white-mica (with a phengitic component) + chlorite + albite + K feldspar. This association is found in both, the Cantabrian zone and the West Asturian–Leonese zone. This homogeneity allows the comparison of parameters obtained by X-ray diffraction. In only one sample (Sample 4), situated in the easternmost part of the cross section, was a small amount of pyrophyllite found, which is coherent with the metamorphic grade obtained from illite 'crystallinity' values. It indicates a sample with a higher aluminum content, which allowed the formation of this mineral.

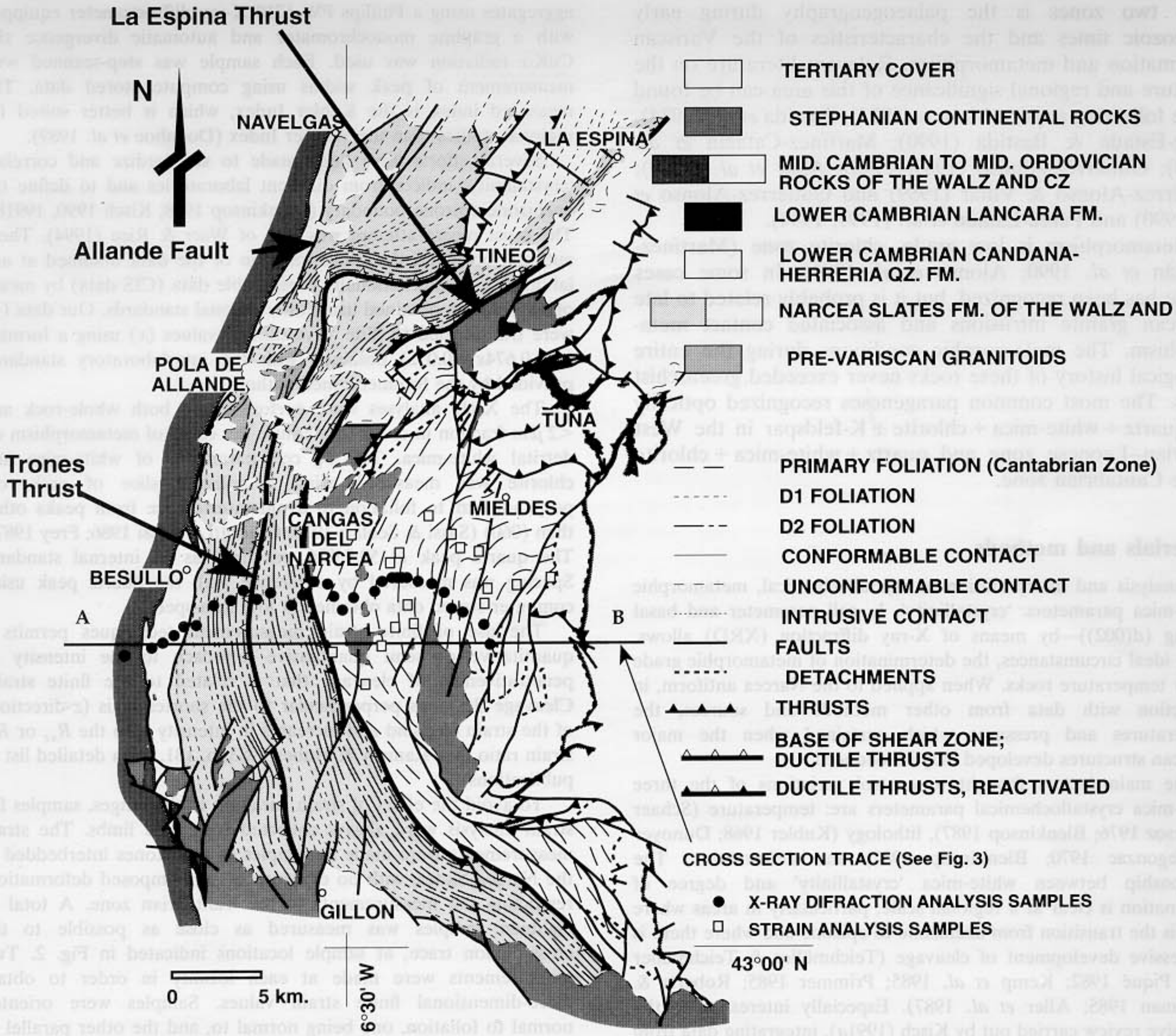

Fig. 2. Geological and sample map of the Narcea antiform showing sampling points. Based on Marcos (1973), Julivert *et al.* (1977*a, b*), Bastida *et al.* (1980) Marcos *et al.* (1980), Marcos & Pulgar (1980), Crespo Zamorano (1982), Gutiérrez-Alonso (1987), Gutiérrez-Alonso & Villar (1989), Aller *et al.* (1989), Bastida & Gutiérrez-Alonso (1989), Gutiérrez-Alonso *et al.* (1990), Alonso *et al.* (1991), and Gutiérrez-Alonso (1992). WALZ, West Asturian–Leonese zone; CZ, Cantabrian zone.

Chlorite is present in all samples. It increases in abundance from the east, where it is scarce, to the west. In the Cantabrian zone, chlorite is hard to distinguish optically due to its small size. In the West Asturian–Leonese zone, small neoformed grains of chlorite parallel to foliation are common in the matrix of some of the rocks. In addition, large chlorite–white-mica aggregates or stacks are common, oblique to foliation, and showing a bluish interference colour. Most of them are kinked, and some examples show pressure shadows, indicating a detrital or pre- or early-kinematic origin. Similar chlorite-mica stacks were studied by Li *et al.* (1994) in an anchizone-grade mudrock from Wales. They concluded that they were large detrital biotite grains subsequently modified during the progression from diagenesis to low-grade metamorphism.

XRD $d(001)$ and b_0 cell parameters, measured in the chlorites are shown in Table 1. These parameters are related to Al and Fe contents respectively, (Albee 1962; Nieto & Rodriguez-Gallego 1983; Brindley 1961), the amounts of which can be calculated from the formulae proposed by Albee (1962) (Table 1). Both the Al content, which ranges from 2.64 to 2.21 afu (atoms per formula unit) and the Fe content, from 2.78 to 1.22, are typical values in metamorphic chlorites of pelitic rocks (e.g. Albee 1962; Lopez-Munguira *et al.* 1991; Laird 1988). The Fe/Fe+Mg ratio, the most highly variable chemical parameter in chlorites, is principally controlled by the composition of the system, particularly in rocks such as those studied here, in which chlorite is the only important ferromagnesian mineral of the paragenesis (e.g. Kawachi 1975; Velde & Medhioub 1988; Cathelineau & Nieva 1985). It is remarkable that except for variations in abundance there are no significant differences in the chlorite composition between the three different described domains (Table 1).

Table 1. *Crystallochemical parameters of the Narcea Slates samples*

	White mica				Chlorite							
	Crystallinity index Warr & Rice (1994)		b_0 cp	d(002)	b_0 cp	d(001)			WR		<2 μm F	
Samples	<2 μm F	W. R.				W R	<2 μm F	Fe*	Al vi†	Al iv†	Al vi†	Al iv†
Data from the WALZ Palaeozoic rocks												
12	0.31	0.23	9.024	9.979	9.3130	14.14	14.15	2.78	1.16	1.55	1.13	1.52
13	0.19	0.15	9.036	9.961	9.2520		14.21	1.14			1.03	1.19
14	0.15	0.19	9.020	9.982	9.2850		14.17	2.03			1.11	1.39
15	0.22	0.20	9.030	9.976	9.3030	14.17	14.20	2.51	1.07	1.43	0.97	1.32
16	0.19	0.20	9.024	9.975	9.2850	14.16	14.19	2.03	1.14	1.43	1.04	1.32
Mean	0.21	0.20	9.027	9.975	9.2876	14.16	14.18	2.10	1.13	1.47	1.05	1.35
σ	0.06	0.03	0.006	0.008	0.0233	0.02	0.02					
Data from the WALZ Precambrian rocks												
17	0.13	0.18	9.029	9.971	9.2990		14.16	2.41			1.12	1.45
18	0.16	0.19	9.026	9.975			14.19					
19	0.15	0.18	9.023	9.982								
20	0.20	0.20	9.023	9.978								
21	0.22	0.23	9.019	9.984	9.2550	14.19	14.18	1.22	1.09	1.26	1.13	1.30
22	0.19	0.20	9.027	9.978		14.17	14.20					
23	0.16	0.16	9.023	9.971	9.2850	14.16	14.16	2.03	1.14	1.43	1.14	1.43
11	0.28	0.22	9.020	9.985	9.2990	14.15	14.14	2.41	1.15	1.49	1.19	1.53
Mean	0.19	0.20	9.024	9.978	9.2845	14.17	14.17	2.01	1.13	1.39	1.14	1.43
σ	0.05	0.03	0.003	0.005	0.0207	0.02	0.02					
Data from CZ Precambrian rocks												
10	0.31	0.29	9.023	9.977								
9	0.22	0.22	9.031	9.966	9.2960	14.18	14.18	2.32	1.05	1.38	1.05	1.38
8	0.22	0.22	9.021	9.967	9.2810	14.15	14.15	1.92	1.19	1.46	1.19	1.46
7	0.26	0.20	9.041	9.961	9.3100	14.15	14.15	2.70	1.13	1.51	1.13	1.51
6	0.28	0.22	9.035	9.966		14.19						
31	0.22	0.25	9.016	9.971	9.2880	14.16	14.18	2.11	1.14	1.43	1.07	1.36
30	0.22	0.19	9.022	9.982	9.2600	14.19	14.15	1.35	1.08	1.27	1.23	1.42
29	0.22	0.20	9.015	9.982	9.2800	14.15	14.15	1.89	1.19	1.45	1.19	1.45
28	0.25	0.22	9.028	9.967								
27	0.22	0.18				14.15	14.15					
26	0.19	0.12	9.036	9.956	9.2990		14.15	2.41			1.15	1.49
25	0.25	0.19	9.039	9.961	9.2930	14.18	14.18	2.24	1.06	1.37	1.06	1.37
24	0.29	0.28				14.15						
5	0.28	0.22			9.2850			2.03				
4	0.29	0.28	9.034	9.954								
3	0.31	0.25	9.037	9.978								
2	0.34	0.28	9.036	9.974								
1	0.40	0.34	9.027	9.968								
Mean	0.26	0.23	9.029	9.969	9.2880	14.17	14.16	2.11	1.12	1.41	1.13	1.43
σ	0.05	0.05	0.008	0.009	0.0141	0.02	0.01					

* Brindley, (1961).
† Albee (1962). Nieto & Rodriguez-Gallego (1983).
WR, Whole rock; cp, cell parameter; 2μmF, 2 μm fraction. WALZ, West Asturian–Leonese Zone; CZ, Cantabrin Zone.

White-mica is a common and widespread mineral in all the studied samples. In the Cantabrian zone, large detrital white-micas are observed as well as small metamorphic ones, arranged parallel to the foliation. The detrital micas are usually oblique to foliation and no evidence of mechanical rotation of phyllosilicates can be found, as stated by Aller *et al.* (1987) although some large white-mica grains are folded locally. In the West Asturian–Leonese sector of the Narcea antiform, white-mica is more abundant, crystals are larger and oblique detrital grains are sparse. Where crenulation and crenulation cleavages occur, two sets of metamorphic white-mica occur, the first related to an earlier deformation phase and the second to a later phase. Sampling in the areas with well-developed crenulation cleavage has been avoided in order to clarify data and ease the possible interpretation.

All the relevant results related to white-mica XRD analysis are shown in Fig. 3. Relations among them are shown and related to the structures within the cross section. The numerical values of white-mica illite 'crystallinity' values (IC), b_0 cell parameter and $d(002)$ ($\approx$10 Å) values are shown in Table 1. The illite 'crystallinity' values range from anchizone (0.40) to epizonal (0.13) values (the limit is set at 0.25) showing a wide variability along the 22 km cross-section. Figure 3 depicts a clear trend in the illite 'crystallinity' values decreasing from east to west, indicating an increase in metamorphic grade in this direction, consistent with the regional geology. This trend can be noticed in results both the whole-rock and the <2 μm fraction. The <2 μm fraction values give higher IC values in the Cantabrian zone and the Palaeozoic rocks of the West Asturian–Leonese zone than the whole-rock values and very close or lower in the West Asturian–Leonese zone sector of the Narcea antiform.

As expected from the optical and mineralogical observations of the studied rocks there are several diferences in the IC values distribution in the three defined previously domains. In the Cantabrian zone the decreasing trend towards the west is clear, reaching the epizone aproximately in the middle of the Cantabrian zone outcrop. According to the <2 μm fraction data, IC values tend to stabilize around 0.22 with the exception of two samples situated near a minor thrust and the sample from the boundary with the West Asturian–Leonese zone. These will be considered separately.

In the West Asturian–Leonese zone sector of the Narcea Slates, a jigsaw pattern can be outlined and corresponds to a decrease in metamorphic conditions from the base of the two thrust sheets towards the top. Close to the base of the shear zones, illite 'crystallinity' values reach 0.14–0.16, while in sectors where no shear related deformation is observed, illite 'crystallinity' values remain higher, indicating a lower metamorphic grade. Within the Palaeozoic rocks of the West Asturian–Leonese zone, illite 'crystallinity' values become chaotic and no interpretation is possible as there are too few samples.

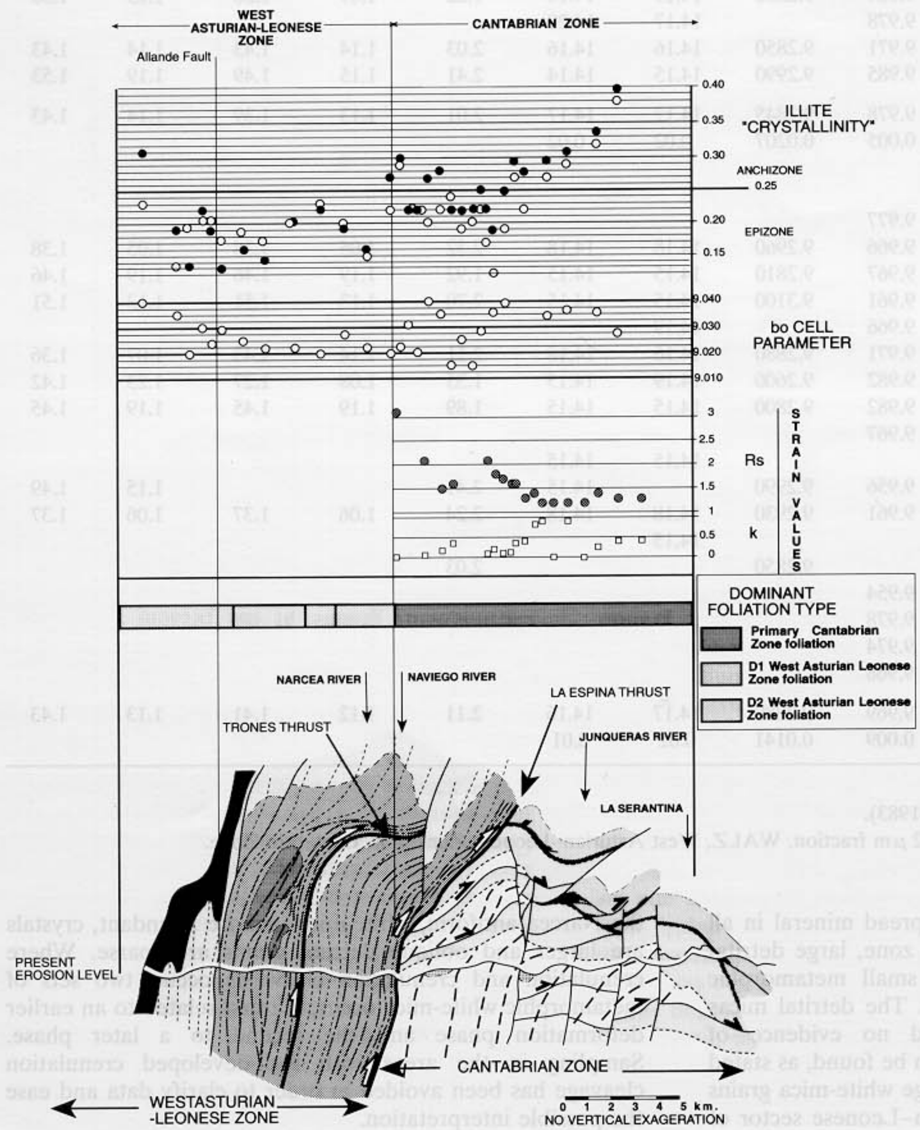

Fig. 3. Results of white mica XRD crystallochemistry, strain analysis and dominant foliation types, plotted along the cross section of the Narcea antiform. Black dots: <2 μm fraction illite 'crystallinity' analysis. White dots: Whole-rock illite 'crystallinity' values and b_0 cell parameter analysis. The different domains described in the text are indicated. Cross-section of the Narcea antiform. No vertical exageration. Legend for the cross section as in Fig. 2.

The two samples in the boundary zone between the Cantabrian zone and the West Asturian–Leonese zone yield unusually high IC values. This is interpreted as the result of late fluid interaction and supergenic alteration, associated with fluid circulation along a fault system of complex movement history including reactivation of main thrust surfaces during Late Variscan and even Alpine movements. Even if smectite has not been detected by XRD in these samples, some individual swelling layers not able to produce XRD coherent domains could be present and be responsible for an increase in the IC, as described by high resolution transmision electron microscopy (e.g. Jiang *et al.* 1990; Nieto *et al.* 1995).

Another important parameter measured in the white-mica is the b_0 cell parameter, which is related to barometric conditions of the white-mica bearing rocks, providing that the samples are homogeneous in composition. This parameter is measured using rock slabs cut normal to foliation. Thus, this parameter, under some circumstances, may reflect average values between detrital and recrystallized white-mica. The values obtained range from 9.015 to 9.041 indicating, intermediate pressure conditions according to Guidotti & Sassi (1986). An important feature of the data is the distribution of this parameter across the studied area. Figure 3 shows that the values of the b_0 cell parameter measured in the Cantabrian zone are highly variable, containing both the maximum and minimum values. This may indicate a large variation in pressure conditions. More probably, because whole-rock slabs were used for analysis, the b_0 cell parameter may reflect the presence of detrital white-mica. In the Narcea slates of the West Asturian–Leonese sector, this parameter is homogeneous, ranging from 9.019 to 9.029, with an average value of 9.024 and a standard deviation of 0.003, revealing that there is no influence of detrital white-mica and white-mica is re-equilibrated in these intermediate-pressure conditions. The limited number of samples from the Palaeozoic rocks of the Narcea antiform precludes interpretation. Additionally, there exists a general coincidence between areas where the white-mica 'crystallinity' shows larger values for the $<2\mu m$ fraction than for the whole-rock samples and those where the b_0 cell parameter gives chaotic and highly variable values. In contrast, in the Narcea Slates of the West Asturian–Leonese sector there is no difference between 'crystallinity' indices of both fractions and the b_0 cell parameter shows small variation. Padan *et al.* (1982) considered the possibilities of application of the b_0 cell parameter to subgreenschist facies terrains. And they postulated that the usual application of this parameter in greenschist facies rocks may be expanded to very low grade metamorphic or diagenetic rocks only if mica has been completely re-equilibrated, which it is limited by the persistence of detrital micas. Our results confirm this.

The distribution of b_0 cell parameter values accross the studied area sugests that this value is influenced by different factors in the Cantabrian and in the West Asturian–Leonese zones and therefore represents different processes. We interpret the b_0 cell parameter values in the Cantabrian zone to be mostly inherited from the detrital mica. This explains the random pattern, and probably indicates a structurally and metamorphically complex, predominantly of volcanic origin (Choutier & Guillou 1988), source area for the Narcea Slates. The higher grade metamorphic conditions undergone by the Narcea Slates in the West Asturian–Leonese zone have obliterated the detrital imprint, homogenizing the white-mica chemistry and allowing the use of this parameter in this sector as a true semi-quantitive geobarometer.

The basal spacing in white-mica $d(002)$ is in principle related to the paragonitic substitution of Na by K in the interlayers, thus reflecting the aproximate temperature of formation. However the phengite content is able to modify the $d(002)$ parameter (Guidotti 1984, figs 14 and 16). The values of this parameter in the Narcea Antiform samples range from 9.961 to 9.985, with no special features observed in their distribution across the area. The relation with b_0 cell parameter values (Fig. 4) indicates that it is controlled by the phengite substitution. Some of these white-micas have low values of Na (Gil Ibarguchi, pers. com.), and the paragonite value is very low. In such a case the influence on $d(002)$ of the phengite relative to the paragonite substitution should be quantitatively significant. The close relation with b_0 cell parameter values (Fig. 4) indicates that the phengitic component is responsible for their small differences, precluding the use of this parameter as a geothermometer. The usual presence of metamorphic albite as a constituent of mineral parageneses in pelitic rocks of this area is taken to be responsible for the generally very low contents of Na in the white-micas.

Finite strain determinations and cleavage description

Finite strain analysis is possible only in the Cantabrian zone rocks because here the Narcea Slates have undergone a single stage of internal deformation and foliation generation.

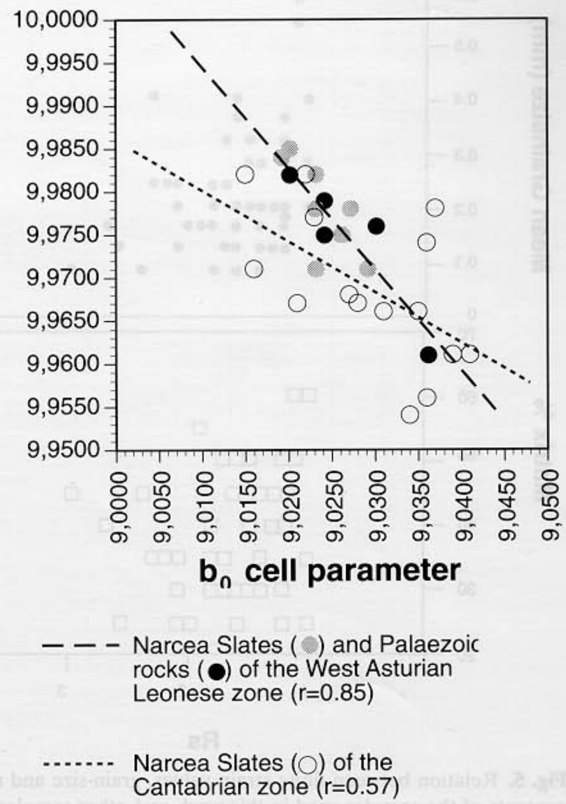

Fig. 4. $d(002)/b_0$ cell parameter plot, with regression lines in the different sectors considered and in the whole region.

The use of finite strain analysis in the West Asturian–Leonese zone would yield results difficult to interpret because of the superposition of deformation events.

Studies of outcrop-scale folds, (Gruner 1976; Flehmig & Langheinrich 1974; Nyk 1985; Fernández Caliani & Galán 1992, among others), have attempted to correlate deformation and white-mica 'crystallinity'. However, they assume erroneously that deformation is greater in the hinges than in the limbs. The most important mechanisms of folding of single beds are flexural folding and tangential longitudinal strain. Slate beds typically fold by flexural folding, particularly flexural flow, where high finite strain is concentrated in the limbs rather than in the hinge. In the event that folding occurs under tangential longitudinal strain, finite strain values vary markedly in the fold hinge, from the outer arc to the finite neutral surface, and then to the inner arc (Ramsay 1967). The combination of these mechanisms with others, such as layer-parallel shear or layer-parallel shortening do not significantly modify the general pattern. For example, similar folding does not produce higher strain values in the hinges. Strong field evidence in favor of low strain in the hinges of folds includes the presence of less penetrative cleavages in the hinges and the presence of pre-existing foliatiations preserved in the hinge zones.

The result of the 18 finite strain determinations are depicted in Fig. 3. R_s values range from 1.2 to 3.1, although only three samples yield values >2. The shape of the finite strain ellipsoids is oblate, as they are in the field of apparent flattening ($1 > k \geq 0$) and most values of the Flinn k parameter range between 0 and 0.5 (Fig. 3). No influence of grain size or matrix content has been recognized (Fig. 5). There is a tendency for R_s values to increase from east to west, and the easternmost ones comprise homogeneous R_s values from 1.2 to 1.4. This continuous pattern indicates that the deformation related to the foliation origin was homogeneous and due to re-tightening of previously formed folds during heterogeneous deformation. Strain produced the axial plane foliation as it parallels the xy plane of the finite strain ellipsoid. No local strain gradients, due to discrete shear zones for example, have been found.

Strain values can be related qualitatively to the intensity of cleavage in the sandstones, which is in all cases a slaty, penetrative type 2 cleavage according to the classification of Durney & Kisch (1994), varying from its incipient form to a fully developed slaty cleavage . In Fig. 6, three examples of analyzed rocks are shown. The less deformed rocks (A) have sparse, discontinuous cleavage planes characterized by the presence of very fine-grained dark material, the insoluble remnant of incipient solution mass transfer processes. No evidence of these processes can be seen in the clasts in the sandstones. Towards the west, where deformation increases, foliation planes become more abundant and pervasive (B). In addition, evidence of solution mass transfer processes are seen in some quartz clasts. Detrital mica is generally oblique to foliation planes and metamorphic white-mica parallels the cleavage surfaces. Where R_s values rise above 2 (C), foliation becomes much more continuous, closely spaced and solution transfer

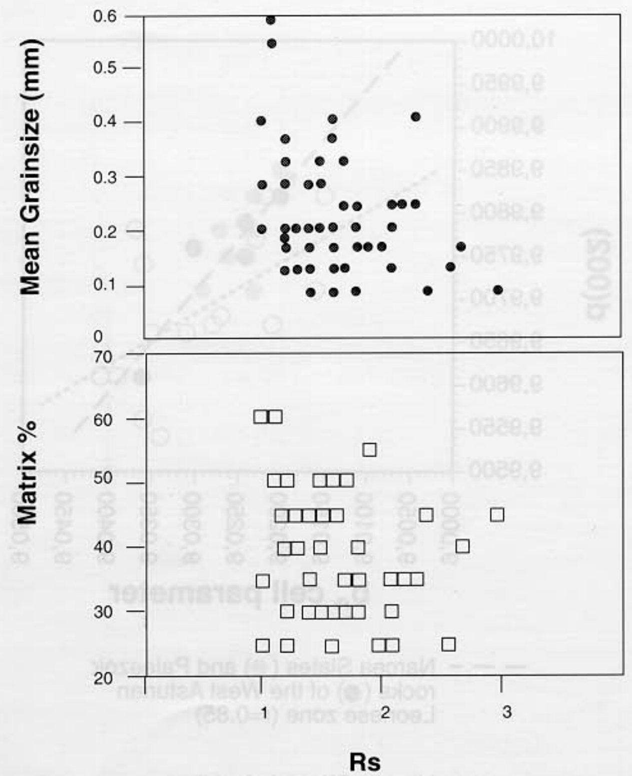

Fig. 5. Relation between finite strain values, grain-size and matrix contents of the samples used in this work and other samples from the Narcea Antiform in areas far from the selected cross-section, from Gutiérrez-Alonso (1992).

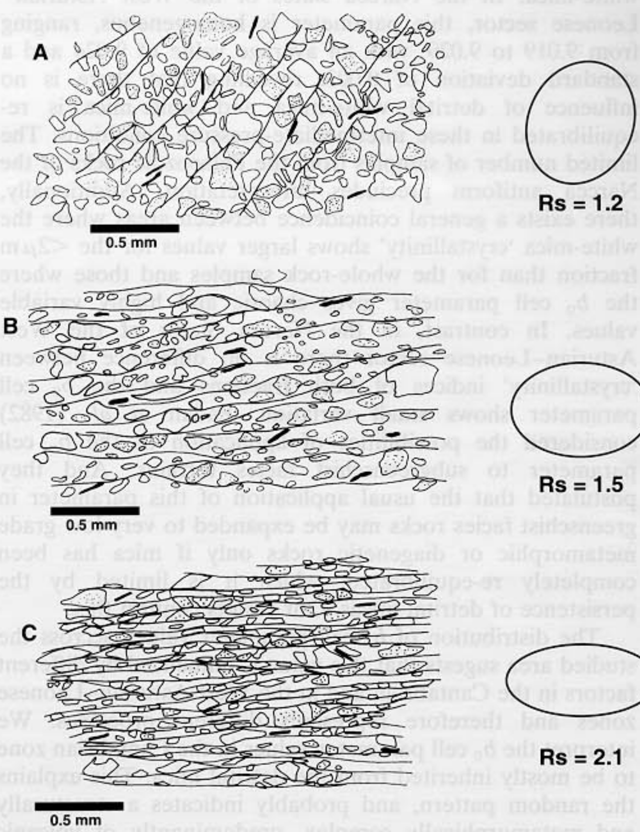

Fig. 6. Different kinds of foliation related to strain values, sketches from samples used in the strain analysis. White, quartz; stippled, plagioclase and K-feldspar; black, white mica.

processes affect almost all clasts, at least those larger than foliation spacing, and the rock becomes intensely cleaved. At this stage, recrystallized white-mica along foliation planes is clearly visible in thin-section.

To the west of the Cantabrian zone, the strain in the West Asturian–Leonese zone is much greater. Some of the phyllonites, rocks highly deformed by the latter deformation phase, have a stretching lineation and in some coarser grained rocks, large cigar-shaped clasts indicate prolate (constrained) finite strain ellipsoids. Intensely deformed rocks, giving rise to phyllonites with evidence of rotational deformation, indicate that simple shear processes were involved. The strain undergone by these rocks cannot be related to strain in the Cantabrian zone rocks, but there is no doubt that strain has been much more intense in the West Asturian–Leonese zone, especially towards the base of the two thrust sheets present in the area. The strain cannot be quantified where the rocks are crenulated.

Discussion

Several relationships can be noted among the different parameters measured. The relationships between the white-mica crystallographic parameters and strain are shown in Fig. 7, where linear regression analysis of the whole-rock and $<2\,\mu m$ fraction illite 'crystallinity' values and strain values, related to the distance from a fixed point, show a consistent trend. Because the samples for illite 'crystallinity' and strain analysis were collected at different locations, due to geological and oucrop constraints, there is no possibility of direct comparison. The number of samples and the presence of thrust faults along the profile precludes the use of curve fitting procedures to compare the illite 'crystallinity' values with the strain values. Therefore, although the relation between both parameters is qualitatively clear, we cannot propose an equation of general use.

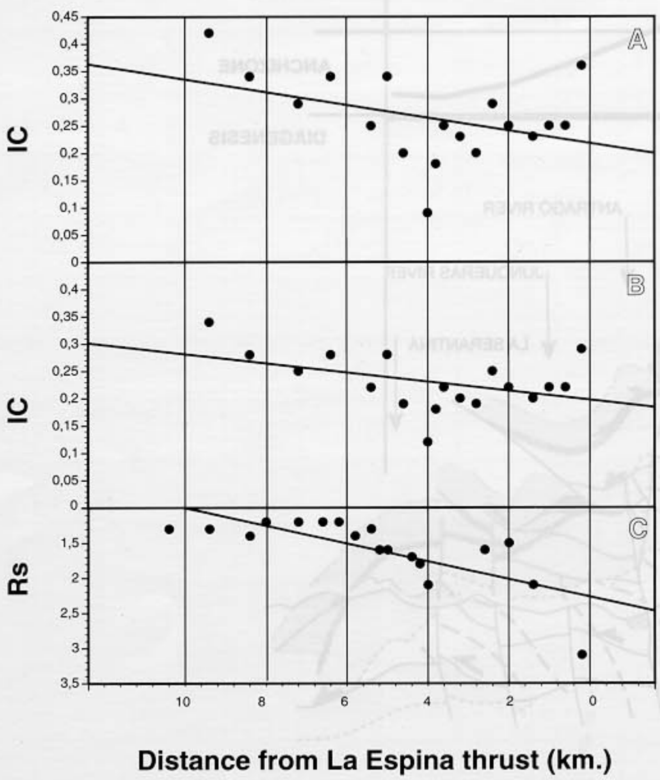

Fig. 7. Relation of illite 'crystallinity' values and finite-strain mean values related to distance from a fixed point in the La Espina thrust that limits the Cantabrian Zone sector of the Narcea antiform to the west. (**A**) Whole-rock illite 'crystallinity' values ($r = 0.40$); (**B**) $<2\,\mu m$ fraction illite 'crystallinity' values ($r = 0.44$); (**C**) R_s values ($r = 0.74$). Notice the similar trend in the three diagrams.

The relations in the West Asturian–Leonese zone therefore remain intuitive as no numerical correlation can be outlined due to the impossibility of strain measurements. A similar correlation exists between foliation development and strain determinations in the Cantabrian zone as no quantification of foliation development can be established. Figure 8 carries a summary of the relations and differences observed.

The relationship between the b_0 cell parameter values and illite 'crystallinity' values is important, and b_0 cell parameter values can only be taken into account in the areas where low IC values occur, (<0.22–23), indicating a higher metamorphic grade. This is evidenced by the chaotic distribution of b_0 cell parameter values accross the Cantabrian zone; and the homogeneous pattern in the West Asturian–Leonese zone. In the West Asturian–Leonese zone, the value of the standard deviation (0.003) is in the usual range of terrains that have been affected by metamorphism under homogeneous pressure, that is from 0.003 to 0.012 (tables 1 and 2 in Gudotti & Sassi 1986). Thus, the uniform values of the b_0 cell parameter in the Narcea Slates in the West Asturian–Leonese zone are related to the detrital white-mica b_0 cell parameter reset to the same values as the newly recrystallized white-mica. The b_0 cell parameter values measured in the Cantabrian zone are an average of the detrital white-mica b_0 cell parameter values and the recrystallized white-mica. There is no way to separate both components and hence no inference of geobarometric conditions from the behaviour of this parameter in the Cantabrian zone can be made. The chaotic behaviour of b_0 cell parameter may suggest a metamorphically complex provenance area for the sediments that comprise the Narcea Slates, as some values are very high and others very low. Therefore geobarometry using the phengitic content of white-mica can only be achieved in the Narcea Slates of the West Asturian–Leonese zone.

Of further interest is the relationship between whole-rock and $<2\,\mu m$ fraction of the IC values. The whole-rock illite 'crystallinity' values are lower than the $<2\,\mu m$ values across the Cantabrian zone and the Palaeozoic rocks of the West Asturian–Leonese zone, while they are almost identical in the West Asturian–Leonese zone. Exceptions are the lowest $<2\,\mu m$ values, where the whole-rock values are a little higher, in a trend opposite to the one found in the Cantabrian zone. This indicates that in the Cantabrian zone and the Palaeozoic rocks of the West Asturian–Leonese zone, metamorphic reequilibrium of the white-mica has not been reached, as concluded previously from the b_0 cell parameter behaviour. The detrital influence tends to lower the real values of the illite 'crystallinity'. Detrital micas may remain chemically non-equilibrated at low grade (Lopez-Munguira *et al.* 1991), or even medium grade (Massone & Scheyrer 1987). Therefore, the provenance of these rocks had 'crystallinity' values lower than those found in the Cantabrian or the Palaeozoic rocks of the West Asturian–Leonese zone and was of a higher metamorphic

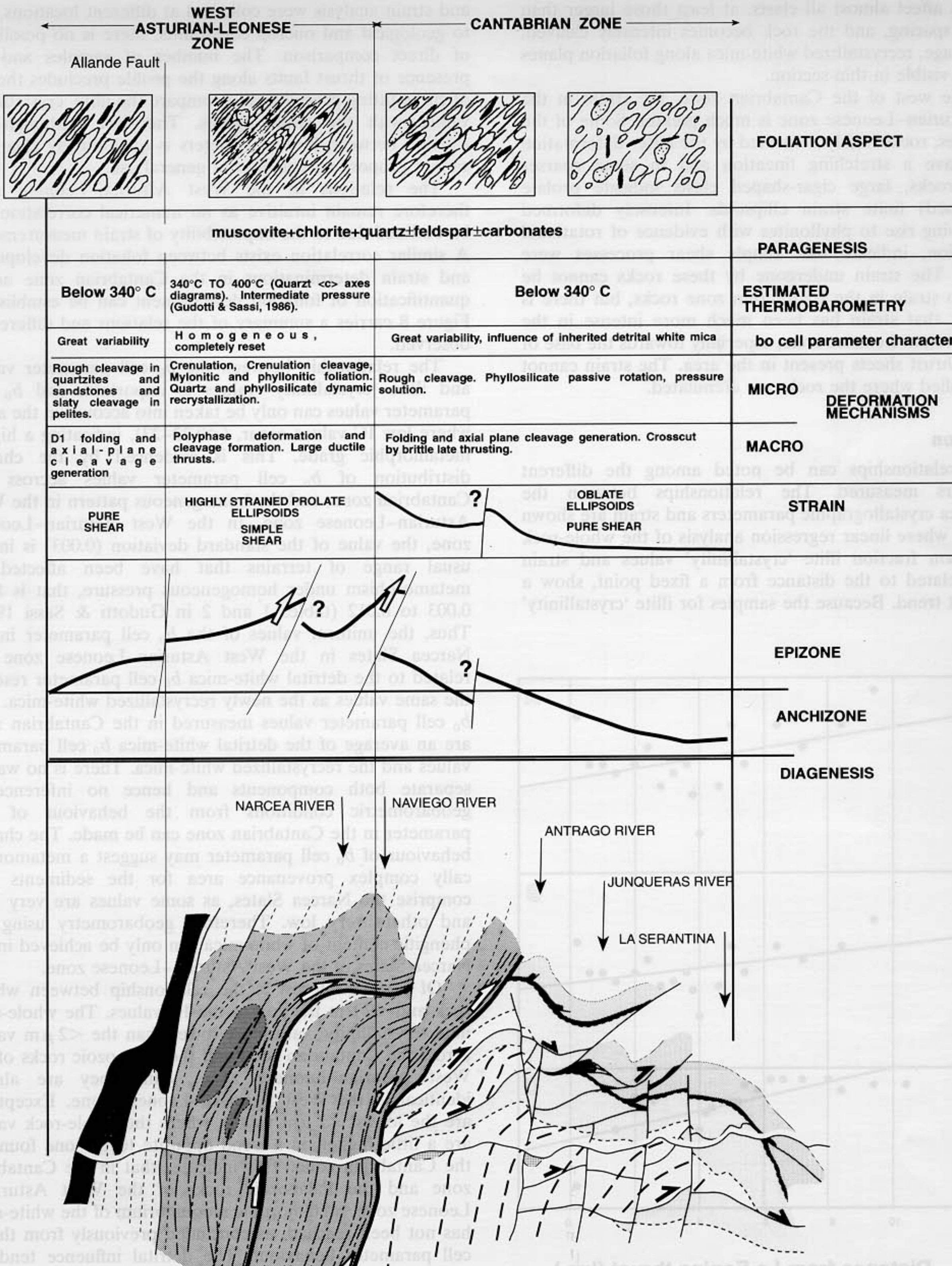

Fig. 8. Summary of the conclusions reached in this work on spatial distribution of foliation types, paragenesis, b_0 cell parameter characteristics, deformation mechanisms and idealized strain and metamorphic distribution related to the general structure of the Narcea antiform.

grade. On the other hand, the IC values are almost reset for the West Asturian–Leonese zone, where both whole-rock and <2 μm fraction values reflect the real metamorphic grade. Only <2 μm fraction values correspond to metamorphic conditions in the Cantabrian zone. We cannot establish accurate thermal conditions for the Cantabrian zone, but data from Blenkinsop (1987) suggest temperatures around 300 °C.

The possibility that the present metamorphic grade might be due to burial prior to deformation seems unlikely. In that case, the metamorphic gradient should have been deformed consistently with the folds found in the Narcea Antiform, which is not apparent. The fact that the metamorphic trend coincides with the Variscan one and that the metamorphic grade increases towards the west, despite the stratigraphic position of the samples, indicates that the IC is related to the Variscan deformation and metamorphism.

The thermal conditions for reequilibration of white-mica in the West Asturian–Leonese zone can only be constrained by an indirect method, as the $d(002)$ parameter is not suitable in this case. IC values in the West Asturian–Leonese zone reflect epizone conditions that may be roughly correlated with the greenschist facies (Kisch 1987). Kisch (1987), taking into account the approximate coincidence of the anchizone and the prehnite–pumpellyite facies, and data obtained from oxygen isotopes, correlates the anchizone with a temperature broadly between 200° and 300 °C. Other authors confine the epizone to temperatures above 370° (Schiffman & Liou 1980). Minimum thermobaric conditions are constrained by the quartz-axis basal slip during ductile deformation (Gutiérrez-Alonso 1992), occuring between 300 °C and 450 °C (Blacic 1975; Bouchez 1977; Bouchez & Pecher 1981). A whole-rock $^{39}Ar/^{40}Ar$ plateau age indicates a cooling age below 340 °C at 321 ± 1 Ma.(Martínez-Catalán *et al*. 1993), consistent with the main deformation and metamorphic event. These data limit the minimum temperature conditions reached in the Narcea Slates in the West Asturian–Leonese zone. Although there are no analytical data to constrain the temperature in the other two zones, the lack of ductile deformation, the existence of illite 'crystallinity' anchizone values and the importance of solution-mass-transfer processes suggests somewhat lower temperatures. The highest temperature for the West Asturian–Leonese zone rocks can be approximately established through the lack of metamorphic biotite or garnet and the absence of prismatic sliding in quartz (Gutiérrez-Alonso 1992), which occurs only above 450 °C (Blacic 1975). The lack of biotite suggest that the maximum temperature is about 400 °C (Bucher & Frey 1994) or, alternatively, that there is some chemical constraint in the production of biotite related to the Fe/Mg content of the rock (Spear 1993). Thus, indirect methods indicate temperatures ranging from 340 °C to 400 °C for the West Asturian–Leonese zone samples.

Geobarometry can also be estimated by indirect methods, using the semiquantitative barometric method of Guidotti & Sassi (1986). It suggests around 4 kbar for the temperatures described above. From geological interpretation of the structure, the deepest rocks outcropping in the Narcea Antiform were around 13–15 km. deep, before being exhumed by thrusting. This depth corresponds 3–4 kbar of pressure.The overall geothermal gradient would aproximate 25 °C km^{-1}.

The finite strain values in the Cantabrian zone increase towards the west. This is interpreted as accompanying the shortening of the Narcea Slates in a 'layer-parallel-shortening' like process (Engelder & Engelder 1977; Geiser & Engelder 1983; Geiser 1988), implying strain partitioning in the footwall of the Cantabrian zone. In this case, shortening is accomodated by folding and subsequent tightening of the folds, accompained by axial plane cleavage generation aproximately normal to the direction of shortening (Gutiérrez-Alonso 1992). With this mechanism, shortening is bound to diminish in the displacement direction and so does strain, as documented in this paper. The finite strain increase is accompanied by a continuous increase in solution-mass-transfer processes, leading to a more penetrative and closely spaced cleavage that accomodates increasing shortening to the west.

Conclusions

The correlation between finite strain and white-mica 'crystallinity' is close. Quantitavely, both parameters show the same tendency across the Cantabrian zone, and qualitatively this relationship can be seen along the whole Narcea antiform. The anchizone-epizone limit can be related to the increase of finite strain above values of $R_s = 1.5$. This is related to the first occurence of visible white-mica in the foliation planes and widespread solution–mass-transfer processes affecting the quartz grains.

From a regional point of view, despite the lack of metamorphic diagnostic metamorphic reactions in the Narcea Slates, the boundary between the anchizone and the epizone can be placed in the allochthonous rearmost part of the foreland fold and thrust belt, the Cantabrian zone. Furthermore, the allochthonous units in the West Asturian–Leonese zone have been subjected to higher-grade metamorphic conditions than the surrounding units, as reflected in the illite 'crystallinity' values and in the resetting of the b_0 cell parameter values of the detrital white-mica. This reveals a Variscan deep deformation history prior to thrusting and implies the existence of a large ramp between the West Asturian–Leonese and the Cantabrian Zones. There is also a close correlation between different metamorphic and structural parameters and different deformation processes, under high anchizone and epizone conditions, and in a complex structure involving a large shortening. There are also limits to the use of these parameters which have been outlined.

Helpful discussions were had with the structural geology groups in Oviedo and Salamanca Universities (Spain), especially F. Bastida, A. Pérez-Estaún and J.R. Martínez-Catalán. We wish to thank M. Conway, G. Draper and M. Gross of Florida International University who corrected and discussed earlier versions of the manuscript. Careful reviews by H. Kisch, B. Roberts and the editor, A. Maltman, improved greatly the manuscript. This project was funded by the DGICYT, grants PB-90-0860-C03-02, PB-93-1149 C03-02, PB-92-0960 and PB-92-0961. Additional funding to G. Gutiérrez-Alonso was provided by a research grant from the University of Salamanca.

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Received 26 April 1995; revised typescript accepted 20 October 1995.
Scientific editing by Alex Maltman.