The structure of the Ollo de Sapo antiform in the Cantabrian coast (NW Spain)

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Abstract: The geological structure of the Ollo de Sapo antiform unit in the Cantabrian coast section (Central-Iberian zone) constitutes an anticlinorium developed during the first deformation phase (D_1) of the Hercynian orogeny. This anticlinorium was strongly modified by subsequent deformation episodes. A thrust with a phyllonite zone was formed in the western part of the section during a second deformation phase (D_2). A post-D_2 extensional episode produced the Viveiro fault and a ductile shear zone in the eastern part of the section. Later, an important refolding event (D_3) gave rise to major folds and a large number of minor structures, developed in hectometric bands and characterized by geometrical variability. Finally, some late structures, mainly faults, were formed. These deformation events took place mainly under greenschist facies conditions. Quartz c-axis fabrics in quartzite and sandstones, with symmetric small circle girdles, were developed during D_1. These fabrics were passively folded by D_3 folds.

Key words: Hercynian belt, Central-Iberian Zone, structure, folds, foliations, shear zones, quartz c-axis fabrics.

Resumen: La estructura del Antiforme del Ollo de Sapo (Zona Centroibérica) en el sector de la costa cantábrica consiste en un anticlinorio originado durante una primera fase de deformación (D_1), que ha sido fuertemente deformado durante etapas posteriores. En una segunda fase (D_2) se originó un cabalgamiento con una zona de filonitización en la parte occidental del corte. Posteriormente, se desarrolló un episodio distensivo durante el cual se produjo la Falla de Viveiro, así como una zona de deformación dúctil en la parte oriental del corte. A continuación, un importante replegamiento (D_3) originó pliegues mayores y numerosas estructuras menores, que aparecen en bandas y se caracterizan por una gran variabilidad en su geometría. Por último, se desarrollaron algunas estructuras tardías, principalmente fallas. El desarrollo de la deformación tuvo lugar principalmente bajo condiciones de la facies de los esquistos verdes. Las fábricas de ejes c del cuarzo se originaron principalmente durante la fase 1, y son en general guirnaldas de círculo menor simétricas y con fuertes máximos periféricos. En los casos estudiados, estas fábricas fueron rotadas pasivamente durante la formación de los pliegues D_3.

Palabras clave: Macizo herciniano, Zona Centroibérica, estructura, pliegues, foliaciones, zonas de cizalla, fábricas de ejes c del cuarzo.

Bastida, F.; Aller, J. and Fernández Viejo, G. (1993): The structure of the Ollo de Sapo antiform in the Cantabrian coast (NW Spain). *Rev. Soc. Geol. España*, 6: 93 - 103.

The Ollo de Sapo antiform unit (OSA) forms the northeastern part of the Central-Iberian zone, and follows the trend of the Hercynian structures in the area (Fig. 1). The eastern boundary of the OSA in its northern sector is the Viveiro fault, an extensional fault with a 10-13 km dip slip, that separates the OSA from the Westasturian-leonese zone (WALZ) on the east (Parga Pondal, 1967; Bastida et al., 1984; Martínez Catalán, 1985). The western boundary of the OSA is the Pontedeume-Valdoviño fault zone (Parga Pondal, 1963; Iglesias & Choukroune, 1980; Díaz García, 1982), that separates the OSA from the Ordenes complex. The Cabo Ortegal allochthonous complex is thrust onto the OSA unit along its northwestern margin (Ries & Shackleton, 1971). The basal thrust of the Cabo Ortegal Complex is the western boundary of the study section.

The structure of the OSA is a good example of superimposed folding on a macroscopic scale. A controversy exists on the deformation history of the OSA. Matte (1968) first interpreted it to be the result of two superimposed folding phases depicting a type 3 interference pattern (Ramsay, 1967). However, Martínez Catalán et al. (1977) re-interpreted the structure in this zone to be the result of a main folding event (D_1) slightly modified by subsequent deformation. More recently, Díaz García (1983) describes a set of structures of an intermediate age between the two folding phases of Matte (op. cit.) which forms a ductile shear zone (D_2) in the northwestern corner of the antiform. In more recent reports on the area, the D_3 folding phase is again stated as an important event (González-Lodeiro et al., 1982; Bastida et al., 1984; Díez Balda et al., 1990; Azor et al., 1992). The understanding of the

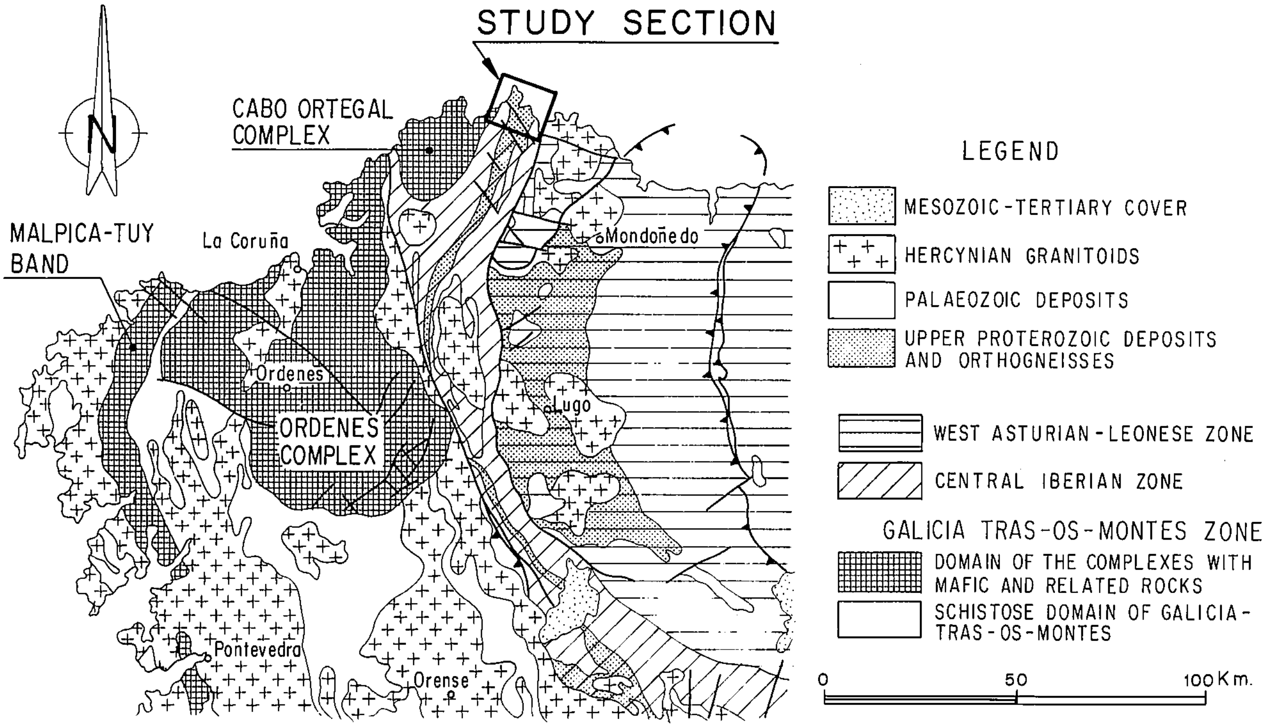

Figura 1.- Geological sketch-map of the northern part of the OSA and adjacent areas with situation of the study section.

structure of the OSA is one of the main aims of this study. In spite of the granitoid intrusions, the high quality of the outcrops in the coastal section allows a detailed structural analysis in the core of the Ollo de Sapo antiform. The analysis of c-axis fabrics in quartzite and sandstones along the section give important insights into the episodes that gave rise to the fabrics and the characteristics of the deformation.

The stratigraphy of the OSA coastal section was described by Matte (1968), Meer Mohr (1975), Iglesias & Robardet (1980) and Bastida et al. (1984). The stratigraphic logs representative of the two limbs of the antiform are shown in Fig 2.

Some characteristics of the OSA stratigraphy are outstanding when comparing it with that of the WALZ. The Ollo de Sapo porphyroid is only found in the OSA in the lowermost part of the section. The Montes slates and the Armorican quartzite (Lower Ordovician) rest on the Ollo de Sapo Formation. Cambrian rocks exist in the WALZ that are not present in the OSA. The Cabos series of the WALZ may be a thicker lateral equivalent to the rocks observed in the OSA. The correlation of the Silurian rocks in the OSA with those in the WALZ is difficult due to the scarce and incomplete outcrops of rocks of this age in the WALZ. The OSA may have a thicker Silurian sucession than the WALZ, evidenced by the thinner Silurian sucession underneath Devonian limestones in the Peñalba syncline (southern part of the WALZ, Pérez-Estaún, 1978).

The differences with the Schistose Domain of Galicia-Tras os Montes (SDGTM) (Farias et al., 1987), located to the west of the OSA, are less evident. The Silurian successions are similar (Iglesias & Robardet, 1980; Farias, 1990). The outcrops of pre-Silurian rocks are scarce in the SDGTM, and usually contain rocks of higher metamorphic grade. These facts make difficult the comparison with the pre-Silurian rocks in the OSA.

The regional metamorphism in the OSA is characterized by the presence of chlorite, biotite, almandine, staurolite-andalusite and sillimanite zones (Capdevila, 1969; Bastida et al., 1984; Arenas, 1991). The metamorphic grade increases towards the core of the Ollo de Sapo antiform, reaching the highest grade in the Guitiriz dome area, located inland; the age of the metamorphic peak is post-D1 and pre-D3. A metamorphic event, reaching staurolite and kyanite zones, developes in a narrow zone along the Viveiro fault (Martínez Catalán, 1985).

In the coastal section, most of the rocks above the Ollo de Sapo porphyroid are in the chlorite zone. Biotite and probably almandine zones are found in the Ollo de Sapo porphyroid, in the core of the antiform (Cuesta, 1980; Bastida et al., 1984; Arenas, 1991). Paragenesis with chloritoid, and locally garnet, are found close to the Viveiro fault. These minerals show pressure shadows parallel to the main foliation (S_1), however, the proximity of the fault in the study area suggests the flattening of the S_1 during fault movement.

Structure

The structural analysis carried out, and illustrated by the cross section (Fig. 3), indicates the successive development in the area of the following structural events:

1) Nearly isoclinal east-facing folds (D_1) with an associated cleavage (S_1).

2) Ductile shearing giving rise to a phyllonitic foliation (S_2) in the western part of the section. This shear

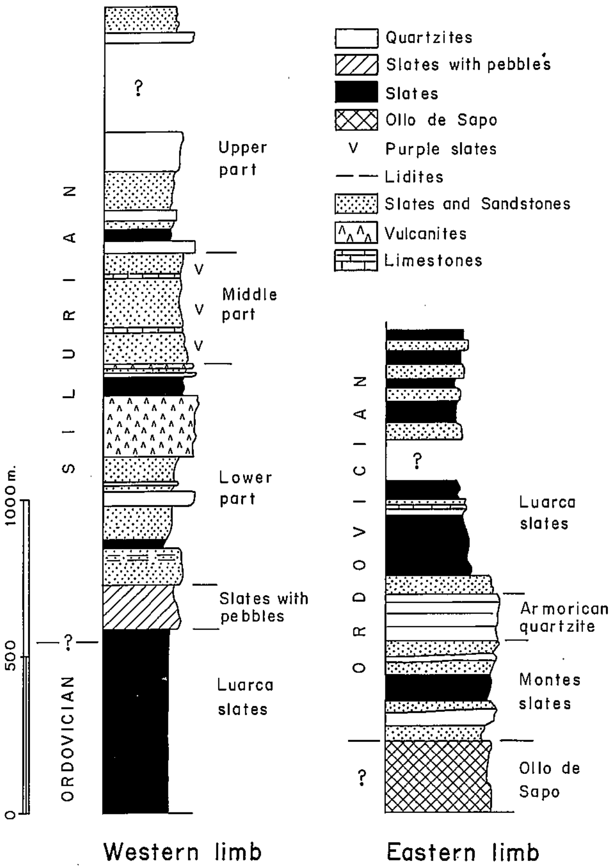

Figura 2.- Stratigraphic columns representative for the two limbs of the OSA.

zone is bounded at its base by a fault. Minor shear zones throughout the section were also formed during this episode.

3) Viveiro fault and San Román shear zone. Both represent an extensional episode.

4) Slightly east-vergent folds (D_3) with an associated crenulation cleavage (S_3). The superposition on D_1 folds gives rise to a type 3 interference pattern (Ramsay, 1967).

5) Late minor structures, mainly faults.

The major structure of the antiform (Fig. 3) can be described as a D_1 anticlinorium refolded by D_3 folds.

The core of the antiform is occupied by the Ollo de Sapo, intruded by the O Barqueiro granite and the Estaca de Bares granodiorite. The massive nature of all the granitoids, with little or no original anisotropy, has hampered the reconstruction of the structure. The rocks of the Ollo de Sapo commonly show only one foliation. This foliation is associated with the San Román shear zone near the eastern contact of the Ollo de Sapo. An exception can be observed in Xilloi beach where two foliations (S_1 and S_3) can be observed, with the latter parallel to the axial planes of folds in quartz veins parallel to the former. The O Barqueiro granite shows some deformation in its borders and some associated dykes have been deformed by D_3 folds (Bastida et al., 1984). The later Estaca de Bares granodiorite shows no evidence of deformation.

The western limb (section A-A' in Fig. 3) of the antiform is dominated by D_1 normal limbs, and in its westernmost part is affected by the D_2 structures. Hectometric D_3 folds can also be observed along the section, together with normal faults with a systematic drop of its western block.

The eastern limb (section B-B' in Fig. 3) is mainly constituted by the reverse limb of the D_1 major anticline, with some minor folds. This limb is refolded by D_3 folds to the east of San Román beach. Nevertheless, a normal D_1 limb outcrops again in the eastern part of the section, to the east of the D_3 fold, whose hinge zone, broken by a reverse fault, is situated in Abrela beach.

First deformation Phase (D_1)

The fact that both the normal and the reverse limbs of the D_1 anticlinorium in the section are strongly refolded by D_3 folds convincingly suggests that this anticlinorium initially was a recumbent and very tight fold. This geometry agrees with the one deduced for this antiform in areas to the south of the coastal section (Matte, 1968; González Lodeiro et al., 1982; Bastida et al., 1984).

The position of hectometric minor D_1 folds distributed along the section can be seen in Fig. 3. On the scale of the outcrop, some folds can also be seen along the section with interlimb angles ranging between 15 and 60°. Axial directions (Fig. 4A) show a large dispersion that can be attributed in part to some local obliquity between D_1 and D_3 axes.

S_1 is generalized and its position along the section (Fig. 4B) shows a dispersion due to D_3 folds. In the slates, S_1 is a well developed slaty cleavage, that becomes a rough slaty cleavage with the increase in quartz content. In the sandstones, S_1 is a rough cleavage, defined by wavy lamellae with phyllosilicates and opaque materials, and to a lesser extent by shape preferred orientation of quartz.

Second deformation phase (D_2)

D_2 structures can be found mainly in the western part of the section. The boundary between the OSA and the Cabo Ortegal complex (to the west of the section in Fig. 3) is an important thrust, that can be attributed to this phase.

A shear zone about 150 m thick with intense ductile deformation and phyllonitization associated to a level of chloritic rocks can be observed in the rocks under Cabo Ortegal Complex. The lower boundary of this zone is a fault which repeats a part of the Silurian succession (Fig. 3). The phyllonitic foliation (S_2) is a domainal foliation defined by the strong orientation of fine grained chlorite and moscovite. These phyllosilicates, especially chlorite, define laminar domains where carbonaceous material is usually concentrated. Equidimensional fine grained dynamically recrystalized quartz is abundant in thicker domains. Domains with carbonates, porphyroclasts of plagioclase and opaque minerals with asymmetric pressure shadows also occur (Fig. 5A).

Small microfolds affect S_2 in some cases and can be interpreted as the result of flow instability mechanisms (Platt, 1983) during a progressive D_2 deformation. A

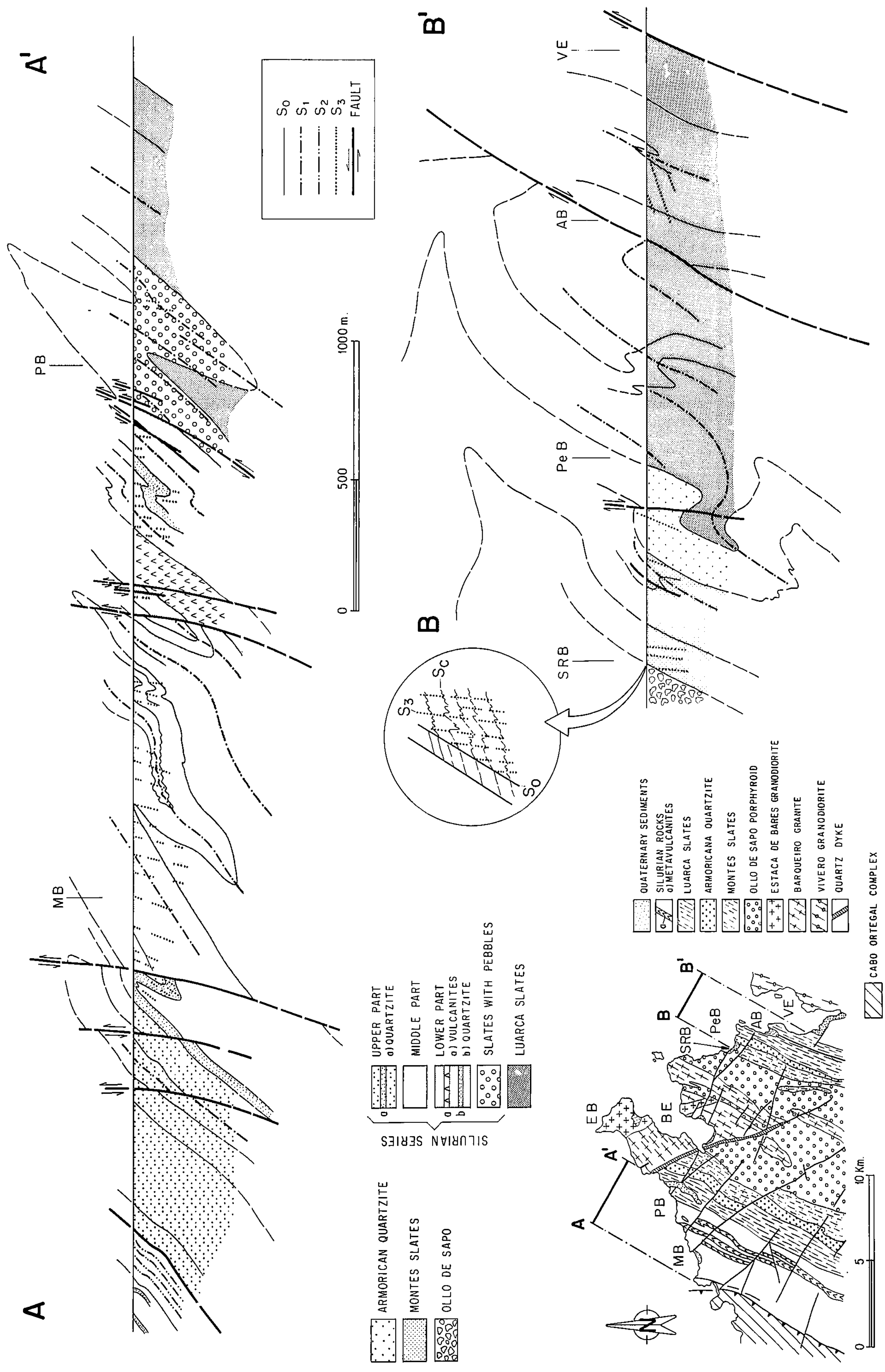

Figura 3.- Geological cross sections along the cantabrian coast for the western (A-A') and eastern (B-B') limbs of the OSA. A-A' and B-B' are the projection planes for the cross sections. MB: Mazorgán beach; PB: Picón beach; EB: Estaca de Bares; BE: Barqueiro Estuary; SRB: San Román beach; PeB: Pereira beach; AB: Abrela beach; VE: Viveiro Estuary.

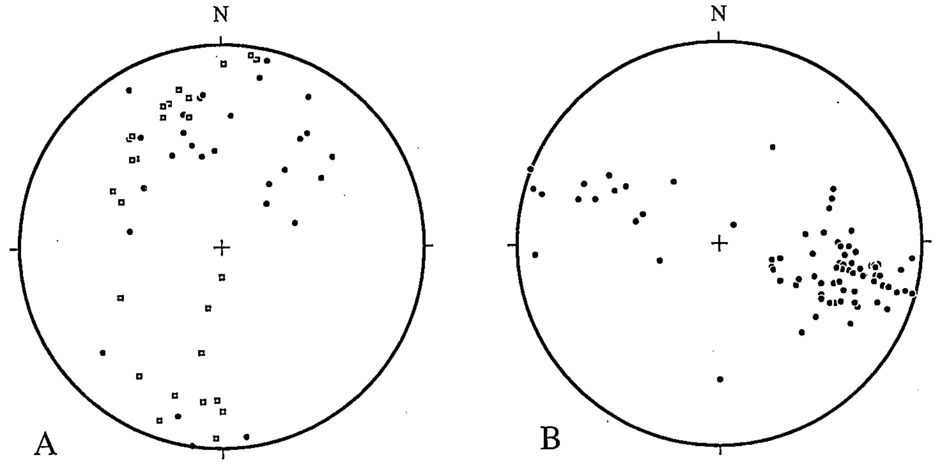

Figura 4.- Stereographic plots of: A) fold axes (dots) and intersection lineation (squares) for D_1; B) poles to S_1 cleavage.

subhorizontal, N-S trending, mineral lineation (L_m) (Fig. 6), mainly defined by chlorite, is commonly observed on S_2. Kinematic markers are scarce in outcrop, and mainly consist of extensional shear bands that deform S_2. Under the microscope, porphyroblasts with σ and δ structures are common. These shear sense indicators point to a top to the south displacement for the shear zone. The accurate knowledge of the geometry and kinematics of the basal fault will require a detailed mapping and structural analysis of its extension inland.

Other manifestations of D_2 can also be observed in Picón beach, with some local phyllonitization, minor folds and an associated crenulation cleavage.

Deformation associated to the Viveiro fault and the San Román shear zone

The Viveiro fault is the eastern border of the OSA along more than 140 Km. Martínez Catalán (1985) described it as a normal fault with the hangingwall down-dropped to the west about 10 Km. The fault has an associated zone, mainly developed in the hangingwall, with intense ductile deformation and a kyanite metamorphic episode. The most important movement along this fault took place between D_2 and D_3 (Martínez Catalán, op. cit.), and has been interpreted as a drop fault in the western limb of the Lugo dome (Pérez-Estaún et al., 1991). The Viveiro estuary hampers the observation of the fault zone in the coastal section, where only some crenulation cleavages can be attributed to this deformation.

The San Román shear zone is situated between San Román and Pereira beaches. In this zone, a generation of structures appears that cannot be observed in the rest of the section. These structures are best developed at the contact zone between the Ollo de Sapo and the Montes slates. The structures that characterize the shear zone consist of a pronounced penetrative crenulation cleavage and some associated minor folds. The cleavage (S_c in Fig. 3) dips to the west less than S_0 and is folded by the S_3 crenulation, that appears in a subvertical position and with an axial plane relation to the D_3 major folds in this area (Fig. 3). The initial position of the shear zone cleavage, its inter D_1-D_3 age and the asymmetry of the associated minor folds point to the interpretation of an extensional shear zone dipping to the west with a down dropped western block. The age and movement agree with those of the Viveiro fault, and in this way the San Román shear zone can be attributed to the same extensional episode that originated the fault.

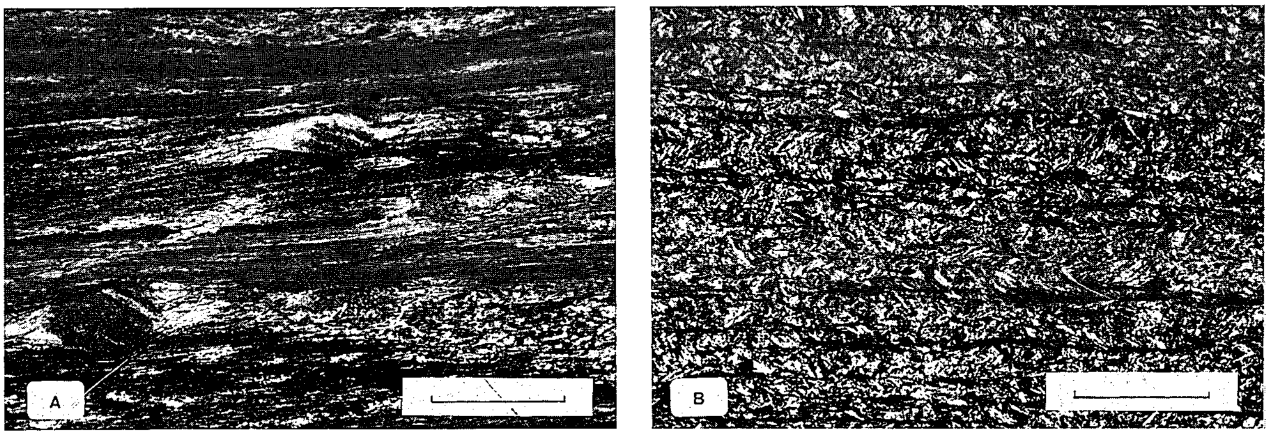

Figura 5.- A) Phyllonitic foliation S_2 in the shear zone developed in the western part of the section. B) Crenulation cleavage S_3 in pelitic rocks. Scale bar 200 mm.

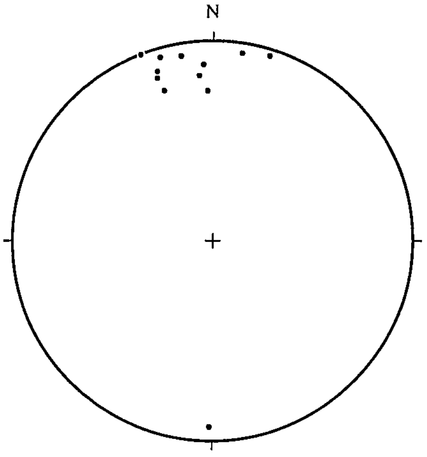

Figura 6.- Stereographic plot of L_m data from the shear zone in the western part of the section.

Third deformation phase (D_3)

Folds on all scales with varied geometries and an associated crenulation cleavage (S_3) formed during this phase.

The largest structure is the Abrela antiform, which folds all the D_1 structures in the eastern part of the section. The strong tightening of this fold gave rise to a limb reverse fault in the zone of Abrela beach (Fig. 3).

D_3 asymmetric folds with short limb lengths of 80 to 200 m can be observed all along the section. The axial plane of these folds is subvertical or indicates a weak vergence to the east.

D_3 folds on the outcrop scale are common in those parts of the section where the previous anisotropy (S_0 or S_1) became less inclined as D_3 major folds developed. This process is similar to the one described in the WALZ (Pulgar, 1980; Alonso et al., 1991). Positions of fold axes can be seen in Fig. 7A. The interlimb angle ranges from 40 to 90° and the geometry of the folded layers is 1C, with some 3-1C forms (Fig. 8). The form of the folded surfaces also shows high dispersion. These folds sometimes deform D_1 minor folds on the outcrop.

The crenulation cleavage (S_3) is mainly developed in the zones with D_3 folds; its position is shown in Fig. 7B. On the outcrop, S_3 is sometimes penetrative and obliterates S_1. It is also posible to see S_3 cutting across previous D_1 folds. Crenulation cleavages show a moderate dip to the west in the eastern limb of the Abrela Antiform (Fig. 3). The presence of this important D_3 antiform suggests that this crenulation cleavage is S_3, though another interpretations could be suggested.

Under the microscope, a crenulation is observed in slates with a good S_1 fabric and low D_3 deformation. This crenulation gives rise to an incipient zonal crenulation cleavage with the increase in D_3 deformation, and, as deformation continues, to a well developed zonal or discrete crenulation cleavage. When S_1 is poorly developed and has a low mechanical continuity, the crenulation cleavage shows smooth well defined cleavage lamellae, and microlithons with poorly developed hinges and a lot of small mica crystals lying across the crenulation cleavage (Fig. 5B).

Late structures

Longitudinal normal faults with the hangingwall down-dropped to the west less than 100 m are common all along the section (Fig. 3). In some cases, subhorizontal kink bands and crenulations are associated to these faults.

Some structures transversal to all those previously described are also found in the zone. These structures include faults, kink bands and crenulations. Crenulations are very common in some localities, for example in Pereira beach.

Both late longitudinal and transversal structures affect D_3 structural elements and therefore they are interpreted to postdate this deformation event.

Analysis of quarzt c-axis fabrics

The analysis of quartz c-axis fabrics in sandstone and quartzite samples of the OSA coastal section was carried out to test what this method could contribute to the knowledge of the deformation conditions, and their history along the section. Some recent c-axis fabrics data in the contiguous Mondoñedo nappe area (Bastida

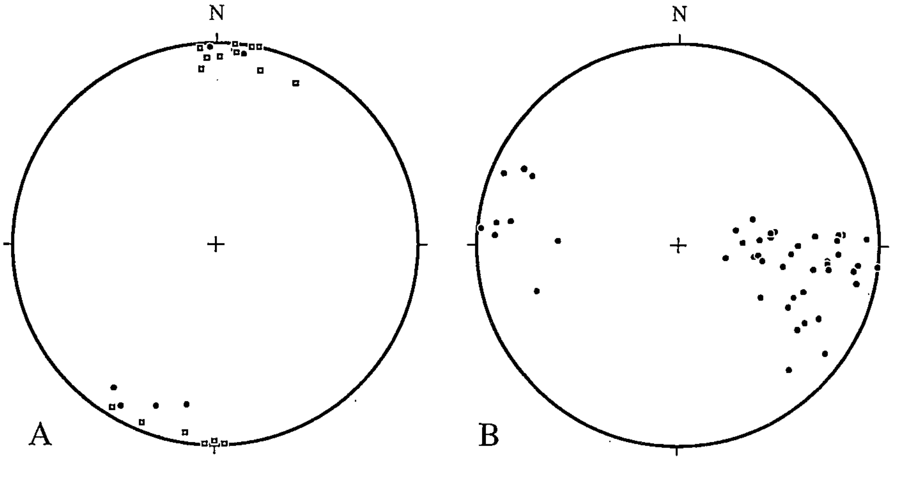

Figura 7.- Stereographic plots of: A) fold axes (dots) and intersection lineation (squares) for D_3; B) poles to S_3 cleavage.

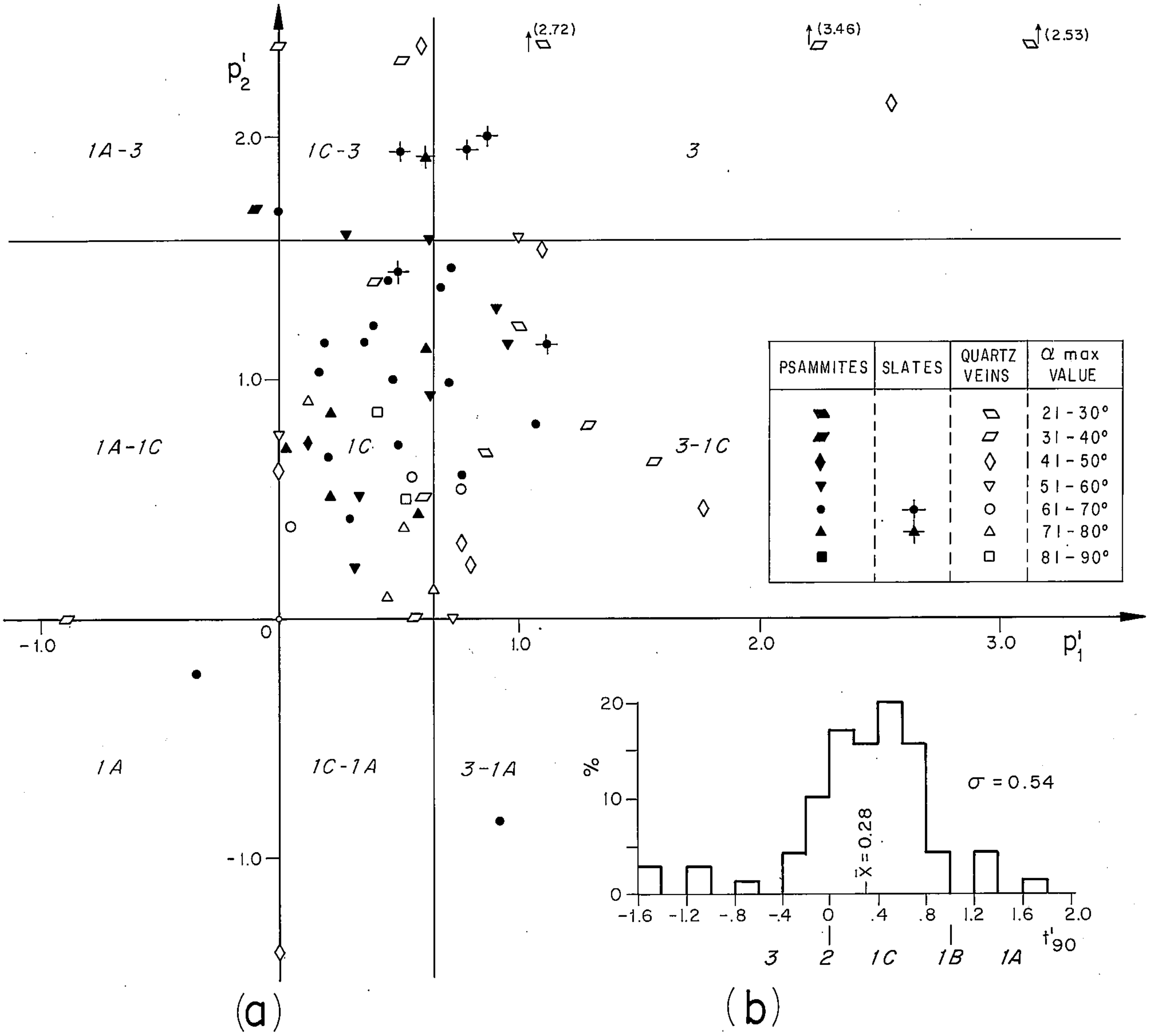

Figura 8.- Classification of D_3 minor folds in the p'_1-p'_2 diagram (Bastida 1993) and histogram of intercept values (t'_{90}).

& Aller, 1992) will allow comparison and integration of the new data in a regional context.

Samples were collected all along the section and studied under the microscope with the help of the U-stage. As D_3 is the last important deformation in the area, some samples were collected along the limbs and hinges of D_3 folds to know the age of the fabrics relative to this deformation event.

From the petrographic point of view, samples from the eastern limb of the OSA are mid-grained quartzites with low deformation features in the grains (non-generalized undulose extinction). These features and the presence of triple points in the grain contacts indicate an important post-tectonic thermal recrystallization in these rocks. Samples from the western limb of the OSA are mainly feldspathic sandstones with deformed quartz grains, smaller than 0.5 mm in size, in a quartz and mica matrix with a grain size too small for the fabric analysis. In all of these rocks S_1 is subparallel to S_0 and forms a weak foliation defined by the low dimensional orientation of the quartz grains and the parallel orientation of mica. S_3, when present, is a rough cleavage, mainly associated to a pressure solution mechanism.

The fabrics obtained are shown in Figs. 9, 10 and 11 with D_3 fold axes (subhorizontal in the field, see Fig. 7A) in the center of the plot and the S_0-S_1 and S_3 (when it appears) planes in its field position (see accompaning section). These projections allow direct comparison between the samples situated in different positions on D_3 folds. The c-axis fabrics do not show a coherent symmetry pattern with respect to S_3. In addition, the fabric is folded in all the cases analysed, and no modifications are observed that can be attributed to D_3 fold deformation. Hence, it is proposed that the fabrics record a deformation that can be attributed to D_1. This result agrees with microstructural evidence indicating pressure solution as the dominant deformation mechanism for quartz during D_3.

The lack of a well developed stretching lineation on S_1 or S_3 in the sampled localities poses a problem to know the position of the X-axis of the strain ellipsoid. However, this lack suggests that strain values on X and

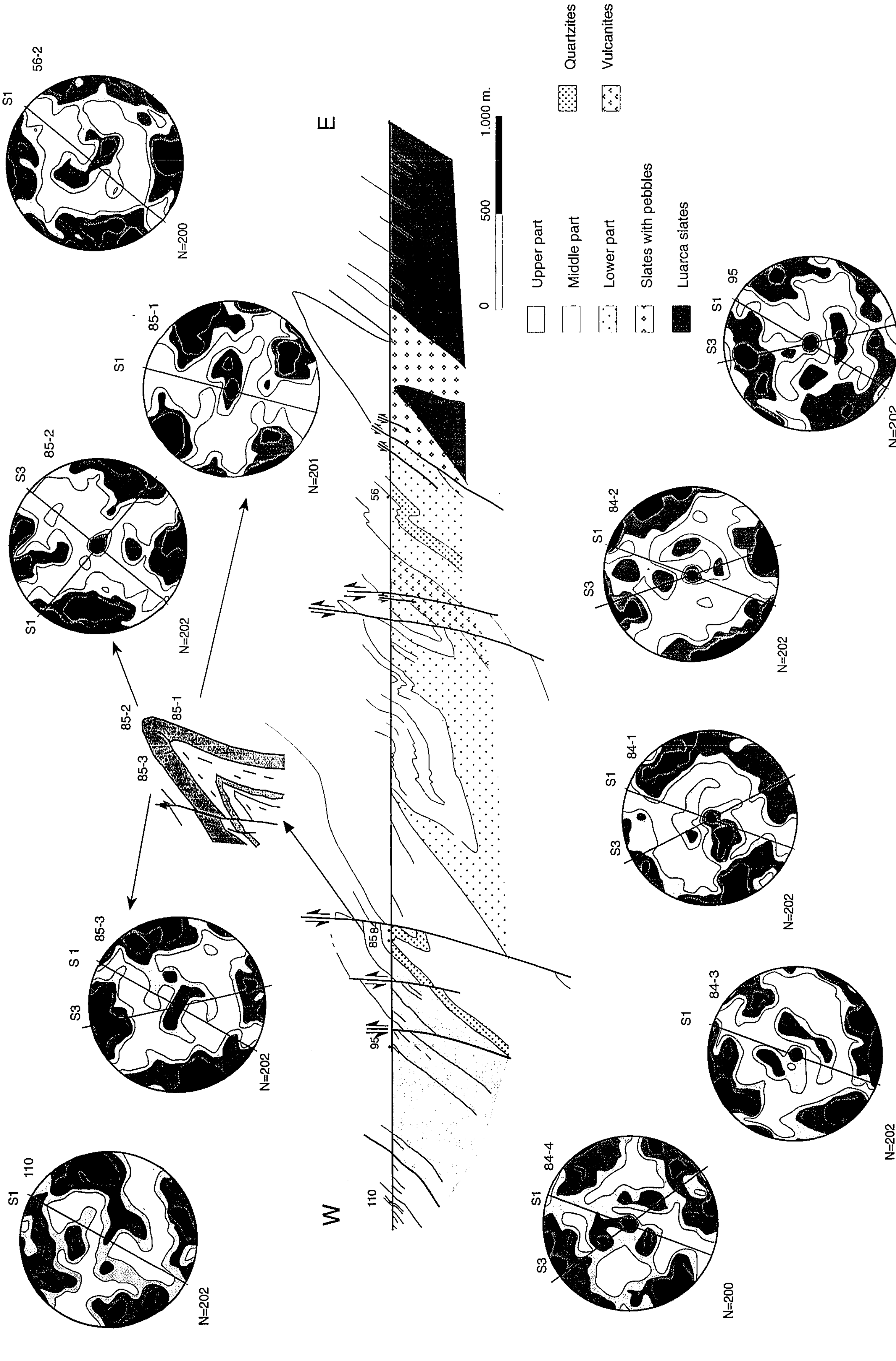

Figura 9.- Quartz c-axis fabrics in quartzites and sandstones from the western limb of the OSA. The position of S_1 and S_3 (when present in thin section) is indicated. Contours: 0.5, 1, 2, 4 and 8 %.

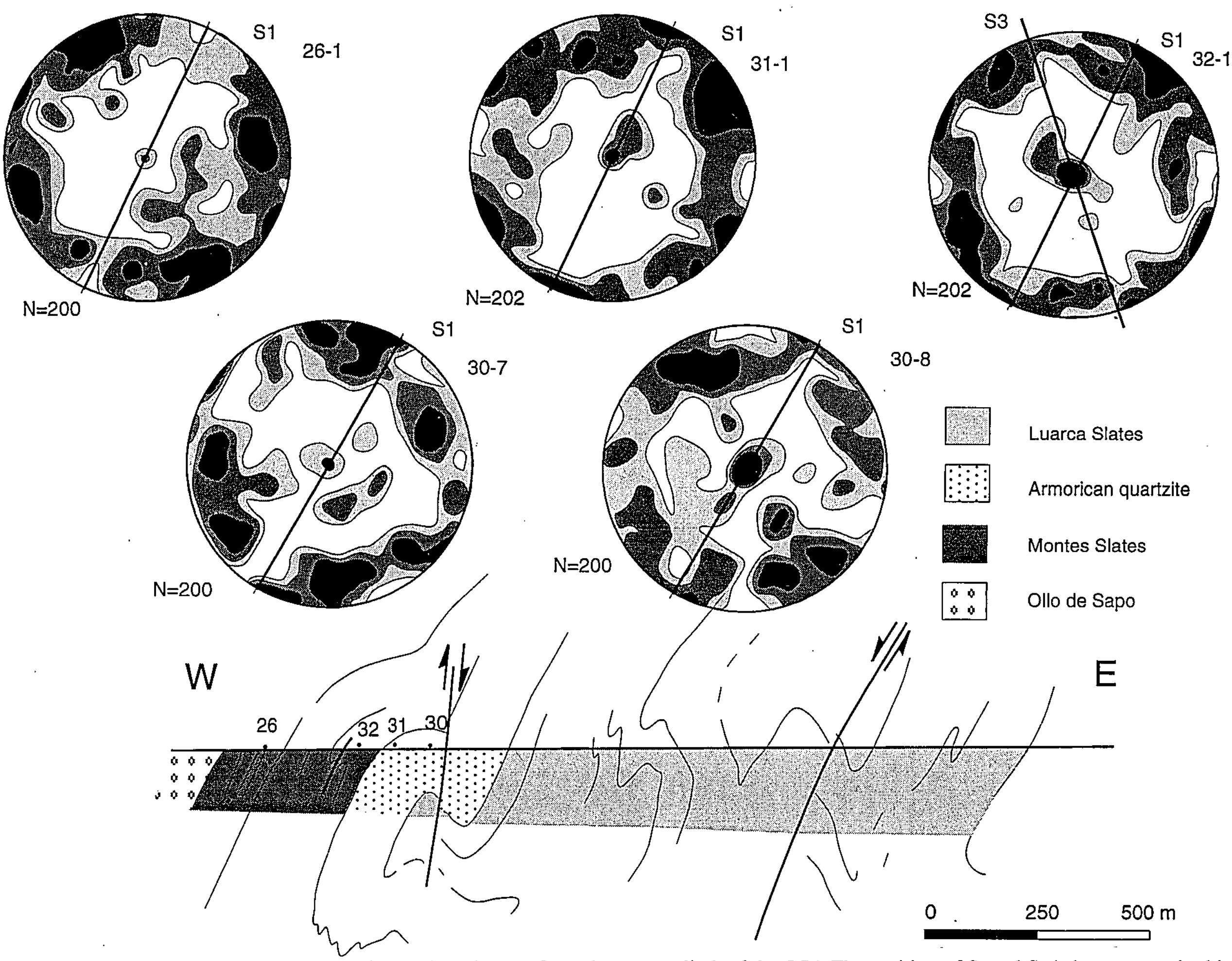

Figura 10.- Quartz c-axis fabrics in quartzites and sandstones from the eastern limb of the OSA.The position of S_1 and S_3 (when present in thin section) is indicated. Contours: 0.5, 1, 2, 4 and 8 %.

Y axes directions are not very different. Stretching lineations have been described in NW Spain only parallel or perpendicular to fold axes. In adition, these are the only two positions for which the orthorhombic symmetry elements of both the c-axis fabrics (Figs. 9 to 11) and the strain ellipsoid coincide in our samples. In most cases, X-axes perpendicular to D_1 and D_3 fold axes (in general nearly parallel) give fabric patterns comparable to those described in areas with good control of the deformation axis position (Price 1985). The high dispersion in all the samples cannot be attributed only to late thermal recrystallization, since this is only observed in the samples from the eastern limb. In spite of the high dispersion, the fabrics can be classified, in general, as small circle girdles with strong peripheral maxima and a variation in half opening angles between 36 and 55°. The girdles have usually orthorhombic symmetry, with the S_0-S_1 plane as a plane of symmetry (Figs. 9 to 11). This suggests a D_1 mainly coaxial deformation.

Comparison with the fabrics analized by Price (1985) shows that the OSA fabrics resemble those corresponding to the flattening field with tendency in some cases to axisymmetric flattening. This tendency agrees with the general lack of a stretching lineation on S_1. D_1 fabrics rotate pasively during D_3 folds formation in the cases analysed. D_3 deformation formed cleavage lamellae with residual phyllosilicates and opaques, and some removal of quartz in the boundaries of the cleavage lamellae, but did not appreciably modify the previous fabrics. These fabrics are similar to those described in the Mondoñedo Nappe area above the basal shear zone (Bastida & Aller, 1992), that also resulted from a D_1 deformation with low vorticity.

Discussion

The structure of the OSA along the Cantabrian coast provides a good base for comparison with the structure of the adjacent WALZ and SDGTM. In the WALZ, three main deformation phases have been described (Marcos, 1973). D_1 resulted in development of east-verging folds and an associated foliation (S_1). D_2 deformation resulted in development of east-verging thrusts and associated shear zones with a local crenulation foliation (S_2). D_3 is representated by near upright or slightly west-vergent open folds with a local associated crenulation cleavage. Large D_1 structures have not been described in the SDGTM, where the S_1 foliation is obliterated in many cases by the S_2 foliation. In this zone, D_3 structures present analogous features to those in the WALZ.

The structures in most of the OSA originated during two deformation phases. This poses a problem in correlating the structure of this zone with that of adjacent zones.

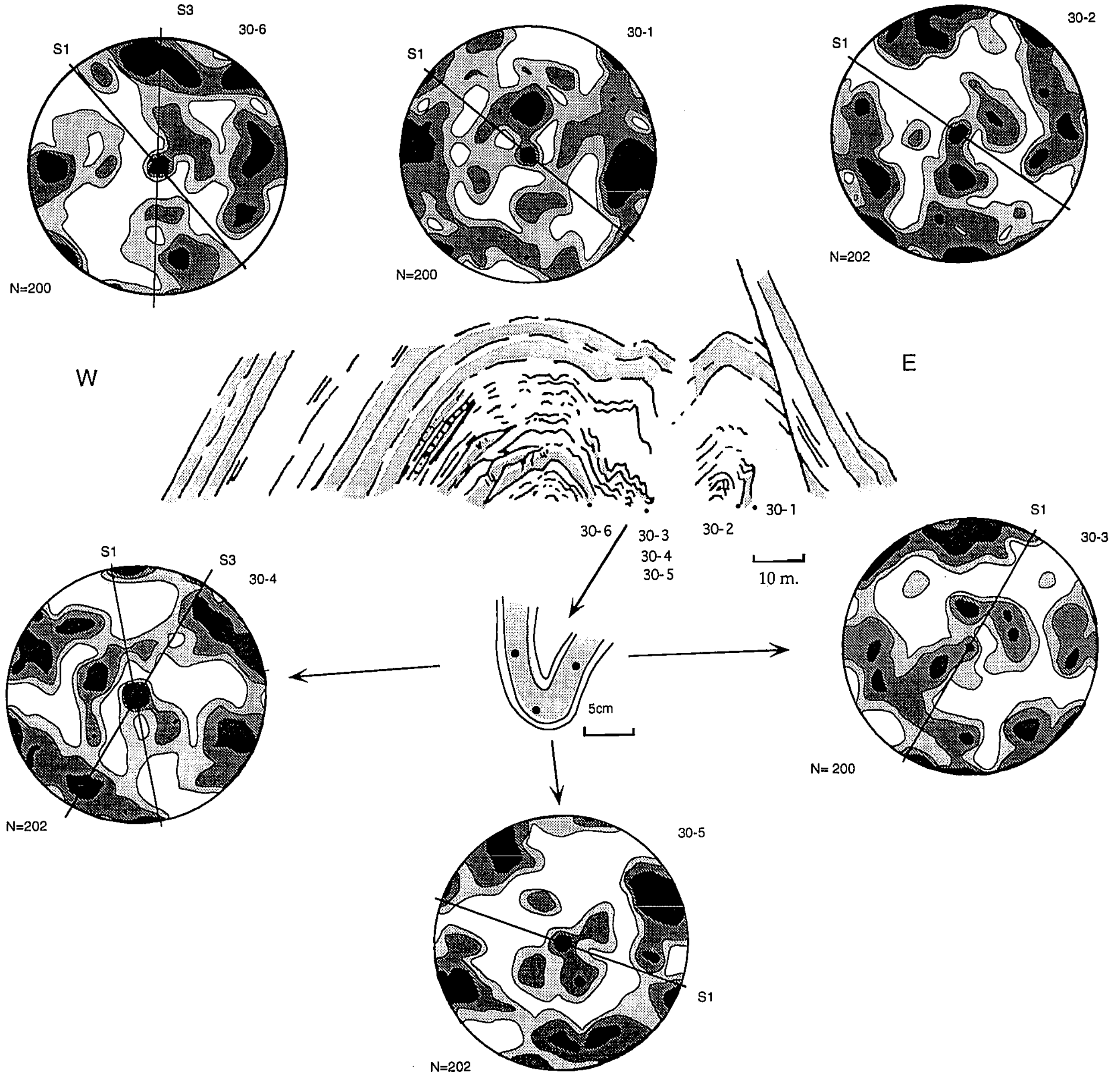

Figura 11.- Quartz c-axis fabrics in quartzites and sandstones from an area with D_3 folds in the eastern limb of the OSA (locality 30 in Fig. 11).The position of S_1 and S_3 (when present in thin section) is indicated. Contours: 0.5, 1, 2, 4 and 8 %.

The presence of a band with micro and mesostructural features different from those in the rest of the section and indicating a strong shear component is in agreement with the character of D_2 in the WALZ and supports the interpretation proposed herein. Nevertheless, the lack of interference patterns affecting structures of the other phases in this band, makes the correlation not so obvious.

Bell & Rubenach (1983) have shown a model for cleavage evolution, in which from an initial homogeneous foliation (stage 1), the development of a crenulation cleavage leads again at the end, to a homogeneous foliation (stage 6) that can be misinterpreted as the initial one. The generalized character of S_2 along wide areas of the SDGTM and with high evolution stages (5 and 6) can lead to think that the S_1 described in this paper is really a highly evolved S_2. Nevertheless, Bell & Rubenach (op. cit.) only found the higher evolution stages in rocks with high metamorphic grade in which porphyroblasts with relict foliations are common. The low metamorphic grade of the rocks in this study and the lack of definite microfold relicts do not support an interpretation of this type.

The regional interpretation of the structures that have been attributed in this paper to D_3 poses another problem, since east verging folds directly developed on S_1 could also be attributed to D_2. However, these folds are more open than D_2 folds in other areas, and their geometry more closely resembles the D_3 folds of the WALZ or the SDGTM. Because of this, these folds have always been attributed to the general refolding phase (D_3; D_2 of Matte, 1968). In addition, quartz c-axis fabrics are folded by these structures and show no other modification; this does not agree with the strong deformation usually associated to D_2 structures. D_2 structures described in the western part of the section are also very different in character to the structures here attributed to D_3. The east vergence of these D_3 structures could have been due to the adjacent massive rocks of the overlying Cabo Ortegal Complex, that originated an important contact strain area during D_3 deformation.

Conclusions

The structure of the OSA in the Cantabrian coast section is constituted by a nearly isoclinal D_1 anticline that originated in a recumbent position and now appears strongly refolded by D_3 structures. D_1 resulted in the formation, also, of a foliation (S_1) that varies in character from a rough cleavage to a slaty cleavage. A crenulation cleavage (S_3) appears distributed in bands and associated to D_3 folds. S_3 locally obliterates S_1. D_2 gave rise to a shear zone with phyllonitization in the western part of the section; the shear zone is bounded at its base by a fault. Kinematic criteria point to a top to the south movement for this shear zone. Between D_2 and D_3 an extensional episode gave rise to the Viveiro fault and the San Román ductile shear zone, both with a movement of its western block down. The analysis of quartz c-axis fabrics shows that these originated during D_1 deformation with low vorticity.

We wish to thank our colleagues of the structural geology group in Oviedo for many helpful comments. Especially, A. Marcos and P. Farias, who visited the section and promoted an interesting discussion about the interpretation of the main deformation phases. J. Gallastegui was our patient teacher in the computer manipulation of the figures. D. L. Brown and I. Méndez-Bedia made helpful comments and revised the english text. The comments by J. R. Martínez Catalán and an anonimous referee are also acknowledged.

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Reicibido el 19 de febrero de 1993; aceptado el manuscrito revisado el 29 de julio de 1993