

GEOLOGY OF THE OLLO DE SAPO ANTIFORM UNIT TO THE SOUTH OF THE CABO ORTEGAL COMPLEX (NW SPAIN)

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Abstract: The Ollo de Sapo antiform is located in the hinterland of the Hercynian Iberian belt in NW Spain. It consists mainly of Lower Paleozoic siliciclastic rocks with important lateral facies changes in the Lower Ordovician. These rocks underwent three main deformation phases during the Hercynian orogeny. D_1 gave rise to close east-facing folds with an associated foliation (S_1). D_2 is responsible for the thrust emplacement of the Cabo Ortegal Complex on the rocks of the Ollo de Sapo antiform. D_3 resulted in the development of a major synform-antiform pair. The competent and massive character of the rocks of the Cabo Ortegal Complex conditioned the geometry of the D_3 structures and resulted in an increase in the tightening of D_3 folds towards the south and the development of a fan of folds in the southern part of the zone. D_3 microstructures include crenulation, crenulation cleavage, differentiated cleavage and schistosity. A peraluminous leucogranite with K-feldspar megacrysts (Forgoselo granite) intruded in the final stages of D_3 in a hinge dilation space of the major D_3 synform and constitutes an example of folding related intrusion in a crustal shortening regime. This type of structural control for granite emplacement is tentatively proposed for some other granites outcropping in the adjoining West-Asturian Leonese zone, which belong to the same compositional group as the Forgoselo granite.

Key words: Hercynian belt, Central-Iberian zone, stratigraphy, structure, folds, foliations, granite intrusions.

Resumen: El área estudiada se sitúa en las zonas internas del Macizo Herciniano Ibérico en el NW de España y está constituida esencialmente por rocas siliciclásticas del Paleozoico Inferior, las cuales presentan importantes cambios de facies en el Ordovícico Inferior. La deformación herciniana tuvo lugar mediante tres fases principales de deformación. La primera (D_1) dio lugar a pliegues apretados vergentes hacia el E y a una foliación tectónica (S_1) asociada a ellos. La segunda (D_2) es la causante del emplazamiento de la unidad alóctona del Complejo de Cabo Ortegal sobre las rocas del área estudiada. Un gran sinforme que ocupa las partes oriental y central del área estudiada y un antiforme en la parte occidental constituyen las estructuras más importantes originadas durante la tercera fase (D_3). El carácter competente y masivo de las rocas del Complejo de Cabo Ortegal fue la causa de un aumento del apretamiento de los pliegues D_3 hacia al S y de la aparición de un abanico de pliegues de dicha fase en la parte meridional de la zona. Durante la tercera fase se originaron diversos tipos microestructurales, entre los que pueden distinguirse: crenulación, clivaje de crenulación, clivaje con diferenciación y esquistosidad. En estadios tardíos de la D_3 tuvo lugar la intrusión de un leucogranito peraluminico con megacrystales de feldespato potásico (granito de Forgoselo) en un espacio de dilatación ariginado en la zona de charnela del granisinforme originado durante dicha fase. Esta granito constituye un buen ejemplo de intrusión asociada a un proceso de plegamiento en un régimen de acortamiento cortical. Este tipo de control estructural para el emplazamiento de granitos es sugerido también para otros granitos del mismo grupo composicional que el de Forgoselo y situados en la Zona Asturoccidental-leonesa.

Palabras clave: Orógeno Herciniano, Zona Centroibérica, estratigrafía, estructura, pliegues, foliaciones, intrusiones graníticas.

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In NW Spain, the Ollo de Sapo antiform unit (OSA) follows the bend of the Asturian Arc in the eastern part of the Central-Iberian zone (ZCI) (Fig. 1). The OSA is formed by a siliciclastic Ordovician and Silurian succession resting on top of a porphyroid (Ollo de Sapo Formation). The structure of this unit is characterized by large east-facing recumbent folds strongly deformed by later folds with steep axial surfaces (Matte, 1968), giving rise to a type 3 interference pattern. The general map pattern is that of a major antiform cored by the

Ollo de Sapo Formation. The OSA constitutes, in its northern part, the para-autochthonous of the Cabo Ortegal Complex, which consists of high grade mafic and ultramafic rocks and forms a gentle synform (Fig. 1).

The aim of this paper is the study of the zone located to the south of the Cabo Ortegal complex synform. The structure of this zone is formed by the prolongation of this synform in the OSA and presents a fan of folds, whose geometry was modified by the intrusion of the Forgoselo granite. The zone was

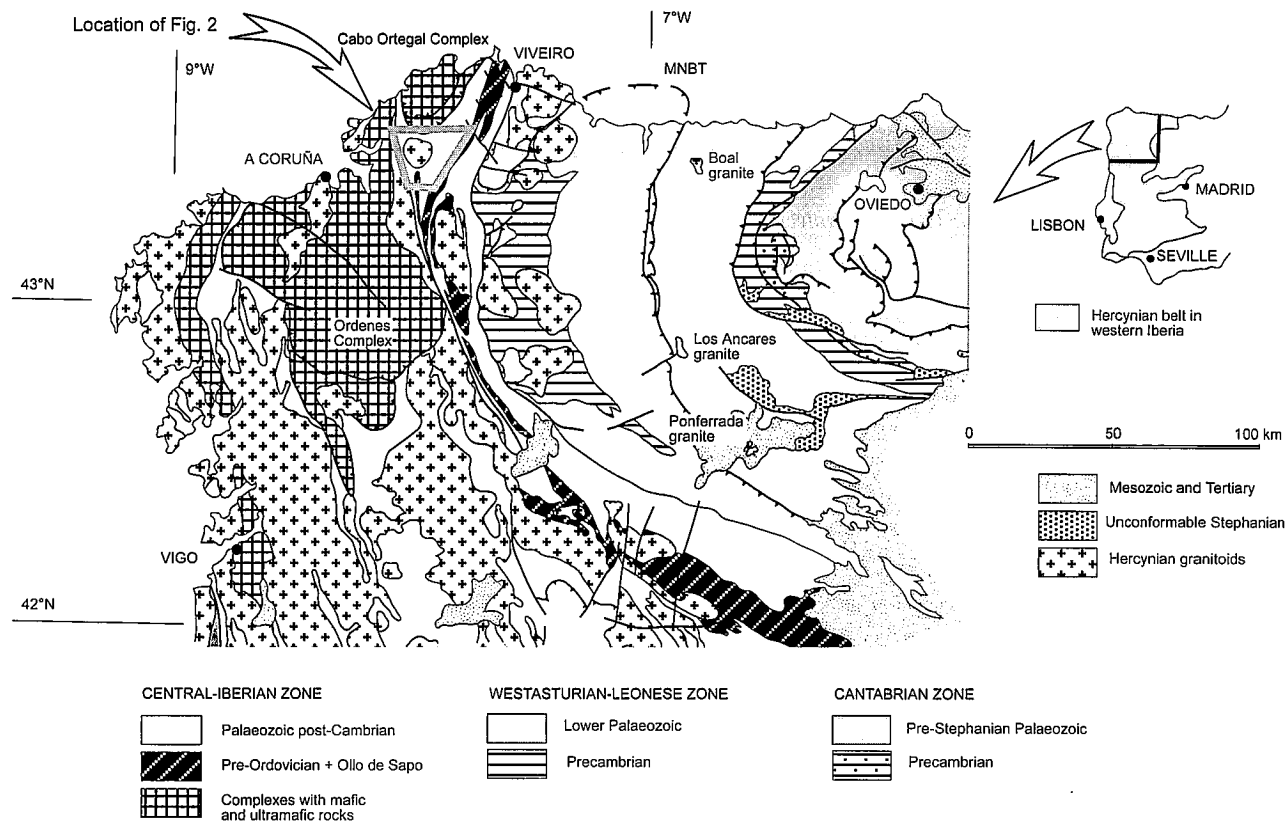


Figure 1. Geological sketch map of northwest Spain showing the location of the study zone. MNBT: Mondoñedo nappe basal thrust. The main geological units are those proposed by Julivert *et al.* (1974).

affected by low to medium grade regional metamorphism, and contact metamorphism in the area around the granite. These features, particularly the relationship between the regional structure and the intrusion of the Forgoselo granite, give interest to the study of this area, whose geology is not well known at present.

Modern noteworthy contributions to the general geological knowledge of the study zone begin with Matte (1968), who described the two main deformation phases of the OSA. Capdevila (1969) made the first systematic analysis of the metamorphism and magmatism of eastern Galice. Fernández Pompa & Piera Rodríguez (1975) and Bastida *et al.* (1984) provided geological maps of the study zone at the scales of 1:50,000 and 1:200,000 respectively. The geology of adjoining areas of the OSA to the N and to the S of the study zone has been described by Bastida *et al.* (1993) and González Lodeiro *et al.* (1982).

Stratigraphy

Ollo de Sapo

The older rocks outcropping in the area belong to the Ollo de Sapo Formation, which consists of porphyroids. Two facies can be distinguished in the Ollo de Sapo Formation: the most common facies contains small feldspar porphyroclasts, whereas the less common facies

contains feldspar porphyroclasts a few centimetres in diameter. It mainly consists of volcanic metagreywackes and schists, composed of quartz, muscovite, biotite, K-feldspar, plagioclase and rarely chlorite and staurolite. In addition to the K-feldspar porphyroclasts, quartz porphyroclasts with corrosion embayments and a typical blue colour in hand sample are also common. The age of this formation has been a matter of controversy; recent radiometric data range from a Rb/Sr and Sm/Nd age of 570-580 Ma (near the Precambrian-Cambrian boundary) (Ortega *et al.*, in press) to a U/Pb crystallization age of 488 Ma (Tremadocian) (Gebauer *et al.*, 1993).

Cabos Series

The Ollo de Sapo Formation is overlain by the siliciclastic Cabos Series, a succession that appears in a gradual but rapid transition which can be seen in a locality in the southeastern corner of the zone. The Cabos Series presents very variable facies that poses a nomenclature problem. Two lithostratigraphic units have been previously distinguished in the OSA above the Ollo de Sapo (Riemer, 1963, 1966; Matte, 1968). The lower one is a slate series 200 to 600 m thick with some sandstone intercalations and a basal quartzite of up to 20 m; this series was named Montes slates by Riemer (1963). The upper one is a massive white quartzite succession up to 250 m thick, that has been informally named Armorican quartzite. Nevertheless,

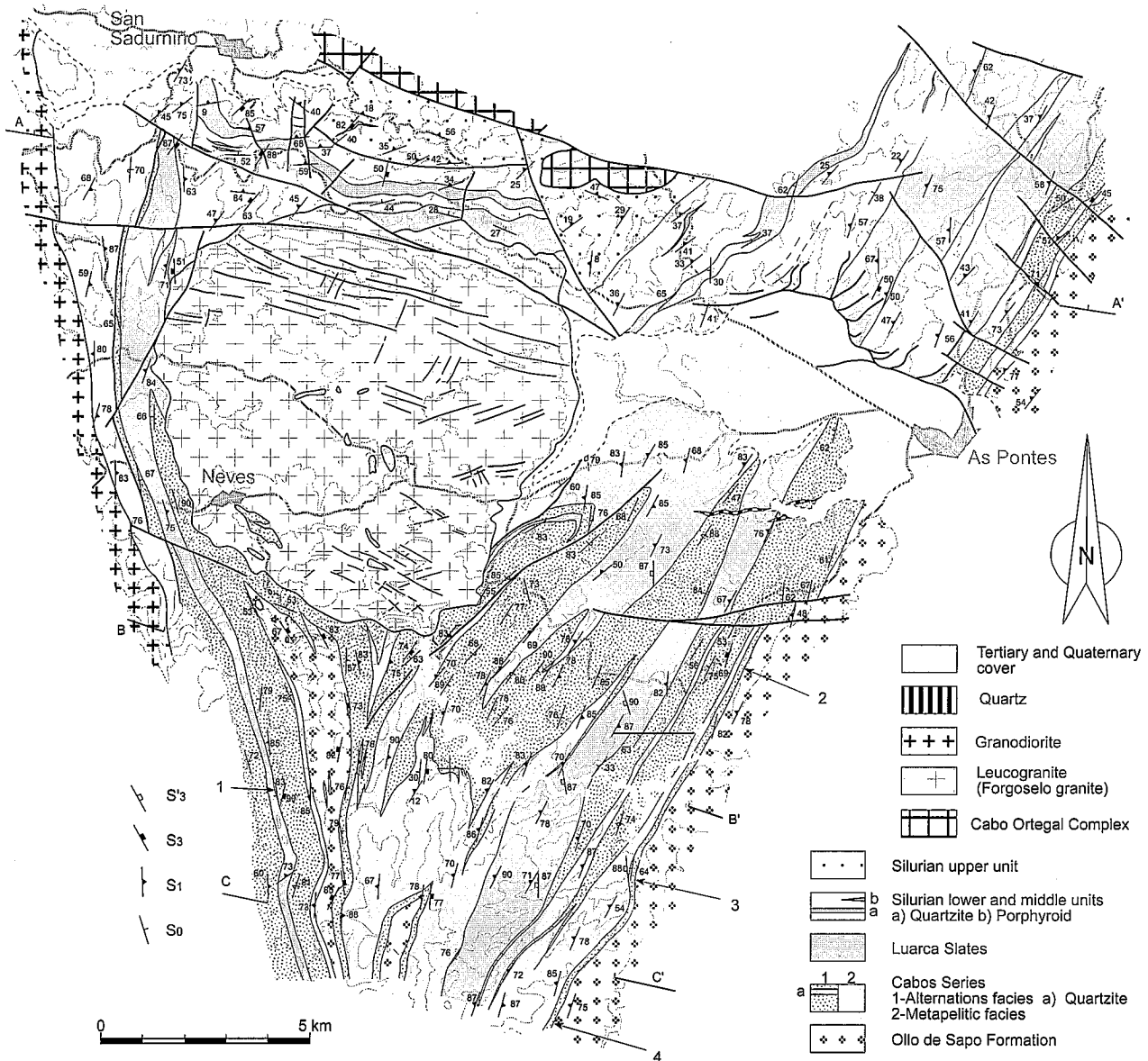


Figure 2.- Geological map of the Forgoselo granite and its country rocks. Mapping of the metasedimentary rocks inside the granite after Fernández Pompa and Píera Rodríguez (1973); faults in the northern boundary of the As Pontes basin after Ferrús Piñol (1994).

the stratigraphy of the rocks in the study area does not fit this pattern. Due to the differences between the successions of this area and the succession described by Riemer (1963, 1966) to the south, the name Cabos Series will be used here; this term is used in the Westasturian-Leonese zone for the siliciclastic succession outcropping immediately below the Luarca Slates (Lotze, 1958) and its use avoids the definition of a new lithostratigraphic term.

In the map, two types of facies have been distinguished in the Cabos series (Fig. 2): a metasandstone-metapelite alternations facies, which is dominant in the northern and western part of the area, and a mainly metapelitic facies, which is restricted to the southern part. Two main types of successions can be distinguished in the zone on the basis of the variable distribution of these facies (Fig. 3): Carballo-Castro type successions with

dominant metasandstone-metapelite alternations facies and Eirabella type successions with dominant metapelitic facies.

The Carballo-Castro type successions, dominant in most of the area, have a thickness between 900 and 1200 m and usually consist of three members which have been distinguished in the type sections (Fig. 3A and B) but are not easy to follow in the map:

- Lower member. It is formed by metasandstones with some metapelites. The thickness is less than 100 m in general.

- Middle member. It consists of black, grey or dark green slates with some metasiltstone laminations and very local metasandstones concentrated in some parts of the succession. The thickness is less than 325 m.

- Upper member. It is mainly formed by metasandstones or metasandstone-slate alternations

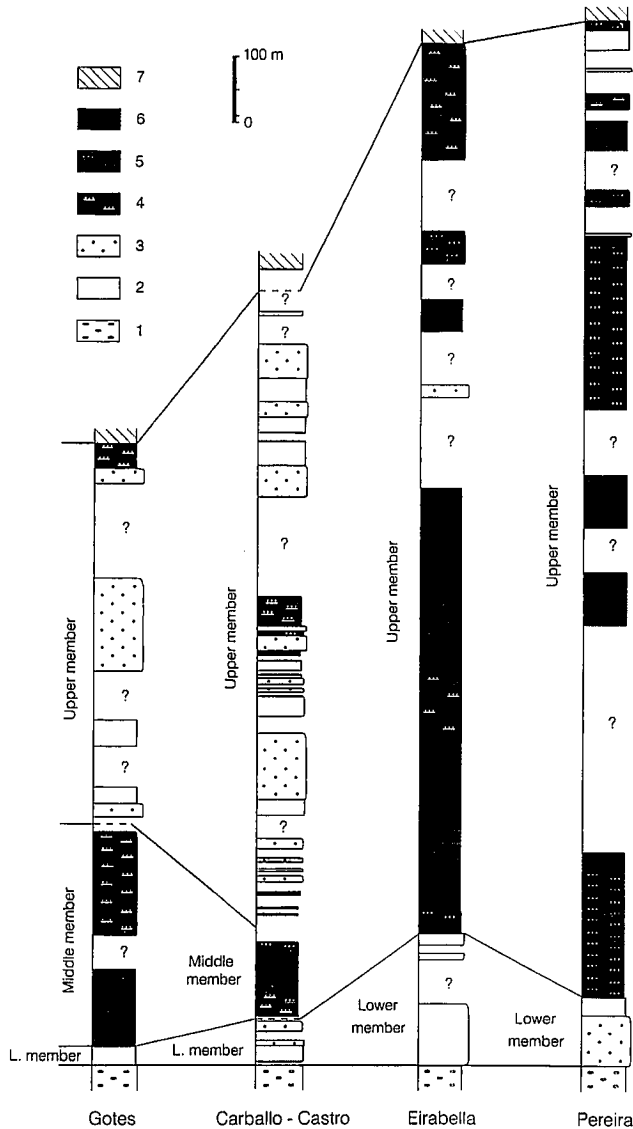


Figure 3.- Representative stratigraphic columns of the Cabos series in the study zone. 1. Olló de Sapo Formation. 2. Alternations of sandstones and slates. 3. Sandstones. 4. Slates with local sandstone beds. 5. Slates with local sandstone laminations. 6. Slates. 7. Luarca Slates.

with dominant metasandstones. Moreover, some slaty levels are sometimes found in this member (Fig. 2). A quartzite level up to 100 m thick is found in the central part of the study area. In this part, the presence of *Cruziana cf. rugosa* (classification of A. Marcos) suggests an Arenigian age. The thickness of this member ranges from 550 to 1000 m.

Eirabella type successions are only found in the southeastern sector of the area and have a thickness of about 1500 m. Two members can be distinguished in these successions:

- Lower member. It consists of alternating metasandstones and slates, with the former dominant. The thickness ranges from 100 to 200 m. This member is similar to the lower member of Carballo-Castro type successions.

- Upper member. It presents black slates, some silty slates and local metasandstone laminations. A metasandstone level a few meters thick is common in the uppermost part of this member. The lithological facies of this member resembles that of the overlying formation (Luarca Slates). This member changes laterally in the map to the middle and upper members of the Carballo-Castro type successions (Figs. 2 and 3).

Luarca Slates

This formation appears on top of the Cabos Series and is constituted by glossy homogeneous black slates with a well developed slaty cleavage; its thickness is about 1000 m.

Silurian

The Silurian consists of an inhomogeneous succession in which black slates are the dominant lithology except in the upper part. No fauna has been found and the attribution to the Silurian is made by correlation with other areas, mainly the northern coast region. Minimum thickness exceeds 3000 m. This succession can be divided in three units.

The lower unit consists of black grey reddish or green slates, often sandy, which contain metasiltstone and metasandstone and local lydites. Some levels with metasandstone pebbles are found in the basal part. Moreover, porphyroid intercalations with little lateral continuity appear in this lower unit; they are acid volcanoclastic rocks composed of quartz, plagioclase, K-feldspar, muscovite and chlorite, and show a very immature texture. The thickness of the lower unit is of c. 1000 m.

The basal part of the middle unit presents one or two levels of white quartzite with very variable thickness up to 400 m. The quartzite is coarse grained with some microconglomerate intercalations. Cross bedding is locally found. The succession between the quartzite levels and on top of them consists mainly of slates. In the upper half of this middle unit, a level of porphyroid similar to those in the lower unit is locally found. The thickness of the middle unit is of c. 1000 m.

The upper unit is featured by the predominance of grey or light green strongly laminated feldspar greywackes. They are very immature rocks both from the perspective of mineral composition and texture. Grey and dark green slates and local lydites appear between the greywacke layers. The minimum thickness of this unit is of c. 1000 m.

Tertiary and Quaternary cover

The Tertiary and Quaternary cover appears unconformable on the Paleozoic rocks. The main element of this cover is the As Pontes basin, located in the eastern part of the study area. This basin consists of up to 200 m of lutites, sandstones and coal (Bacelar *et al.*, 1988).

The Forgoselo granite

The Forgoselo granite has a roughly rounded shape

in outcrop (Fig. 3) and sharp boundaries with the wall rocks. It is a leucogranite mainly composed of quartz, K-feldspar, plagioclase (oligoclase), muscovite and biotite, with abundant megacrysts of K-feldspar. It belongs to the group of granites with megacrysts of the two mica granites series (Capdevila & Floor, 1970), which comprises syntectonic, peraluminous two mica leucogranites with dominant muscovite. Late veins are common inside the granitic body and in the wall rocks. These veins are mainly composed of biotite rich granite or quartz. Schist and quartzite xenoliths are common. A Rb/Sr radiometric age of 317 ± 6 Ma has been obtained for this granite (Capdevila & Vialette, 1970; Cocherie, 1978; Gil Ibarra, 1983; Serrano Pinto *et al.*, 1987). Capdevila *et al.* (1973) proposed an origin by wet anatexis at midcrustal levels for the granitic series to which this granite belongs.

Structure

The structure of the study area is shown in the cross sections of Fig. 4. The main structural features of the zone can be explained by the superposition of three deformation phases, which correspond with those usually recognized in the hinterland of the Hercynian belt in NW Spain (Marcos, 1973).

The first phase of deformation (D_1) gave rise to tight east-vergent kilometric-scale folds with an associated cleavage (S_1) whose orientation is shown in Fig. 5A. D_1 fold traces trend NNE-SSW and the axial directions are indicated by the L_1 orientations of Fig. 5B. A D_1 anticline-syncline pair with an overturned limb 5 to 7 km long can be observed in the eastern part of all the sections (Fig. 4).

During the second phase of deformation (D_2) the Cabo Ortegal Complex was emplaced along a thrust with associated mylonitization and phyllonitization. D_2 structures can only be observed near to the northern boundary of the study zone.

The third phase of deformation (D_3) gave rise to folds with mainly sub-horizontal axial directions and an associated crenulation cleavage (S_3) whose orientation is shown in Fig. 6A. The style of D_3 folds changes from the northern to the southern part of the study zone (Fig. 4). In the northern part (cross section I-I' of Fig. 4), D_3 folds are open and upright, with a general structure constituted by a wide synform plunging to the north, which can be followed further north in the Cabo Ortegal complex (Fig. 1). In this northern sector, S_3 crenulation cleavage is only found in the western part. Immediately to the south of the granite (cross section II-II' of Fig. 4), a D_3 synclinorium, formed by close to tight folds, displays a fan pattern formed by upright folds in the central part of this sector and folds moderately inclined to the east in the western part. In this sector, D_3 folds plunge gently to the north. Southwards (cross section III-III' of Fig. 4), D_3 gave rise to close to tight upright folds. In the area to the south of the granite, S_3 is well developed.

A subvertical crenulation cleavage, which cuts with low angle both limbs of D_3 folds, is found in the sector to the east of the granite, where S_3 is not common. This relationship can be observed on the map (Fig. 2) and in some outcrops. According to the interpretation that will be presented below, this cleavage was formed in the late stages of D_3 ; hence, it will be labeled S'_3 . Its orientation is shown in Fig. 6B. The coexistence of S_3 and S'_3 is rare, but occurs in some outcrops.

Elliptical oxidation spots with subhorizontal major axis have been found on S_1 in several outcrops of the Cabos series. These spots are difficult to interpret since their age and origin are not well known, but it can be suggested that they reflect the strain undergone by the rocks from the moment when the spots originated. A mainly subhorizontal orientation for the maximum elongation of the finite strain ellipsoid has been proposed for the northern part of the OSA by Rathore *et al.* (1983) on the basis of mica and magnetic fabric studies.

The superposition of D_3 folds on D_1 folds gave rise to type 3 interference patterns (Fig. 4) which have been interpreted from the relationships between D_1 and D_3 structures observed in the field and under the microscope (Fig. 7). This interpretation suggests that D_1 folds were originally recumbent.

There are faults in the study area which originated at different times. The older and most important of these faults is the Pontedeume-Valdoviño fault zone (Fig. 4), which forms the western boundary of the study area and along which different types of granites have intruded (Courrioux, 1983, 1984). A zone with ductile deformation involving the development of mylonites and a local subhorizontal stretching lineation is found in the metasedimentary rocks located immediately to the west of the fault; in addition, shear bands are widespread indicating a sinistral strike-slip movement in these rocks. Mylonites deformed by D_3 folds are also found, indicating that the movement of the fault is, at least in part, pre- D_3 . There are other longitudinal faults in the zone, such as that located to the east of the Pontedeume-Valdoviño fault zone which involves a downthrow of the western block.

In addition, there is a set of mainly transversal normal faults, which are concentrated in the northern part of the area and in many cases have the hangingwall down-dropped to the north. Alpine deformation gave rise to faults with a reverse movement that uplifted the northern block. These faults affect the Tertiary rocks of the As Pontes basin (Fig. 2) (Bacelar *et al.*, 1988; Ferrús Piñol, 1994).

A great part of the granitic body shows a random fabric. Nevertheless, slight preferred shape orientation of K-feldspar megacrysts is commonly observed. This orientation has a local character and often several orientations coexist in the same outcrop. The orientation variation suggests an origin of these foliations mainly determined by local irregularities of the magma flow which can have been influenced by the

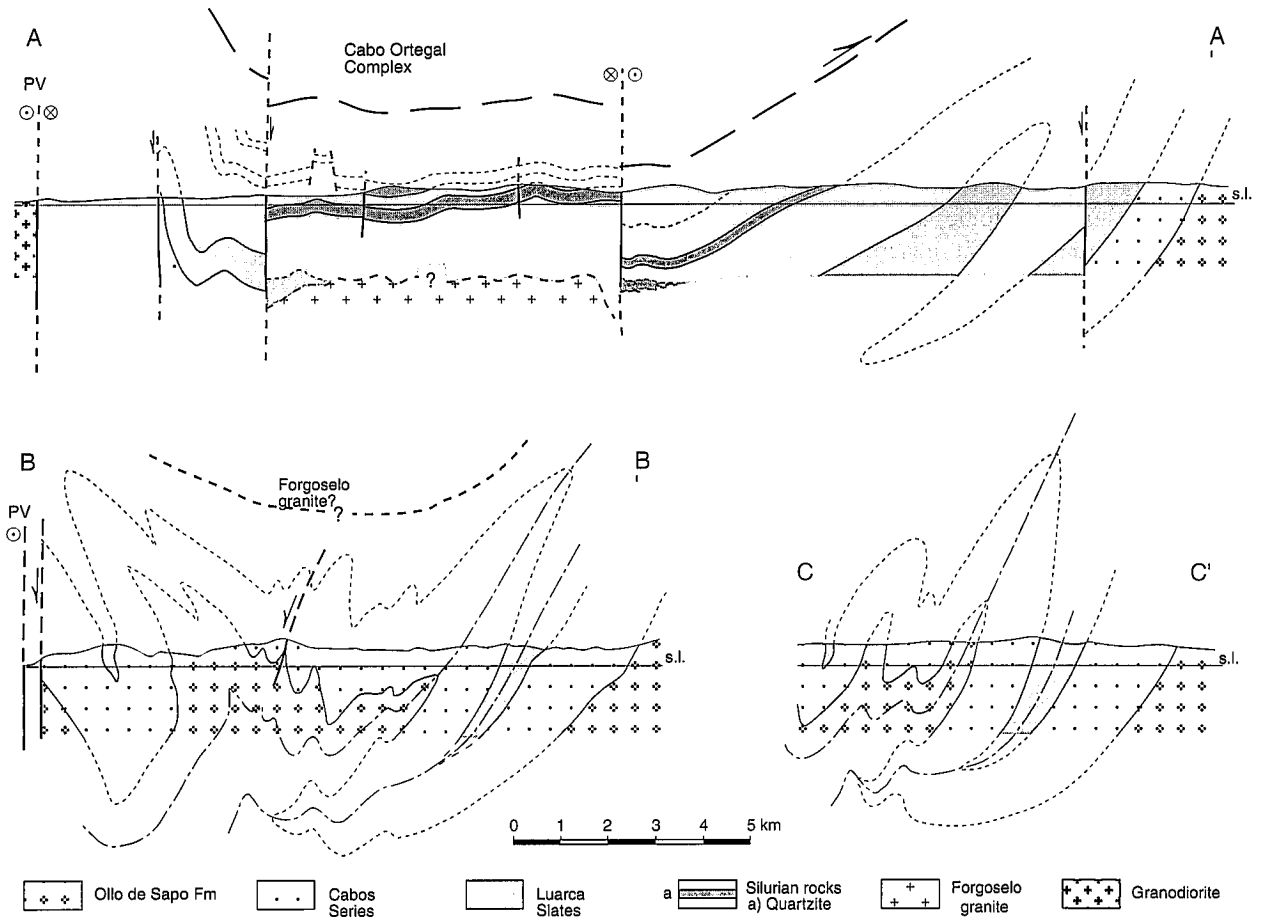


Figure 4.- Geological cross sections through the study zone. For location of the sections see Fig. 2. PVF: Pontedeume-Valdoviño fault.

existence of less deformable zones of the magma (cf. percolation mechanism of Blanchard, 1978).

Locally, some solid-state deformation can be found in the granite near to the borders. Courrioux (1984) analysed this deformation in the southern border of the intrusion by using folded and boudined veins, and found a nearly N-S directed maximum shortening. This orientation is perpendicular to the regional E-W directed maximum shortening during the intrusion, as deduced from the

orientation of the S_3 cleavage, synchronous with the intrusion.

The granite contains late joints, the most conspicuous of which are represented on the map (Fig. 2).

Microstructural analysis

The S_1 foliation is better observed in the northern part of the area, where S_3 is rare. In mudrocks S_1 forms a slaty cleavage or a penetrative domainal cleavage,

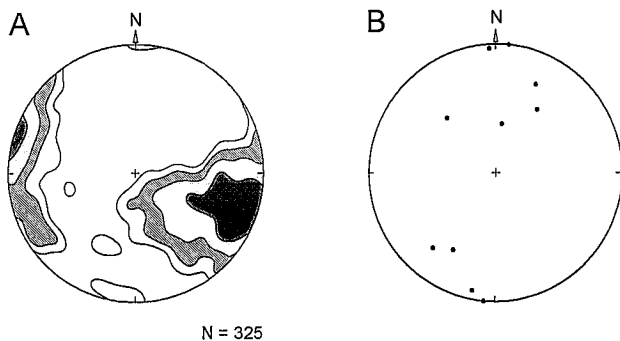


Figure 5.- Stereographic plots showing the orientation of: A) poles to S_1 (contours: 0.5, 1, 2, 4 %); B) L_1 .

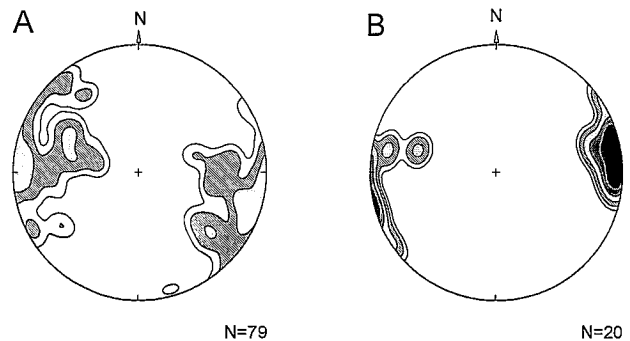


Figure 6.- Stereographic plots showing the orientation of: A) poles to S_3 (contours: 1, 2, 4 %); and B) poles to S'_3 (contours: 1, 2, 4, 8, 16 %)



Figure 7.- Microscopic type 3 interference pattern of D_1 and D_3 folds. Width of view 3.84 mm.

whereas in sandstones it is a rough cleavage defined by discontinuous wavy anastomosing cleavage domains, formed by phyllosilicates and opaque material, and/or orientated mica beards.

In the quartzites, S_1 is not present or is poorly developed. In this latter case, it is defined by a weak shape orientation of the quartz grains and/or the orientation of sparse mica crystals. The microstructure of the quartzites ranges from quartzites with slightly to moderately deformed detrital grains without recrystallization to quartzites with old and new grains (Wilson, 1973). Evidences of post- S_1 static recrystallization are common, mainly in the quartzites

of the eastern part of the zone.

The S_3 foliation is well developed in all the zone, except in the northern part. Several types of S_3 can be distinguished in mudrocks which indicate different evolution stages: crenulation folding, crenulation cleavage, differentiated cleavage, and schistosity.

The crenulation folding represents the less evolved D_3 microstructural stage (Fig. 9A). In most cases, these folds are asymmetric with axial surfaces oblique to S_1 .

The crenulation cleavage is usually oblique to S_1 and commonly presents smooth nearly parallel discrete to zonal cleavage domains (Fig. 9B). Microfolds, generally asymmetrical, are widespread, although the presence of not folded crossed micas is not rare (Fig. 9C).

The differentiated cleavage is a zonal cleavage with dark and light smooth nearly parallel domains (Fig. 9E). The dark domains are the thickest and are formed by chlorite, graphite and muscovite; a flattened S_1 is the dominant foliation within these domains. The light domains are formed by quartz and muscovite and they present crossed micas and some single microfolds which indicate evolution from a crenulation cleavage. The quartz commonly presents straight boundaries and microstructural features indicating intracrystalline deformation are rare, suggesting a late event of static recrystallization. A differentiated crenulation cleavage appears in some cases (Fig. 9D) and it represents a transitional term with the crenulation cleavage.

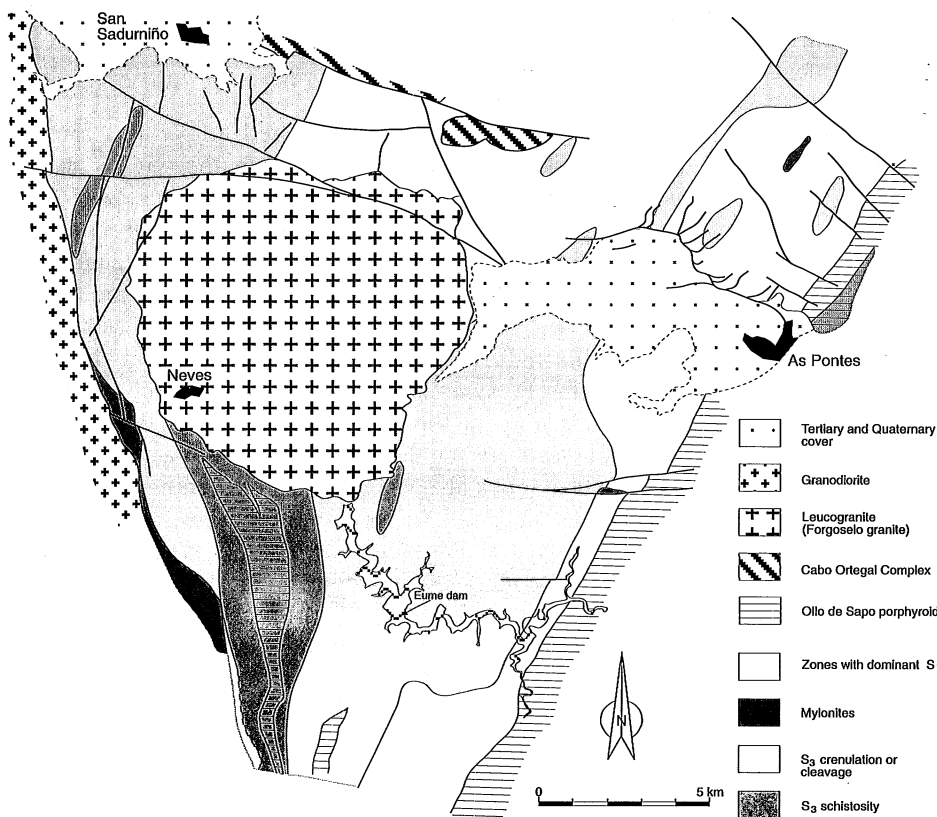


Figure 8.-Distribution in the area of different D_3 microstructural types.

The schistosity presents similar features as those of the differentiated cleavage but with a larger mica grain size (Fig. 9F). Staurolite commonly includes open microfolds which represent an early stage in the development of the schistosity.

The map distribution of the S_3 types does not show a simple pattern. Only three types of zones have been distinguished in the geological scheme of Fig. 8: zones without S_3 , which present dominantly S_1 (northern part) or mylonites (eastern part); zones with crenulation folding, crenulation cleavage or differentiated cleavage, which represent most of the study area, and zones with schistosity, mainly located in the southern part along the N-S oriented band with a higher metamorphic grade.

The transitions of S_3 from crenulation to differentiated cleavage/schistosity can be related with an increase in D_3 maximum shortening. The main factor controlling the development of schistosity instead of a differentiated cleavage is the increase of metamorphic grade.

The nature of the pre- D_3 fabric also has an important control on the type of S_3 developed. If the pre- D_3 fabric was a well developed slaty cleavage, S_3 microfolds are well defined and the S_3 cleavage domains are smooth and parallel. On the other hand, if the pre- D_3 fabric was a rough cleavage, S_3 microfolds are poorly defined and the S_3 cleavage domains are wavy and anastomosing. Late- to post- D_3 thermally induced mimetic growth of mica on this type of S_3 probably gave rise to crossed mica fabrics.

The general asymmetric character of S_3 microfolds indicates that the maximum compressive stress during D_3 was oblique to S_1 . As a result, the light quartz rich domains of the differentiated cleavage developed on the short limbs and the hinges of the S_3 microfolds as a consequence of pressure solution. These domains are usually less thick than the dark domains and their distribution is irregular, depending on the relative length of both limbs. In the long limbs, D_3 only gave rise to rotation and flattening of S_1 .

Metamorphism

Rocks in the study area were affected by a regional metamorphism. Moreover, a contact metamorphism aureole is observed around the Forgoselo granite.

Regional metamorphism

Most of the study area is included in the chlorite zone (Fig. 10), with chlorite + muscovite + quartz as the common mineral assemblage.

A biotite zone can not be mapped in the study area. Nevertheless, a small zone containing chloritoid has been mapped in the southern part of the area. The most common assemblage in this zone is: chloritoid + chlorite + muscovite + quartz.

In the southern part, a staurolite zone has been mapped along a band following the core of the western antiform. The characteristic mineral assemblage in the metapelitic rocks of this zone is: staurolite + chloritoid + muscovite + quartz. In the metagraywacke of the Ollo de Sapo Formation, the assemblage is: staurolite + biotite + muscovite + quartz. Chlorite appears in this zone as a product of retrograde metamorphism.

It is noteworthy that garnet rarely occurs, even in the higher metamorphic grade areas. Lack of almandine suggests a low P/T ratio metamorphism. Nevertheless, the presence of staurolite suggests a gradient close to medium P/T ratio conditions. The absence of a kyanite or regional andalusite hampers a final decision about this point.

Contact metamorphism

In the contact aureole around the Forgoselo granite, an andalusite isograd has been mapped that cuts the staurolite isograd of the regional metamorphism (Fig. 10). Relicts of staurolite included in andalusite are common in the area where the andalusite zone is superposed on the staurolite zone. Small garnets have been found in a few cases in the andalusite zone. Adjacent to the Forgoselo granite a hornfels with decussate textures is developed.

As regards the relationships between metamorphic crystallization and deformation, the staurolite is pre- to syn- S_3 , which agrees with the folding of the staurolite isograd by a D_3 antiform. Andalusite is syn- to post- S_3 .

Structural control in the intrusion of the Forgoselo granite

The D_3 structure described above indicates a remarkable disharmony between the wide synform observed in the basal part of the Cabo Ortegal Complex and in the northern sector of the study area (section I-I' of Fig. 4), and the folds with minor wavelength that appear in the other sections (sections II-II' and III-III' of Fig. 4). On the other hand, comparison of sections I-I' and II-II' (Fig. 4) shows a more rounded geometry for the D_3 synclinorium of the former section, with a thickening in the hinge zone. Map analysis of the contacts between the Silurian, the Luarca slates and the Cabos Series also suggests this thickening.

From a mechanical perspective, the features described above can be explained by the D_3 buckle folding of an incompetent layer (Luarca slates and Silurian rocks, with a thickness of c. 4000 m) intercalated between two thick competent layers: the Cabo Ortegal Complex on top with a minimum thickness of 3500 m, and the Cabos Series, together perhaps with the Ollo de Sapo Formation, at the bottom with a minimum thickness of 1000 m. The observed disharmony between sections I-I' and II-II' (Fig. 4) can

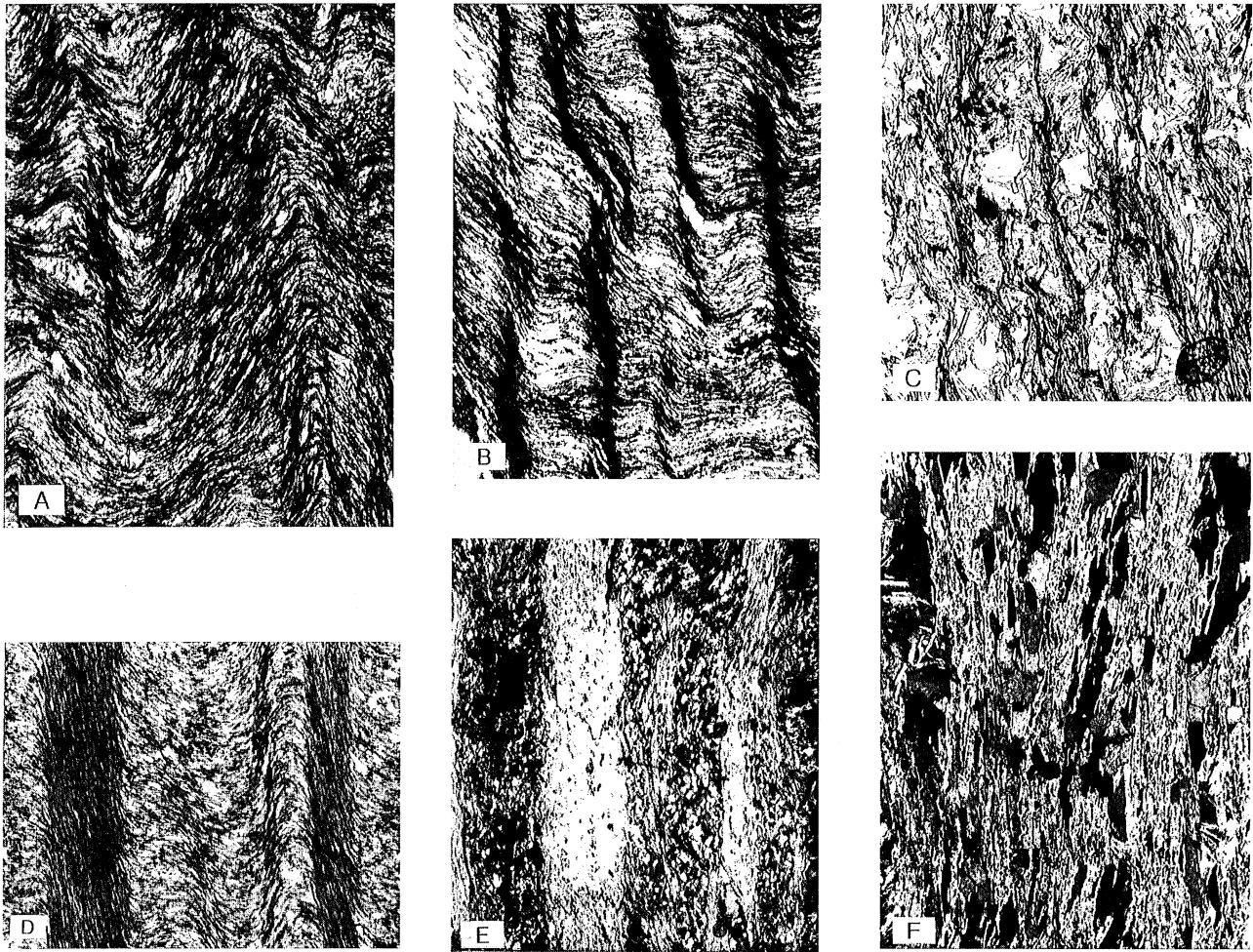


Figure 9.- D_3 microstructural types: A) Crenulation folding; B) Crenulation cleavage; C) Cleavage with crossed micas; D) Differentiated crenulation cleavage; E) Differentiated cleavage; F) Schistosity. Width of view for A and C 0.72 mm, for B, E and F 2.84 mm, and for D 3.65 mm.

be explained in terms of the competence, anisotropy and thickness of the two competent layers, since the higher anisotropy and minor thickness of the lower competent layer could have favoured the minor wavelength of the D_3 folds in this layer. On the other hand, the final geometry that results from the buckle folding of this set of three thick layers was probably dominated by the competent layers, which according with all the folding mechanisms active in them (flexural mechanisms, tangential longitudinal strain and perhaps some flattening) should have developed class 1 geometries. Hence, the geometry of the incompetent layer must have accommodated those of the adjacent competent layers and resulted in a class 3 geometry (e. g. Ramsay, 1967, Fig. 7-102). This geometry involves the development of a dilation space in the hinge zone, comparable to those deduced by Ramsay (1974) and Ramsay & Huber (1987) for chevron folds. According to these authors, these spaces can be occupied by flow of incompetent material, saddle reef structures formed by recrystallization from solutions, or can result in the formation of hinge collapse structures. The location of the Forgoselo

granite suggests that the potential hinge space was occupied by the magma flow leading to the formation of the granite.

The N-S maximum shortening inferred by Courrioux (1984) in the southern part of the Forgoselo granite, together with the presence of dykes in the wall rocks, suggest a dominant ballooning mechanism in the later stages of the granite intrusion. This mechanism accounts for the deformation of the wall rocks, which can be mainly recognized on the map near the western border of the granite, where the stratigraphic contacts and the axial trace of the D_3 folds appear pushed aside by the granite (Fig. 2). Moreover, this mechanism also explains why the area occupied by the granite appears to be greater than that correspondent to the hinge dilation space.

The crenulation cleavage (S'_3) that cuts both limbs of D_3 folds can be explained as an effect of the late- D_3 regional stress system acting on the host rocks after the granite intrusion. This stress system was probably active after intrusion with an orientation similar than before, and due to the rotated position of the D_3 folds as a consequence of the ballooning, it gave rise to a

transecting crenulation cleavage.

According to the age of the contact metamorphism (syn- to post- S_3), the deformation of the D_3 folds due to the ballooning of the granite and the interpretation given to the S'_3 , the intrusion postdates the main D_3 structures but was before the last episodes of this deformation phase, represented by S'_3 . This age agrees with Ramsay's model for the geometrical evolution of chevron folds, that involves an important increment of the dilation spaces in the advanced stages of folding (Ramsay, 1974, equations 9 and 10).

Discussion and conclusions

A remarkable stratigraphic feature of the study zone is the presence, on top of the Ollo de Sapo porphyroid formation, of a siliciclastic series with important lateral changes of facies. This series has been named Cabos Series since it presents some dominantly pelitic successions which are different to that described by Riemer (1963) to the south. A distinctive characteristic of these successions is the absence of a quartzite level (Armorican quartzite) in the upper part of the series.

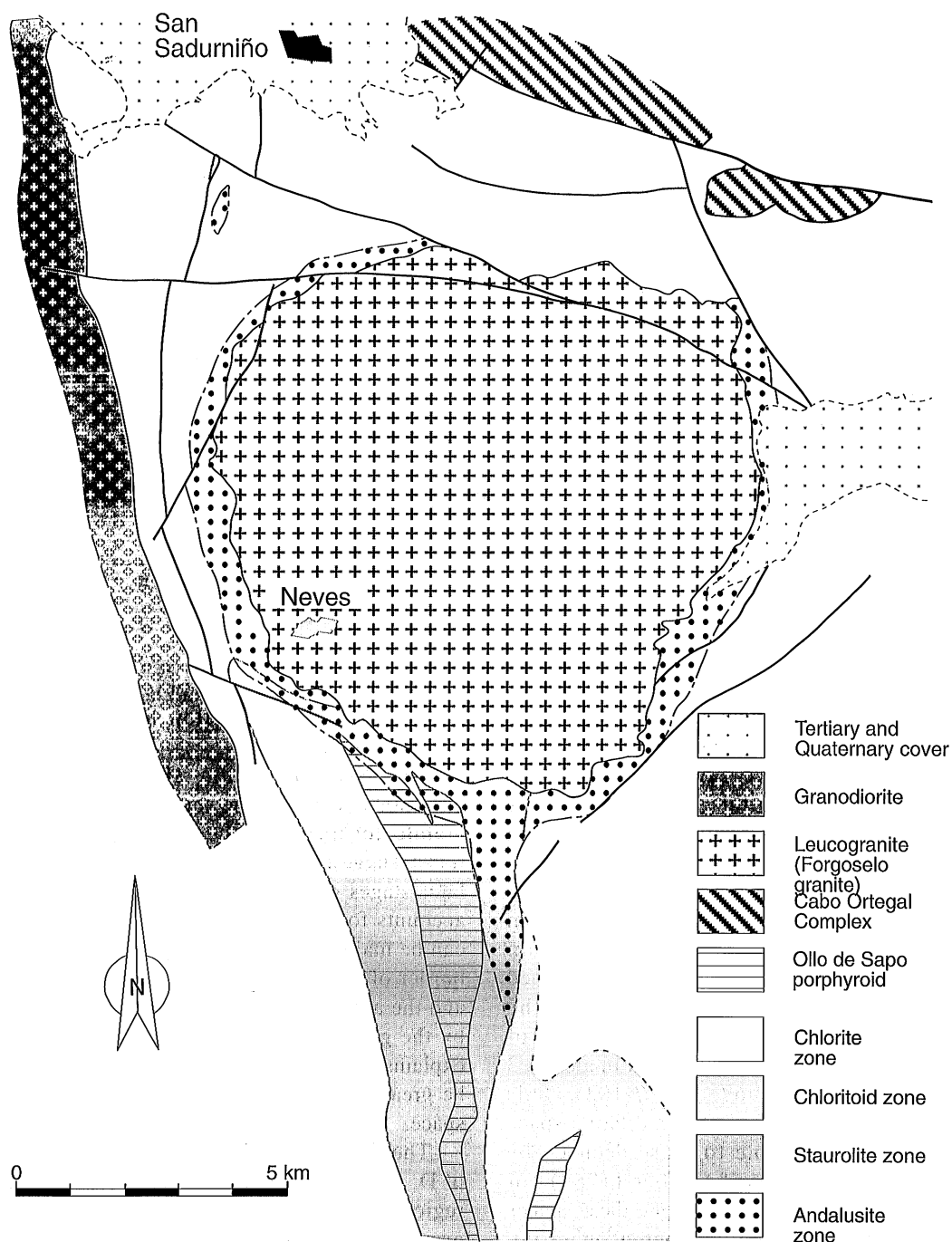


Figure 10.- Distribution of metamorphic zones in the country rocks of the Forgoselo granite.

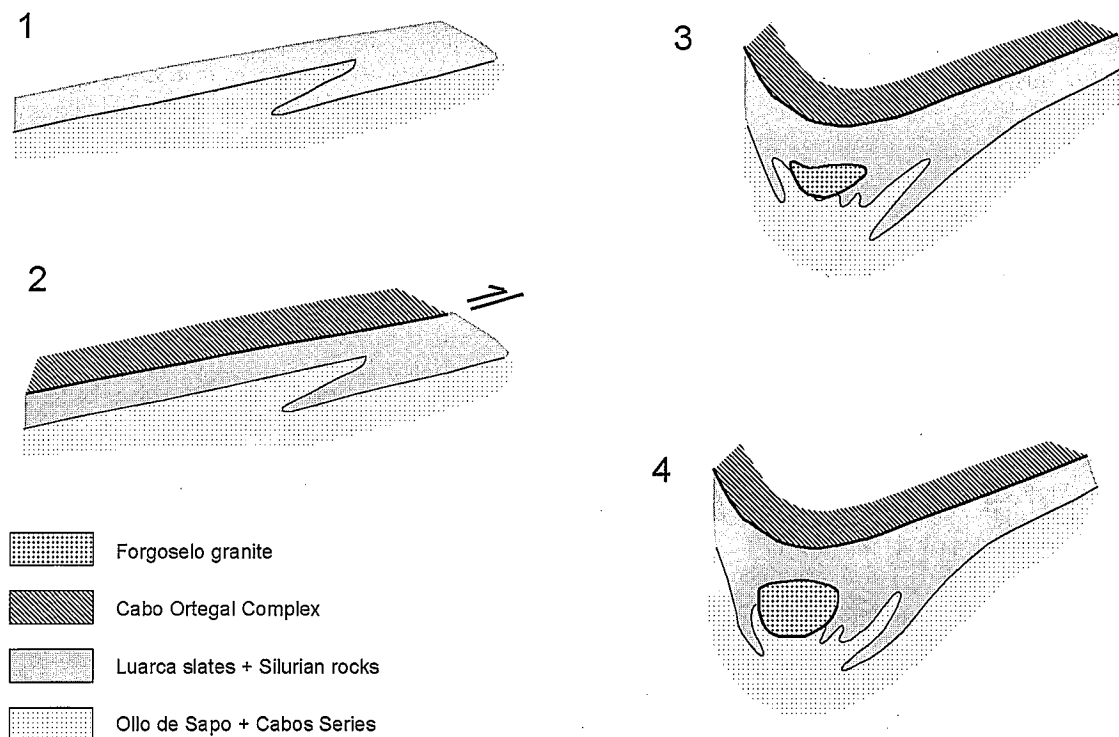


Figure 11.- Sketches showing the structural evolution of the study area. 1. Formation of tight east-vergent folds (D_1) with an associated foliation (S_1). 2. Development of the basal thrust of the Cabo Ortegal Complex and associated structures (D_2). 3. Formation of the D_3 folds and associated crenulation cleavage (S_3). When the tightening of the synform reached a threshold, magma flow to fill the dilation space began. 4. Ballooning of the granite and pushing aside of D_3 structures in the wall rocks. Magma alocation during stages 3 and 4 is supposed to be lateral.

The deformation of the rocks in the zone resulted from the superposition of structures originated in three main phases as commonly occurs in the hinterland of the Hercynian belt in NW Spain. The most remarkable structural feature is the inhomogeneous development of D_3 structures through the zone. D_3 folds vary from the wide gentle synform observed in the northern part of the zone to a fan of very close folds in the southern part (Fig. 4). This variation is caused by the location of the area in the contact strain zone of the Cabo Ortegal Complex synform, whose span is controlled by the dominantly competent and massive character of the rocks of this complex.

The Forgoselo granite intruded during the final stages of D_3 in a dilation space associated to the Cabo Ortegal Complex synform. This granite provides a good example of intrusion related to folding and shows how magmas generated in a compressive regimewhich gives rise to folds can intrude in local decompressive areas originated by the folding mechanism, as hinge dilation spaces (Fig. 11).

Granitoids synkinematic with a compressional deformation phase can be found in many orogens. Nevertheless, examples of the intrusion of granitic rock into compressional structures are rare in the geological literature (McCaffrey 1992; Ingram & Hutton 1994). In fact, most of the intrusions described in the literature have been related to extensional shear zones (Hutton, 1988; Hutton *et al.*, 1990; Gapais *et al.*, 1993) or transcurrent shear zones (Brun & Pons, 1981; Hutton,

1982; Courrioux, 1983; White & Hutton, 1985; Castro, 1986; Guineberteau *et al.*, 1987; Hutton, 1988; D'Lemos *et al.*, 1992; Hutton & Reavy, 1992). The emplacement model proposed for the Forgoselo granite constitutes an example of how local favourable conditions for the accomodation of intrusive material within country rocks can be found in compressive regimes with folding as dominant process.

Conditions comparable to those described for the Forgoselo granite probably occur in the band of intrusive late- to post- D_3 leucogranites (Boal, Los Ancares and Ponferrada granites, Fig. 1), which appear in the Westasturian-Leonese zone in the footwall to the Mondoñedo nappe basal thrust (MNBt, Fig. 1). These granites belong to the same group of the Forgoselo granite. The band occupies a zone where D_3 folds appear, giving rise to a fold train with a subhorizontal enveloping surface, and is bounded by two zones with a steep and nearly constant dip of S_1 , resulting in an asymmetric stair-like structure. This geometry involves an extension subperpendicular to the general orientation of the anisotropy in the band with D_3 folds and subhorizontal S_1 . This extension could have given rise to an opening of the S_1 and S_0 , and to local dilation spaces -similar to those described for kink-bands or chevron folds (Ramsay, 1967, 1974; Ramsay & Huber, 1987)- which could have favoured the displacement of magma, and, through a concentration of fluids, also the formation of magma. The motion and final emplacement of these granites continued after the end of D_3 . Dilation

spaces at the scale of the outcrop, related to the subhorizontal limbs of D_3 stairlike folds, with formation of quartz veins or tectonic banding have been described in the Westasturian-Leonese zone (Pulgar, 1981) and also indicate a migration of fluids towards these limbs.

The Forgoselo granite area presents some features in common with the Boal-Los Ancares-Ponferrada granitic band, and some of the arguments used for explaining granite intrusion in this band can be also applied to the Forgoselo granite, as the location in a band with strong development of D_3 structures.

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