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PROJECT 276
Paleozoic of the Tethys

The Hercynian structure of the Catalonian Coastal Ranges (NE Spain)

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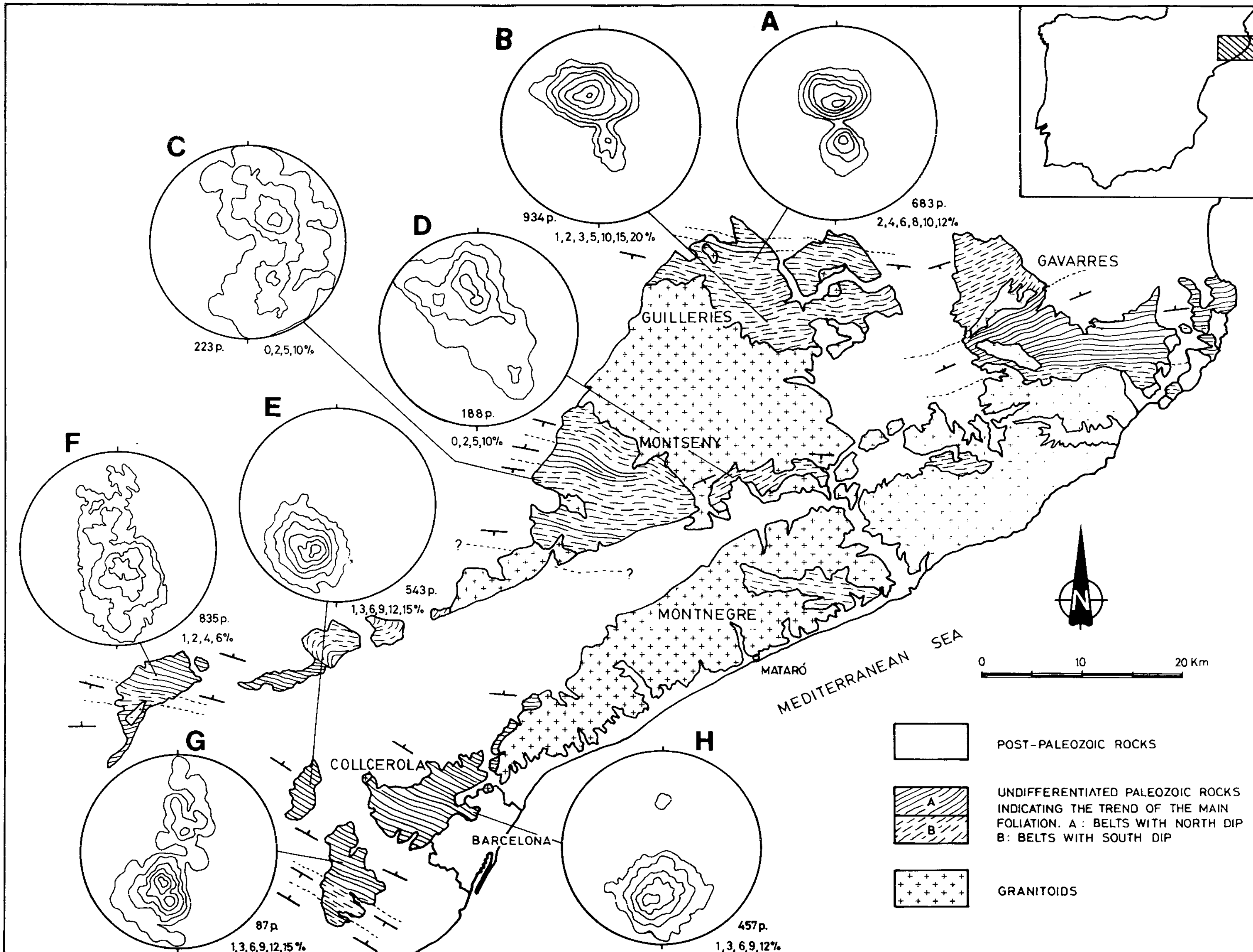
ABSTRACT

In the Catalonian Coastal Ranges, Paleozoic sedimentary and meta-sedimentary rocks crop out in several areas, intruded by late tectonic Hercynian granitoids and separated by Mesozoic and Tertiary cover sediments. Large structures are often difficult to recognize, although a general east-west trend can be observed on the geological map. Deformation was accompanied by the development of cleavages and regional metamorphism. Green-schist facies rocks are prominent throughout the Ranges, while amphibolite facies are restricted to small areas. In low-grade areas, the main deformation phase generated south-facing folds with an axial plane cleavage (slaty cleavage in metapelitic rocks). The intersection lineation (Ss/S1) and the axes of minor folds trend east-west, as do all mapable structures. Late deformations generated coarse crenulations, small chevrons and kink-bands, all intersecting the slaty cleavage at high angles. In medium- to high-grade areas no major folds have been observed. In these areas, the main foliation is a schistosity and is often folded, giving centimetric to decimetric, nearly isoclinal intrafolial folds. In schists, these folds are much more common than in other lithologies, and can be associated with a crenulation cleavage. All these planar structures in high-grade rocks are roughly parallel. The late Hercynian deformational events, which gave rise to the crenulations and small chevrons, also produced large (often kilometric) open folds which fold the slaty cleavage and schistosity. As a consequence, alternating belts with opposite dip (north and south) of the main foliation were formed. With respect to the Hercynian orogenic belt, the Paleozoic outcrops of the Catalonian Coastal Ranges are located within the northern branch of the Ibero-Armorican arc, and have a relatively frontal position within the belt. The Carboniferous of the Priorat-Prades area, together with other outcrops in the Castellón Province, the Montalbán massif (Iberian Chain) and the Cantabrian zone (specially the Pisuerga-Carrión Province) probably form part of a wide area of foreland Carboniferous deposition placed at the core of the arc.

Key words: Hercynian fold belt. Hercynian foliations.

RESUMEN

En las Cadenas Costeras Catalanas, las rocas sedimentarias y metasedimentarias paleozoicas afloran en varias areas de extensión variable, intruidas por granitoides hercinianos tardíos y separadas por materiales de cobertera mesozoicos y terciarios. Las estructuras de primer orden son a menudo difíciles de reconocer, aunque el mapa geológico pone de manifiesto una dirección Este-Oeste de las estructuras. La deformación estuvo acompañada del desarrollo de foliaciones y metamorfismo, en general en la facies de los esquistos verdes. Las facies anfibolíticas se encuentran restringidas a unas pocas áreas. En las zonas de bajo grado, la fase principal de deformación dio lugar a pliegues vergentes al Sur, con una esquistosidad axial (slaty cleavage) en las rocas metapelíticas. La lineación de intersección (Ss/S1) y los ejes de los pliegues menores muestran una dirección Este-Oeste, al igual que las estructuras cartografiables. Las deformaciones tardías dieron lugar a la formación de crenulaciones, heterogeneamente distribuidas, pequeños chevrons y kink-bands. En las zonas de grado medio a alto no se han observado pliegues de orden mayor, singenéticos con la foliación dominante que tiene las características de una «schistosity». La esquistosidad presenta pliegues intrafoliales, mucho más comunes en los esquistos que en otras rocas. En los esquistos, estos pliegues pueden estar asociados a una fuerte crenulación, con desarrollo de bandeado tectónico. Todas estas estructuras planares, en las rocas de alto grado, son aproximadamente paralelas.Las deformaciones hercinianas tardías, responsables de la formación de crenulaciones y pequeños chevron, originaron también pliegues de órdenes de dimensiones mayores, que afectan a las foliaciones dominantes («slaty cleavage» y «schistosity» de las zonas de bajo y alto grado respectivamente). Como consecuencia, se formaron fajas alternantes con inclinaciones opuestas (al Norte y al Sur) de las foliaciones. Respecto a su posición dentro del orógeno herciniano, los afloramientos paleozoicos de las Cadenas Costeras Catalanas se situarían en la rama Norte del arco ibero-armoricano, en una posición bastante frontal. Los afloramientos carboníferos del área del Priorat-Prades, junto con los de la provincia de Castellón, del macizo de Montalbán (Cordillera Ibérica) y de la zona cantábrica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UNDIFFERENTIATED PALEOZOIC ROCKS INDICATING THE TREND OF THE MAIN FOLIATION. A : BELTS WITH NORTH DIP B: BELTS WITH SOUTH DIP
GRANITOIDS

(principalmente la región del Pisuerga-Carrión), forman parte probablemente de una amplia área de sedimentación carbonífera de antepaís, situada en el núcleo del arco.

Palabras clave: Orógeno herciniano. Foliaciones hercinianas.

INTRODUCTION

The Catalonian Coastal Ranges trend parallel to the Mediterranean coast in northeastern Spain, and consist of uplifted faulted blocks forming two small mountain ranges separated by a Neogene graben, trending in the same direction. From Barcelona to the northeast, they consist mainly of Paleozoic rocks, including a large amount of Late-Hercynian granitoids, while from Barcelona to the southwest Mesozoic rocks predominate. Paleozoic sedimentary and metasedimentary rocks form a number of scattered outcrops of variable size, intruded by Late-Hercynian granitoids and separated by Mesozoic and Tertiary cover sediments (Fig. 1).

Most Paleozoic rocks are affected by greenschist facies metamorphism. Amphibolite facies conditions are essentially restricted to the Guilleries and southeastern Montseny massifs (Van der Sijp, 1951; Viladevall, 1978; Durán, 1985, 1990; Julivert and Martínez, 1980; Sebastián *et al.*, 1990) and to the lowest stratigraphical levels. A small outcrop of amphibolite facies rocks has also been quoted in Les Pedritxes area, north of Sabadell (Ubach, 1990). The highest stratigraphical levels (Carboniferous) are anchi- or non-metamorphic, except where late granitoids induced a contact metamorphism.

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Figure 1.- The attitude of the main foliation (slaty cleavage in low grade metamorphic areas and schistosity in medium- and high-grade). The belts of north and south dip and the stereoplots for several areas, with indication of the number of points plotted, are given in the figure (equal area, lower hemisphere projection). A: Northern Guilleries (low-grade). B: Southern Guilleries (high-grade). C: Northwestern Montseny (low-grade). D: Southeastern Montseny (high-grade). E: Martorell area (low-grade). F: Capellades area (low-grade). G: Gavà area (low-grade). H: Collcerola (low-grade). A and B, according to Durán (1990). D, According to Huerta (1990). E, Data from Benet (1990). F, According to Serra (1990). G, Data from Fernández-Martos (1980). C and H according to Julivert & Durán (this paper).

OUTCROP DISTRIBUTION AND MAPABLE STRUCTURES

First order structures are not very often seen in the Catalonian Coastal Ranges, due to the monotony of the stratigraphical sequence. The Paleozoic massifs to the north (Montnegre, Montseny, Guilleries, Gavarres) consist mainly of granitoids and pre-Silurian rocks. Metapelites and metapsamites are the predominant rock-types in the pre-Silurian sequence. In this sequence, the only key-horizons occur in the lowermost part (Cambrian and older ?) and consist of marbles, amphibolites and gneisses found in Les Guilleries and southeastern Montseny (Van der Sijp 1951; Durán, 1990; Huerta, 1990). Silurian and Pridoli-Devonian rocks (essentially black shales and carbonates respectively) always form small outcrops. To the south (Priorat, Prades) the Carboniferous is predominant, forming a thick and monotonous turbiditic sequence, with chert and limestone horizons in its lower part. For more stratigraphical information see Julivert and Durán (1990).

Constructing a cross-section to show the Hercynian structure is rather difficult due to the scarcity of large structures observed and to the scattered disposition of the Paleozoic outcrops. However, this can be attempted by the combination of data from the outcrop pattern, the few metric to hectometric structures visible and the minor structures.

The outcrop pattern allows to distinguish a zone to the north, where the oldest and deepest rocks are exposed (southern Guilleries and southeastern Montseny) and a zone to the south where the Carboniferous is largely predominant (Miramar, Prades and El Priorat). In the remaining areas Ordovician rocks predominate, with comparatively small amount of Silurian, Devonian and Carboniferous outcrops, preserved in syncline cores.

Besides this broad outcrop distribution, the Devonian, the Silurian and the few existing key-horizons make it possible to trace some mapable structures. Among the most relevant is the Silurian-Devonian syncline zone in the Montnegre massif, which can be traced to the west into the southwestern part of the Montseny massif (Fig. 1). Also, the outcrops of Ordovician acid volcanic rocks in Les Pedritxes can be linked to the Mataró Gneisses, preserved as roof pendants within the granitoids of this area and described by Carreras and Santanach (1975). Finally, some key-horizons, such as the carbonate layers (Ashgill ?) and the dolerite sheets in Collcerola as well as some Carboniferous beds in the Priorat area, permit a few structures to be mapped, or at least to trace their trend. All these data indicate an east-west trend for the Hercynian mapable structures.

THE STRUCTURES IN LOW-GRADE AREAS

Metric to decametric structures

Apart from the mapable structures, folds of metric to decametric size can be observed where competent beds (mainly quartzites) occur. Folds can be frequently seen in Collcerola, and in general in the outcrops around Barcelona. These are asymmetrical south-facing folds, visible in quartzites. A southern vergence can also be observed in folds in the highest and non metamorphic part of the stratigraphical sequence, as for example in the Carboniferous area of El Priorat.

Except for the highest stratigraphical levels (Devonian and Carboniferous essentially), all Paleozoic rocks exhibit a tectonic foliation, heterogeneously affected by later crenulations and kink-bands or small chevrons.

The dominant foliation in low-grade metamorphic areas

Most pre-Devonian rocks of the Catalonian Coastal Ranges are metapelites and metapsamites with an abundant micaceous matrix. The dominant foliation is a slaty cleavage which completely conceals the bedding, except where a certain depositional layering exists (silt layers in the slates). Where this is the case the silt layers are strongly transposed, and an intersection lineation can be observed on the cleavage planes. Bedding can also be recognized where quartzite beds exist. The quartzites show a rough cleavage and the intersection lineation can also be observed.

Cleavage in pelites is defined by the preferential orientation of platy minerals (phylosilicates), although pre- or early syn-tectonic chlorite crystals with pressure shadows are often observed (Durán 1990). Quartz grains dispersed in the micaceous matrix of metapelites or metagreywackes and quartz grains in quartzites occasionally show a preferred dimensional orientation parallel to the cleavage, but most commonly they lack any visible orientation. For micaceous quartzites, micas define the cleavage planes.

In very low-grade and anchimetamorphic zones, an intersection pencil structure can be found in pelites, due to the intersection of a very weak cleavage with the bedding or with a diagenetic foliation parallel to bedding. This pencil structure can be often observed in fold cores of the Carboniferous pelites in the Priorat and also in the Ashgill (?) pelites in the north-western part of the Montseny massif. Very low-grade carbonate rocks (Pridoli-Devonian) often portray a weak pressure solution cleavage, especially where carbonates are not massive.

Trend and dip of slaty cleavage and related lineations

Slaty cleavage trend roughly east-west. The intersection lineation and fold axes (less frequently observed) plunge slightly (0-15°, in general) either to the east or to the west. These trends are maintained fairly constantly in the Catalonian Coastal Ranges, with only gentle variations, suggesting the existence of some weak cross-structures.

Crenulations, small chevrons and kink-bands

Crenulations are common in all low-grade areas in metapelites, but they do not usually form a well-developed cleavage, to overprint the first slaty cleavage. For this reason, an accurate measurement of the crenulation planes is often difficult. Where measurements of crenulations exist (Serra, 1990), they show a rather high dispersion. This could be due to the existence of several deformational phases giving rise to more than one crenulation. This viewpoint may be supported by the existence of several superimposed minor structures, recognized on occasions in a single outcrop. However this can also be interpreted as being due to the generation of a sequence of structures during the same progresssive deformational process. The stereoplots show the existence of a dominant trend in the crenulation lineation, subparallel to the first phase intersection lineation (Durán, 1990; Serra, 1990). The dip of the crenulation planes is more variable, changing from subvertical to subhorizontal, but in general it intersects the slaty cleavage at a high angle. The existence of a well developed lineation trend, indicating that the crenulation planes also have a dominant trend, supports the existence of a main crenulation phase, even if some other events of lesser importance could have existed.

Cross structures (close-jointing and open chevrons) have been observed in many localities (Guilleries, Durán, 1990; Collcerola). These structures were probably the last to be formed and can be related to the small changes in trend observed in the dominant foliation.

Belts of south and north dip of the slaty cleavage

Besides trend variations, due to weak cross-structures, exist dip changes in the slaty cleavage. Some of them are important enough to rotate the cleavage until it dips in the opposite direction. In this way, alternating belts of north and south dip were formed. These belts exist at different scales, from metric to kilometric, and smaller belts with opposing dip are often found within a wide belt. In figure 1, the zones of north and south dip for the central and northern part of the Ranges, and

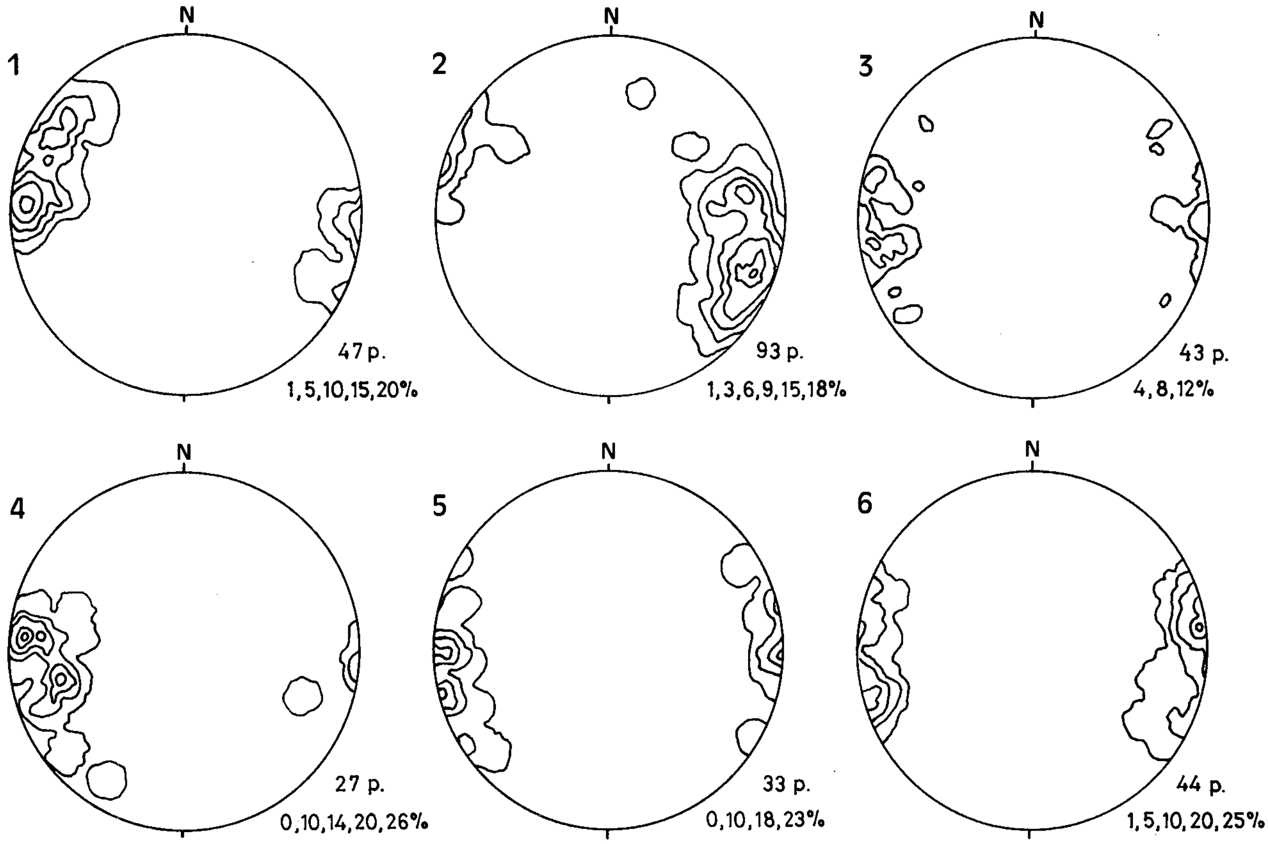

Figure 2.- 1-5: Intersection lineations (bedding/cleavage) in low-grade areas (equal area, lower hemisphere projection). 1: Collcerola. 2: Martorell (data from Benet, 1990). 3: Capellades (according to Serra, 1990). 4: Northwestern Montseny (Julivert and Durán, this paper). 5: Northern Guilleries (according to Durán, 1990). 6: Stretching lineation in high-grade areas (southern Guilleries, according to Durán, 1990).

the stereoplots for the dominant foliation in different areas are shown. Figure 2 gives the stereoplots of fold axes and intersection lineations. To the south (Priorat), the cleavage is poorly developed, and so the zone has not been included in the map.

THE STRUCTURE IN MEDIUM- AND HIGH-GRADE AREAS

No major structures are clearly observed in medium- and high-grade zones, although in Les Guilleries some features in the gneiss cartographic pattern could be interpreted as being due to folding (Durán 1990). Consequently, the following discussion will be based on minor structures.

The schistosity in medium- and high-grade zones

Four main lithologies exist in medium- and high-grade metamorphic areas: schists, gneisses, amphibolites and marbles. Medium-grade schists show the typical coarse-grain schistosity, with andalusite or cordierite porphyroblasts in a phylosilicate matrix, defining the schistosity. With increasing metamorphic grade, the schistosity becomes less apparent and the rocks become more granoblastic. The relatioships between deformation and metamorphic crystal growth have been described by Durán (1989) and Sebastián *et al.* (1990).

The gneisses show in the field a well-developed foliation, which is mainly defined under the microscope by a parallel orientation of the mica crystals.

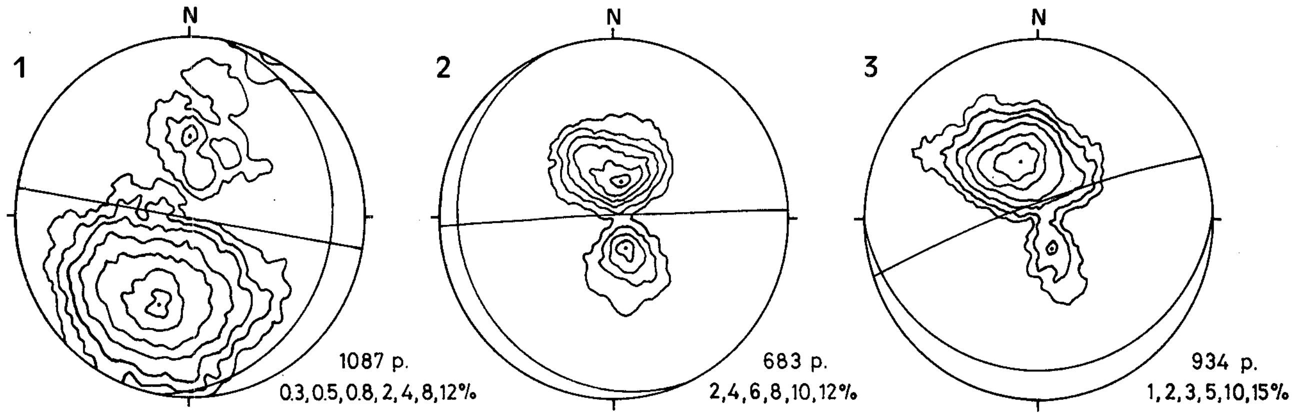

Figure 3.- Stereoplots of slaty cleavage and schistosity (equal area, lower hemisphere projection) for three different areas showing the two concentrations and the position of the two intersecting planes (see explanation in the text). 1: Cleavage planes from Collcerola, Martorell and Gavá, plotted together. 2: Northern Guilleries (low-grade). 3: Southern Guilleries (high-grade).

The amphibolites have a compositional layering and a linear texture defined by the parallel orientation of the amphiboles. Finally, the marbles show a foliation mainly evidenced by color variations.

A peculiarity of medium- and high-grade zones is the existence of folds on the microscopic and the decimetric scales. These folds are very common in schists and marbles, whereas in gneisses they are restricted to the vicinity of the schists. The folds are intrafolial, asymmetrical to nearly isoclinal, with axial planes parallel to the main foliation and developing frequently, in the schists, a crenulation foliation. In the schists, a compositional layering with alternating phylosilicate and quartz-rich layers is often observed. This can be in some cases of a primary sedimentary origin, but in others it is a tectonic banding related to the above quoted crenulation foliation. All planar structures in high-grade rocks (axial planes of folds and crenulations deforming the first foliation, and the first foliation itself) are subparallel, so that in schists it can be difficult to determine in the field to which foliation corresponds the observed schistosity. In rocks showing only one foliation (gneisses, amphibolites), this is also parallel to the foliation in schists. In stereoplots all these foliations show a single concentration (Durán, 1990).

Later deformations in high-grade areas

In the high-grade zones, a well-developed crenulation cleavage intersecting the schistosity at a high angle is seldom observed; this is perhaps due to the coarse nature of the rocks (schists, gneisses). Furthermore, the schistosity, as the slaty cleavage in low-grade areas, shows areas with opposing north and south dips. In Les Guilleries massif, the stereoplot shows two pole concentrations: a very strong concentration around 164/38 and a weaker one around 334/20. Both pole concentrations do not differ significantly in strike and dip from those of the low-grade areas, found in the same massif more to the north.

NORTH AND SOUTH DIPPING BELTS OF THE MAIN FOLIATION

In figure 1, the trace of the main foliation in low- and high-grade zones and the belts of north and south dip are represented. It may be observed in the figure that dips to the north predominate in the north, while dips to the south are prevalent in the Barcelona area.

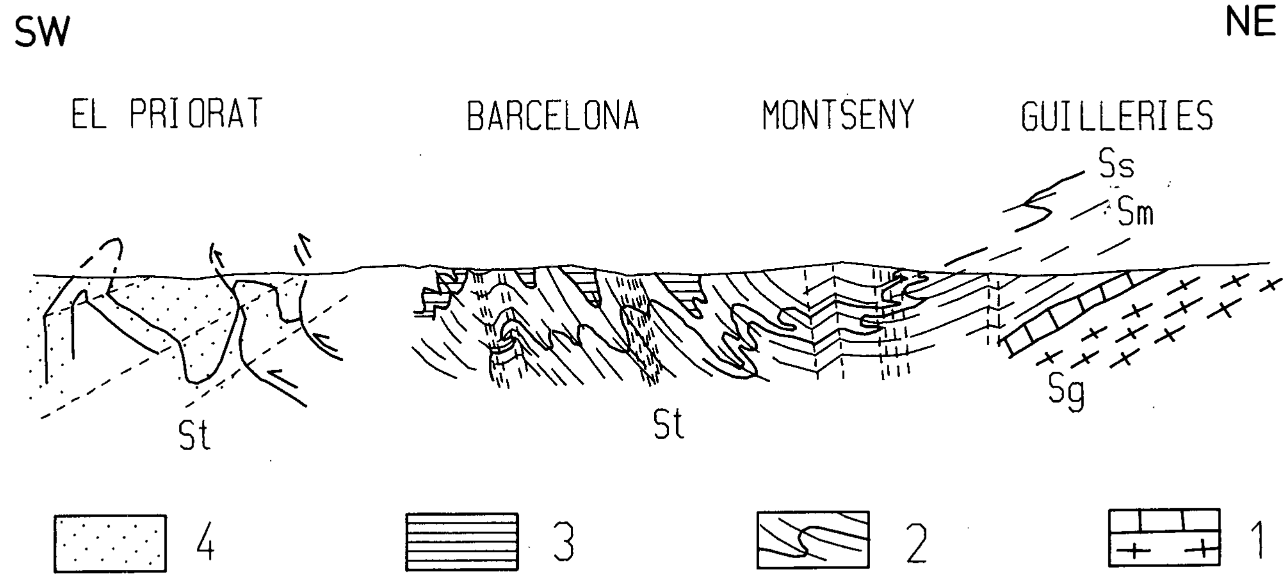

Figure 4.- Schematic cross-section of the Paleozoic of the Catalonian Coastal Ranges, showing changes in the attitude of the foliations (not to scale). 1: Gneisses and marbles of Les Guilleries (Cambrian and older?). 2: Cambrian? and Ordovician. 3: Silurian and Devonian. 4: Carboniferous. Ss: Bedding. Sm: Foliation in schists and slates. Sg: Foliation in gneisses. St: Crenulations and axial planes of late folds.

If a number of cleavage and/or schistosity planes are plotted together, two pole concentrations are shown (Fig. 3). From these two maxima, two bisectrix planes can be determined, one of them dipping about 75-90° and trending roughly east, and the other being nearly horizontal. These planes are the two possible solutions which represent the axial planes of the folds responsible for the belts of opposing dip of the dominant foliation. Field data, showing the existence of steeply and gently deeping crenulation foliations and small chevron planes, are in accordance with the dip and strike of the two planes found.

In practice, it is often difficult in the field to choose between both possible planes to explain a dip change, although there is enough evidence for the existence of both. In the Priorat area, for example, the existence of late folds with gently dipping axial planes can be easily observed. In this area, there are changes in the bedding dip, from one direction to its opposite, but without changing the stratigraphical polarity of the sequence, which eliminates one of the two possible bisectrix planes. These folds, with a gently south-dipping axial plane, are late folds of kink geometry, which must have been generated during the same deformational phase which gave way to the folding of the dominant foliation more to the north.

THE RELATIONSHIPS BETWEEN THE DIFFERENT FOLIATIONS: CONCLUSIONS ON THE STRUCTURAL EVOLUTION

The Hercynian evolution in the Catalonian Coastal Ranges is similar to that of the main Hercynian fold-belt. It starts by a main deformational phase giving tight folds (and thrusts ?) facing towards the frontal part of the belt, and associated with the generation of a regional foliation. This was followed by the generation of more open and upright folds accompanied by crenulation cleavages.

In green-schist facies areas, the dominant foliation is a slaty cleavage, developed during the first, and main, deformation phase. This cleavage is equivalent to the slaty cleavage which is the dominant and first phase cleavage in the northern part of the Iberian massif.

Later deformations in low-grade areas gave way to crenulations, small chevron folds and kink-bands, whose axial planes intersect the slaty cleavage at high angles. These are equivalent to the so-called «third phase» structures in the northern Iberian Massif or to the «phase de serrage» of French authors.

Thus, leaving aside the very late deformations (some cross structures and kinks), the structure as shown in the low-grade areas can be essentially explained by a two-phase model, as in the low-grade zones of the Northern Iberian Massif and areas of the Pyrenees such as the Upper Segre valley (Hartevelt, 1970).

In high-grade areas, the two phases quoted above can also be recognized. In them, there is a schistosity related to the main deformation, and this schistosity has later been deformed to give open folds. However, whilst in low-grade areas the main cleavage is a slaty cleavage, the schistosity in high-grade areas is, at least in part, a crenulation. The existence of such a crenulation, often observed in the high-grade zones of the Hercynian belt, has led to the three-phase model, usually accepted for the Iberian Massif.

Thus, for high-grade zones one more deformation phase than for low-grade areas has been identified. In the Iberian Massif, the correlation between the first foliation in high-grade zones and the slaty cleavage is generally accepted; the crenulation (S2) of high-grade zones would be restricted to such areas, perhaps due to differential movements coinciding with a certain isograde. However, it has to be pointed out that, at least in the Catalonian Coastal Ranges, no field evidence exists for such a correlation.

No pre-schistose deformational phases have been recognized. This is also the case for the northern Iberian Massif, where pre-schistose folds have only been described from the Pisuerga-Carrión province, and contrasts with many low-grade areas of the Pyrenees, where such folds have been often found (Mey, 1968; Zwart, 1979; Speksnijder, 1987).

AN ATTEMPT TOWARDS A GENERAL CROSS-SECTION

Taking into account the structural data available, the following tentative cross-section is presented (Fig. 4):

1) In the Guilleries massif, where a normal and subhorizontal stratigraphic sequence exists, with a schistosity or cleavage nearly parallel to bedding, the structure may correspond to the subhorizontal limb of a major fold (Durán, 1985; 1989). A later tilting would be the cause for the present day southward dip of the tectonic foliations, prevailing in most of the massif.

2) In the area near Barcelona (Collcerola and neighbouring massifs) many folds of metric scale can be observed. These are either normal or reverse limb minor folds. Also in this area many small outcrops of Devonian and even Carboniferous rocks are preserved in the cores of somewhat larger synclines. The Montnegre and soutwestern Montseny massifs appear to have the same characteristics. These areas seem to represent a zone with small scale periodic folds, perhaps at the vicinity of the hinge zone of a larger structure.

3) The Priorat area, to the south, is essentially a synclinorial area in which Carboniferous rocks have been preserved.

The areas distinguished above do not represent a full cross-section. Between them there are areas poorly known (part of the Montseny massif), cut by granitoids (Montnegre), or buried below the post-Paleozoic cover. For these reasons only a very schematic cross-setion can be presented (Fig. 4).

The present day structure is shown in the cross-section of Fig.4 as the result of superimposition of late open folds, associated with crenulations. To the

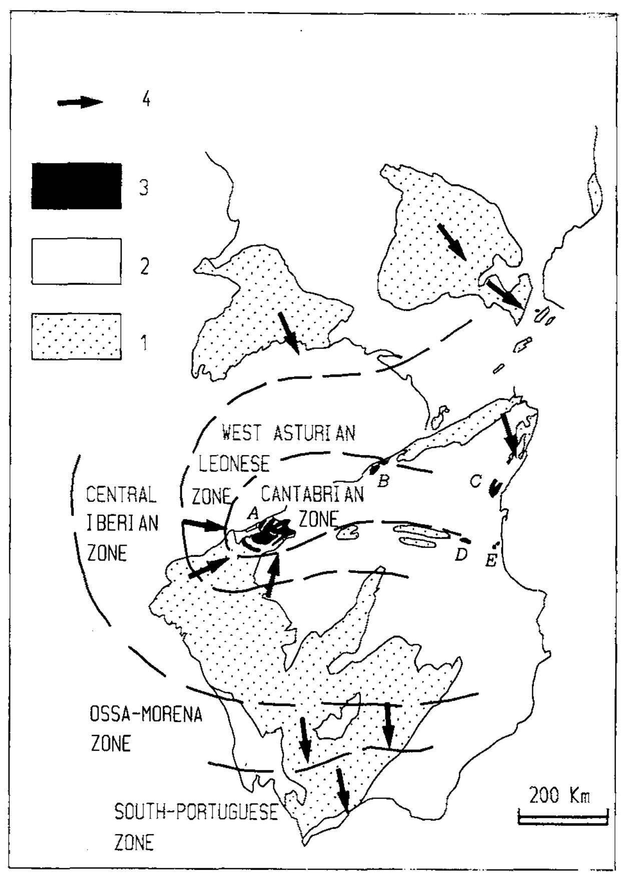

Figure 5.- The Ibero-Armorican arc and the position of the Carboniferous outcrops at its core. 1: Undifferentiated Paleozoic and Precambrian rocks. 2: Carboniferous pre-Stephanian rocks in the core of the arc. 3: Post-Paleozoic rocks. 4: Vergence direction. *A*: Carboniferous outcrops of the Cantabrian zone. *B*: Carboniferous outcrops of the Pyrenean Basque massifs. *C*: Priorat. *D*: Montalban massif. *E*: Carboniferous outcrops of the Castellón Province.

south (Priorat) these folds show axial planes often dipping moderately to gently to the south. To the north steep dipping axial planes seem to predominate.

POSITION WITH RESPECT TO THE HERCYNIAN FOLDBELT

As it is well-known, the Hercynian orogenic belt in western Europe describes a sharp arc (Ibero-Armorican Arc) which is one of the outstanding structural features of the belt. Another important feature is the existence of two branches with opposite polarity in the belt. The structure of the «Cantabrian branch» is best shown by a cross-section parallel to the Cantabrian coast, in northwestern Spain (Matte, 1968; Julivert, 1981; Matte, 1986; Julivert and Martínez,1987; Perez-Estaún *et al.*, 1988). This cross-section shows a structure of folds and thrusts facing towards the core of the arc, where the foreland is found (Cantabrian zone, forming the core of the arc). Most of the Armorican massif as well as the French Massif Central are the extension of this branch, after it forms the Ibero-Armorican arc.

In northeastern Spain and southern France, scattered outcrops of Paleozoic rocks are found in the Iberian Chain, the Catalonian Coastal Ranges and the Pyrenees. The Paleozoic outcrops in the Iberian Chain clearly belong to the southern limb of the arc, and those of the Pyrenees to the northern limb. The Paleozoic of the Catalonian Coastal Ranges, although located to the south of the Pyrenees, still corresponds to the northern limb of the arc. The frontal part of the orogenic belt in this cross-section is the Carboniferous area of El Priorat. This is probably a part of a wider area of Carboniferous foreland deposition, whose present day outcrops are the Priorat itself, the small outcrops of Castellón, farther to the south, and the Montalbán massif, in the Iberian chain (Fig. 5). These deposits have the same significance as the Carboniferous of the Cantabrian zone (and especially of the Pisuerga-Carrión Province), in the core of the Asturian arc. All of them bring evidence of the existence in the core of the arc of a significant area of Carboniferous foreland deposition, in which thick culm sequences were laid down during the progress of the Hercinian orogeny.

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