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Hercynian mylonite belts in the eastern Pyrenees: an example of shear zones associated with late folding

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Abstract—In the eastern Pyrenees mylonite belts are related to a late phase of Hercynian folding leading to the development of an open antiform-tight synform large-scale structure. These belts consist of steep dipping and anastomosing bands ranging in width from a few centimetres to some tens of metres, broadly parallel to the folds and preferentially developed in crystalline rocks on the cusped synformal hinges. The mylonite bands are zones of ductile high deformation related to displacements essentially parallel to the banding. The attitudes of the stretching lineations in the mylonites indicates that dip–slip dominates in the E–W trending mylonitic bands while strike–slip becomes common in the NW–SE trending zones. The mylonitic bands correspond to shear zones which have an opposite sense of displacement on each limb of any one fold.

The geometry of the individual banded structures is dependant on both the degree of the pre-existing anisotropy and its orientation. In isotropic crystalline rocks the mylonite bands correspond to simple shear zones, while in well-foliated schists these form transposition bands related to stretched and thinned limbs of asymmetric folds. A gradation between the two types exists.

Increasing crystallinity with depth causes a change in structural style of late Hercynian deformation from fold related banded structures to ductile shear zones.

INTRODUCTION AND GEOLOGICAL SETTING

THREE main lithological units can be distinguished in the Hercynian basement which crops out along the axial zone of the Pyrenees. They are: (i) Palaeozoic sedimentary rocks and their metamorphic equivalents; (ii) augengneisses mainly of orthotype; and (iii) granitoids.

The Palaeozoic rocks and augengneisses have been affected by polyphase deformation while the granitoids are mainly late intrusions. The main large scale features of the zone are: (i) the presence of gneissic domes; (ii) tight synforms with vertical to near vertical axial planes; (iii) the W–E to WNW–ESE trend of the dominant folds; (iv) the development of major mylonite belts broadly parallel to the trend of the folds; and (v) the common occurrence of granitoid sheets.

In the lower structural levels, the dominant regional foliation has a flat-lying attitude in the crestal zone of the domes but is steep around them and in the synforms. In higher structural levels this foliation always has a steep attitude and forms the axial plane cleavage of the large-scale folds.

The mylonite bands are zones of intense ductile deformation and are associated with displacements which are essentially parallel to the mylonitic banding (*s*-bands, according to Cobbold 1977). Although they cut across diverse lithologies, they are mainly developed in crystalline rocks (medium and high grade schists, gneisses and granitoids). The associated mylonites are well-foliated rocks produced by grain refinement, mainly achieved by recrystallization and neocrystallization of retrograde minerals of greenschists facies. Mylonitization may be accompanied in some cases by significant mineralogical and chemical transformations. Most marked is the development of quartz-depleted chlorite, muscovite (± albite) phyllonites in sheared granites or gneisses.

Their age has been a subject of controversy and is still not well established. There is also some confusion about the setting of these mylonites. They are often considered with other structures, such as brittle faults, which have similar trends although these differ in significance and age (Arthaud & Matte 1975). Some authors (Raguin 1933, Destombes & Raguin 1955, Estevez 1970, 1973) consider that the dominant deformation is related to Alpine faulting, but the faults might be superimposed on older Hercynian ones. Others (Zwart 1958, 1965, Fontboté & Guitard 1958, Guitard 1970, Matte 1976) consider that the dominant deformation along these faults is late Hercynian. However some of the latter do not discount later Alpine movements. On the other hand, Soula *et al.* (1977) believe that there are two separate mylonite systems, one Hercynian and one Alpine, which are slightly oblique to each other.

In the eastern Pyrenees, south of the North Pyrenean Fault, there are arguments pointing to a late Hercynian age for the mylonite belts (Carreras 1975). They are: (i) the mylonites cut across the late intrusive granitoids; (ii) they are intersected by undeformed lamprophyre dykes which have been dated as late Triassic – early Jurassic (Chessex *et al.* 1965); (iii) they show microstructures and mineralogies indicating deformation under greenschist facies conditions, whereas the Alpine faulting produces breccias, fault gouges or, at most,

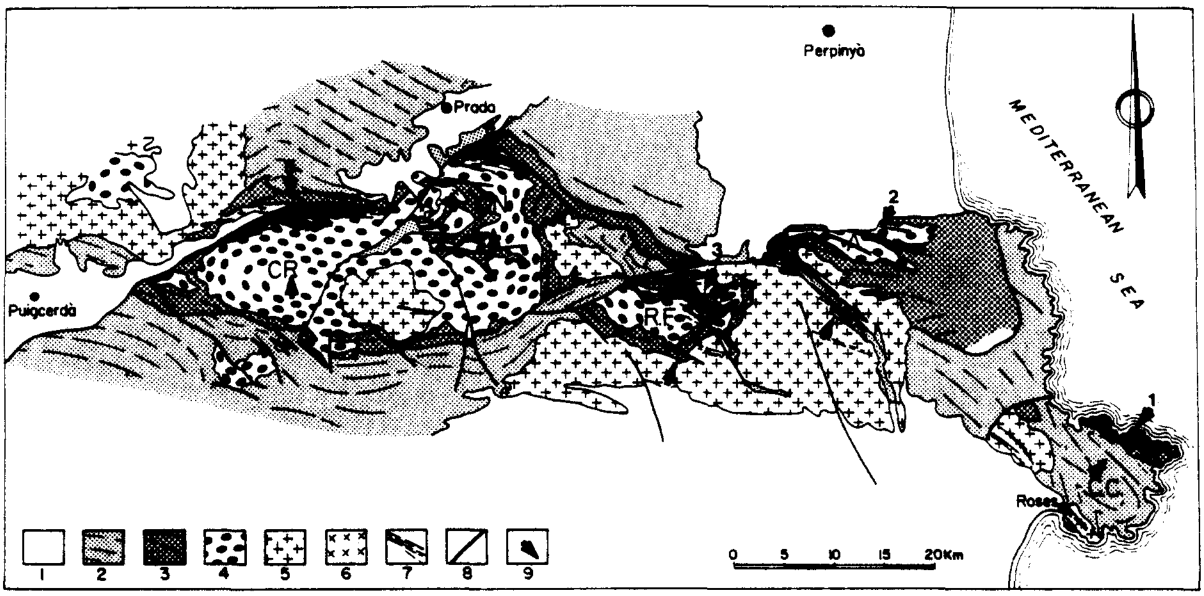

Fig. 1. Geological setting of the Hercynian mylonite belts in the eastern Pyrenees. 1. Post-Hercynian terrains. 2. Low or very low metamorphic grade Palaeozoic sediments. 3. Medium and high grade metasediments. 4. Augengneisses. 5. Granodiorites. 6. Leucogranites. 7. Mylonite bands. 8. Post-Hercynian faults. 9. Location of the cross-sections in Fig. 2.

cleaved shales (Els Banys d'Arles o d'Amèlia) under non-metamorphic conditions; and (iv) the mylonite belts are geometrically related to the late Hercynian large-scale folds, as will be described later.

GEOMETRY

The widths of the mylonite belts are variable but most range from several centimetres to some tens of metres. They commonly form anastomosing patterns and a concentration of these gives rise to a complex mylonite belt which can reach a width of a few hundreds of metres.

The mylonite belts have a trend varying from WSW–ENE to W–E, that is, they are parallel to the mappable folds and are preferentially located on the borders of the gneissic domes (Canigó-Carançà, Roc de Fraussa, Albera, see Figs. 1 and 2). In general the mylonite foliation within the belts is steep and dips to the north. Some of the mylonites, specially those that are quartz-rich have a stretching lineation which generally dips to the NW, although locally it may be nearly horizontal. There is a variation in the pitch of the stretching lineations along the belt. The indication from the variations is that dip–slip movement predominates in the E–W trending mylonitic bands of the western part (Canigó-Carançà) and strike–slip dominates, in the NW–SE trending shear zones in the eastern areas (Albera, Cap de Creus, Fig. 2). However, a similar variation in the attitudes of the stretching lineations is also observed in any area within a belt where there are differently oriented individual mylonite bands constituting the anastomosing pattern referred to previously.

In rocks without any initial anistropy (i.e. granitoids) the mylonites are generally developed in shear zones which have the typical sigmoidal pattern to their foliation development. In rocks with a pre-existing foliation (i.e. gneisses and schists) there is normally a progressive rotation of the foliation into parallelism with the mylonite foliation. In some cases the boundaries between the mylonite bands and the country rock are sharp and parallel to the mylonitic foliation.

The regional foliation between contiguous mylonite bands can be either sigmoidally shaped, indicating a differential extension, or crenulated, indicating shortening. The latter situation is found where the mylonite foliation is at a high angle to the earlier foliation. In both cases there is evidence that deformation also occurred within the area between two contiguous and closely-spaced mylonite bands. Furthermore, both patterns can coexist in the same area, and each may result from the different initial attitude of the regional foliation with respect to the strain field associated with the shear zones.

Individual mylonite bands in isotropic rocks correspond to simple shear zones (Ramsay & Graham 1970), the rocks outside the bands remain undeformed (Fig. 3). Whereas, in rocks with a pre-exisiting anisotropy (i.e. well-foliated gneisses and schists) the shear zones are associated with folding, and the mylonites form transposition bands related to stretched and thinned limbs of asymmetric folds (Fig. 3) A gradation between the two types can be observed. The above variations in the structures described indicate that the geometry of an individual shear zone depends on: (i) the degree of pre-existing anisotropy, and (ii) its orientation with respect to the strain field (Fig. 3). This is similar to the experimental observations of Cobbold *et al.* (1971) on structures developed in anisotropic rocks.

MYLONITE ZONES AND LARGE-SCALE FOLDING

The mylonite belts are broadly parallel to the trend of the large-scale folds, that is, the dome-shaped antiforms and tight synforms. In the gneiss massifs this is shown by

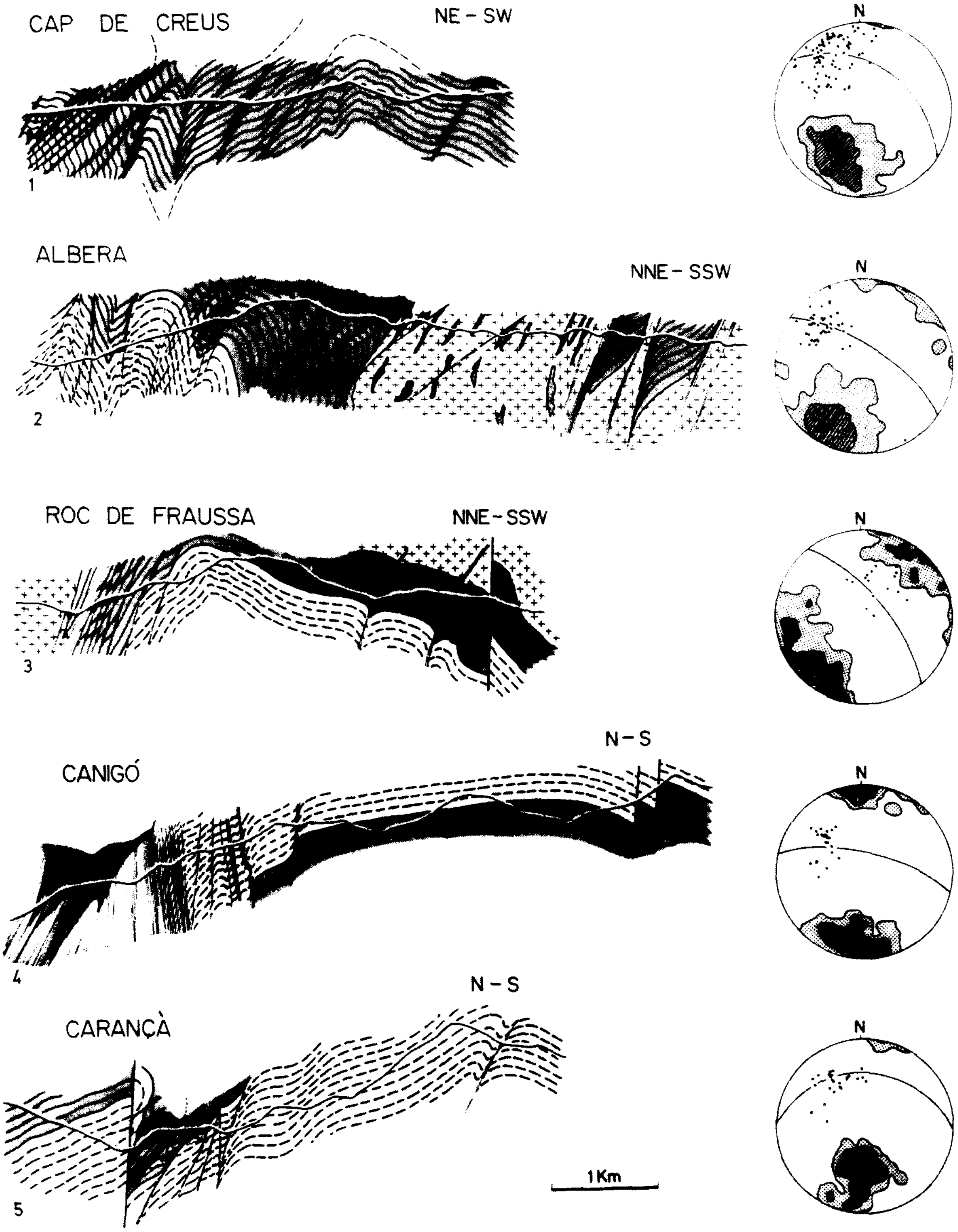

Fig. 2. Five cross-sections through the mylonite belts in the eastern Pyrenees together with their respective stereoplots of poles to mylonite foliation (*Sm*) and associated stretching lineations (*Lm*). In the cross-sections; metasediments (grey), augengneisses (dashed lines) and granodiorites (crosses). Stereoplots: *Sm* contours; 1–4–11–22%, *Lm*; dots. Number of *Sm* poles, (1)–164, (2)–171, (3)–106, (4)–114, (5)–132.

the parallelism of the large mylonite belts and the long axes of the domes. On the other hand the smaller mylonite zones inside the massifs can have a more variable orientation. In the medium and high grade metasediments both a detailed examination of the outcrops and detailed mapping reveal that the mylonite bands are either parallel to, or slightly oblique to, the axial traces of the folds. In low grade terrains typical shear zones are not found. Instead, banded structures consisting of crenulation or transposition zones form parallel to the axial planes of the late, asymmetric folds. It appears that spatially the mylonite belts are confined to the cusped synformal hinges of the major folds and to the short upright limbs of these if they are asymmetric (Fig. 2). The mylonites on the northern limbs of the antiforms display a very steep foliation and correspond to shear zones with displacements which indicate a downthrow of the northern side with respect to the southern. On the

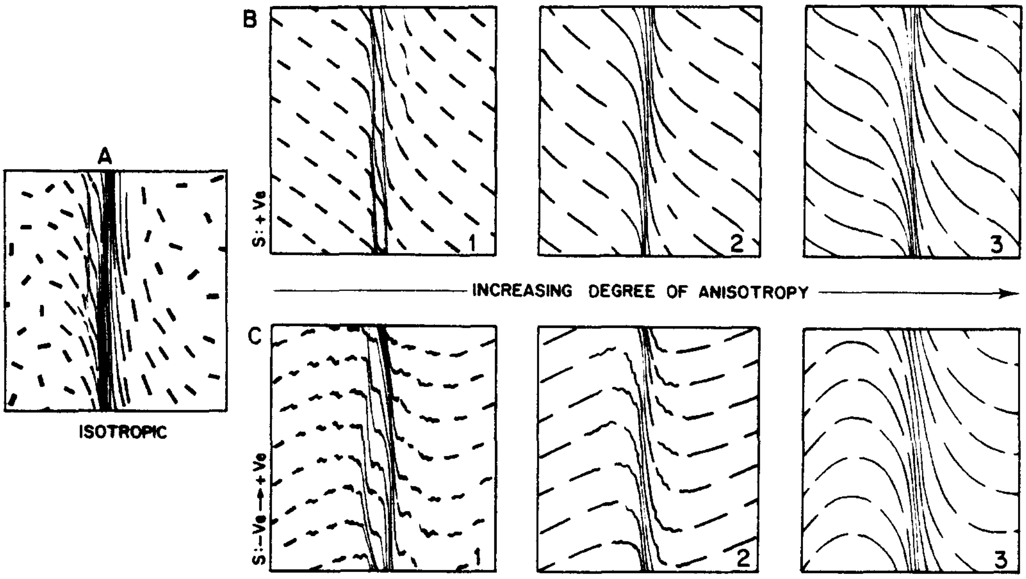

Fig. 3. Variation of type of structure developed in decimetric sized *S* bands as result of degree of anisotropy and its angle with respect to the sense of displacement. (A) for isotropic rocks. In (B) and (C) for anisotropic rocks the anisotropy increases from 1 to 3. In (B) the pre-existing foliation (*S*) becomes extended as result of increasing strain towards the centre of the band. In (C) (*S*) becomes first shortened and then extended.

southern limbs, the mylonite foliation is less steep. It always dips to the north and displays the opposite sense of movement, that is reverse (± dextral) slip (Fig. 4).

Summarizing, the above geometrical relationship indicates that the shear zones are related to large-scale fold structures and are preferentially developed in crystalline rocks at deep structural levels.

CONCLUSIONS

1. The eastern Pyrenees mylonite zones are related to a late phase of Hercynian folding. This is indicated by geometrical relationships and is consistent with a crustal shortening event.

2. The mylonites were formed under greenschist facies conditions, and represent the retrogression of higher grade assemblages which were formed during the metamorphic climax.

3. The shear zones were formed in deep seated crystalline rocks during the same late folding event which gave rise to the asymmetric folds in the low grade cover metasediments. In transitional structural levels, fold-related mylonite bands coexist with slightly oblique shear zones which have the same trend as the deep seated ones. They may correspond to shear zones formed in deeper levels.

4. Increasing crystallinity at crustal depth is responsible for the open antiform – tight synform geometry of the late folds. Shearing in the crystalline rocks might account for the deformation leading to the development of these fold structures with the shear zones concentrated in the tight synforms.

5. The distribution of shear zones with a normal or reverse movement is controlled by the folding. The regional shortening direction lies on the obtuse angle. Both sets cannot be regarded as 'true conjugates'.

6. The change in style of the banded structures with

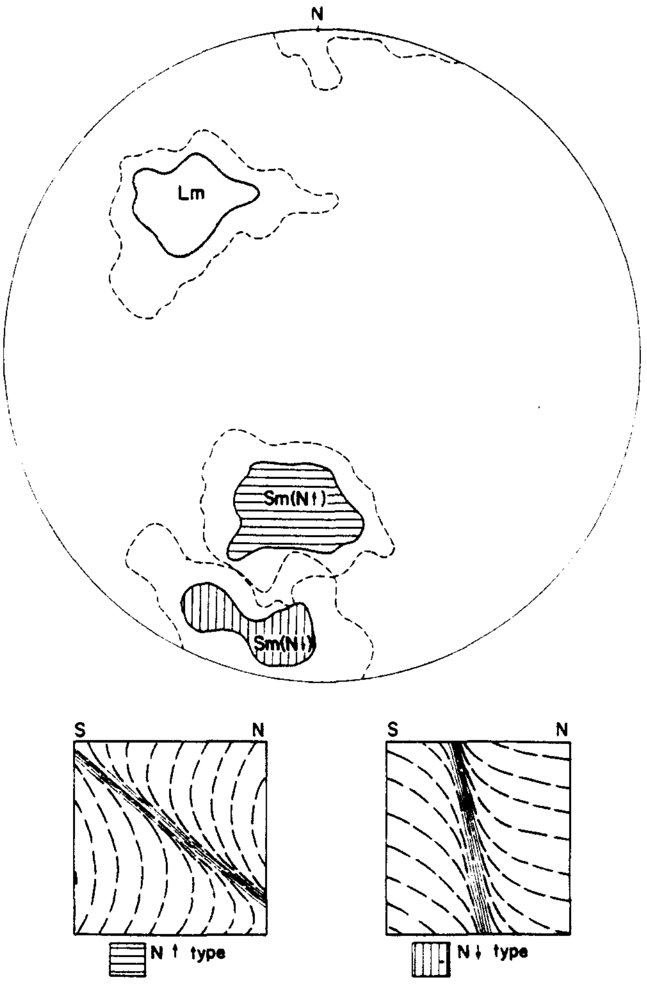

Fig. 4. Lower hemisphere stereoplot showing 5 and 10% contours of poles to mylonite bands. N↗ type (left square) correspond to North dipping *S* bands acting as reverse ductile faults. N↙ type (right square) correspond to very steep *S* bands with the opposite sense of movement, usually normal faults. Both types are plotted and contoured separately in the stereoplot. *Sm*(N↗); 106 poles. *Sm*(N↙); 91 poles.

increasing depth is due to an increase in rock crystallinity and a decrease in anisotropy. However, the progressive decrease in anisotropy with depth is modified by the presence of sheet-like isotropic granitoid bodies in the anisotropic metasediments. Thus the deformation style may be modified and the trend from folds to shear zones with depth is reversed, and typical shear zones may overlie folded structures.

7. The geometry of an individual shear zone is dependent on both the degree of pre-existing anisotropy and the orientation of this anisotropy with respect to the strain field associated with the shear zone. Increasing previous anisotropy in the rocks produces changes in the type of banded structures from ductile faults (ductile shear zones) to folds.

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