Journal of Structural Geology, Vol. 8, No. 6, pp. 693 to 699, 1986
Printed in Great Britain

0191–8141/86 $03.00 + 0.00
Pergamon Journals Ltd.

Shear bands and related extensional structures in a mylonitized quartz dyke

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(*Received* 20 *February* 1985; *accepted in revised form* 31 *October* 1985)

Abstract—Chiefly monomineralic quartz dykes in the Canigó massif (Eastern Pyrenees) are affected by mylonitic deformation. Deformation took place under low-temperature conditions and produced incipient to well-developed mylonitic foliation. In the deformed quartz, grainsize reduction was mainly achieved by brittle failure of crystals along two conjugate sets of cracks. Two sets of conjugate shear bands are also present even in samples with poorly developed mylonitic foliation. Cracks and shear bands are consistent with an extension parallel to foliation. Both are simultaneously present in all the studied samples. Hydrolytic weakening may have aided the development of ductile structures.

INTRODUCTION

MYLONITES commonly exhibit composite planar fabrics due to sets of crenulation cleavages which affect the mylonitic foliation. These cleavages form at low angles to the foliation and show 'normal fault' geometry.

These structures, named "extensional crenulation cleavages" by Platt & Vissers (1980), represent ductile and ductile–brittle micro-shears closely related to mylonitic foliation development in rocks deformed mainly by shear strain. Some authors consider that the 'shear bands' form in advanced stages of deformation because the foliation cannot undergo further extension (White 1979, White *et al.* 1980, Watts & Williams 1979). Other authors relate the formation of conjugate sets to subsequent flattening (Platt & Vissers 1980), or to a coaxial deformation confined in some domains due to a shear strain partitioning (Platt 1984). On the other hand, Harris & Cobbold (1985) describe conjugate sets, in natural and experimental examples, in well-layered rocks and rock-analogues deformed only by shear strain.

This paper deals with the development of conjugate shear bands in a mylonitized quartz dyke. Deformation took place under low-grade temperature conditions, and the dyke did not have any previous planar anisotropy. This case provides a good example to consider the relationship between shear bands and other brittle extensional structures. The development of mylonitic foliation in heterogeneously deformed monomineralic rocks can also be seen. The work was carried out in the Esquerdes de Rojà quartz dyke, located in the southern slope of the Canigó Massif (eastern Pyrenees).

REGIONAL GEOLOGY

The Canigó Massif is one of the Hercynian massifs which form the eastern Pyrenean axial zone. It consists of a gneissic core enclosed by pre-Hercynian metasediments. Both are affected by complex polyphase Hercynian tectonics and by related regional metamorphism under amphibolite facies. As a result, the gneisses (mainly granitic orthogneisses) and metasediments acquired a regional foliation prior to the temperature peak. After this peak some granitic bodies were emplaced, cutting the regional isograds and the regional deformational structures. More information about the characteristics of the Hercynian tectono-metamorphic events can be found in Guitard (1970), Autran *et al.* (1970) and Casas (1984).

On the southern slope of the massif the gneisses, metasediments and one of the above-mentioned intrusive granitic bodies (the Costabona granite), are crossed by a group of monomineralic quartz dykes (Fig. 1). Both the dykes and the enclosing rocks are cut by a series of reverse shear zones (Casas 1982). These shear zones are related to the mylonite belt present in the northern part of the massif (Carreras *et al.* 1980, Geyssant *et al.* 1980, Casas 1984). Carreras *et al.* 1980 associate it with the group of mylonite belts which cut across the crystalline rocks of the other Hercynian Pyrenean massifs. These authors suggests that mylonitization was related to late Hercynian folding, which postdated the granite emplacement and took place under low-grade (greenschist facies) conditions.

THE QUARTZ DYKE OF THE ESQUERDES DE ROJÀ

The quartz dykes have a rectilinear geometry and form a subparallel system trending E–W to ENE–WSW (Fig. 1). The width of the most important one (the Esquerdes de Rojà dyke) varies from 10 to 25 m and has an approximate length of fifteen km. Despite the fact that its vertical dimensions are difficult to evaluate, cartographical estimates place them at around one km.

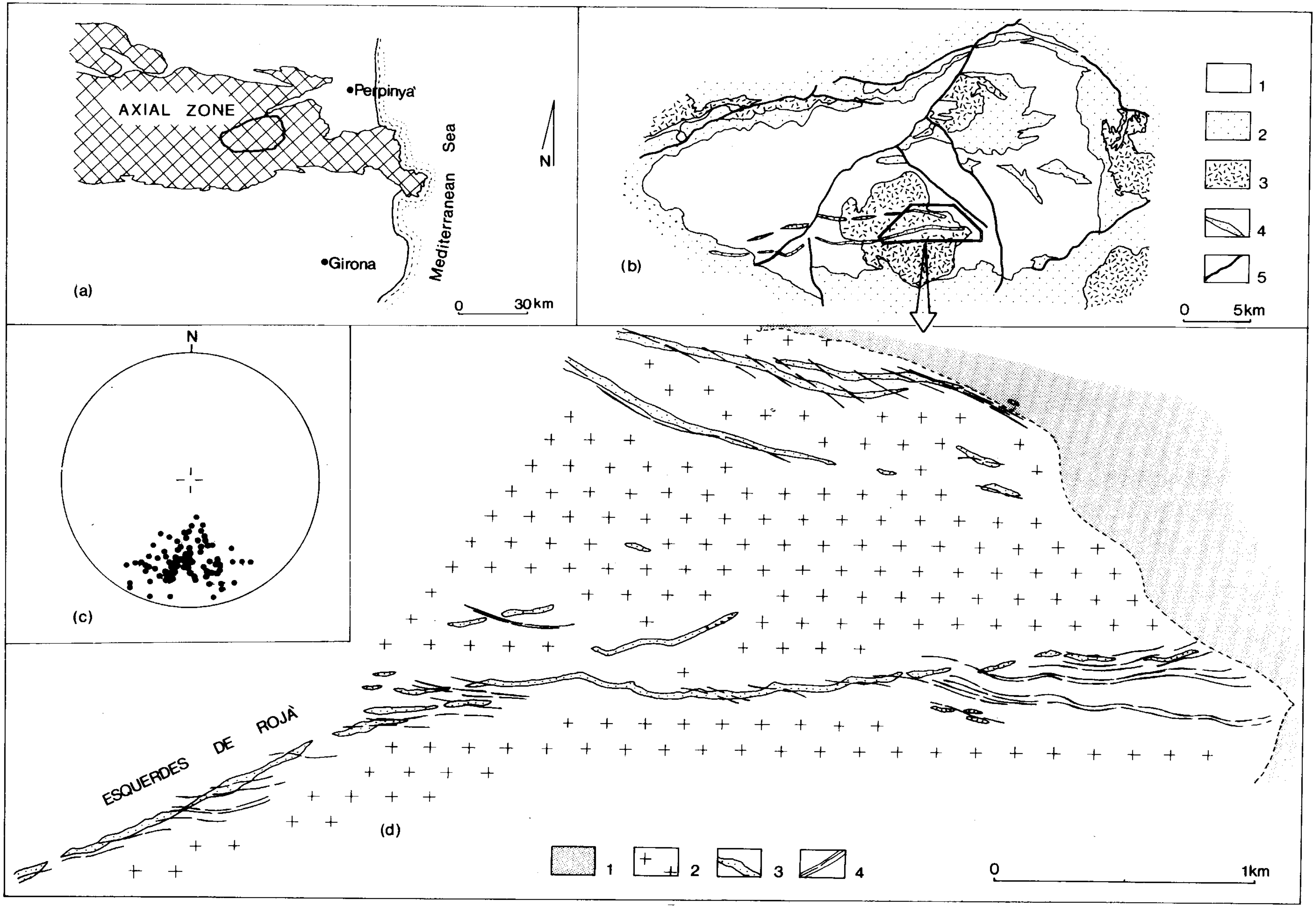

Fig. 1. Location of the Esquerdes de Rojà quartz dykes. (a) The Canigó massif within the eastern Pyrenean Axial Zone. (b) Geological sketch of the massif modified after Guitard (1970). Legend: 1, Canigó gneisses; 2, metasediments; 3, intrusive granitoids; 4, quartz dykes; 5, main Alpine faults. (c) Orientation of the mylonitic foliation planes in the Esquerdes de Rojà dyke. (d) Sketch of the eastern end of the Esquerdes de Rojà quartz dyke. Legend: 1, gneisses; 2, Costabona granite; 3, quartz dyke; 4, mylonitic foliation.

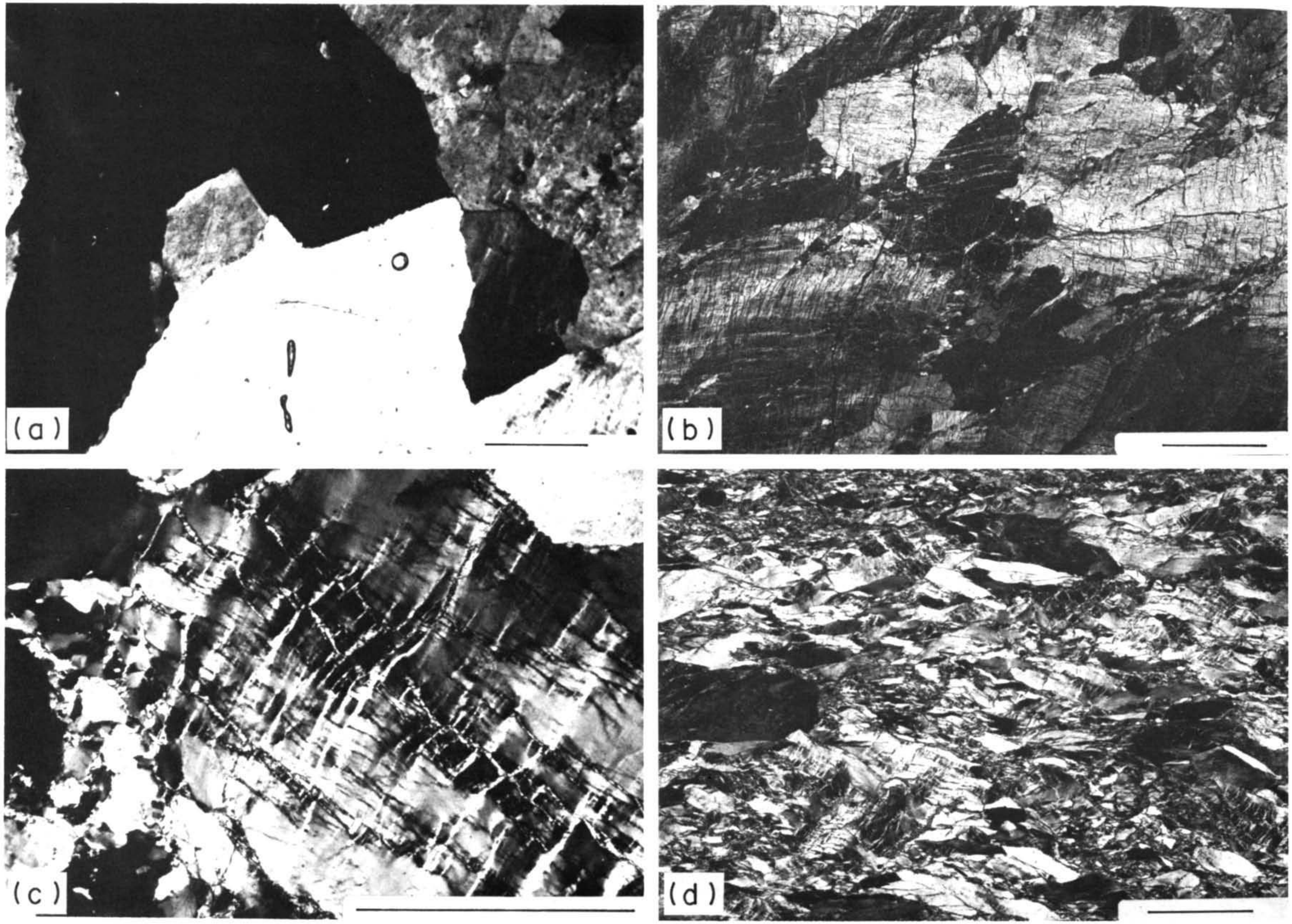

Fig. 2. (a) Undeformed heterogranular quartz aggregate (crossed nicols). (b) Intracrystalline deformation features in low-strained quartz grains. Microtension cracks coexist with undulose extinction (crossed nicols). (c) Detail of quartz porphyroclast affected by two systems of cracks oblique to the photograph margins. Foliation (not visible) is horizontal. The quartz shows undulose extinction along bands roughly parallel to the crack alignment (crossed nicols). (d) Foliation in quartz protomylonite defined by elongate quartz grains with sigmoidal shape (crossed nicols). Scale bars are 1 mm long.

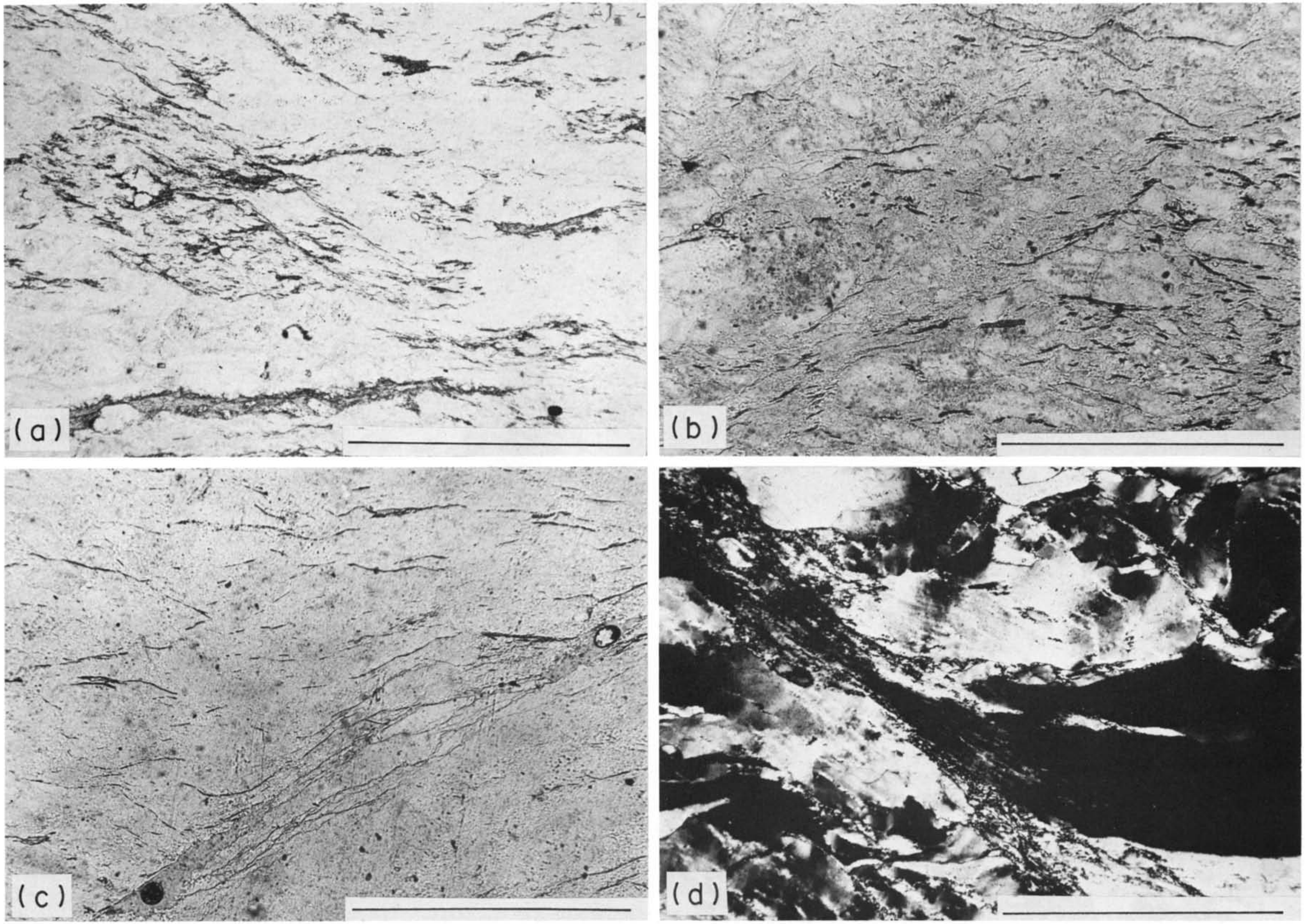

Fig. 3. (a) and (b) Shear bands that affect foliation and cause sigmoidal shapes in the latter. The planes are defined by phyllosilicates (parallel nicols). (c) and (d) Details of shear-band planes. Near these planes the phyllosilicates and the elongate quartz crystals that define the foliation rotate until parallel with the crenulation planes (c, parallel nicols; d, crossed nicols). Scale bar is 1 mm long.

The undeformed dyke is composed of white, translucent microcrystalline quartz of slightly heterogranular subhedral texture. Grainsize varies from 1 to 6 mm (Fig. 2a). The dyke is not zoned and contains some syngenetic inclusions of muscovite which form microscopic aggregates or cm-scale masses. A textural and microthermometric study of the quartz and fluid inclusions (Ayora & Casas 1984) reveals that the crystallization of quartz took place between 290 and 240°C, in two different episodes, from mineralizing brines with a salinity equivalent to 20% by weight of NaCl.

DEFORMATION STRUCTURES

The central and eastern part of the Esquerdes de Rojà dyke are affected by the outer ends of two sets of anastomosing shear zones. The width of these zones ranges from 1 to 10 m. They trend E–W and dip northwards. Within these zones, the quartz dyke and the enclosing granite have a mylonitic foliation, and a related stretching lineation plunging 40–50° to the N–NE. This lineation is chiefly developed in the granite-derived ultramylonites of the central part of these shear zones (Casas 1982). The deformed quartz exhibits drastic grain refinement, a protomylonitic texture and various deformational structures (Figs. 2 and 3). In less deformed samples the foliation is ill-defined and is marked only by some elongate quartz crystals and by dimensional orientation of phyllosilicates. The quartz crystals show evidence of internal strain manifested by intracrystalline brittle deformation that coexists with undulose extinction. The crystals are affected by microcracks that may be grouped into two oblique sets. These crack sets are conjugate and have en échelon geometry. The acute angle between the two crack systems is roughly 80°, tending to increase with increasing strain. There is no evidence of significant offsets along the cracks. They have curviplanar geometry and are filled with recrystallized quartz grains between 10 and 25 μm (Figs. 2b & c). Moreover, the quartz crystals exhibit undulose extinction along bands roughly parallel to the crack alignment (Fig. 2b) and symmetrically arranged to the above cracks. The crystals do not show a clear pattern of preferred orientation of the *c*-axes (Fig. 4a).

The protomylonites and mylonites are made up of 0.2–2 mm quartz porphyroclasts in a matrix of smaller 30–100 μm quartz crystals and phyllosilicates. The foliation is marked by preferred dimensional orientation of elongate lens-shaped quartz porphyroclasts, and by the alignment of muscovite crystals parallel to the maximum length of the quartz grains (Fig. 2d). The foliation has a sigmoidal shape, due to the presence of two sets of extensional crenulation cleavage planes. These appear to be conjugate and are compatible with an extension parallel to the foliation. The crenulation cleavage planes tend to curve into the foliation and are defined by the same elements: quartz porphyroclasts and small muscovite grains. Both show marked curvature and rotation until parallel with the crenulation cleavage planes. In the samples studied, there is no evidence of changes in the muscovite–quartz proportion within or outside the cleavage planes. This probably indicates that there was no volume loss during crenulation formation. The planes represent micro-shears with normal-fault geometry, and are morphologically akin to the shear bands which usually form in well-foliated mylonites (Platt & Vissers 1980). In protomylonites and less-deformed samples both systems of shear bands form an angle of 55° with the normal to the foliation (Fig. 4b). Nevertheless, this angle is variable, and in more deformed samples reached 60–65° (Figs. 4c & d).

The quartz porphyroclasts also exhibit two sets of intracrystalline microtension cracks. As in the case of the shear bands, the angle they form is variable. The angle between the two systems increases progressively to 90–100° as strain increases, and reaches 110° in the mylonites (Figs. 4b–d). In the more deformed samples, the cracks are roughly parallel to shear-band planes. In crystals near shear bands, the cracks show offsets with two movements, both 'normal' and compatible with the shear-band displacement.

The cracks are chiefly responsible for the reduction in porphyroclast grainsize through failure, and for their change in shape. The intersection of the two systems gives rise to the elongate sigmoidal shapes of the crystals (Fig. 2d).

These protomylonites and mylonites show *c*-axis fabric patterns with two crossed girdles. The girdles are equally populated and centred around the *Y* axes of strain. Within them the maxima form oblique angles to the foliation, between 60 and 80°, and show a 'pseudo-two-girdle' pattern. The angle between the two girdles varies between 55 and 70°. Because in some cases the girdles are not well-defined, it has not been possible to detect significant variations in these angles and relate them clearly to the position of shear bands and cracks (Casas 1982, Carreras & Garcia-Celma 1982).

DISCUSSION

In the deformed quartz of the Esquerdes de Rojà dyke, brittle and ductile deformation structures are associated with the formation of a mylonitic foliation. In less deformed samples, intracrystalline failure and plastic deformation of quartz coexist, while as strain increases ductile deformation becomes more important. This type of evolution could be the result of the conditions in which deformation took place, around 250°, and could reveal a hydrolitic weakening effect. The water lowers the transition temperature for brittle to ductile, and favours the intracrystalline plastic deformation mechanism. In other environmental conditions Tullis & Yund (1980) obtained a similar effect deforming experimentally 'dry' and 'wet' samples. In the case considered here, this type of situation might arise if the water contained initially in fluid inclusions played an important role during deformation. The breaking up of such inclusions would favour the plastic deformation of the quartz under relatively low-temperature conditions.

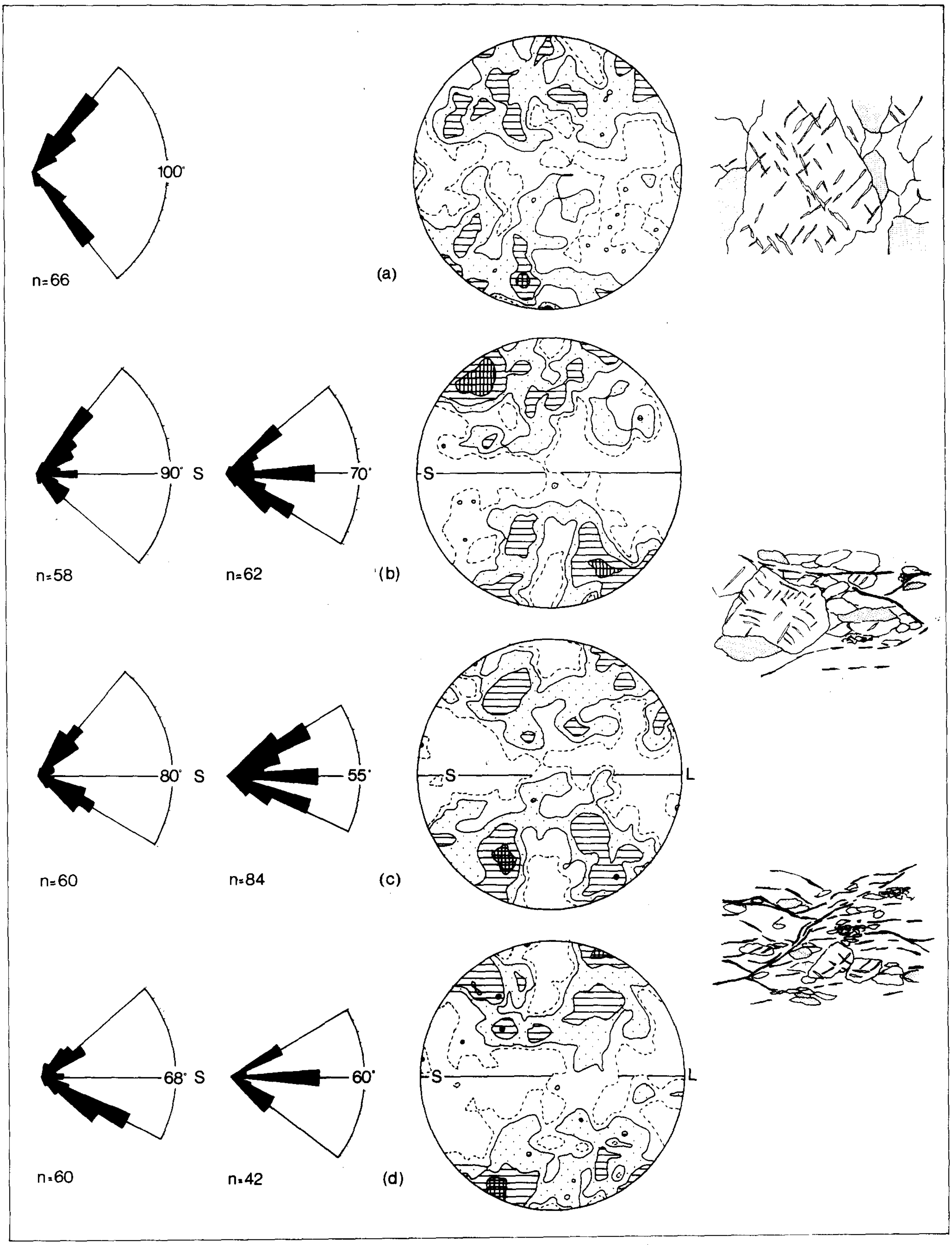

Fig. 4. Quartz *c*-axis fabric diagrams (200 measurements, 0.5–1–2 and 4% contours) and orientation of tension cracks (left-hand column) and shear bands (centre column) in samples of different microstructure. *S* indicates the foliation, *L* the lineation and *n* the number of measurements. The samples are taken from the eastern end of Esquerdes de Rojà. (a) Little-deformed quartz with incipient foliation, (b) quartz protomylonite, (c) and (d) quartz mylonite. The sketches on the right summarise the evolution of the measured structures, with relation to quartz grainsize refinement and the development of foliation.

The formation of mylonitic foliation in these rocks is found to be associated with brittle and ductile extensional structures. Microtension cracks and shear bands are consistent with an extension parallel to the foliation. They formed during the early stages of deformation and continued to be active during deformation, as suggested by the following factors: (a) the presence of recrystallized grains within the cracks, (b) the cracks were responsible for grainsize reduction and for the geometry of porphyroclasts, even in more deformed samples with fewer augen, (c) the shear bands appear in samples (protomylonites) in which the 'relict' crystals are still abundant and (d) the shear bands and cracks rotated towards the extension direction as strain increased.

The shear bands described here are very similar to those found in well-foliated mylonites deformed under higher-temperature conditions. However, in this case, their characteristics do not allow a fully satisfactory explanation of their formation by means of previously proposed mechanisms. Their early formation is inconsistent with the idea that shear bands form only in shear zones in advanced stages of deformation. Moreover, their conjugate nature cannot be explained as resulting from 'reverse' slip favoured by a particular orientation of the layering (Harris & Cobbold 1985), as there was no previous well-defined planar anisotropy. In the Cap de Creus shear zones, Carreras & Garcia-Celma (1982) also describe two conjugate sets of shear bands that affect mylonitic foliation in shear-zone margins. As in the case considered in this paper, the above leads to the idea that the formation of this type of structure is often not solely due to late-stage deformation processes, but that it is associated with the group of microstructural transformations that take place in the mylonites right from the start of deformation (leading to foliation and preferred orientation of minerals).

Acknowledgements—I would like to acknowledge the help given to me by P. Santanach and J. Carreras. The research was carried out thanks to the programme Ajuts a la Investigació 1981 and 1982, Universitat de Barcelona.

REFERENCES

Autran, A., Fonteilles, M. & Guitard, G. 1970. Rélations entre les intrusions de granitoïdes, l'anatexie et le métamorphisme régional considerées principalement du point de vue du rôle de l'eau: cas de la chaîne hercynienne des Pyrénées Orientales. *Bull. Soc. géol. Fr.* **12**, 673–731.

Ayora, C. & Casas, J. M. 1984. Estudi microtermomètric dels filons de quars de les Esquerdes de Rojà. *Acta Geol. Hisp.* **18**, 35–46.

Carreras, J., Julivert, M. & Santanach, P. 1980. Hercynian mylonite belts in the eastern Pyrenees: an example of shear zones associated with late folding. *J. Struct. Geol.* **2**, 5–9.

Carreras, J. & Garcia-Celma, A. 1982. Quartz *c*-axis fabric variation at the margins of a shear zone developed in schists from Cap de Creus (Spain). *Acta Geol. Hisp.* **17**, 137–149.

Casas, J. M. 1982. Pseudo-two-girdles c-axis fabric patterns in a quartz–feldspar mylonite (Costabona granodiorite, Canigó massif). *Acta Geol. Hisp.* **17**, 151–157.

Casas, J. M. 1984. Estudi de la deformació en els gneiss del massís del Canigó. Unpublished Ph.D. thesis, University of Barcelona.

Geyssant, J., Guitard, G. & Laumonier, B. 1980. Analyse structurale des gneiss oeillés blastomylonitiques du versant nord du Canigou (P.O.). *C. r. hebd. Séanc. Acad. Sci. Paris* **290**, 1103–1106.

Guitard, G. 1970. Le métamorphisme hercynien mésozonal et les gneiss oeillés du massif du Canigou (Pyrénées orientales). *Mém. Bur. Rech. Géol. Min.* **63**.

Harris, L. B. & Cobbold, P. R. 1985. Development of conjugate shear bands during bulk simple shearing. *J. Struct. Geol.* **7**, 37–44.

Platt, J. P. 1984. Secondary cleavages in ductile shear zones. *J. Struct. Geol.* **6**, 439–442.

Platt, J. P. & Vissers, R. L. M. 1980. Extensional structures in anisotropic rocks. *J. Struct. Geol.* **2**, 397–410.

Tullis, J. & Yund, R. A. 1980. Hydrolytic weakening of experimentally deformed Westerly granite and Hale albite rock. *J. Struct. Geol..* **2**, 439–451.

Watts, M. J. & Williams, G. D. 1979. Fault rocks as indicators of progressive shear deformation in the Guingamp region, Brittany. *J. Struct. Geol.* **1**, 323–332.

White, S. H. 1979, Large strain deformation: report on a tectonic studies group discussion meeting held at Imperial College, London on 14 November 1979. *J. Struct. Geol.* **1**, 333–339.

White, S. H., Burrows, S. E., Carreras, J., Shaw, N. D. & Humphreys, F. J. 1980. On mylonites in ductile shear zones. *J. Struct. Geol.* **2**, 175–187.