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Inhomogeneous deformation in roses granodiorite, N.E. Spain

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RESUMEN

Se pone de manifiesto la extrema heterogeneidad en la intensidad de la deformación que afectó a la grandiorita de Roses durante las fases tardías hercínicas. Se desarrolló en primer lugar, una débil foliación que posteriormente fue retomada en zonas de cizalla dúctiles, anastomosadas, de espesor y deformación finita variables. Durante los estadios tardíos de la deformación se generaron zonas de cizalla de carácter más frágil. Se propone que todas estas estructuras se produjeron durante el mismo evento deformacional y al tiempo que se producía el levantamiento regional.

SUMMARY

Evidence is presented for extreme heterogeneity of deformation intensity in the Roses granodiorite during the late-Hercynian. A weak foliation was first developed and was deflected into a major zone of anastomosing ductile shear zones of variable width and finite strain. In the later stages of the deformation more brittle shear zones developed. It is proposed that all the structures in the Roses granodiorite were produced during the same deformation event as progressive uplift of the region occurred.

INTRODUCTION

The late-Hercynian aged Roses granodiorite outcrops on the southern edge of the Cap de Creus Peninsular and constitutes the easternmost exposure of intrusive granitoids along the Axial Zone of the Pyrenees (Fig. 1). The granodiorite is intrusive into a suite of metasedimentary rocks that exhibit a penetrative foliation associated with a low grade regional metamorphism. On the basis of lithological similarities between these metasedimentary host rocks and sedimentary sequences of known Upper Ordovician age in the NE Iberian Peninsular and Pyrenees, Carreras and Losantos (in press) have assigued an Upper Ordovician age to the metasediments. Near the boundary with the Roses granodiorite the metasediments have undergone a contact metamorphism resulting in the formation of spotted phyllites and hornfelses.

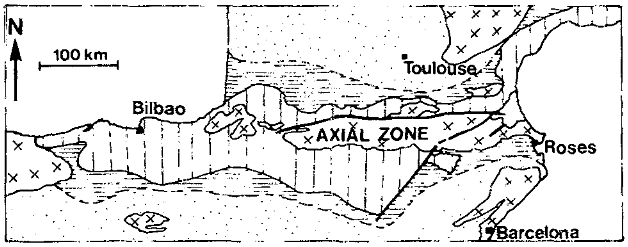

Fig. 1. Simplified structural map of the Pyrenees (after Solé-Sugrañes, 1978).
Stipple marked-in north, Aquitane Basin; in south, Ebro Basin. Horizontal ruled-northern and southern Folded Foreland. Vertical ruled-northern and southern Pyrenean Zone. Crosses-Hercynian basement massifs.

Carreras (1973) and Carreras and Losantos (in press) have shown that post-intrusive deformation has affected all of the rocks types in the Cap de Creus area. In the metasediments this post-intrusive deformation produced minor folds and crenulations that wrap around the nodular porphyroblasts in the spotted phyllites and produced kinked micas in the hornfelses. These late minor folds also affect small granodiorite veins that cut across the regional foliation in the metasediments. The main body of the Roses granodiorite exhibits heterogeneous deformation in the form of ductile, brittle-ductile and brittle shear zones. These shear zones were formed under predominantly lower greenschist facies conditions and contain minor folds that have hinges parallel to the late crenulation fold hinges in the metasediments (Carreras and Losantos, in press). This parallelism of all the minor fold hinges, and the presence of undeformed, presumed late Triassic –early Jurassic aged, basic dykes that cut across the sheared granodiorite (Fig. 2), has led Carreras and Losantos to suggest that all of the post-intrusion deformation in this area is of late-Hercynian age.

This paper presents the preliminary results of a study of the deformation in the Roses granodiorite along a 2

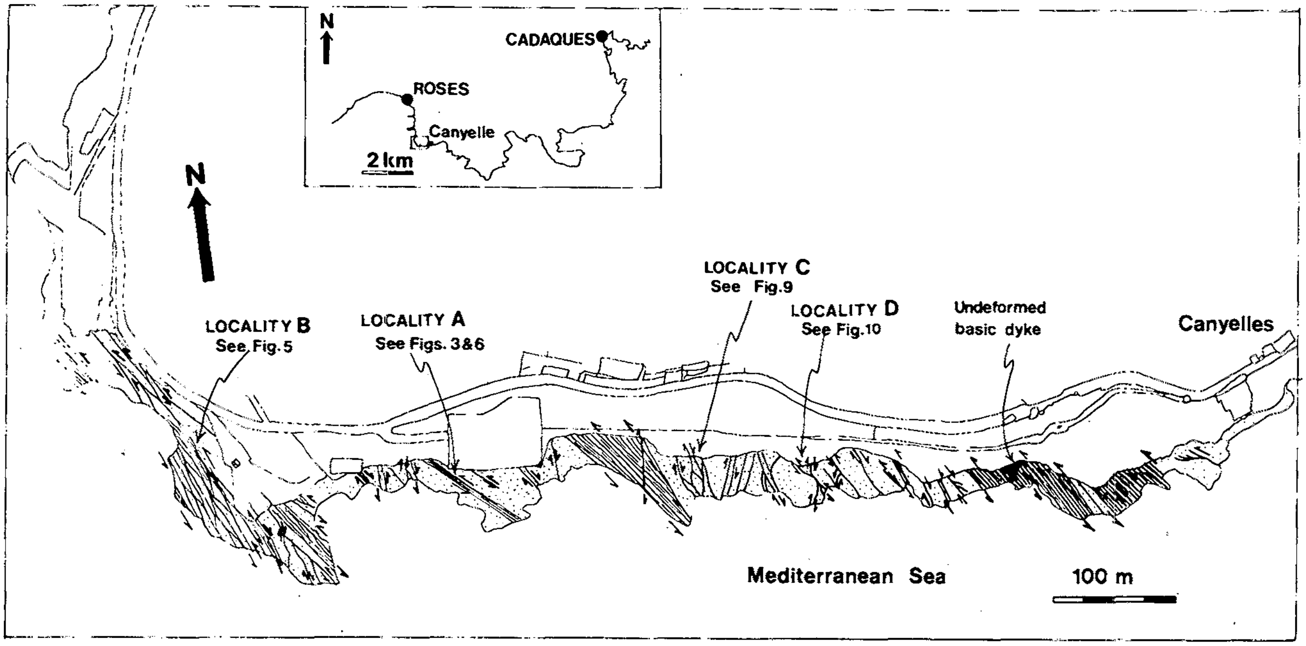

Fig. 2. Coastal exposure of Roses granodiorite west of Canyelles. The granodiorite (stipple) is cut by a series of predominantly NW-SE trending shear zones (schematically represented by heavy lines) the majority of which have a left-lateral sense of displacement. In one locality the sheared rock is cut by an undeformed basic dyke of presumed late Triassic-early Jurassic age. Inset: locality map for Figure 2.

km coastal exposure west of the village of Canyelles (Fig. 2). Mapping was carried out on scales ranging from 1:100 to 1:10 using tape-and-compass and meter-grid methods.

INHOMOGENEOUS DEFORMATION OF THE GRANODIORITE

In its undeformed state the Roses granodiorite is generally isotropic, although a primary igneous flow texture occurs locally and is defined by the alignment of elongate mafic xenoliths and magmatic schlieren. The granodiorite is cut by a suite of aplite dykes that have a predominantly NNE-SSW orientation where unaffected by the later deformation (Fig. 3). In thin section the undeformed granodiorite consists of quartz, plagioclase, K-feldspar, biotite and hornblende that show good igneous textural relationships.

Along the coastal section west of Canyelles (Fig. 2) the granodiorite is deformed by a series of shear zones, the most prominent of which are a set of subparallel, left-lateral, NW-SE trending and steeply dipping zones ranging in width from a few centimeters or less to about 500m. The dip of the foliation within the shear zones may be

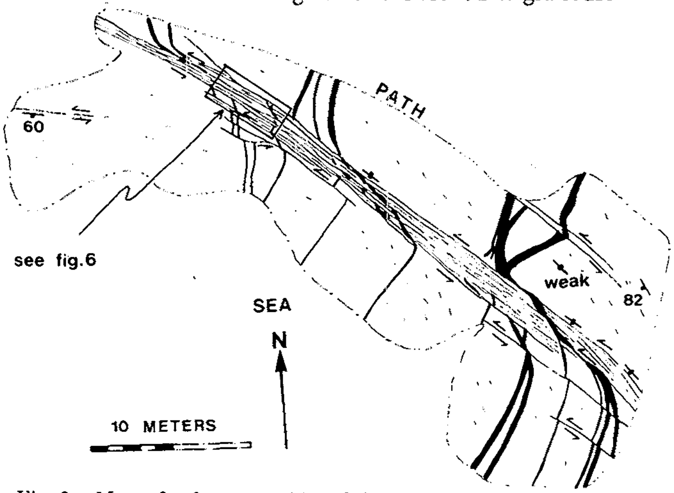

Fig. 3. Map of a 3 meter wide left-lateral ductile shear zone in granodiorite from locality A on Figure 2. Note left-lateral offset of NE-trending aplite dykes (marked in heavy black) in a more or less continuous manner across the shear zone. For complete legend to this and all other maps, see Figure 5.

Fig. 4. Small aplite vein in granodiorite, offset along a narrow ductile right-lateral shear zone. From area of relatively low deformation between localities C and D on Figure 2. Coin diameter approximately 2.3 cms.

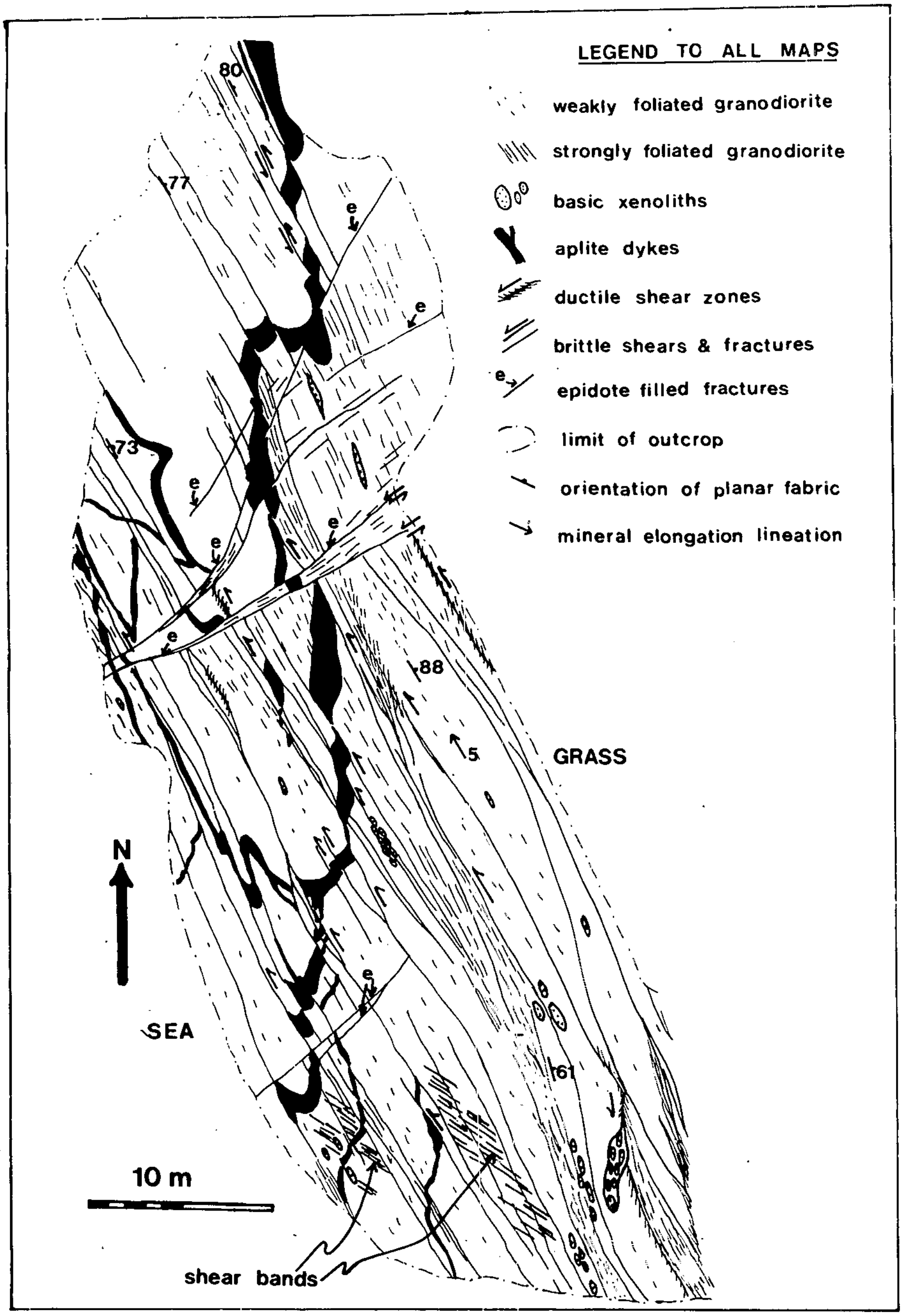

Fig. 5. Map of part of a left-lateral shear zone of at least 40 meters width in granodiorite from locality on Figure 2. An anastomosing network of small left-lateral shear offsets the large aplite dyke. Between the small shear zones, the granodiorite with its xenoliths and aplite dykes shows a less intense but more homogeneous strain. A late, NE-trending fracture system with associated epidote mineralization cuts across the main shear zone.

to the northeast or southwest, reflecting an upright fan-like disposition of the shear zones over the Roses granodiorite body as a whole (Carreras and Losantos, in press).

Outside the zones affected by ductile shearing, the granodiorite commonly displays a very weakly penetrative, flat-lying foliation with an associated sub-horizontal mineral elongation lineation that is defined by elongate clots of the mafic minerals. The weakly developed planar fabric is locally observed to be deflected into the later discrete shear zones, with little or no change in the orientation of the mineral elongation lineation. At the margins of shear zones of more than about 2 centimeters width a new foliation is observed to develop at an angle of approximately 45° to the shear zone boundary, conforming to the model of Ramsay and Graham (1970). This new foliation becomes progressively more intense with increasing strain into the shear zones and a foliated and lineated gneiss is developed. The aplite dykes are deflected into these shear zones and can be traced continuously across them, illustrating that the deformation in the bulk rock was predominantly ductile in nature (Fig. 4).

Microstructurally, the foliated gneiss exhibits a drastic reduction in grain size due to brittle deformation of feldspar grains together with ductile deformation (dynamic recrystallization) of the quartz. Mafic minerals are generally altered to chlorite and epidote, and new growth of muscovite and albite grains is commonly observed. Carreras and Losantos (in press) report the occurrence of quartz-depleted chlorite-albite mylonites in some localities within the Roses granodiorite body.

The shear zones anastomose and surround lozenge-shaped pods of relatively undeformed rock (Fig. 5) to give a style of deformation that has been observed in deformed granitoids elsewhere (Coward, 1976, Ramsay and Allison, 1979, Simpson, in press). Within many of the larger shear zones (more than one meter wide) foliated gneiss development is also heterogeneous. Figure 6 illustrates a typical 2 meter wide left-lateral shear zone that is made up of a large number of smaller discrete centimeter-scale shear zones, each of which forms part of an anastomosing network surrounding areas of less highly strained rock. Each of these small shear zones has a left-lateral displacement sense with the weaker fabric between the zones of high strain tending to be aligned at approximately 45° to the overall trend of the main shear zone.

A typical example of the extreme heterogeneity of deformation intensity in the Roses granodiorite is illustrated in Figure 7. A 3 centimeter wide left-lateral zone of mylonitic granodiorite records the highest shear strain in the rock. All of the minerals within this mylonitic band have undergone a severe reduction in grain size by dyna-

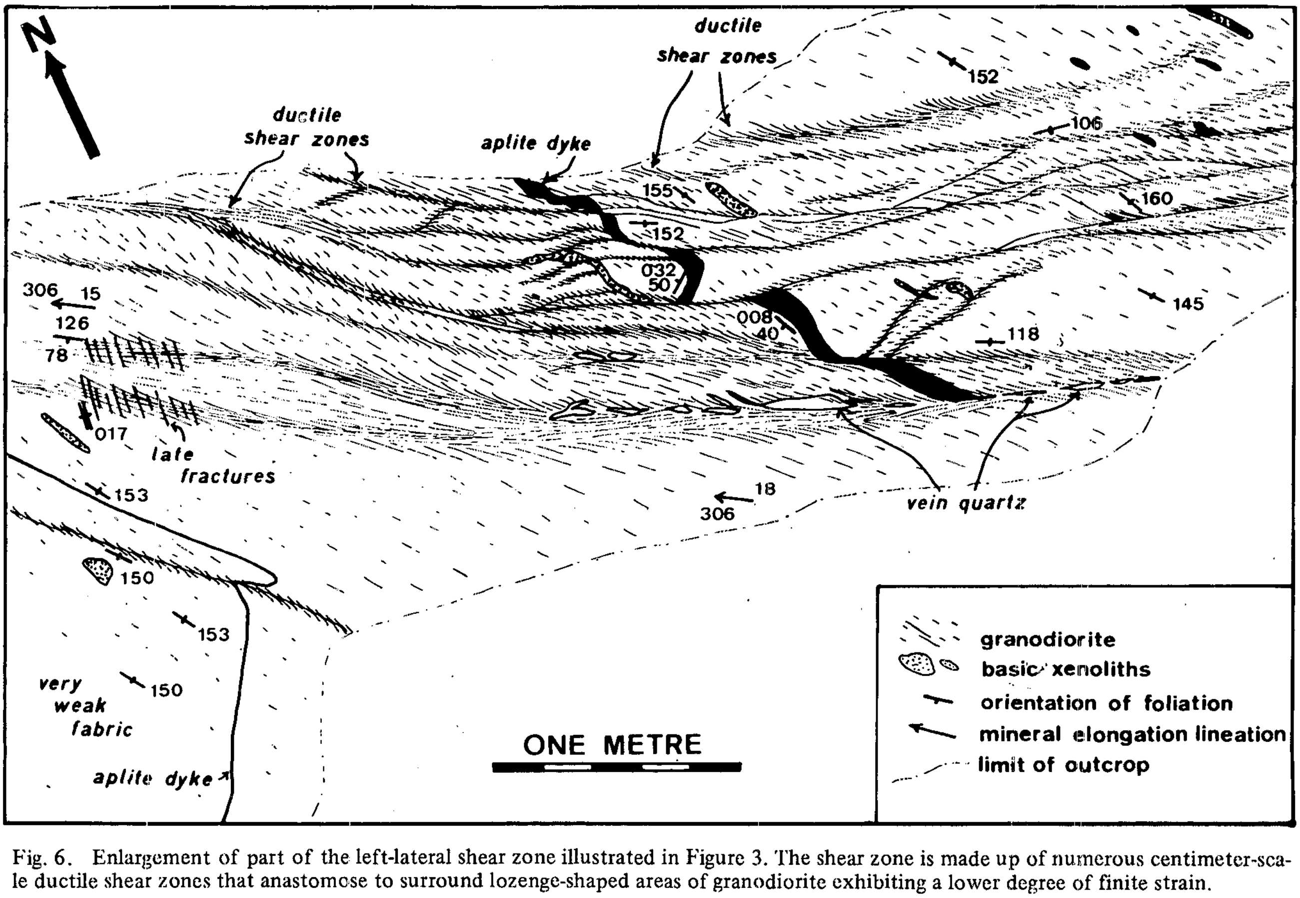

Fig. 6. Enlargement of part of the left-lateral shear zone illustrated in Figure 3. The shear zone is made up of numerous centimeter-scale ductile shear zones that anastomose to surround lozenge-shaped areas of granodiorite exhibiting a lower degree of finite strain.

mic recrystallization associated with strain softening (White *et al.*, 1980). In Area A of Figure 7 the rock remains essentially undeformed. In areas B, C and E on Figure 7, a weak foliation occurs at a low angle to the mylonite zone boundary. This foliation is deflected into a series of left-lateral shear bands within areas B and E (Fig. 7). The shear bands do not affect the unfoliated rock on either side of the main shear zone, nor do they transect the mylonite zones. This close spatial association of the shear bands with the mylonite zone, and the left-lateral displacement sense recorded by both structures, suggests that all of the features illustrated in Figure 7 were formed during the same deformation event (Berthé *et al.,* 1979, Simpson and Schmid, in press).

Even within zones of relatively uniformly sheared and mylonitized granodiorite, the deformation is heterogeneous in intensity. In Figure 8, a 3 centimeter wide left-lateral ductile shear zone contains small relict lens-shaped zones of less highly strained rock, as well as relict feldspar porphyroclasts. In thin-section the feldspar crystals within this mylonite zone are fractured and pulled apart whereas the quartz and mafic minerals have deformed ductilely by dynamic recrystallization.

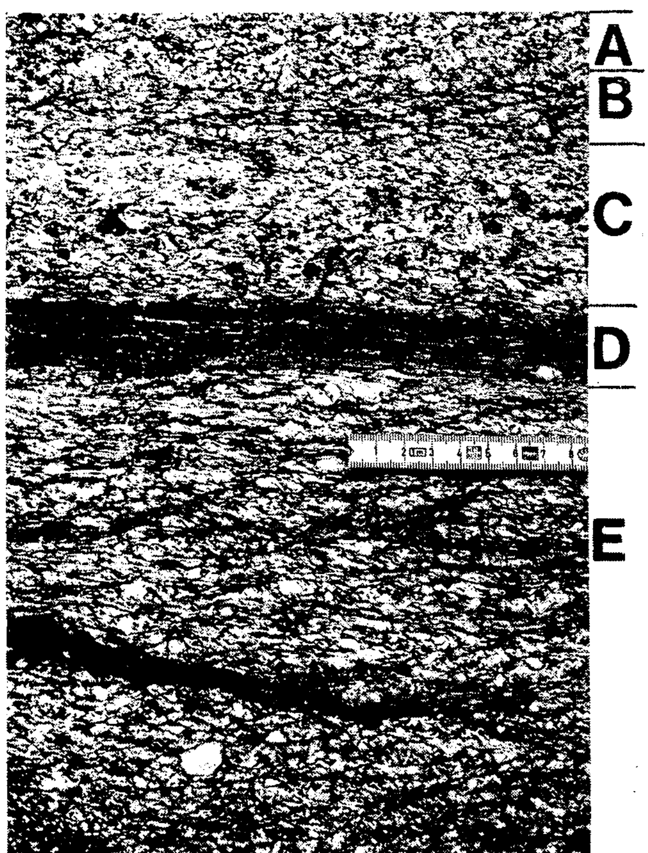

Fig. 7. Outcrop photograph from locality B (Figure 5) illustrating heterogeneous deformation in granodiorite containing a mafic xenolith (black). A 3 cm wide left-lateral mylonite zone (D) records the maximum finite strain. For discussion of areas marked A-E, see text. Ruler marked in cms.

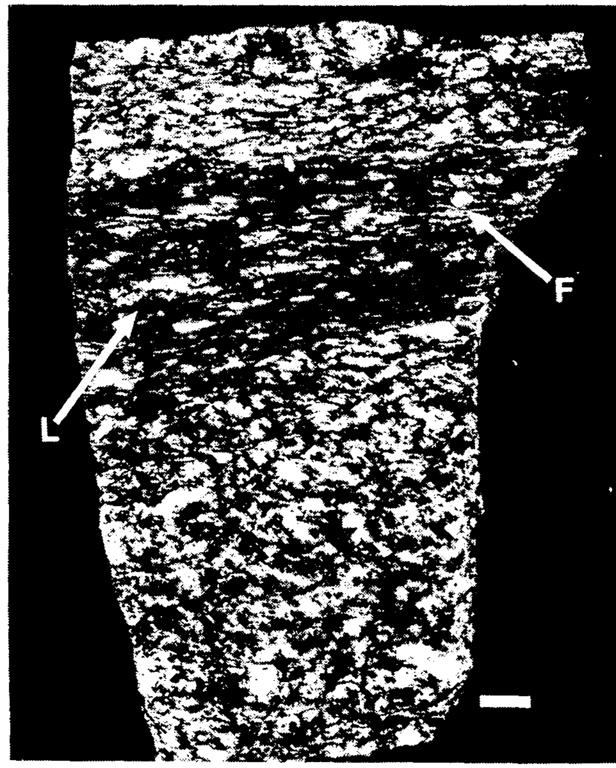

Fig. 8. Photograph of polished hand specimen illustrating heterogeneous deformation of granodiorite within a 3 cm wide left-lateral mylonite zone. Relic feldspar porphyroclasts (arrowed F) and small lenses of less highly strained rock (arrowed L) occur within the mylonite zone. Development of foliation becomes gradually less intense on either side of the mylonite zone, passing into undeformed rock in the lower third of the photograph. Scale bar: 1 cm.

AGE RELATIONSHIPS AMONG THE SHEAR ZONES

The NW-SE trending, left-lateral ductile shear zones predominate over most of the coastal exposure of Roses granodiorite. However, within less deformed areas of the granodiorite narrow shear zones occur that have a more variable orientation. Some right-lateral shear zones also occur and may occasionally cut across earlier left-lateral shear zones (Figs. 9 and 10). Age relationships between right- and left-lateral shear zones are far from uniform over the outcrop as a whole, however, as in some localities left-lateral shear zones may cross earlier right-lateral shear zones. Rarely, conjugate systems of right-and left-lateral shear zones are observed, but in each case the displacement on one set of shear zones predates displacement on the other set. In general the later shear zones, whatever their sense of displacement, tend to be much narrower than the earlier shear zones and often terminate in brittle fractures (Fig. 9).

Shear bands similar to those illustrated in Figure 7 occur in many of the wider regions of highly strained rock. Although these shear bands clearly post-date the development of the foliated granodiorite, they always have the same sense of displacement as the main shear zone with which they are associated, which suggests that both the main foliation and the shear bands formed during different stages of the same deformation phase.

DISCUSSION

Heterogeneous deformation of granitoid rocks in ductile shear zones has been reported from a wide variety of geological terrains by many authors (e.g. Ramsay and Graham, 1970, Burg and Laurent, 1977, Mitra, 1978, 1979, Berthé *et al.,* 1979, Ramsay and Allison, 1979). However, within the majority of ductile shear zones a relatively uniformly foliated rock is developed that shows a progressive increase in finite strain towards the center of the zone (Ramsay and Graham, 1970, Ramsay and Allison, 1979, Ramsay, 1980, Simpson, in press). Extreme heterogeneity of fabric development within even the smallest scale shear zones, as reported here, appears to be relatively uncommon and may reflect locally higher strains associated with heterogeneous strain softening (White *et al.,* 1980).

The absence of any consistent age relationships between left- and right-lateral shear zones in the area of Roses granodiorite mapped, suggests that all these struc-

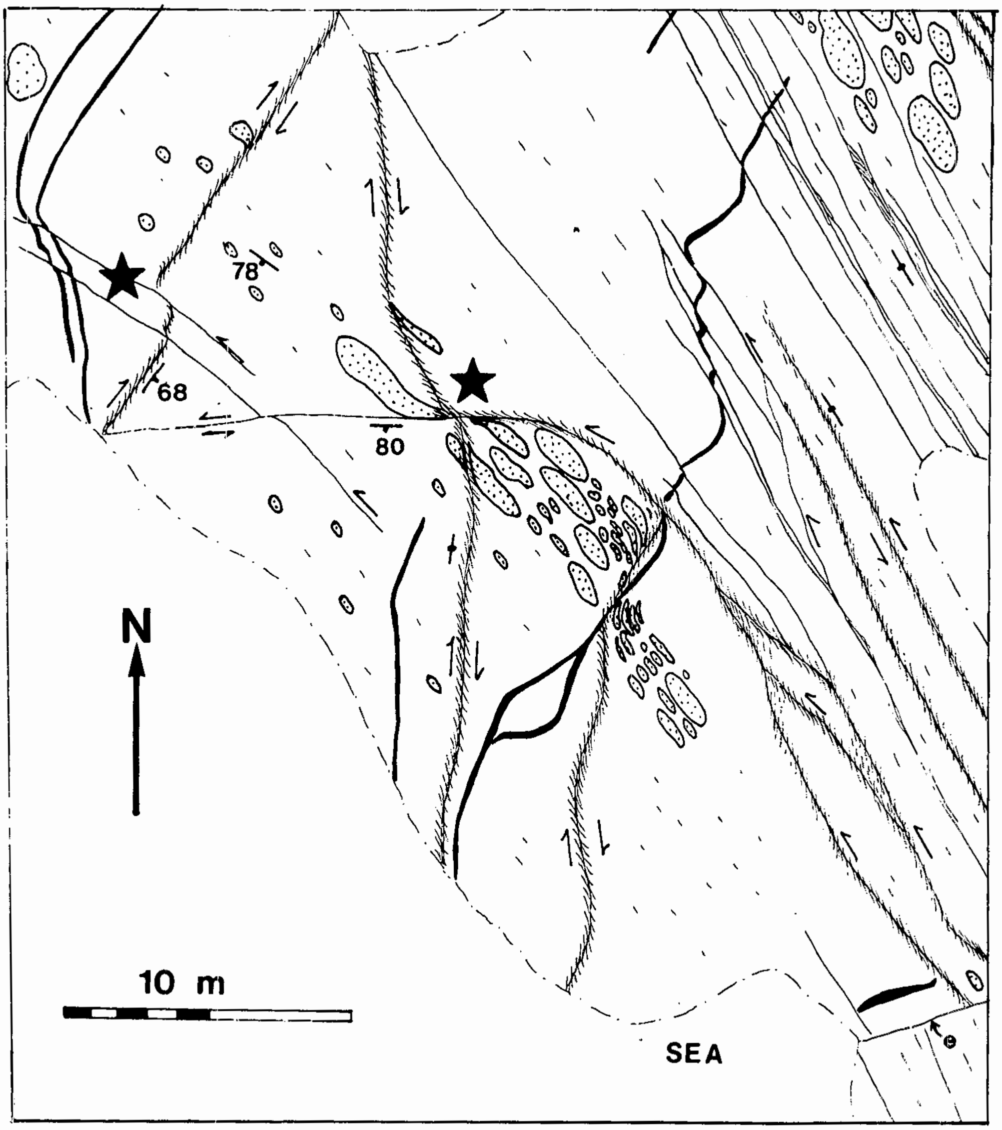

Fig. 9. Small shear zones of variable orientacion in an area of relatively low deformation in the granodiorite. From locality C on Figure 2. A series of small left-lateral shear zones offset earlier right-lateral zones (areas marked by stars). Many of the later shear zones terminate in brittle fractures. For legend see Figure 5.

tures formed during the same deformation phase, along with the formation of shear bands in regions of higher strain. Deformation along conjugate sets of left- and right-lateral shear zones could more easily accommodate any regional shape changes in the rock than could deformation along shear zones of one displacement sense only (Mitra, 1978, Ramsay, 1980). However, such conjugate sets of shear zones are relatively uncommon in the area studied, indicating that in this region the main deformation occurred along an anastomosing network of left-lateral shear zones, with only minor displacement along right-lateral zones.

The parallelism of linear and planar fabrics developed at shear zone boundaries and in regions of lower strain between anastomosing shear zones with the weak and

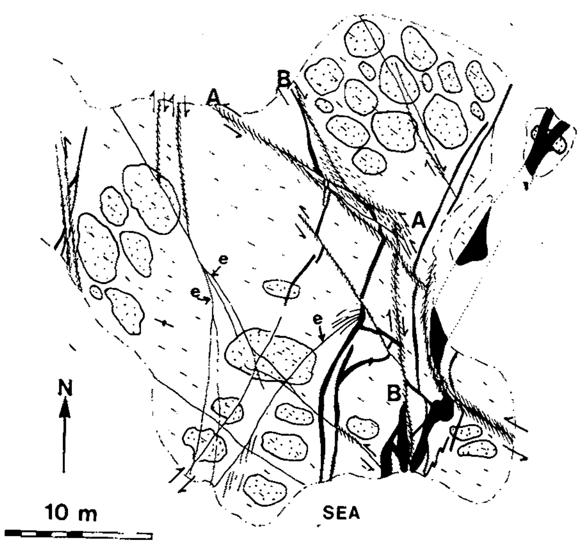

Fig. 10. Small shear zones of variable orientation in a weakly foliated area of the granodiorite. From Locality D on Figure 2. A left-lateral shear zone (A-A) offsets an earlier right-lateral shear zone (B-B') forming an area of complex strain patterns at the cross-over point. For legend see Figure 5.

sporadically developed fabric of the host rocks, suggests a common origin for these features. One possible model will now be outlined that could account for this parallelism of fabric elements as well as provide an explanation for the age relationships of all deformation structures observed in the Roses granodiorite.

MODEL FOR THE PROGRESSIVE DEFORMATION OF THE ROSES GRANODIORITE

Homogeneous ductile deformation of the granodiorite began while the rock was buried to a depth compatible with at least upper greenschist facies metamorphism and resulted in the development of a weak planar and linear fabric (Fig. 11a). Micaceous minerals became aligned with their planar aspects perpendicular to the maximum compression direction in the rock. With increasing deformation, as temperature and pressure conditions gradually reduced to those of lower greenschist facies, it became energetically more favourable for the rock to accommodate the strain by heterogeneous deformation in a system of ductile shear zones (Fig. 11b). These shear zones were probably initiated at sites of rheological instability such as aplite dyke boundaries. Coward (1976) proposed a similar model for the formation of lozenge-shaped blocks of relatively undeformed rock between zones of higher strain.

As conditions became less favourable for bulk ductile deformation of the granodiorite (due to increasing strain rates or decreasing temperatures) the deformation within the already formed ductile shear zones became concentrated along narrower, localized zones. This resulted in narrow mylonite zones, many of which now contain feldspar crystals displaying evidence of brittle deformation. At the same time as the main displacements in the rock were taken up along these mylonite zones, a series of shear bands formed in the adjacent foliated granodiorite, all structures having the same sense of displacement.

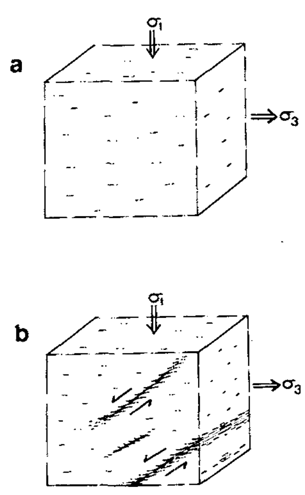

Fig. 11. Sketches to illustrate a possible mechanism for the parallelism of fabric elements in the vicinity of ductile shear zones. (a) Development of a weak planar fabric due fairly homogeneous deformation. (b) With increasing deformation the strain becomes accommodated by heterogeneous deformation in ductile shear zones.

The latest shear zones to develop were also the most brittle in nature, often terminating in brittle fractures. This again suggests either an increase in the strain rate with time, or, more probably, a progressive cooling and/or uplift of the area during the deformation such that the latest shear zones formed under more brittle conditions at shallower levels in the crust.

Further investigations of the mineralogical and chemical changes associated with the deformation in these shear zones are still in progress. It is hoped that this work will produce more precise estimates of the temperature and pressure conditions prevailing during the deformation of the Roses granodiorite.

CONCLUSIONS

Late Hercynian deformation of the Roses granodiorite was extremely heterogeneous in nature. A weak fabric was initially developed throughout the rock and at a later stage of the same phase of deformation this was deflected into a major zone of NW-SE trending anastomosing left-lateral ductile shear zones in the region west of Canyelles. Towards the end of the deformation event, some crosscutting left- and right-lateral shear zones developed that show a more variable orientation in areas of lower strain. In areas of higher strain the formation of narrow mylonite zones and shear bands occurred. The latest shear zones to develop in this region have a more brittle nature. This sequence of deformation may reflect a progressive uplift of the Roses granodiorite during a single, late-Hercynian deformation event.

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