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Structural zonation as a result of inhomogeneous non-coaxial deformation and its control on syntectonic intrusions: an example from the Cap de Creus area, eastern-Pyrenees

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Abstract—The Hercynian structure in the Pyrenees is characterized by the overprinting of several deformational events, each one associated with spatial changes in tectonic style. The variations in tectonic style depend on the lithological setting and on the tectonic regime, both changing in space and time. However, structural zonations also arise from inhomogeneity of deformation during one event. The studied area in the Cap de Creus is an example of the transition from low strain domains, where an earlier foliation is slightly folded, to a high strain domain, where tight or isoclinal folding caused the transposition of the earlier foliation. This structural inhomogeneity was developed from progressive deformation involving the generation of minor S-shaped folds and a major shear zone-like structure consisting on an open Z-bend. Both structures display steeply plunging axes. Initial flexural flow folding followed by limb stretching and shearing of the major structure is invoked to explain apparently contradictory symmetries and shear senses. This folding event, and the associated strain distribution, controlled the emplacement of a syntectonic pegmatite dike swarm. Dikes occur preferentially within the high strain domain, and are either boudinaged or folded depending on their orientation. A late system of narrow ductile shear zones overprint all earlier structures.

INTRODUCTION

Vertical and longitudinal structural zonations across orogenic belts result from changes in lithology, in *P/T* conditions that affect rock ductility, and in regional geothermal gradients and strain fields in the crust. The variations of timing of these parameters result in an overprinting of different structural zonations in a given crustal domain. Close examinations reveal that in both vertical and transverse cross-sections drastic changes in tectonic style, that are superimposed on the broader spatial variation, may be present. Otherwise, it is quite common that local changes in strain regime control, induce or intensify associated processes like metamorphism or magmatism.

Inhomogeneity of deformation within the crust is not restricted to shallow tectonic levels or to late deformation. Shear zones at all scales and in different geotectonic settings are the best examples of tectonically induced structural differentiation in the crust (e.g. Escher *et al.* 1975). However, strain gradients on a regional scale may exhibit a far more complex pattern than that generated by ductile simple shear, generating banded strain zones with high shear strain components (e.g. Bell 1981). An example of a spatial change of tectonic style due to inhomogeneity of a non-coaxial deformation in the Cap de Creus area will be presented in this paper.

The Cap de Creus peninsula (Fig. 1) forms the most easterly outcrop of Hercynian basement exposed along the Pyrenees Axial Zone. There are two main lithological units in the area (Carreras 1975): (i) rather monotonous sequences attributed to the lower Paleozoic and perhaps Precambrian, essentially made of metapsammites (mainly metagreywackes) and lesser metapelites and including some layers and bodies of pre-Hercynian igneous rocks (Navidad & Carreras 1992); and (ii) inhomogeneously mylonitized Hercynian granodiorites which form two small northwest–southwest elongated bodies, the Rodes and Roses massifs (Carreras & Losantos 1982).

A prograde low pressure Hercynian regional metamorphism affects the metasedimentary sequences and grades northwards from the chlorite–muscovite zone to the sillimanite–K-feldspar zone. Medium grade schists are extensively intruded by pegmatite bodies (Carreras *et al.* 1975, Corbella 1990, Damm *et al.* 1992, Corbella & Melgarejo 1993). Migmatite domains are restricted to a few small areas located on the northwestern coast of the Cap de Creus peninsula (Druguet 1992). The Roses and Rodes granodiorite stocks are emplaced in low grade metasediments.

The Hercynian structural framework of the Cap de Creus area, as elsewhere in the eastern Pyrenees, is rather complex, arising from polyphase tectonics in which individual deformation phases recognizable in a given domain are difficult to correlate across the whole area. An added difficulty is that structures and deduced deformation histories may differ when comparing low grade metamorphic with higher grade domains. In medium to high grade domains, the following structures can usually be recognized. A first schistosity (S_1) generally subparallel to bedding was formed prior to the metamorphic climax. Later folds were formed around the time of the metamorphic peak and lasted until the emplacement of the pegmatites shortly after the peak of metamorphism. These folds have a predominantly E–W axial trace, and often variably oriented fold axes and sheared

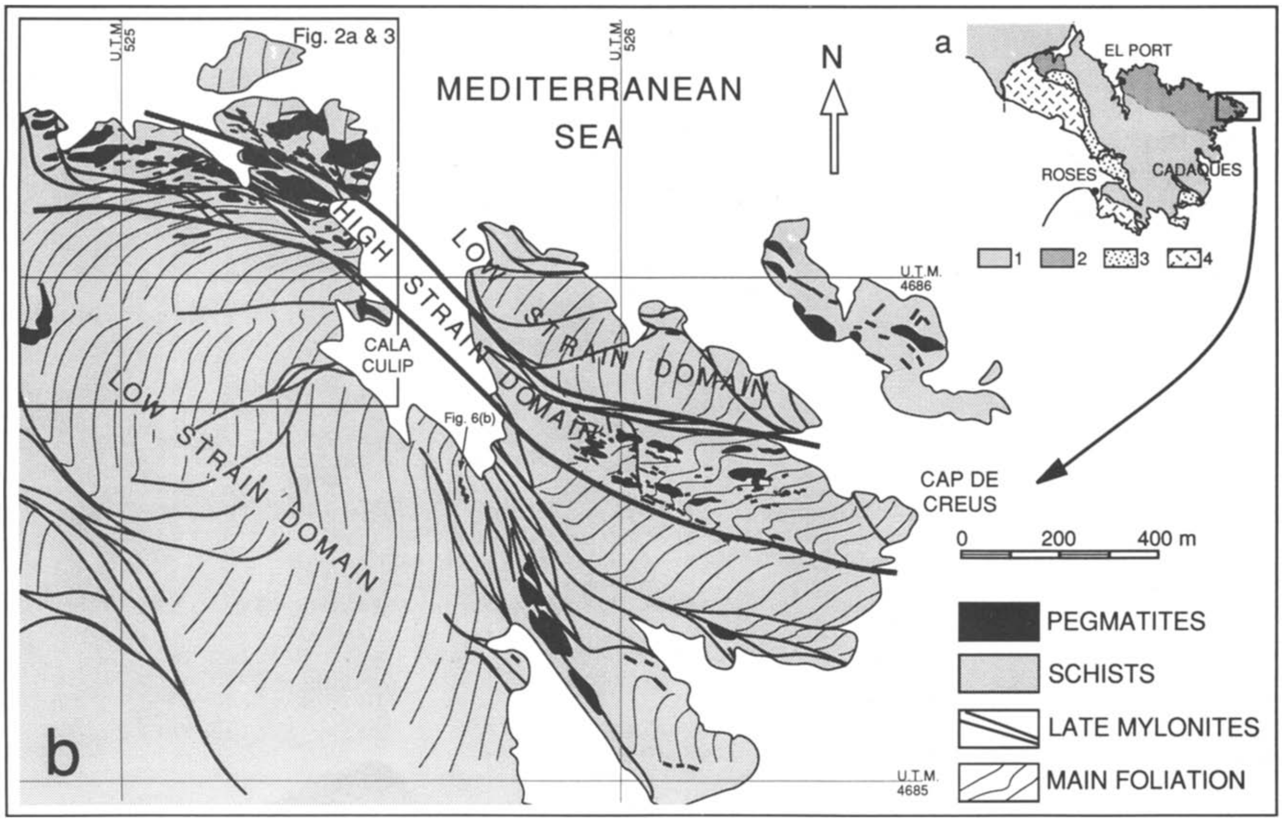

Fig. 1. Geological setting of the study area. Coordinate system refers to the Universal Transverse Mercator Grid (U.T.M.), Zone 31-European Datum. (a) Main lithological units in the Cap de Creus peninsula: 1—metagreywackes and metapelites of low metamorphic grade, 2—the same of medium-high grade, 3—clastic and carbonatic rocks, 4—granodiorites. (b) Geological setting of the Culip–Cap de Creus area.

limbs. They bear an associated axial plane crenulation cleavage (*Scr*). The last major deformational event gave rise to E–W and NW–SE trending shear zones (the 'northern mylonite belt') developed under retrograde metamorphic conditions (Carreras *et al.* 1977). These shear zones form an anastomosing three-dimensional network, leading to the isolation of all sized lozenge-shaped domains of rocks not affected by mylonitization. While in the lower part of the medium grade domain, crenulation-related folding and shearing took place in a progressive way (Carreras & Casas 1987); in the higher grade domains (Fig. 1) the folding and the shearing events can clearly be separated on the basis of the drop of metamorphic conditions.

FOLDS AND EMPLACEMENT OF PEGMATITES: STRUCTURAL ZONATION

The studied area is located in the medium to high grade metamorphic zone. The exposed rocks consist essentially of a metagreywacke sequence which includes thin layers of pale quartzite. It is affected by E–W axial tracing folds with upright or steeply inclined axial surfaces and sub-vertical or steeply plunging axes. The dimensions of the area mapped in detail (about 1 km^2 at 1:1000 scale) and exceptional exposures (Fig. 2a) enable a continuous study of the geometry of the structures and their relations with pegmatite emplacement.

The metasedimentary sequence displays an earlier foliation (called S_1), formed during the prograde metamorphism, which is predominantly sub-parallel to the bedding. Neither minor nor major structures related to this first deformational event have been recognized in this area.

Throughout the area, the bedding-S_1 foliation displays an open Z-sigmoidal pattern with a shear zone-like geometry (Fig. 3). This pattern is related to strain gradients which arose during the development of the folds with E–W axial trace, and were intensified by the overprinting of the later shearing. The pegmatitic dikes display a heterogeneous distribution and exhibit clear cross-cutting relationships with respect to the bedding parallel S_1-schistosity. On the other hand, dikes are stretched, boudinaged, or even displaced, and pegmatites are mylonitized by late shear zones. These shear zones cut obliquely across the high strain domain forming discrete bands of fine-grained mylonites and inducing the offset of the pegmatite dikes. The effect of this late shearing event can in general be easily removed (Carreras & Druguet 1994). Leaving aside the shear zones, it appears that a single folding event, prior to the shearing event, was responsible for both the sigmoidal pattern and the inhomogeneous distribution of deformation across the area. A high strain E–W trending zone of tight folds separates southern and northern lesser deformed domains, where asymmetric S-shaped folds affect an approximately N–S-trending bedding and

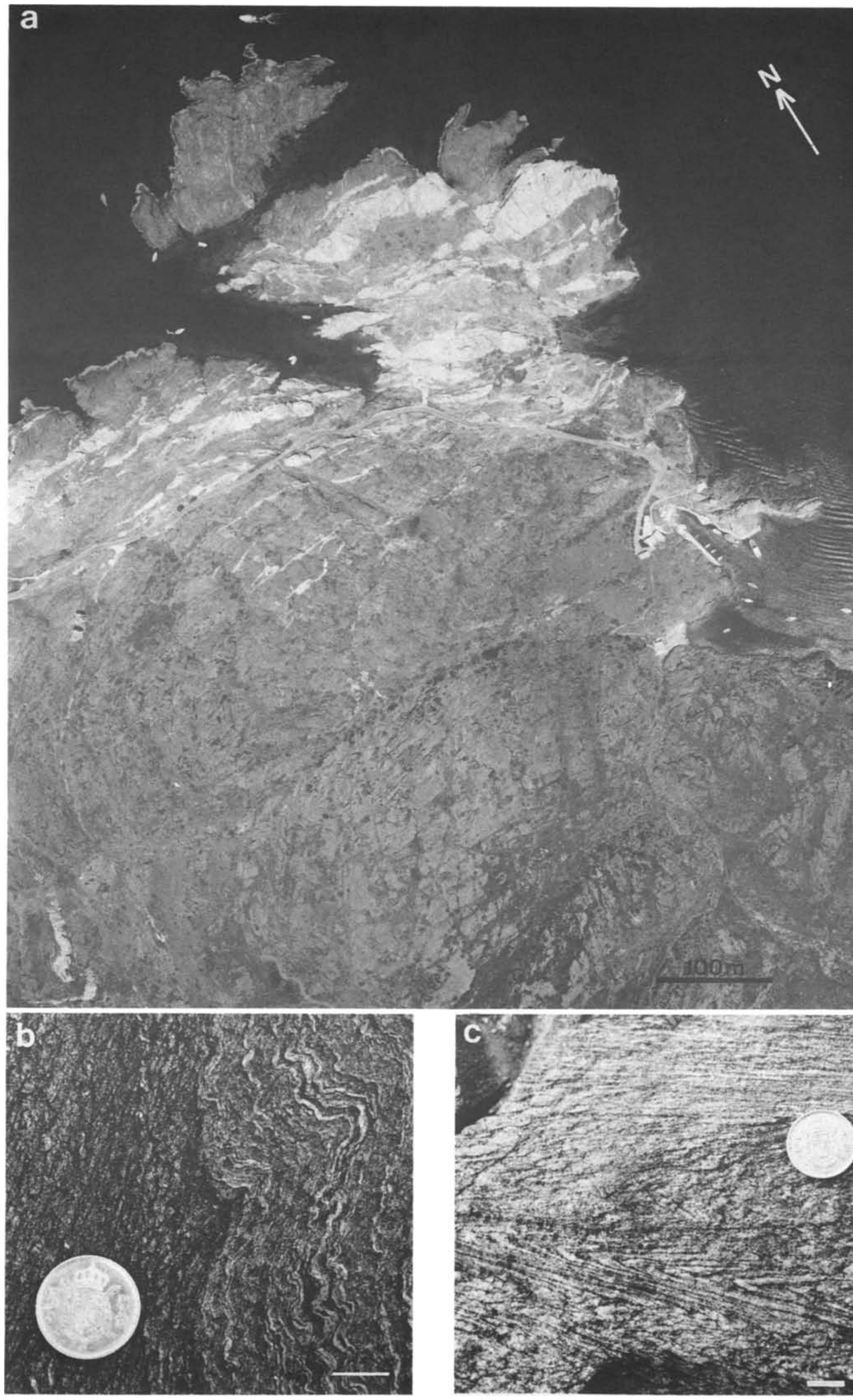

Fig. 2. General and close-up views of structures in the Culip area. (a) Aerial photograph of the Culip area. (b) & (c) Fold geometries in different domains. Scale bar is 1 cm. (b) S-shaped folds in the low strain domain. (c) Tight folds in the high strain domain.

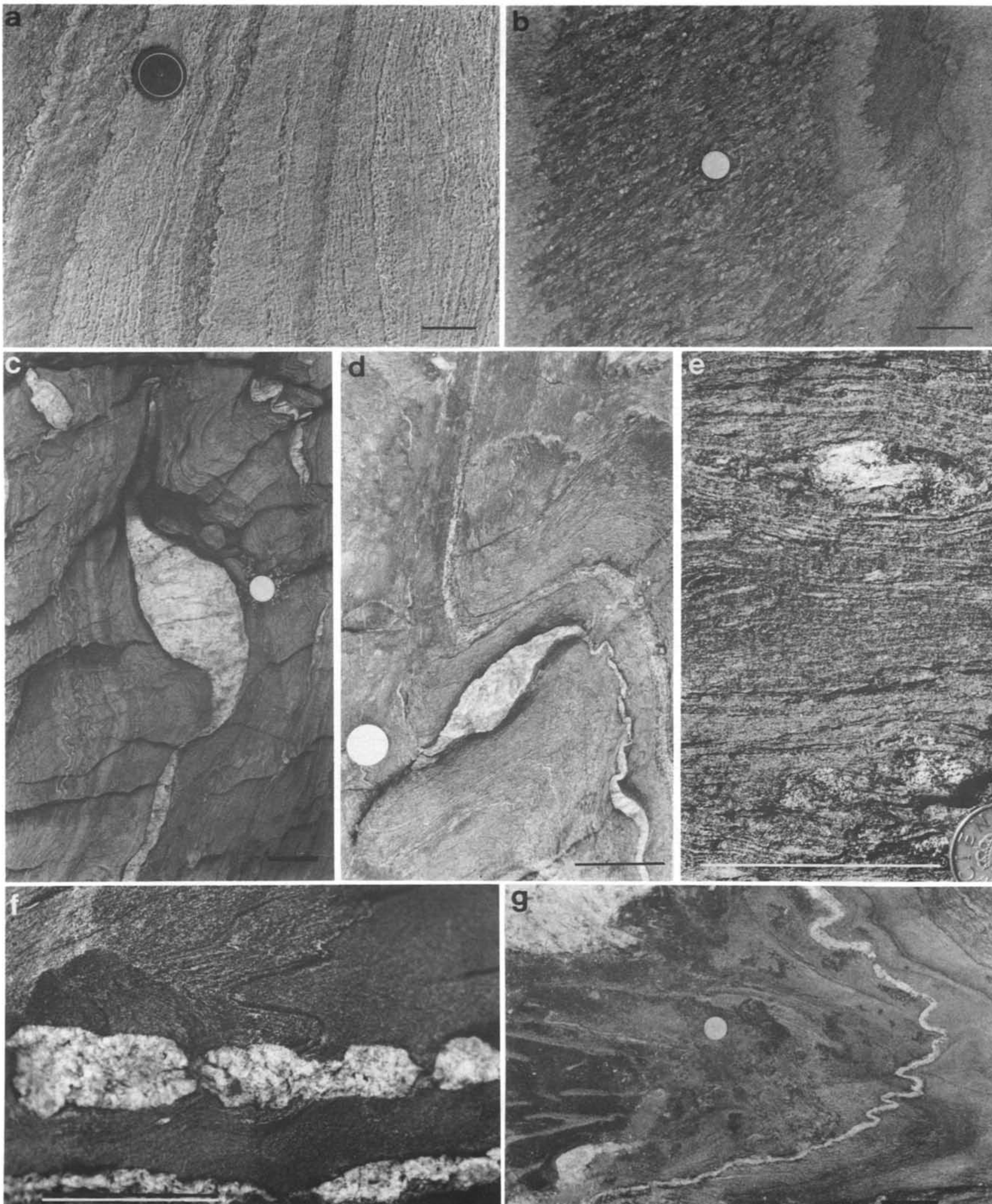

Fig. 4. Field photographs. Scale bar is 5 cm. (a) Bedding in metagreywacke and metapelite from the low strain domain, with S_1-schistosity parallel to bedding. (b) Crenulation cleavage is well marked in metapelitic layers from the low strain domain. (c) & (d) Two examples of anti-clockwise rotation of quartz boudins during folding in the low strain domain. (e) Transposition foliation wrapping around an andalusite porphyroblast in the high strain domain. (f) Axial planar boudinaged pegmatite in the southern margin of the high strain domain. (g) Folded pegmatite in the high strain domain.

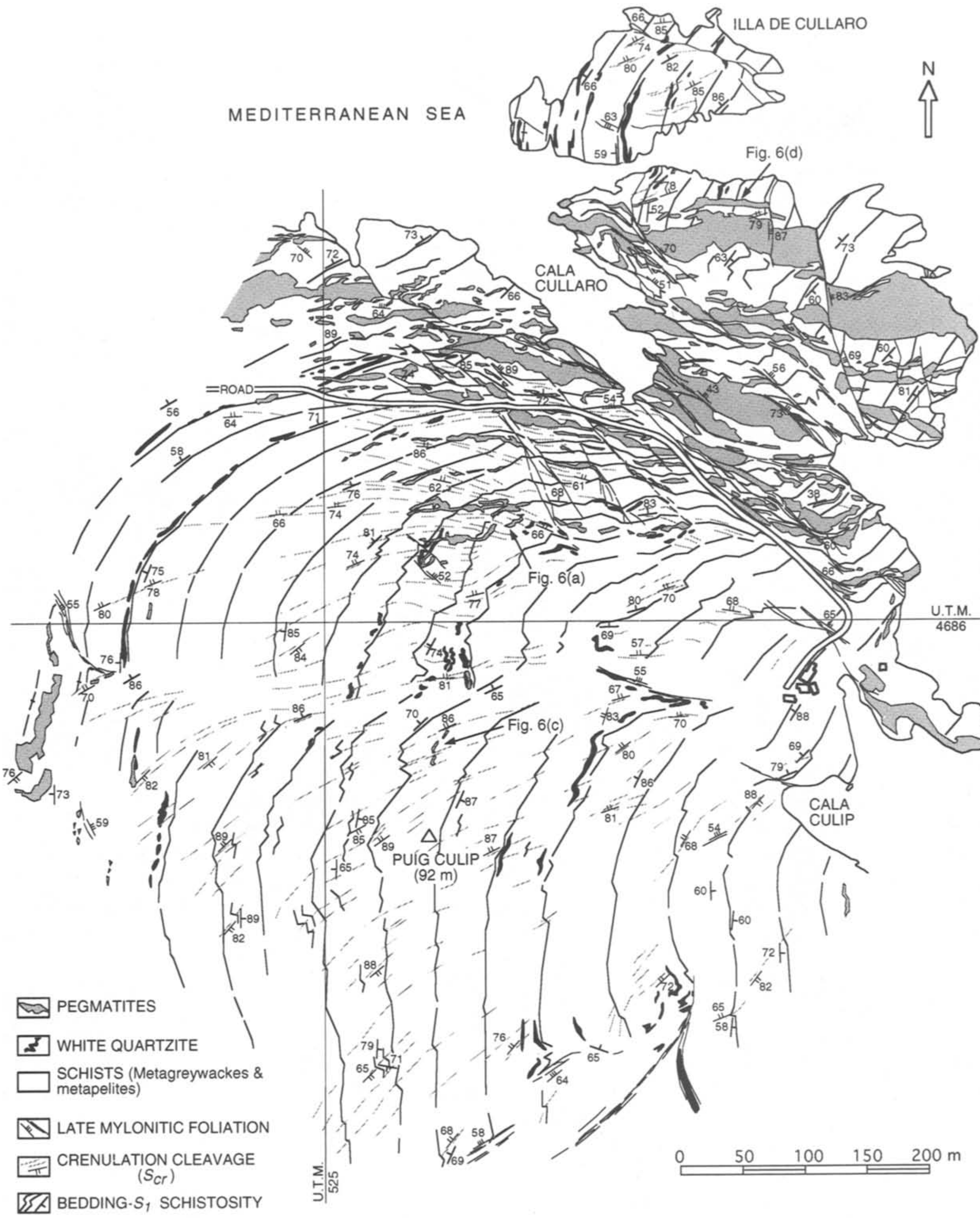

Fig. 3. Structural map of the Culip area.

associated S_1 foliation. Axial planes and related crenulation cleavage trajectories also display a similar sigmoidal pattern. The localization of the largest and most abundant pegmatite dikes approximately tracks the high strain zone.

The existence of fold-related strain gradients across the area enable us to distinguish between two low strain domains and an intervening elongate high strain domain. In fact, second-order inhomogeneities are responsible for the presence, in the low strain domains, of narrow bands marked by tight folds that indicate strain intensification.

Structures in the low strain domain

As shown in Figs. 1(b) and 2(a), the low strain domains are characterized by a general N–S trend of the bedding that is folded into upright open and asymmetrical S-shaped folds with sub-vertical axes (Fig. 2b). The axial planes of these folds trend WSW–ENE and an axial planar crenulation cleavage, with preferred orientation of biotite growth, developed selectively in metapelites. This cleavage is weak or absent in metagreywackes (Figs. 4a & b). The angle between the mean bedding orientation and the axial plane crenulation cleavage decreases gradually towards the high strain domains from about 45°–35°, with the simultaneous clockwise rotation of both surfaces (see Fig. 5). This rotation and the decrease of the angle between these two structural elements is interpreted as the result of increasing strain, as shown by the increasing tightness of the folds. Earlier boudinaged quartz segregation veins (parallel to S_1) are folded with an anti-clockwise rotation of the boudins, systematically located in the short limbs (Figs. 4c & d). Porphyroblasts of cordierite or andalusite grown over S_1 are wrapped by the crenulation cleavage and systematically display an anti-clockwise rotation.

Pegmatites in the low strain domains are rather scarce except for the zones adjacent to high strain domains (Figs. 2a and 3). When present, they are generally emplaced parallel to bedding in domains of local fold intensification. Such pegmatites are coaxially folded with the enclosing metasediments, but in a more open form, with abundant examples of pegmatite fold patterns analogous to the example described by Ramsay (1967, fig. 7–2, p. 344). No penetrative solid-state tectonic fabric is present in the folded pegmatites. Cuspate-lobate structures (Ramsay 1982) around the folded pegmatites indicate a more competent behavior of the magmatic crystal mush than the enclosing metasediments. These facts, and the systematic congruent folding and/or boudinage of isotropic pegmatites and the enclosing schists, suggest a syntectonic emplacement of pegmatite dikes.

Structures in the high strain domain

The high strain domain is characterized by a low angle between the crenulation cleavage and bedding-S_1 foliation. This angle decreases to an average value of about 15°–20°, although parallelism of both structural elements, with the local development of a transposition foliation (S_{tr}) is quite frequent. In this case crenulation cleavage replaces S_1 as the dominant foliation and an E–W trend of foliations becomes predominant. Folds, when recognizable, are usually very tight (Fig. 2c). In spite of the change in orientation of the axial surfaces, no significant change in fold axis orientation occurs. Porphyroblasts appear entirely wrapped by the dominant foliation and they look pre-kinematic, although they are post-kinematic with regard to S_1 (Fig. 4e). Pegmatites are abundant and form huge bodies, up to a few 100 m long and 40 m wide. Dikes and more irregular bodies generally exhibit an elongate shape, with their long axis in close parallelism with the trend of the transposed foliation. The dike swarm forms a band closely parallel with the trend of the high strain domain, although some dikes also intrude marginal lesser deformed domains. Additional criteria indicating that the pegmatites in this area are syntectonic are, for instance, the parallelism of enclaves and different compositional inhomogeneities in the pegmatites with the transposition foliation (see Vernon *et al.* 1989) and the presence of foliation triple points (see Paterson & Tobisch 1988). Boudinage or pinch and swell, and folding of the pegmatites (Figs. 4f & g and 6) show similar relationships as observed in lower strain domains, enabling us to conclude that the dikes were emplaced here also synkinematically. The close parallelism of fold structures and dike swarms suggest a tectonic control on pegmatite emplacement. The high strain domain was partially reworked by a framework of shear zones (Carreras 1975, Carreras & Casas 1987). On the broader scale, it is apparent that the shear belt is an anastomosing framework of shear zones superimposed on all earlier structures, and thus not uniquely related to the high strain domain.

DISCUSSION

Although the general structural pattern is rather simple and there is good order to the geometric arrangement of the structures, the intensification of deformation in the high strain domain is not easy to explain.

As a first approach, the fold-related sigmoidal structure does not appear to be the result of an interference pattern. Folds and their related axes and crenulation cleavages are undisturbed except in the vicinity of shear zones where shearing-related folds can appear. There can be no doubt that local transposition foliation is the effect of stretching of the previous foliation and/or the tightening of folds, leading to the parallelism between both foliation surfaces.

It is reasonable to assume that the fan-like structure delineated by the trends of the crenulation cleavage and axial planes across the area are the result of a single or progressive deformation event. Thus, the development of a high strain domain, localized where axial trace trajectories narrow and the dihedral angle of bedding-S_1 and crenulation cleavage diminishes (Fig. 5), appears to arise from strain localization during the progress of the folding event.

Assuming that the fan-like pattern of the crenulation cleavage trajectories (Figs. 3 and 5) in rocks with low mechanical anisotropy should track approximately the trace of the XY plane of the finite strain ellipsoid generated during the folding event, it follows that there is a non-coaxial component to the deformation. The fact that, as a result of deformation increase, the trace of the XY plane rotates dextrally about a sub-vertical axis, suggests that on the regional scale a dextral shear component must be involved, and the bulk deformation ranges between transpressive and transtensive tectonic regimes. If the general structure is interpreted as a large dextral simple shear zone, Z-shaped folds should predominate throughout the area, or at least in high strain domains. However this fact is in manifest contradiction with the asymmetry of the minor folds and with the sense of the rotated boudins and porphyroblasts; all these

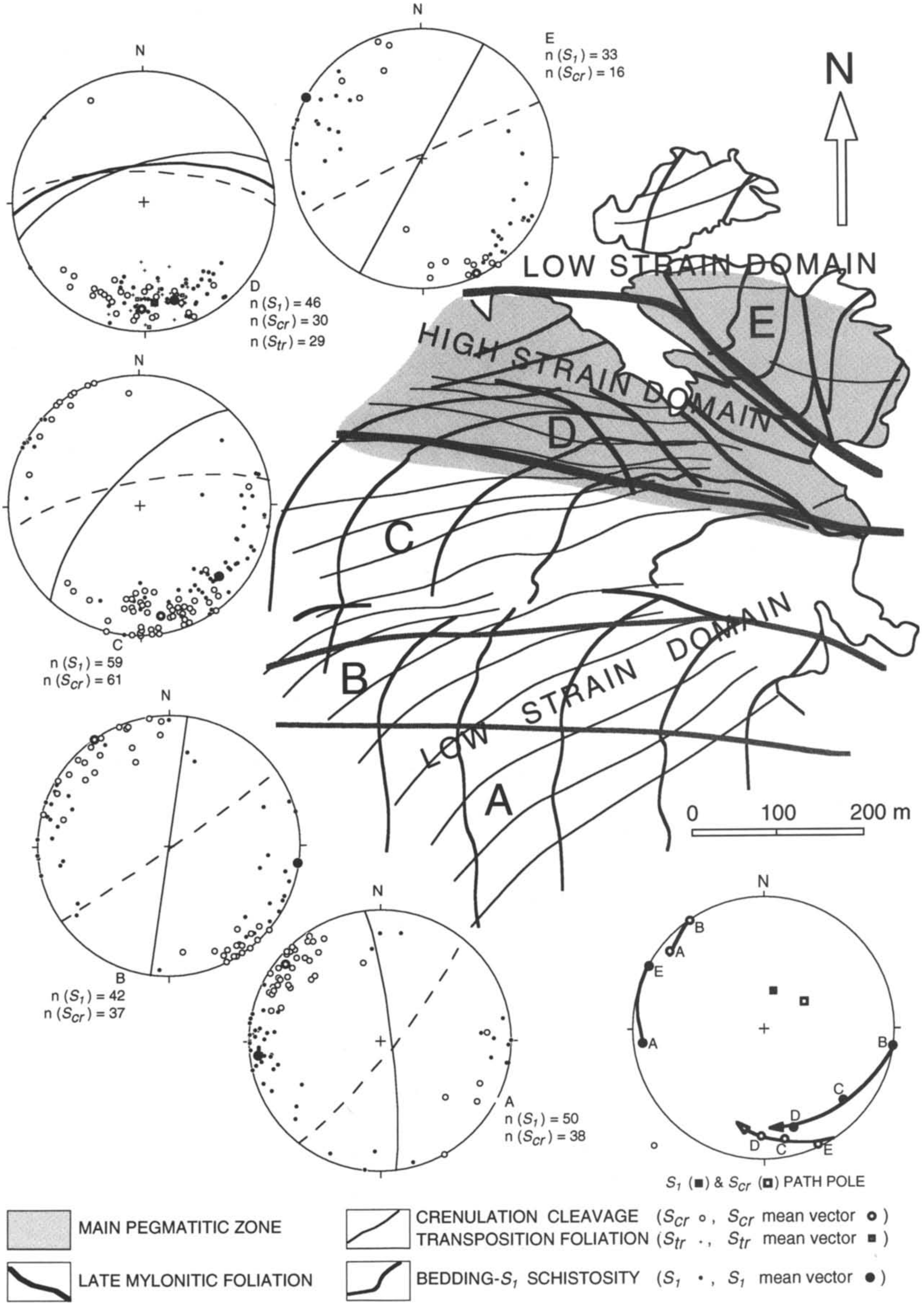

Fig. 5. Equal-area lower-hemisphere projections for the area. In each plot, the great circles correspond to the main value of S_1 (solid) and S_{cr} (dashed) and correspond to each sub-area indicated on the map (A–E). In plot D, thick solid curve corresponds to the main value of the transposition foliation (S_{tr}). The pole path projection refers to the clockwise rotation of S_1 and S_{cr}, the poles in each path are the main values of each domain. The location of poles of best cylindrical fit of each path is also shown (squares).

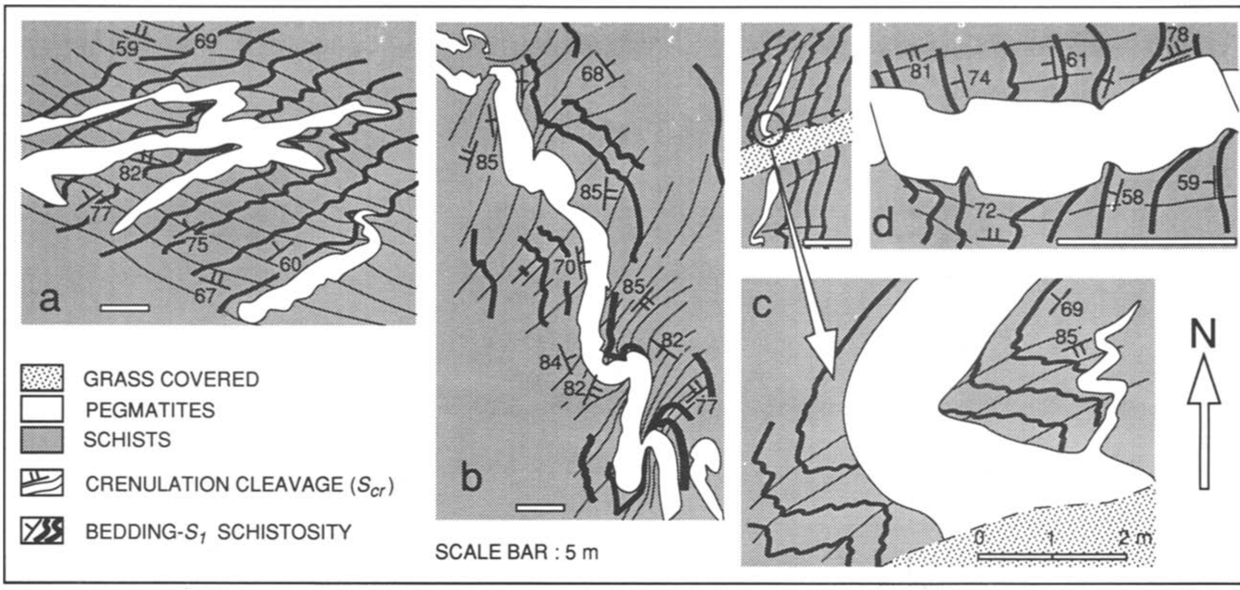

Fig. 6. Different shapes of pegmatitic dikes. Locations of (a), (c) and (d) are shown in Fig. 3, and (b) is shown in Fig. 1. (a) Complex pattern in a pegmatite with differentially oriented apophyses. (b) Cuspate structures in a bedding parallel pegmatite. The dike forms a relatively high angle with S_{cr}. (c) Similar setting to (b) with detail of S_1-dike relationship. (d) Pinch and swell pegmatitic dike cross-cutting bedding-S_1 at a high angle. The trend of the dike is closely parallel to S_{cr}.

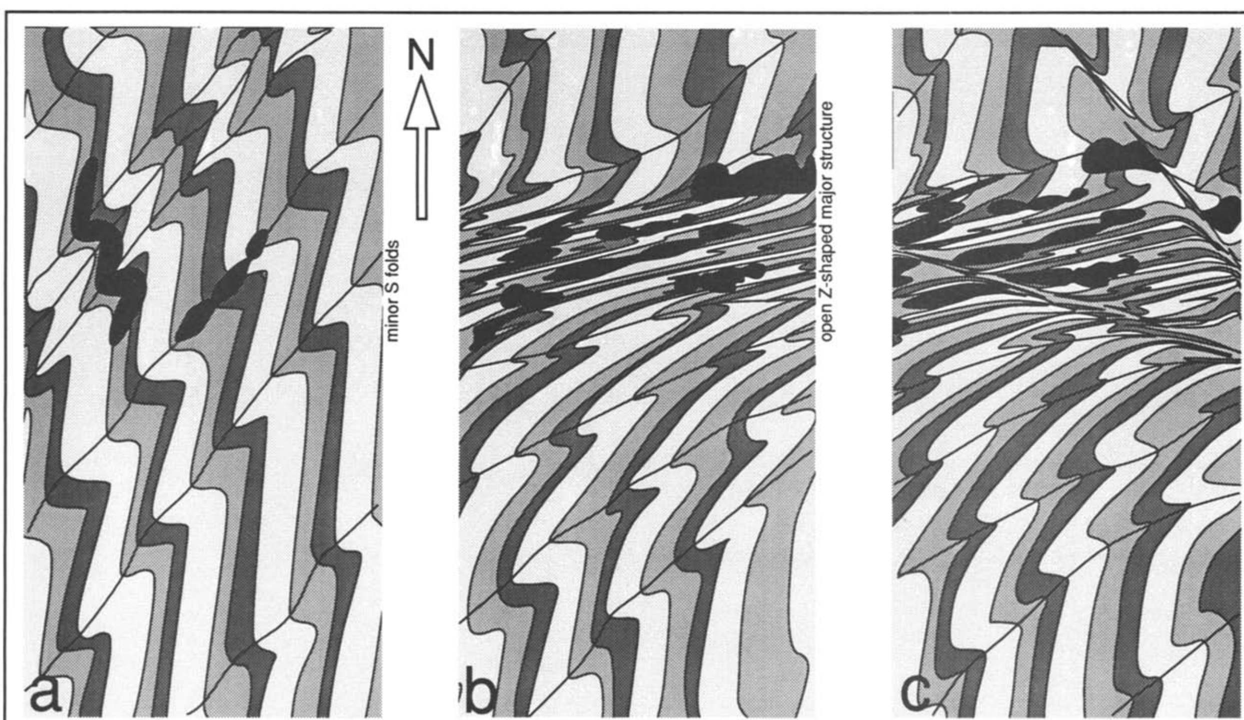

Fig. 7. Schematic interpretation of the fold structures and pegmatite emplacement in the Culip area. (a) Early stage of the folding event. Some pegmatitic dikes were emplaced preferentially parallel to the bedding or to S_{cr}. (b) Main stage of the folding event, with development of a major open Z-shaped shear zone-like structure. The pegmatites occur within the high strain domain. (c) Late shear event cutting across the pegmatites and all earlier structures.

show the prevalence of a sinistral layer-parallel shearing throughout the zone.

Thus, the observed S-fold asymmetries challenge the expected Z-shapes in a dextral shear zone (Carreras & Santanach 1973, Berthé & Brun 1980, Hudleston & Lan 1993).

The way we propose to reconcile the observed structures and the deformation is to consider that the minor folds were formed under a crustal shortening induced by bulk dextral shearing or transpression. A bulk NNW–SSE incremental shortening direction, induced by such a non-coaxial deformation, would generate S-shaped asymmetric folds in N–S vertical trending bedding and foliation, (see Ramberg 1959, p. 125; Price & Cosgrove 1990, fig. 13.16, p. 340). Minor folds (Fig. 7a) could be formed earlier than the larger scale open Z-structure. The progress of deformation would lead to the development of the sigmoidal shape of bedding-S_1 (Fig. 7b). The larger structure was formed initially as a vertical flexural flow fold with 'monocline-like' geometry, in which the high strain domain would represent the limb probably containing pinched hinges of second-order folds (Fig. 7b). This way the low strain domains would represent areas close to a broad hinge zone, and the general pattern of crenulation cleavage trace trajectories would be that expected in a vertical flexural 'monocline-like' fold. However, the map in Fig. 3 shows that in the high strain domain the orthogonal thickness of bedding decreases, and this fact indicates that the bulk structure departs from a parallel fold model formed exclusively by buckling. A further approach would be to consider the decrease in orthogonal thickness as the result of shearing, or a combination of shearing and flattening (subsimple shear, De Paor 1983), concentrated in the high strain domains (Fig. 7b) while the deformation continues.

The above suggested model of strain intensification along a sheared limb of a fold is analogous to that proposed for the development of shear zones in foliated rocks (Carreras 1992), where shear zones nucleate as flexural instabilities and grow by shear strain concentration along a stretched fold limb.

The narrow retrograde shear zones, developed under greenschist facies conditions, overprint the former structure (Fig. 7c).

Pegmatite dikes emplacement

As previously explained, there is good evidence that the pegmatites were emplaced syntectonically with the folding event, and preferentially within the high strain domain. Discarding a transtensional setting not compatible with the observed structure, a space problem arises. The amount of space filled up by melted pegmatitic material represents about 20% outcrop in surface. Although there is a certain degree of preferred orientation of pegmatite dikes parallel with the trend of the high strain domain, no systematic geometry seems to govern the opening of the space occupied by the pegmatites. It appears that most of the pegmatite bodies have side-walls disposed parallel with the bedding-S_1 foliation, indicating that pre-existing planes of weakness were major controlling elements. Furthermore, folding is expected to induce bedding-S_1 parallel openings used by the pegmatite melts. Due to the variable attitude of bedding with respect to the XY plane of the fold-related strain ellipsoid, pegmatites at high angles to the crenulation cleavage are folded while the majority at low angles to the crenulation are boudinaged and/or asymmetrically folded (Fig. 6). Pegmatite dikes in some instances cut across bedding, possibly following tension fractures or opened shear fractures as proposed elsewhere by Hudleston (1989). In such a situation, dikes are also subjected to folding and/or boudinage by progressive deformation.

The abundance of melts located in the high strain zone parallel with the axial planes of the folds (Fig. 7b), is comparable to many smaller scale structures with axial-planar leucosomes, leucogranites or pegmatites described in similar structural settings (e.g. Edelman 1973, Ramsay & Huber 1987, fig. 20.12, p. 416; McLellan 1988, Passchier *et al.* 1990, Hand & Dirks 1992). At larger scales, more general relationships between deformation and melting have also been described (see Pitcher 1979, Hutton & Reavy 1992).

The asymmetric distribution of pegmatites within the high strain zone, with the predominance of the larger bodies, is interpreted as the result of the north dip of the foliation in the high strain domain. If magmas were channeled along the high strain zone one should expect that the upward rising melts could preferentially ascend along newly created weakness planes above the high strain zone.

The use of the different structures generated in differently oriented dikes will presumably furnish in the future some new data concerning the vorticity of deformation and the bulk tectonic regime of the area.

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