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Regional shear variation in relation to diapirism and folding

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Abstract—Regional structural trends in the Lévézou area (southern Massif Central, France) delineate an antiformal structure. Deformed granitoids display changes along strike in *S–C* plane relationships, and therefore in sense of shear. These variations are interpreted to be strain accommodation features that developed during the diapiric emplacement and folding of the granitoid sheets, and so cannot be used as kinematic indicators on a regional scale.

INTRODUCTION

S–C GNEISSES and mylonites (Berthé *et al.* 1979a,b, Lister & Snoke 1984) are characterized by two sets of planes: foliation planes (*S*), which are related to the accumulation of finite strain; and shear planes (*C*), which are related to displacement discontinuities and/or zones of high shear strain, sub-parallel to the shear plane during a non-coaxial deformation history. The angular relationship between *S* and *C* planes is therefore directly related to the sense of shear and has been widely used as a kinematic indicator in mylonites and shear zones on all scales (e.g. Jégouzo 1980, White *et al.* 1980, Burg *et al.* 1981, Simpson & Schmid 1983). In thrust systems, this sense of shear has often been equated with the sense of transport (e.g. Bouchez & Pécher 1981, Boullier & Quenardel 1981) and a common temptation is to make use of *S–C* relationships together with other shear-sense criteria in determining the general vergence of an orogenic belt (e.g. Laurent & Etchecopar 1976, Brun & Burg 1982, Faure 1985, Harris 1985). The aim of this paper is to interpret the kinematic significance of complex patterns of *S–C* structures that occur on a regional scale, but which are not due to the intimate superposition or juxtaposition of zones with different or opposite senses of shear, as has been reported elsewhere (e.g. Burg *et al.* 1984a, Harris 1985). The example is taken from the southern Massif Central (France), where continuous changes in *S–C* relationships are best interpreted in terms of strain accommodation structures between layers of different rheologies involved in large-scale (diapiric?) folding.

GEOLOGICAL SETTING

The Lévézou Massif (southern part of the French Massif Central) displays a conspicuous arcuate pattern in which foliations are everywhere parallel to lithologic boundaries or major contacts (Collomb 1970, Burg *et al.* 1986) (Fig. 1). The Massif is conveniently sub-divided by a mafic to ultramafic unit (the leptyno-amphibolitic sequence) into an internal domain centred on Lévézou, and an external domain, both of which consist of metasedimentary rocks and various metagranites (Burg *et al.* 1986). The gravimetric and magnetic signature of the leptyno-amphibolitic sequence has permitted its extension to be extrapolated below the sedimentary cover to the east (Bayer & Hirn 1987), revealing that it forms a circular to elliptical structure (Fig. 1) (Bayer personal communication). The leptyno-amphibolitic sequence comprises peridotite and eclogite bodies enclosed in a matrix of amphibolite, quartz–feldspar gneiss and some mica-schist, all which were last metamorphosed, along with the internal domain, under lower amphibolite-facies conditions. Major and trace element analyses suggest that the basic rocks are tholeiites with oceanic (MORB) affinities, with which are associated ultrabasic cumulates with a related trace element signature (Bodinier *et al.* 1986). There must therefore be a thrust contact between the leptyno-amphibolitic sequence and the pelitic–semi-pelitic metasediments, although this is not apparent in the field. Both the leptyno-amphibolites and the internal domain have been affected by several phases of tight to isoclinal folding broadly associated with the amphibolite-facies metamorphic culmination (Burg *et al.* 1986).

The deformation history of the external domain involved two phases of tight to isoclinal folding, F_1 and F_2, accompanied by a low-grade (chlorite + muscovite + quartz in metapelite, well-preserved sedimentary structures) to medium-grade (biotite + garnet + staurolite) metamorphism of intermediate-pressure type. Both folding and metamorphism in the external domain are ascribed to a S-directed thrusting event represented by the emplacement of the Le Vibal klippe (Fig. 1).

Of particular interest to this study are the orthogneisses, which are in fact sheet-like granitoid bodies and their apophyses (laccoliths, Burg & Teyssier 1983), which occur in both the external and internal domains, and are characterized by K-feldspar megacrysts. They are variably foliated 2-mica S-type plutonic rocks in the sense of Chappell & White (1974), which are interpreted to be syn-kinematic intrusions emplaced, at least in part, along the pre-existing thrust contact between the leptyno-amphibolites and the metasediments. They have

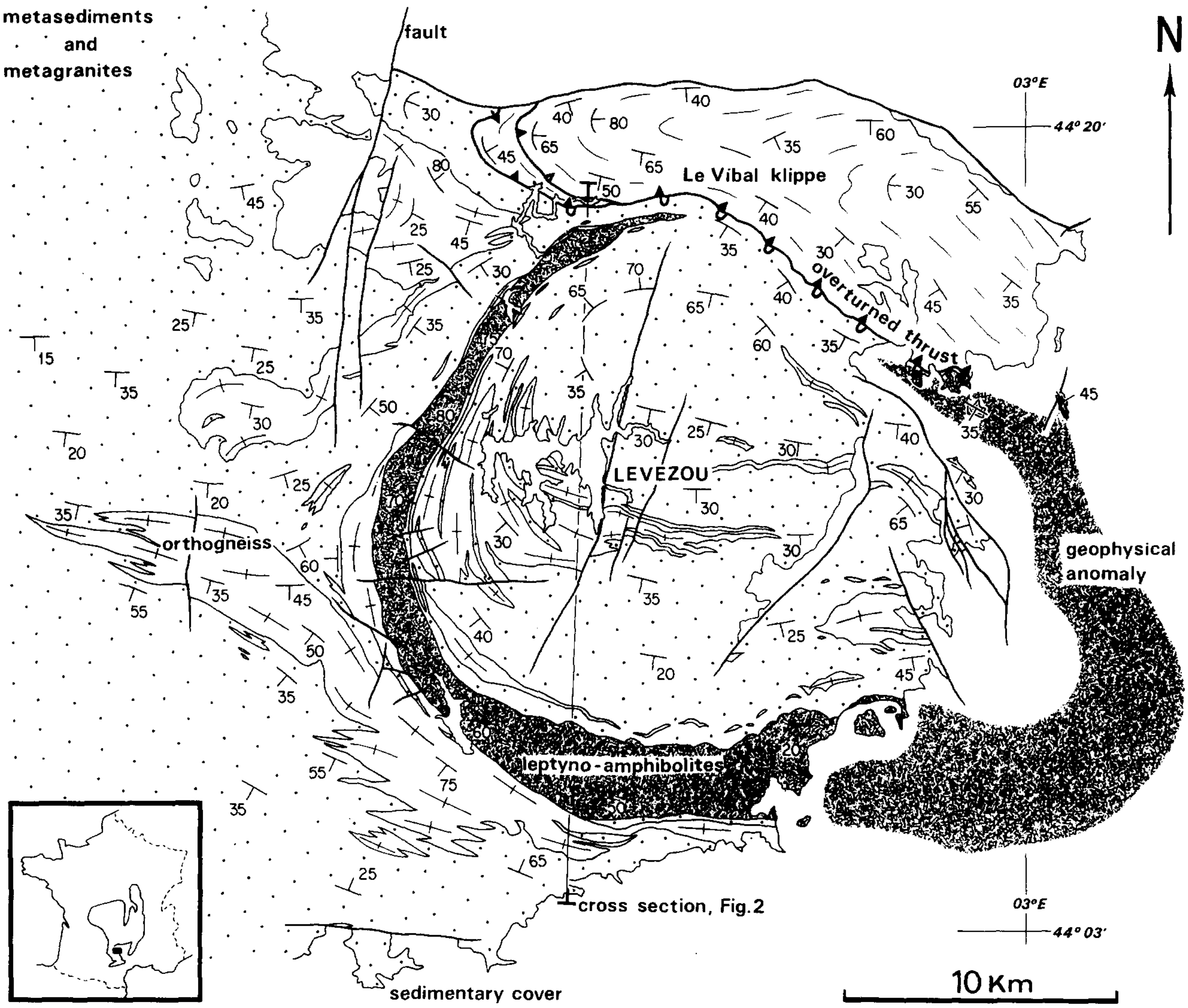

Fig. 1. Lithology and structure of the Lévézou area, southern Massif Central, France. Dip and strike symbols refer to foliation planes (*XY* planes of finite strain). A thrust contact is suspected between the leptyno-amphibolites and the metasediments and metagranites of the external domain (see text).

been dated at *ca* 350 Ma (Pin 1981). In the external domain the orthogneisses are overprinted by thermal aureoles that developed in late to post F_2 time, and which demonstrate an increase in temperature in pelitic rocks from the sub-biotite zone through biotite, garnet and staurolite zones, the latter containing kyanite (Delor *et al.* 1984). Undeformed granitoid rocks are preserved between wide zones of ductile deformation. The undeformed granitoids consist of coarse- to medium-grained monzogranite–syenogranite–granodiorite and contain randomly orientated quartz, oligoclase–andesine, microperthitic orthoclase, biotite and muscovite. Accessory minerals include ilmenite, apatite, zircon and monazite, and locally garnet and cordierite. Hornblende occurs in dioritic facies.

The ductile deformation zones are marked by the development of augen-gneisses with typical *S–C* structures (Burg & Teyssier 1983). In contrast to the country rocks, which have recorded a polyphase penetrative deformation in both the external and internal domains, the augen-gneisses exhibit a simple history of fabric generation. Narrow zones of very high shear strain are exceptional.

S–C structures and finite-strain patterns in the synkinematic orthogneisses were studied in order to understand better the kinematics (i.e. the rotation pattern of finite-strain axes) involved in the emplacement of the leptyno-amphibolites in the Lévézou structure. The approximate contemporaneity of mineral ages throughout the area (Delbos *et al.* 1964–1965) supports the assertion that all the fabrics formed during the same deformational and metamorphic event.

STRUCTURE

Foliations

Dips of the foliation (*S* planes) are very shallow near the centre of the Lévézou Massif, but become increasingly steep towards the marginal zones. Foliation planes define an asymmetric antiform, verging N–NW, with an

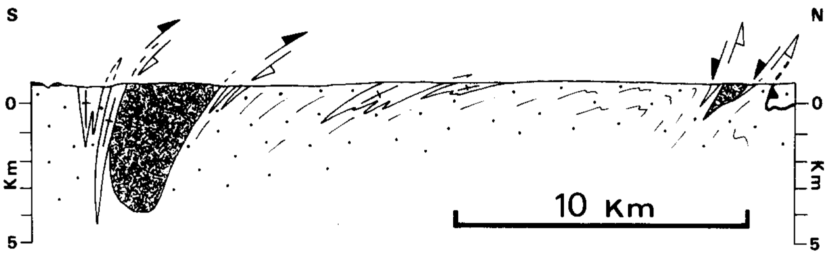

Fig. 2. N–S section (location shown in Fig. 1) across the Lévézou structure. Legend as in Fig. 1. Arrows indicating sense of shear were derived from analysis of small-scale structures; see Fig. 5 and text for details. The extrapolation of the leptyno–amphibolites at depth is consistent with geophysical constraints (Bayer & Hirn 1987).

overturned northern limb dipping approximately 40°S (Fig. 2). In the orthogneisses the relatively irregular foliation *S* is defined by the average flattening plane of grains or grain aggregates and the preferred orientation of micas deflected around the K-feldspar porphyroclasts (Fig. 3a). Because the material was initially isotropic and homogeneous on the scale of the hand specimen, *S* is likely to correspond to the λ_1/λ_2 plane of finite strain (e.g. Nicolas & Poirier 1976). The trend of the *S* planes in the orthogneisses is parallel to the foliation (i.e. the flattening) planes in the country rocks, and outlines the shape of the antiform (Fig. 1).

C planes

C planes constitute a set of more or less regular and discontinuous micro-shear zones with a width equivalent to that of individual matrix grains and a spacing of some centimetres. On the regional scale they change in orientation sympathetically with the foliation *S*, suggesting they are not a late cleavage transecting the Lévézou structure. This, together with the observation that both *S* and *C* surfaces are defined by similar mineral assemblages that can be related to a simple P–T–time metamorphic path, suggests that they were formed during the same deformational and metamorphic event (Burg & Teyssier 1983, Burg *et al.* 1986).

Lineations

In the orthogneisses a pronounced penetrative stretching lineation, *L*, defined by the long axes of grains and grain aggregates and by a streaking of felsic and mafic minerals, is widely developed within *S* planes and is equated with the λ_1 direction of finite strain. Quartz–mica fibres and slickensides on the *C* planes are parallel to the *L* direction within the *S* planes, and thus show that the movement direction on the shear planes was coplanar (i.e. it lay in the same plane orthogonal to the flow plane) with the direction of bulk flow. Kinematic analysis of quartz *c*-axis fabrics from these rocks also supports this interpretation (Burg & Teyssier 1983). In the external domain the elongation directions in the orthogneisses are markedly oblique and locally sub-perpendicular to the regional mineral-extension direction L_2 (which is parallel to F_2 hinges) in the adjacent metasediments and metagranites (Fig. 4). However, *L* and L_2 are essentially concordant in the internal domain and in the southwestern part of the area (Fig. 4).

S–C RELATIONSHIP

Angles between the enveloping surface of *S* and *C* planes were measured on varnished λ_1/λ_3 sections of rock in order to corroborate field observations. Four situations corresponding to four areas can be recognized, keeping in mind that the patterns of foliation, lineation and sense of shear are in continuity along strike (Fig. 5).

(1) Foliation and *C* planes dip S with a steeply-plunging lineation and the *S–C* angular relationship indicates a dominant S (apparently normal) sense of shear. This is particularly the case in the northern part of the area studied.

(2) Foliation and *C* planes dip S with a steeply plunging lineation, and the *S–C* angular relationship indicates a predominant N (apparently reverse) sense of shear. This is the case for the southern part of the area.

(3) Foliation and *C* planes are subvertical with a moderately- to steeply-plunging lineation, and the *S–C* angular relationship indicates an apparently normal (± dextral) sense of shear. This situation occurs along and on both sides of the N–S segment of the leptyno-amphibolitic sequence.

(4) Foliation and *C* planes are flat-lying with a gently-plunging lineation, and the *S–C* angular relationship indicates a westward sense of shear. This situation occurs in the core of the Lévézou structure.

The four different shearing directions are confirmed by microscopic shear-sense criteria such as spindle-shaped micas, elongate new grains in quartz ribbons, displacement patterns on intracrystalline micro-shear zones and asymmetric strain shadows adjacent to large feldspars (for review of criteria see Simpson & Schmid 1983). As a first conclusion it is clear that the Lévézou structure is not bordered by consistent detachment of thrusting horizons, as would be expected in a nappe configuration. The convergent trends of structures in the immediate surroundings of the massif suggest that the leptyno-amphibolites moved relatively southward on the northern side of the massif and northward on the southern side (Fig. 2).

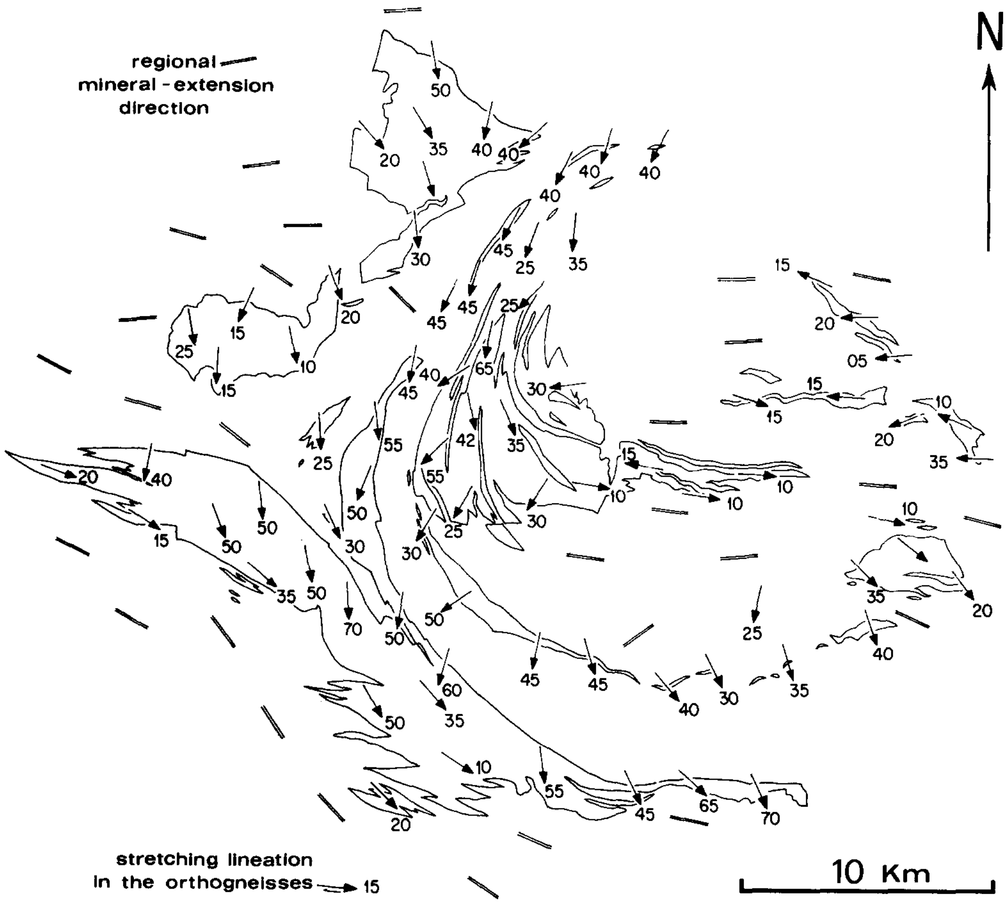

Fig. 4. Orientations of stretching lineations in the Lévézou area.

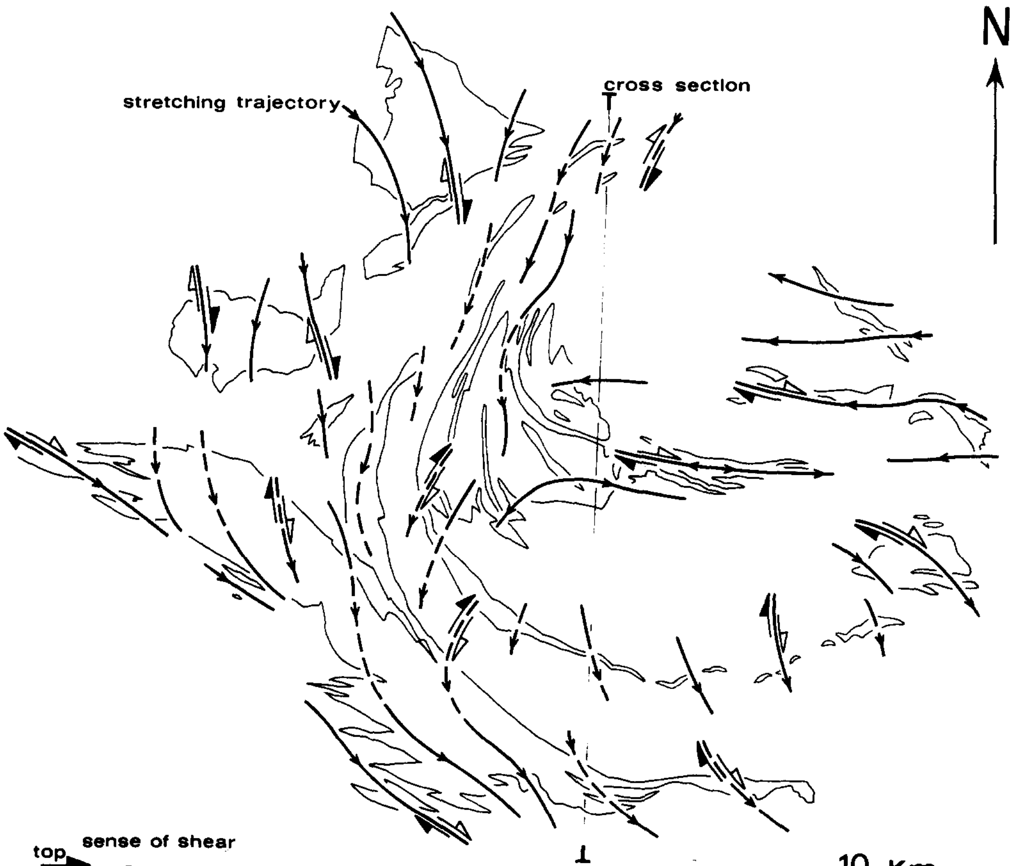

Fig. 5. Stretching trajectories and associated component of sense of shear in a vertical plane as determined from the angular relationship of *S–C* planes. V marks along the trajectories point towards the average plunge direction. Dashed trajectories correspond to areas where the plunge is >45°.

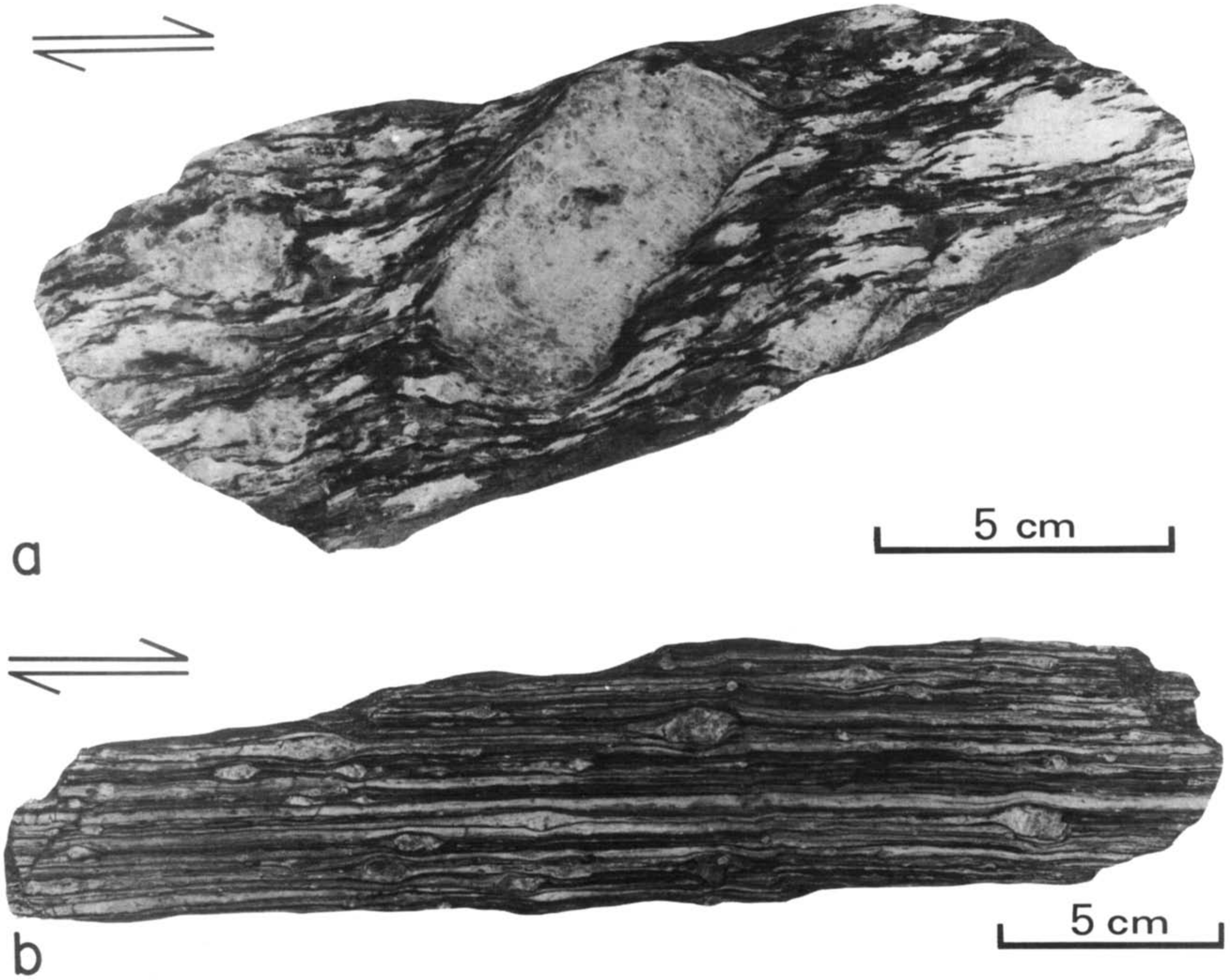

Fig. 3. (a) Example of a moderately deformed Lévézou orthogneiss with foliation deflected around a K-feldspar porphyroclast. Sense of shear indicated. *XZ* section. (b) Example of intense deformation leading to sub-parallelism of *S* and *C* planes in an orthogneiss. Sense of shear indicated. *XZ* section.

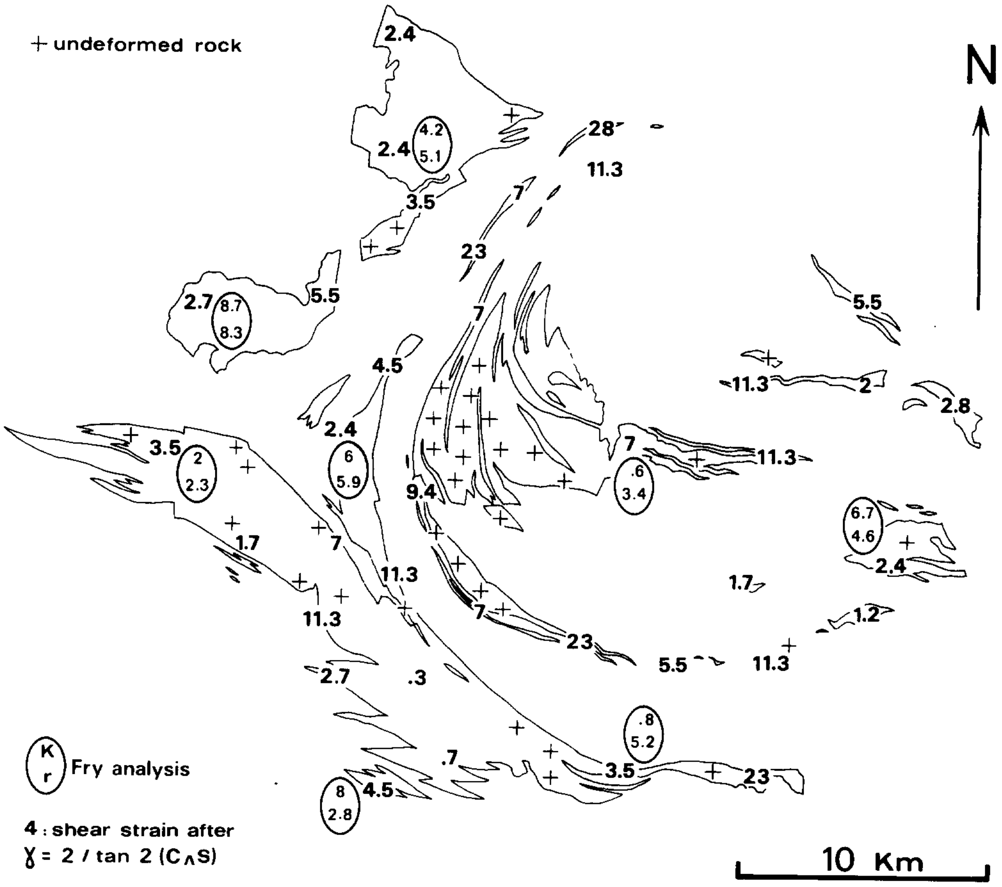

Fig. 6. Finite-strain measurements (results of a Fry analysis using K-feldspar porphyroclasts as centre point markers) in ellipses. Bold numbers indicate the shear strain γ as obtained from the angular relationships of S–C planes.

FINITE STRAIN

Determination of the finite strain was greatly hampered by the lack of a reliable method to measure strains in augen-gneisses with almost no mafic xenoliths. No measurements were obtainable in the most deformed rocks and so all strain data relate to moderately sheared rocks. For some outcrops however, it was possible to perform a Fry analysis (Fry 1979) using the K-feldspars as centre point markers. Elsewhere the shape of the strain ellipsoid (K factor of Flinn 1962) was estimated by visual inspection of the principal strain planes in large rock specimens, assuming strongly planar gneisses (S tectonites) indicate oblate strain ellipsoids and marked L (or L/S) fabrics indicate prolate strain ellipsoids. Such analyses made in the field gave an indication of the average strain within the gneisses at the sample locality. The central zone of the Lévézou is one of flattening strain ($K < 1$) whereas the contact and outer regions possess K values reflecting predominantly constrictional strain ($K > 1$).

More thorough analyses made in the laboratory, and Fry analysis, permitted a check of the range of K as judged in the field and allowed more precise estimates of the amount and type of strain (Fig. 6). Total strain intensities are referred to as r-values ($r = X/Y + Y/Z - 1$, where $X \geqslant Y \geqslant Z$ are the axes of finite-strain ellipsoid, Watterson 1968) and range from 2.3 to 8.3, reaching a maximum in a small laccolith of the external domain (Fig. 6). There is no clear relationship between K ($K = (X/Y - 1)/(Y/Z - 1)$, Flinn 1962) and r, but this is not surprising since the most deformed rocks are not susceptible to strain analysis.

Finite shear-strain distribution as crudely estimated from the S–C angles is homogeneous on the outcrop (several metres) scale. Variations in intensity of shear deformation from locality to locality have been deduced from the angular relationship (θ) between the foliation S and the shear planes C, where shear strain γ is given by the relation $\gamma = 2/\tan 2\theta$ (Ramsay & Graham 1970). A grid sample of γ values for each locality is presented in Fig. 6. In the deformed parts of the orthogneisses angles vary between 45° and very small angles, taken as 2°, which would correspond to a range of shear strains $0 < \gamma < 28$ (Fig. 6). It is recognized that the latter value is quite approximate because at low angles of θ any error in reading off the angles will result in large differences in γ (i.e. if $\theta = 3°$, $\gamma \simeq 19$ and if $\theta = 1°$ $\gamma \simeq 67$). Thus these γ shear strains have little significance in themselves, in particular the extreme values which reflect sub-parallelism between S and C planes in the most deformed zones (Fig. 3b), which are narrow and relatively rare. Yet shear strain values provide an image of the overall shear strain pattern of the area. Most strongly sheared rocks appear along the contact zone with the leptyno-amphibolites and within the core of the structure, whereas relatively small shear deformations are measured in the external domain (Fig. 6). Highest γ

values also occur in the narrowest segments of the laccoliths. The total displacement D across a deformed zone of width W can be specified from $D = \gamma W$ (Ramsay & Graham 1970). Approximate calculations indicate that some 100 m of displacement across the laccoliths can be accounted for by the strain pattern of Fig. 6 ($500 \leq D \leq 3200$ m).

DISCUSSION

Any reasonable hypothesis for the origin of the *S–C* structure development in the Lévézou area must account for the following geological constraints. (a) The natural strain pattern is dominated by prolate ellipsoids in the outer and contact regions and by oblate strain ellipsoids in the core of the Lévézou structure. (b) The use of *S–C* relationships in the contact regions as a kinematic indicator clearly shows that the core of the Lévézou Massif has subsided with respect to the external domain, a relative movement which at first sight is in contradiction with the antiformal structure defined by the attitudes of the foliation. (c) According to the *S–C* relationships there is also a top towards the west sense of shear in the axial zone of the Lévézou structure.

One interpretation discussed recently (Burg *et al.* 1984b) is that the sub-circular pattern represents an allochthonous downward-facing synformal fold nappe. This hypothesis is consistent with the metamorphic data and ascribes a kinematic significance to the *S–C* structures, but there are some outstanding problems. Firstly there is no clear change in the apparent vergence of minor-folds across any possible axial plane; secondly we can nowhere observe a hinge zone with the foliation at a high angle to lithological contacts; and thirdly point (c) above indicates that the hangingwall rocks were moving away from the axial zone, a relative movement which contradicts the inferred subsidence of the axial zone. Thus, the fold nappe model needs to be re-examined.

As an alternative hypothesis, the combined structural features can be discussed in terms of a (diapiric?) foliation fold. Two-dimensional analytical models (Fletcher 1972) and experimental models (Dixon 1975) of diapirs emphasize three characteristics that are seen in the Lévézou area, as follows. (i) The finite strain is heterogeneous during every stage of the progressive deformation. (ii) There are strong strain gradients controlled by interfaces between units of different rheological properties. The maximum strain is generally localized in the roof of the dome with shear oriented towards the external parts of the dome. In addition, Schwerdtner *et al.* (1978) have emphasized the strong possibility of movement (and therefore highest shear strains) along the interface between the diapir and its cover. (iii) The core of the dome is characterized by a vertical stretching and the roof by a horizontal extension.

From Dixon's (1975) experimental models it can be seen that initially square shaped elements assume shapes that approximate parallelograms after deformation (Fig. 7). Thus, these shapes can be directly used to define the apparent sense of shear between two adjacent regions across the limb of a domal structure. Note that some elements undergo a complex deformation history and may return to their initial configuration before showing reversals in extension direction. There also exist rows of elements where strains are uniformly low throughout progressive deformation so that the fabric within the corresponding rocks in a geological structure is expected to be poorly developed.

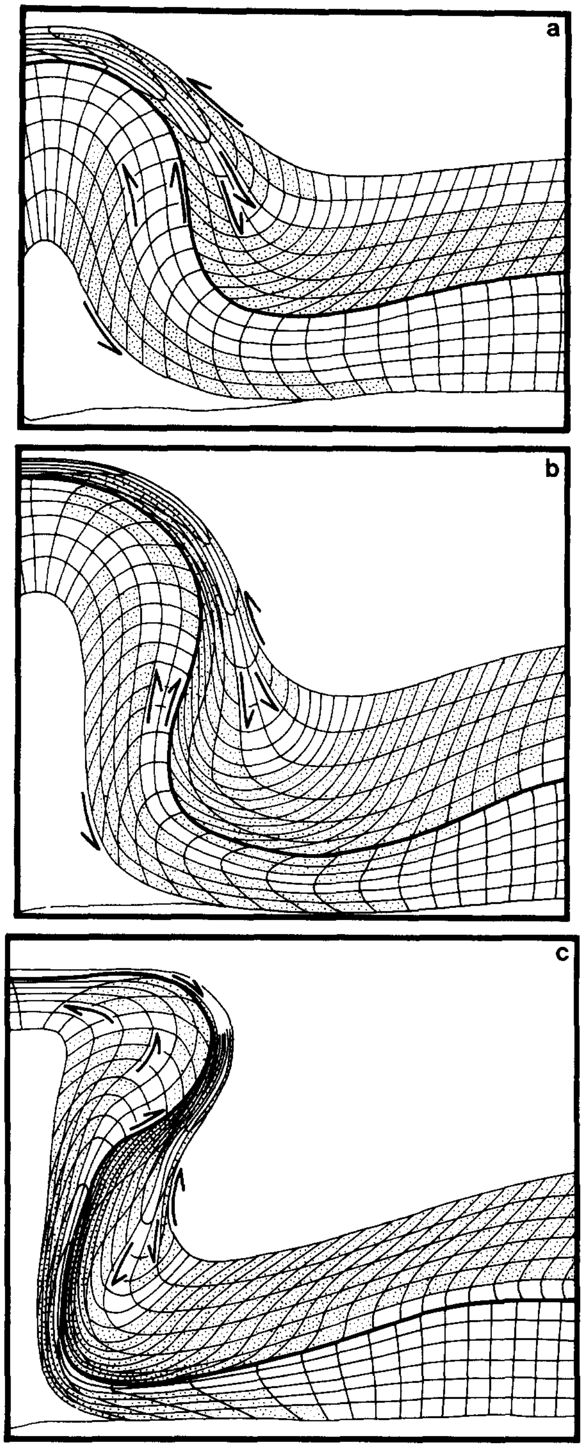

Fig. 7. Cross-section grid of the deformed elements in model WD-4 of Dixon (1975). Stippled pattern corresponds to non-coaxially sheared regions in the sense as indicated by the arrows.

This analysis yields some surprising results when applied to the Lévézou structure, as in both the external and internal domains the model shows several rows of elements with a paradoxical sense of shear. At first sight this appears to argue against a diapiric origin for the dome (Fig. 7). In fact the strains in the contact regions are so strong that they dominate and assume most of the movement necessary for the emplacement of the dome, since they are characterized by a sense of shear consistent with that of the uprising dome. The opposite sense of movement in the inner and outer domains is a strain accommodation feature necessary to maintain lithologic continuity, or minimize displacements along lithological discontinuities, and is a minor feature of the domal structure as a whole. The *S–C* structures reported in this paper can be compared to such strain accommodation features, and consequently *S–C* relationships indicating subsidence of the Lévézou do not preclude a diapiric emplacement. The area of undeformed granitic rocks within the western Lévézou structure (Fig. 6) could be equivalent to the elements with low strains as mentioned above. From this analysis, a diapiric origin for the fold seems possible, although the following features observable in Dixon's (1975) models are not reflected in the Lévézou structure. (1) Senses of shear should internally oppose each other on each of the diapiric flanks, but this has not been observed. (2) Diapirism involves large domains of coaxial deformation, a prediction which is incompatible with the data and observations presented here. An answer to this second point of contention may be found in the discrepancy between high finite-strain measurements with $K < 1$ in rocks with S and C planes at relatively high angles, and therefore low shear strains (Fig. 6). In this case the high finite strain value could be attributed to intense irrotational deformation prior to shear strain responsible for the *S–C* structures. Note also that the diapir model explains the lack of parallelism between lineations in orthogneisses of the internal and external domains.

CONCLUSIONS

(1) The analysis of the development of *S–C* structures and other shear-sense criteria in orthogneisses of the Lévézou massif, combined with finite-strain analysis, indicates that ductile deformation proceeded by non-coaxial flow with a consistent sense of shear sub-parallel to the lineation.

(2) The close spatial association between the zones of highest deformation and the boundaries of the Lévézou Massif strongly suggests a causal relationship. Contradictory senses of shear recorded along this boundary do not indicate a consistent sense of thrusting.

(3) The senses of shear determined around the Lévézou structure are consistent with both an anticlinal diapiric structure in which opposed senses of shear can develop across abrupt strain gradients, and with a subsiding downward-facing fold nappe. However, the pattern of fold vergence and lack of axial planar fabrics within the Lévézou lead us to prefer the anticlinal diapiric fold. Detailed P–T studies of the Lévézou structure are needed to test this model.

(4) Rheological contrasts (in the Lévézou between leptyno-amphibolities and the syn-kinematic magma) may account for distinct strain domains developed independently with different sense of shear. Consequently kinematic axes from the microstructural and crystallographic fabrics may vary regionally in sense and direction.

(5) As a more general consequence of (4) care must be taken when extrapolating the sense of shear obtained from local observation of *S–C* structures to any regional-scale model, especially on the scale of a whole orogenic system.

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