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An example of three-dimensional analysis of thrust-related tectonites

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Abstract—A spaced pressure-solution cleavage related to Alpine thrusts in Mallorca (Balearic Isles) is deformed by several sets of shear planes and minor folds. All these structures formed synchronously, related to the thrust sheet movement. Shear plane sets show different orientations irrespective of the cleavage disposition. Slip along these shear planes shows that deformation did not result in plane strain. Minor fold axes show a wide range of orientations. Neither folds nor shear planes enable us to directly deduce the sense of thrust motion, indicating that these criteria must be used with care. Previous strain characterization is required for definite conclusions to be reached.

INTRODUCTION

COMPOSITE planar fabrics are widely present in mylonites and other well-foliated fault-rocks essentially deformed by simple shearing. In such rocks the mylonitic foliation may be affected by one or more sets of ductile or ductile–brittle micro-shears. These shear planes, described as *c*-planes (Berthé *et al.* 1979, Iglesias & Choukroune 1980, Simpson 1983, 1984) or 'shear bands' (White 1979, White *et al.* 1980, Platt & Vissers 1980) form at low angles to the foliation and have been widely used as kinematic indicators to deduce the sense of shear when a single set of shear planes exists (e.g. Simpson & Schmid 1983, Lister & Snoke 1984, Weijermans & Rondeel 1984, Obee & White 1985). Nevertheless, in many cases cleavage planes are affected by more than one set of shear planes, which may exhibit apparent conjugate disposition (Carreras & Garcia-Celma 1982, Casas 1982, 1986, Platt 1984, Harris & Cobbold 1985) or can be grouped into several oblique sets (Platt & Vissers 1980). However, there is no agreement about the significance and the origin of this kind of composite planar fabric. One opinion held is that 'shear bands' are the result of advanced stages of deformation when extension cannot occur along earlier foliation planes (Watts & Williams 1979, White 1979 and White *et al.* 1980). Alternatively, a relationship has been inferred between conjugate sets and subsequent flattening (Platt & Vissers 1980) or with strain partitioning producing restricted coaxial deformation (Platt 1984). Harris & Cobbold (1985), in turn, attribute the formation of conjugate sets in simple-shear strain environments to reverse slip favoured by well-developed layering. Most of the research concerning this topic deals with mylonites developed in ductile conditions where metamorphism and intracrystalline deformation mechanisms predominate. The deformation in such shear zones is virtually plane, and most of the geometrical analyses have been carried out on the basis of two-dimensional studies.

This paper deals with an example of composite planar fabric related to thrusts formed at shallow crustal levels, where metamorphism is practically non-existent, and pressure-solution cleavage formation coexists with fractures. The geometry and significance of multiple composite fabrics are analysed in 3-D. Data were collected from the cleavage-containing deformation zones related to Alpine thrusts in Mallorca (Balearic Isles). This case provides an example which enables us to consider the use of complex fabrics as kinematic indicators in shallow-depth thrust systems.

GEOLOGICAL SETTING

In Mallorca, a great number of Alpine thrusts developed, which produced a shortening of about 50% deduced from balanced sections (Sàbat 1986). The thrusts form an imbricate fan in Mesozoic and Cenozoic cover rocks and climb up-section toward the NW. The Mallorca thrust system constitutes the eastern end of the NE–SW-trending Betic Range (Fig. 1).

The thrusts are well exposed in two mountainous areas, one along the western coast (Serra de Tramuntana), and the other in the eastern margin (Serres de Llevant). We describe the thrust-related structures found in the latter area (Fig. 1b). The rest of the island is covered by post-tectonic material.

The Serres de Llevant thrusts are mainly horizontal or slightly dipping to the SE (Figs. 2 and 3a). This, and the occurrence of transverse structures related to lateral ramps, causes the thrusts to produce sinuous outcrop lines. The detachment level is located in Triassic marls and evaporites. The thrust sheets are made up of Liassic dolomites, Dogger-Malm and Neocomian limestones and marly-limestones paraconformably overlain by Paleogene conglomerates and sandstones. Lower Miocene sandstones, also involved in the thrust sheets, overlie this sequence unconformably. Upper Miocene detrital limestones are the oldest post-tectonic rocks. Hence, the age of the compressive structures ranges from the Upper Paleogene to Middle Miocene.

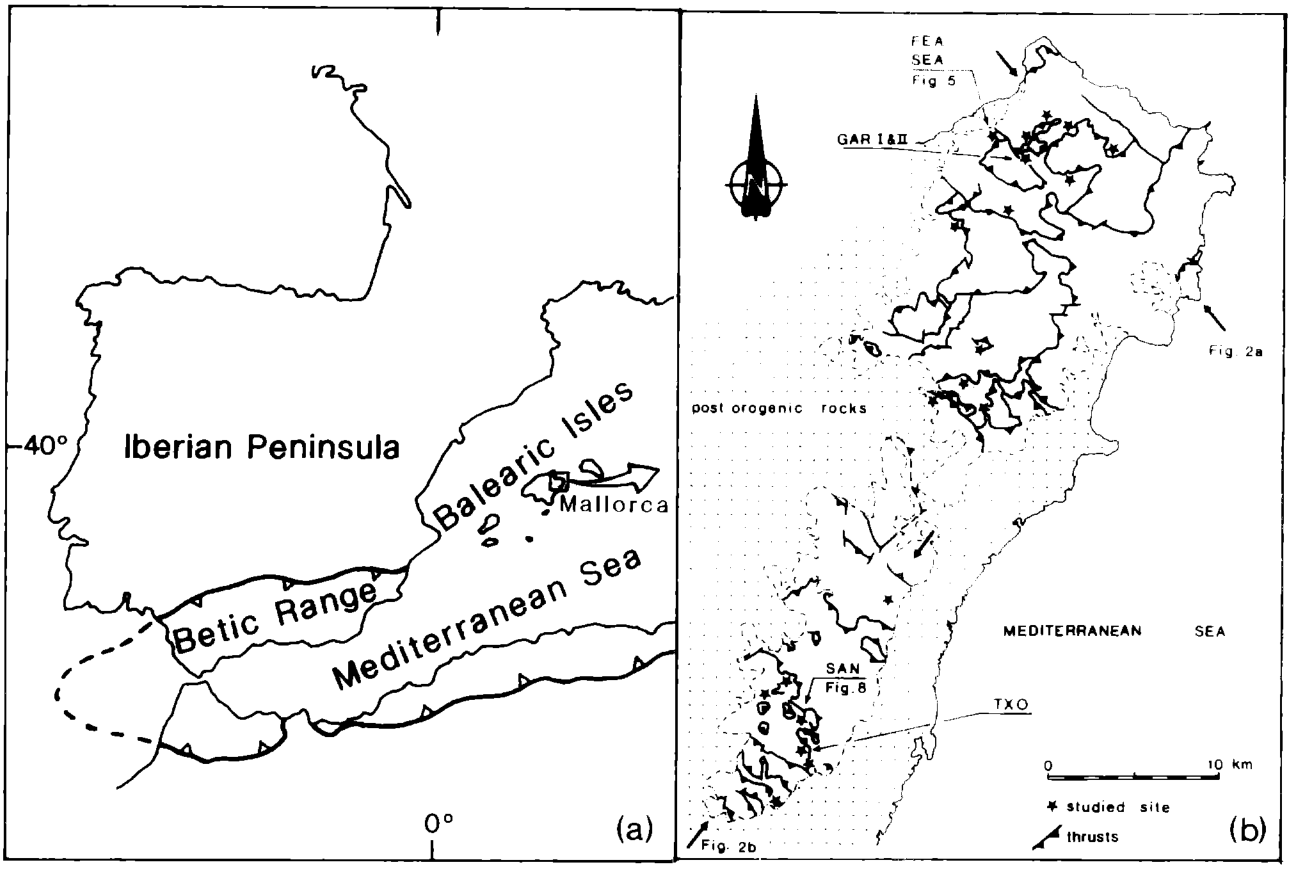

Fig. 1(a). Location of Mallorca NE of the Betic Range. (b) Structural sketch of the Serres de Llevant, showing location of the outcrops studied and cross-sections.

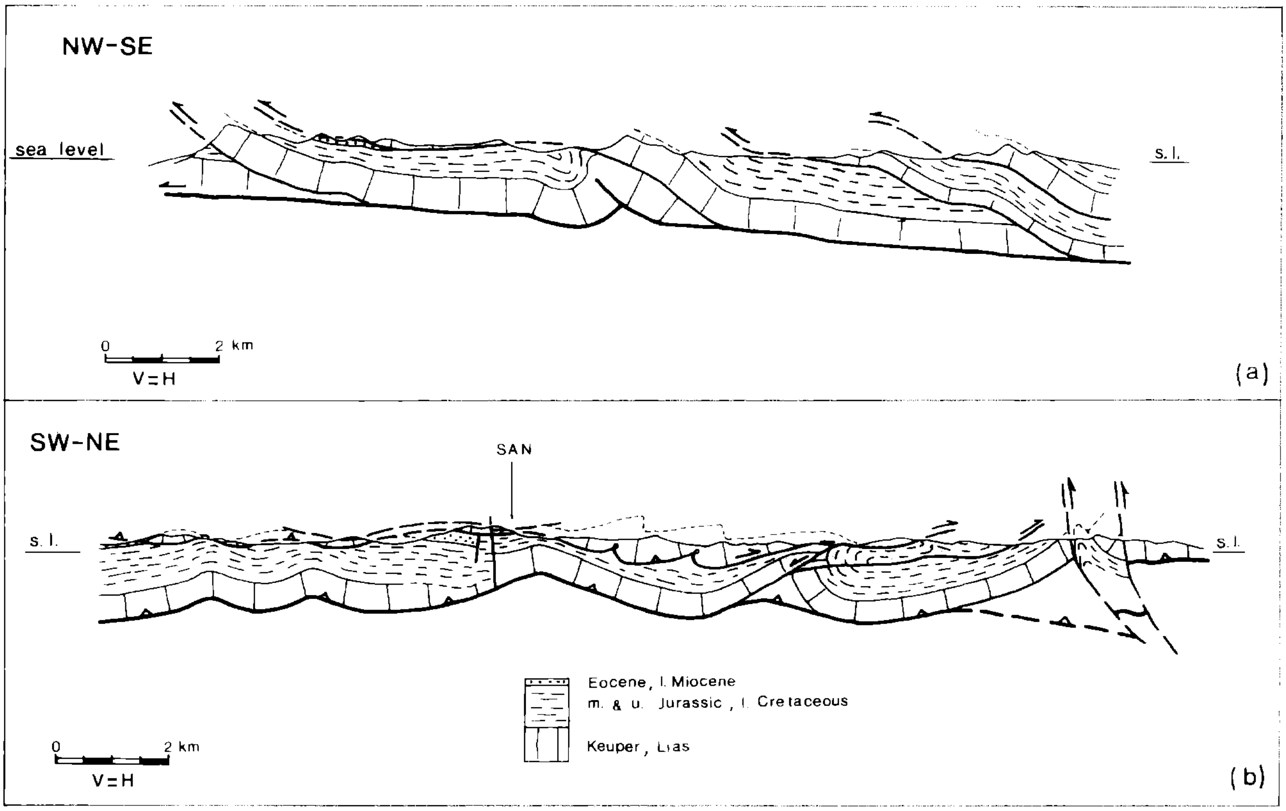

Fig. 2. Simplified geological sections of Serres de Llevant. (a) Cross-section. (b) Along-strike section across the southern part of the mountain range.

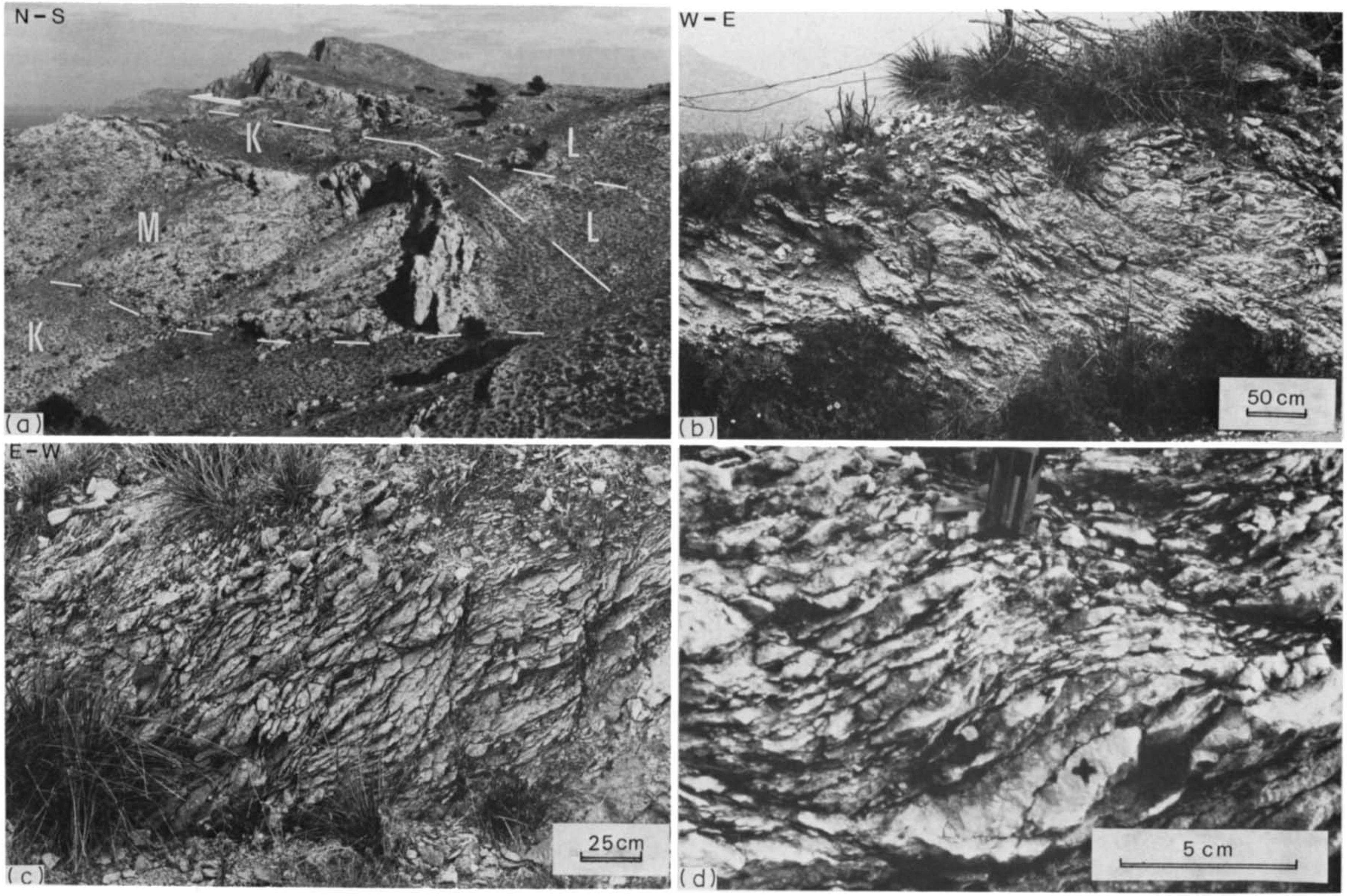

Fig. 3(a). The Serres de Llevant thrusts at the SEA and FEA site areas. Liassic dolomites (L) thrust on a syncline of Miocene rocks (M), in turn thrust on Cretaceous marly-limestones (K). Between the Liassic and Miocene rocks there is a horse of Cretaceous rocks. (b) Composite planar fabric in Cretaceous marly limestones about 60 m below a main thrust (type B–C site). (c) Tectonites at site SEA. Cleavage is cut by, or slightly curved around, two sets of shear planes (S_h). The S_{h1} set is gently developed and the S_{h2} set is clearly visible in the right half. (d) Close-up of the cleavage in site TXO. Cleavage domains show a slightly stylolitic appearance.

DEFORMATION STRUCTURES

The Serres de Llevant thrusts are accompanied by penetrative deformation, concentrated in zones of variable thickness (*ca* 50 m) underneath the thrust plane. The intensity of this penetrative deformation decreases away from the thrust. Bedding has been destroyed within this deformation zone. More competent rocks such as limestones and dolomites are fragmented in lenses of all sizes, within highly sheared marly-limestones showing a well-developed cleavage.

The cleavage is affected by sets of minor shear surfaces which, together with the cleavage, define a composite planar fabric. The cleavage is locally deformed by minor folds. The geometry and degree of development of this group of minor structures depend on both the lithology of the deformed rock and their distance to the thrust surface.

Data about cleavage, shear planes and related slickensides have been collected in the deformation zones (22 sites) of the Serres de Llevant thrust system (Fig. 1b). Special attention has been devoted to shear plane and slickenside orientations, to their relationships with the cleavage and to the determination of their sense of movement.

Cleavage

A disjunctive pressure-solution cleavage is the most conspicuous structure present in all the studied deformation zones. Its morphology is variable. In general, it is anastomosing, smooth to rough (non-sutured in the sense of Borradaile *et al.* 1982) in the marls and marly-limestones. It is stylolitic and weakly developed in the limestones and dolomites (Fig. 3d). Maximum cleavage intensity occurs in the Cretaceous marly-limestones. The width of the microlithons ranges from a few millimetres to several centimetres (Fig. 3c), generally increasing away from the thrust while becoming more anastomosing. Slip indicated by slickensides and calcite fibres has locally occurred along the cleavage planes.

Shear surfaces

Cleavage is deformed by single or multiple sets of minor shear planes (Fig. 3b & c). Their length ranges from a few centimetres to several (2–5) metres, and their thickness reaches a maximum of 2 or 3 cm. Shear surfaces are generally curvi-planar and can splay or join, forming anastomosing systems which isolate lenses of rock. At their ends they locally merge with the cleavage planes. Near the shear surfaces the cleavage may either be cut or gradually curved towards parallelism with the shear planes. The latter has resulted in the sigmoidal shape of the cleavage. The sense of displacement inferred from the bending of the cleavage coincides with that determined by slickensides and calcite fibres located in the shear planes.

The shear-plane attitude is variable. Shear planes can be grouped into different sets oblique to cleavage, but these merge into or cut one another without clear relative chronology. Movements along these sets of shears seem to have taken place synchronously. Where shear planes of more than one set coexist, the cleavage bisects the acute angle between them. The sense of displacement in the shear planes is consistent with a shortening direction sub-perpendicular to cleavage, and indicates principal extension roughly parallel to it. This relationship applies, irrespective of the shear plane and cleavage orientations.

Quantification of strain from faults without knowledge of the amount of slip along each surface is impossible. As we deal with brittle shear surfaces, we have tried to use the Arthaud (1969) method for motion-plane determination for each individual fault; that is, the plane which is perpendicular to the fault and contains slickenside. This treatment together with the analysis of minor structures may give an indication of the attitude of bulk strain axes.

Cleavage and shear plane relationships

The attitude and development of cleavage and shear planes in the sites studied vary between two end cases, A and C; all stages in the intermediate case (B) can be recognized.

Type A. Near the thrust, cleavage forms an angle of 30–40° to the thrust plane. Two sets of shear planes, S_{h1} and S_{h2}, can be distinguished. They are unequally developed and exhibit an opposite sense of displacement. One set (S_{h1}) dips in the same direction as the cleavage or is subhorizontal, that is, subparallel to the thrust plane. Its sense of movement is the same as the thrusting. The other set (S_{h2}) dips more than the cleavage in the same direction or is subvertical. Its sense of movement is chiefly 'normal', opposite to the thrusting. The flat-lying set (S_{h1}) is more closely spaced and is better developed than the S_{h2} set.

The two sets are comparable with the synthetic and antithetic shear zones found in deformation zones of other thrust systems (e.g. Koopman 1983). They can also be compared with the conjugate sets of extensional crenulations or shear bands described in mylonitic metamorphic rocks (Platt & Vissers 1980).

The SEA site provides a clear example of type A association (Figs. 3c and 4a). This site is located in the deformed Cretaceous marly-limestones which form a thin, decametric-sized horse above Miocene rocks and are overthrusted by Liassic dolomites (Fig. 5). The thrust strikes NE–SW and dips 30° to the SE. The cleavage strikes N–S and dips around 50° to the E (Fig. 4a). Shear planes strike N–S (chiefly parallel to the cleavage) and their dip is variable (Figs. 4a, 6 and 7). S_{h1} planes are subhorizontal or dip gently to the E (less than the cleavage) and their hangingwall movement is towards the W. S_{h2} planes dip strongly to the E between 70–85° and show normal displacement. Slickensides are around the E–W-trend, ranging between 040 and 135° (Fig. 4a). Poles to motion planes obtained from the two

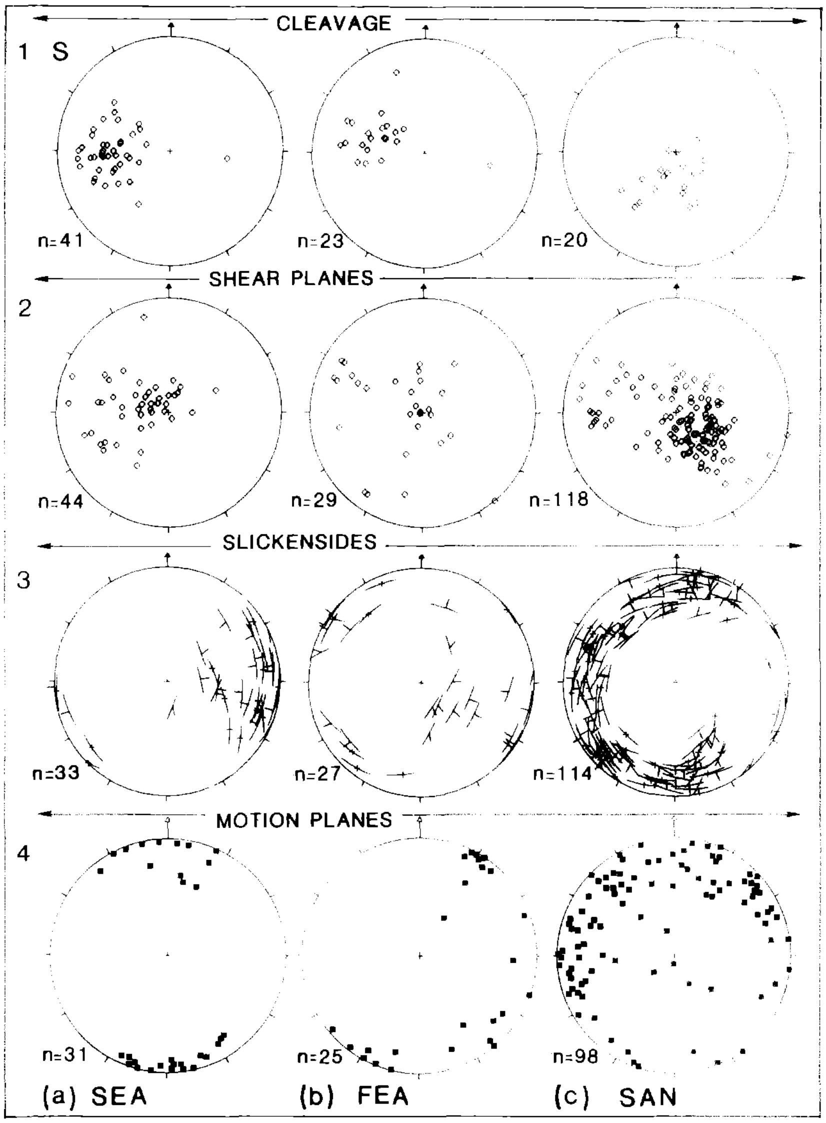

Fig. 4. Stereograms for sites SEA (a), FEA (b) and SAN (c) (lower hemisphere).

shear plane sets are grouped around N–S (Fig. 4a). They are subhorizontal and perpendicular to the pole to cleavage. This means that the shortening deduced from cleavage is contained in the average movement plane. This suggests that the bulk principal extension direction, also contained in the average movement plane, is roughly perpendicular to the pole to cleavage.

Type B. This kind of situation is located further away from the thrust plane. The shear planes show a more scattered distribution than in type A sites. Site FEA (Fig. 4b) illustrates type B associations. The data were collected in the Cretaceous marly-limestones below thrusted Miocene rocks (Fig. 5). Cleavage strikes N–S and dips 40° to the E (Fig. 4b). Most shear planes correspond to S_{h1} and S_{h2} sets, described at SEA. However, other shear planes strike E–W, that is, perpendicular to the cleavage (Fig. 4b). They form two conjugate sets dipping to the N and to the S. These two sets show normal fault displacement. S_{h1} and S_{h2} slickensides trend mainly N130°E, and the slickensides on E–W shear planes trend N030–060°E, roughly perpendicular to the

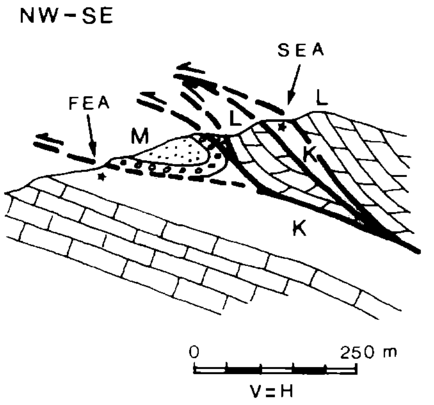

Fig. 5. Cross-section showing the position of sites SEA and FEA relative to thrusts. (L) Liassic dolomites, (K) Cretaceous marls, (M) Miocene detrital rocks.

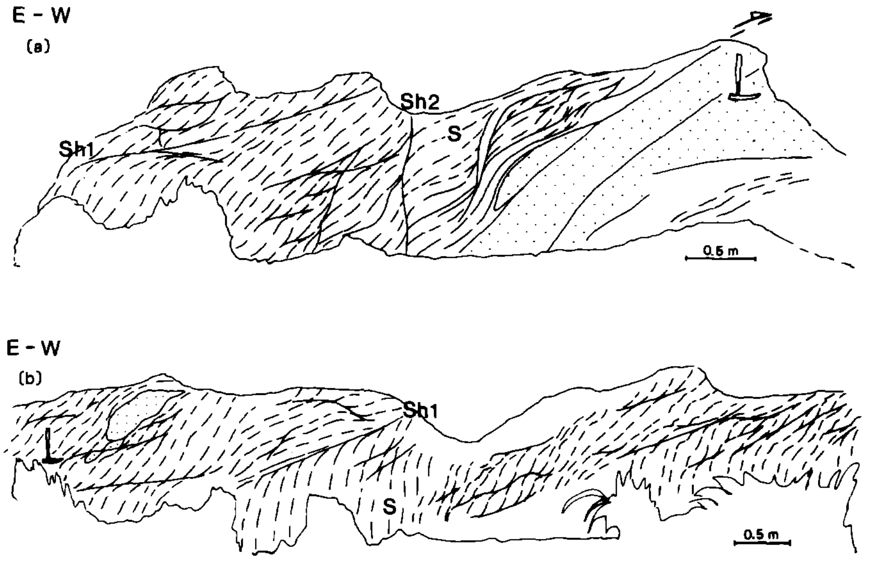

Fig. 6. Sketches of parts of the SEA outcrop (type A associations). Bodies of more competent rock (dotted) are surrounded by highly sheared marly limestones. Cleavage (S) and two sets of shear planes (S_{h1} and S_{h2}) are well-developed.

former (Fig. 4b). In this case poles to movement planes are distributed in a great-circle pattern but two maxima are recognizable (Fig. 4b). The pole to this girdle coincides with the pole to cleavage, that is, with the bulk shortening direction. On the other hand, the bulk principal extension direction must be contained in this girdle, but the distribution of movement planes suggest that two different extension directions can be considered.

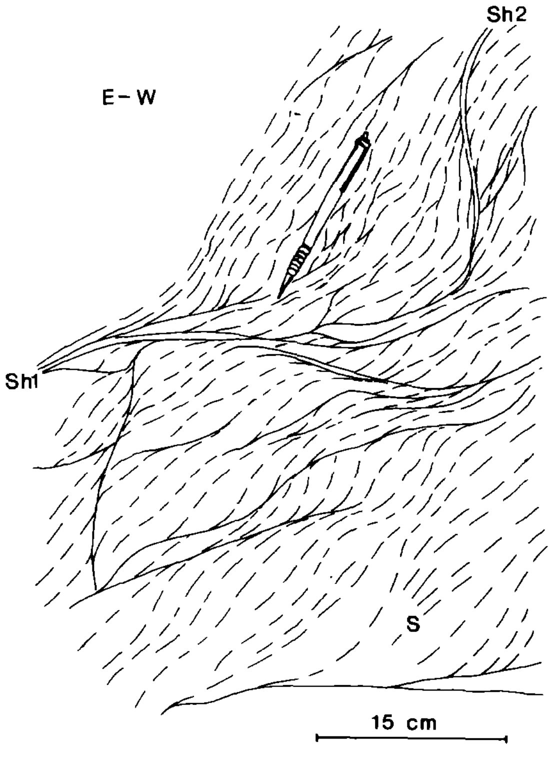

Fig. 7. Detail of the SEA outcrop. Note the curviplanar shape of shear planes (S_h) joining and splaying, and the S shape of cleavage (S) slightly curved close to shear planes indicating a hangingwall movement along S_{h1} towards the W and a normal movement of S_{h2}.

Type C. The further away from the thrust surface, the more flat-lying the cleavage becomes, and the attitude of shear planes changes gradually. Shear planes may be grouped into several sets, all of them equally developed and with the same spacing. They can also join and splay and form a low to moderate angle with the cleavage. They show mainly 'normal' fault geometry, and their disposition is also consistent with an extension direction along the cleavage. They are responsible for a wavy morphology of the cleavage. The shear planes and related slickensides exhibit a wide range of orientation. An example of this kind of cleavage and shear-plane distribution follows.

The SAN site (Figs. 8 and 9) is located within Cretaceous marly-limestones in the footwall of a main thrust striking N–S and dipping around 15° to the E, at about 80 m below the thrust (Fig. 8). Cleavage planes are widespread but mostly flat-lying (Fig. 4c). Shear planes show both variable dip, ranging from subhorizontal to 80°, and variable strike. There are no easily distinguish-

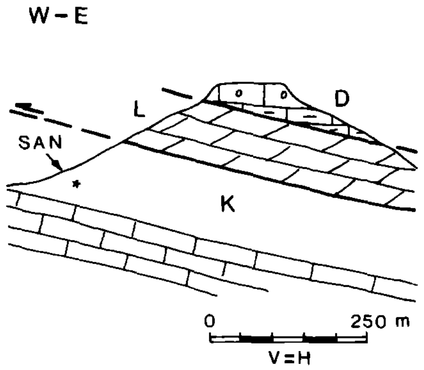

Fig. 8. Cross-section showing the location of the SAN site with respect to the main thrust. (L) Liassic dolomites, (D) Dogger limestones, (K) Cretaceous marls.

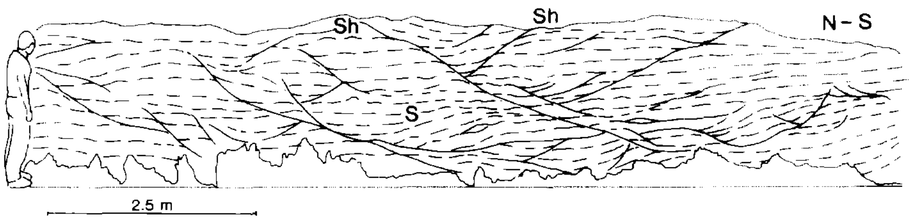

Fig. 9. Sketch of part of site SAN (type C associations). Cleavage (*S*) is flat-lying with shear planes at a moderate angle.

able sets of similarly oriented shear planes (Fig. 4c). Slickensides exhibit a wide range of orientations and show axially symmetric disposition about the vertical (Fig. 4c). Poles to motion planes are widely scattered showing an almost circular distribution (Fig. 4c); the pole to this girdle lies on the average pole to cleavage. Thus, whereas a subvertical bulk shortening direction may be recognized, no definite extension direction can be distinguished, suggesting an almost radial extension.

Folds

The cleavage is locally affected by small-scale folds (1–10 cm). The folds are restricted to zones between two adjacent shear surfaces. The folds are disharmonic and gradually give way to a slight bending of the cleavage within the same zone (Fig. 11). They are common in all the deformation zones near the thrust but exhibit a very irregular spatial development within individual outcrops. They are strongly asymmetric and can display both Z or S geometry. Fold axes do not show a constant attitude, but vary over a wide range of orientations with plunges between 0 and 80°. In the latter case, they are not distributed in a great-circle pattern parallel to the cleavage. Generally, they do not exhibit a clearly-defined relationship to the cleavage orientation.

Some examples of the relationship between fold axes and other minor structures are cited below.

In the SEA site most fold axes trend N–S, that is, parallel to the cleavage and shear planes. They are gently plunging, between 5–20° and perpendicular to the slickenside maximum (Fig. 12a). However, others differ both in trend and plunge, do not lie on the cleavage or shear plane average, and are oblique to the mean slickenside trend.

Sites GAR I and GAR II resemble the type A described above. These outcrops display similar relationships between fold axes, cleavage and shear planes. In both outcrops, fold axes plunge gently, between 0–20°, and are perpendicular to the slickensides despite their different orientation (Fig. 12b & c).

Site TXO exhibits a B-type cleavage and shear plane disposition. Slickensides show a distribution in two maxima, the main one trending N060–090°E, and the other, N150–180°E (Fig. 12d). Fold axes are not contained in the mean cleavage plane and trend around N090°E, a direction perpendicular to the less developed slickenside maximum.

DISCUSSION

The minor structural associations found in the Serres de Llevant thrusts are comparable to composite planar fabrics known in mylonites. In contrast, brittle deformation in the studied rocks contributed to the development

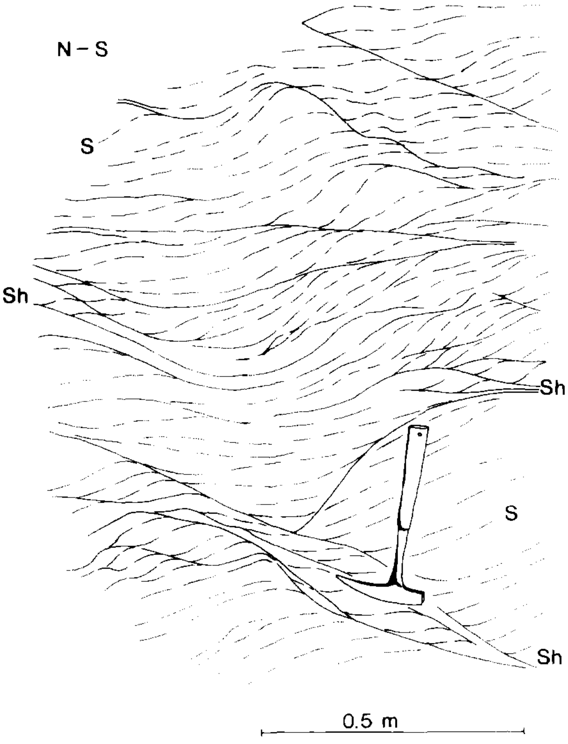

Fig. 10. Detail of the SAN site (Fig. 9), showing shear planes (S_h) and cleavage (*S*).

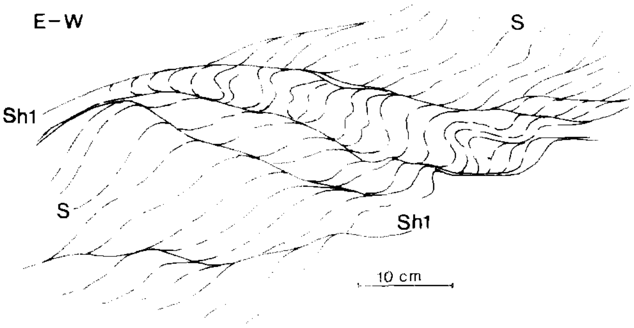

Fig. 11. Folded cleavage with Z asymmetry developed between two shear planes.

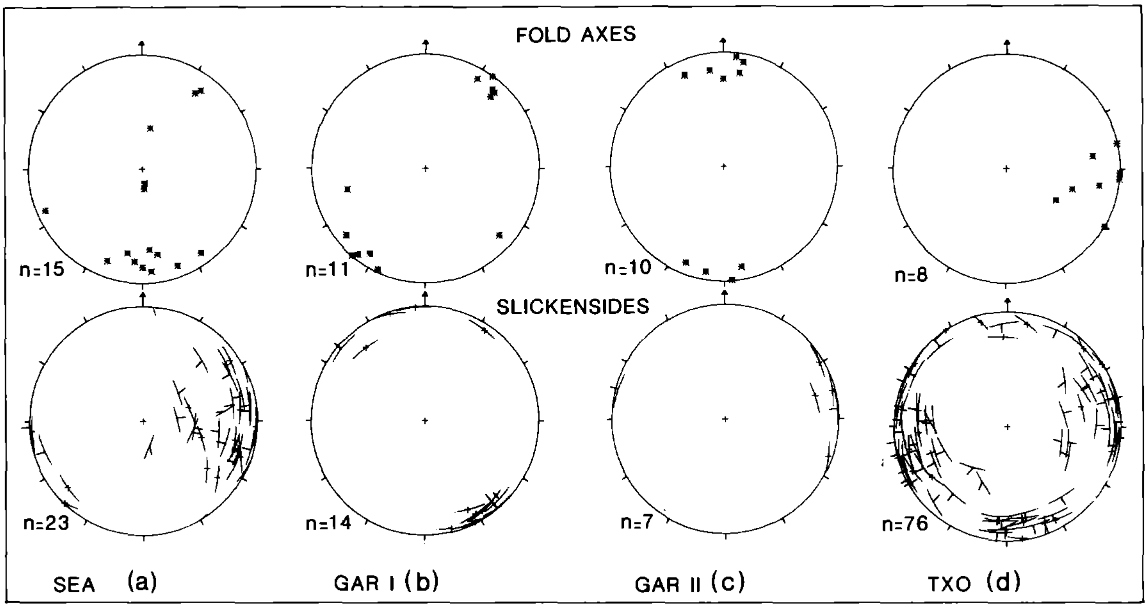

Fig. 12. Stereograms of structural data from sites SEA (a), GAR I (b), GAR II (c) and TXO (d) (lower hemisphere).

of deformation structures, as shown by slickensides and calcite fibres on shear planes and cleavage truncated by the shear planes. These deformed rocks are characterized by: (i) the syngenetic development of a penetrative cleavage together with discrete shear surfaces; (ii) the complexity of cleavage–shear plane relationships; and (iii) the occasional presence of folded cleavage.

(i) Although different conjugate systems of shear planes can be recognized they always exhibit a constant relationship with cleavage; that is: (1) cleavage bisects the acute angle between differently orientated shear plane sets; and (2) slip along shear planes is always consistent with principal extension directions contained in the cleavage. These facts are consistent with a syngenetic development, in a broad sense, of cleavage and shear surfaces as described in other shear-zone environments (e.g. Berthé *et al.* 1979, Mitra 1979, Platt & Vissers 1980, Koopman 1983, Bosworth 1984, Lister & Snoke 1984), although cleavage formation probably began before the shear planes formed.

(ii) Shear planes can exhibit a synthetic or antithetic disposition to the thrust movement or can be strongly divergent from the main bulk shear plane. Although the strain associated with cleavage development has not been established, we aim to discuss some aspects of the deformation relative to shear planes. In type A, extension marked by the two conjugate shear sets and slickensides is roughly parallel to the movement direction of the thrust. In other cases (type B associations) the extension, marked by shear planes and slickensides, took place in a wider range of orientations. A gradual change to an almost radial extension (type C associations), marked by a highly variable orientation of shear planes and slickensides seems to occur further from the thrust (Fig. 13). Thus, shear plane-related deformation departs from plane strain in several sites. A situation similar to type C has been described using minor normal faults related to vertical compaction of soft sediments (Guiraud & Seguret 1986). In addition, a progressive change of the strain ellipsoid from a cigar-like to a pancake shape with increasing distance from the thrust has been documented in the Blue Ridge area using cleavage strain-related analysis (Mitra 1979). Other cases of slight or marked departures from plane strain related to the development

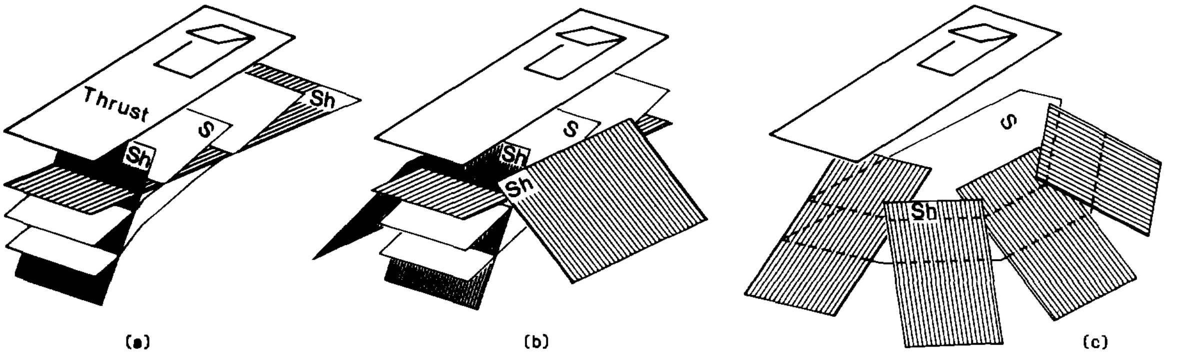

Fig. 13. Three-dimensional sketch summarizing different cleavage-shear plane associations: (a) type A, (b) type B and (c) type C.

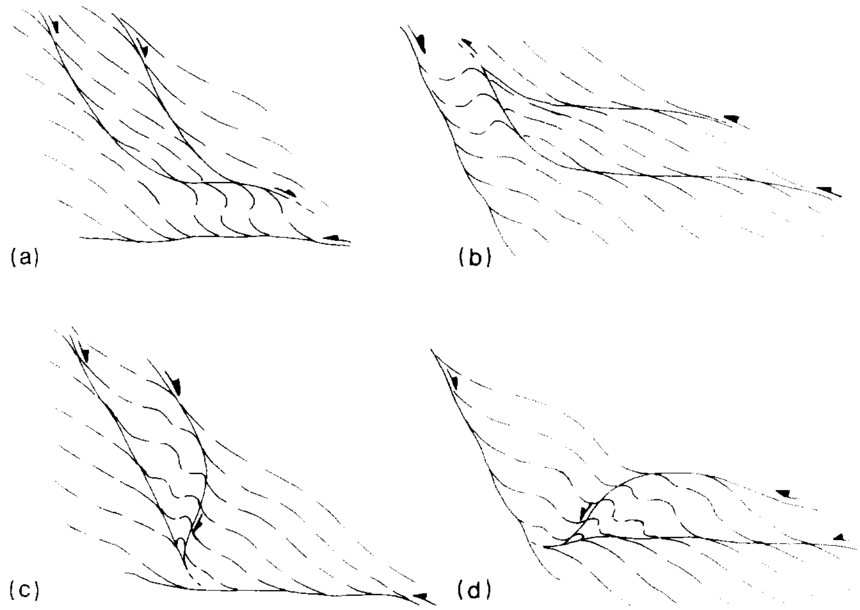

Fig. 14. Diagrams showing theoretical cleavage-fold formation. (a) and (b). Shear planes with the same attitude undergo opposite movement; (c) and (d), a plane departs from its main dip sense. See text for explanation.

of shear zones have been reported (Hossack 1968, Coward 1976, Berthé *et al.* 1979; see also discussions in Coward & Kim 1981 and Coward & Potts 1983). In the present case, the spatial distribution of different structural associations suggests that deformation increasingly departs from plane strain away from the thrust plane.

Type A and B associations can be considered reliable criteria to determine the thrust movement sense. However, where shear planes and slickensides range from parallel to perpendicular with respect to the thrust transport direction, as in the case of type C, the usefulness of these tectonites as kinematic indicators is limited. Moreover, this kind of fabric implies that a significant component of coaxial strain contributes to the total deformation; that is, where deformation history differs from simple shear, shear criteria related to composite planar fabrics must be used with care. A thorough 3-D analysis is required for definite conclusions to be reached.

(iii) The presence of folded cleavage deserves attention if we consider that cleavage forms and lies in the extension field of the finite-strain ellipsoid in simple shear deformation. Hence, intrafolial folds in high-strain mylonites are usually interpreted as the result of local strain heterogeneities (Carreras *et al.* 1977, Bell 1978). On the other hand, asymmetric folds in shear strain environments may develop when marker elements are oblique to the shear zone boundaries, and lie in the shortening field of the finite-strain ellipsoid (e.g. Ghosh 1966, Sanderson 1979, Lister & Snoke 1984). These folds can modify their sense of asymmetry due to increasing strain (Ramsay *et al.* 1983). In the Serres de Llevant thrust system, folds share a close spatial relationship with shear planes. As they join and splay, shear planes with the same attitude can undergo opposite movement (Fig. 14a & b) or the same plane can depart from its main dip sense. Both cases lead to a change in their original relationship to cleavage (Fig. 14c & d). Previously lengthened cleavage may thus become shortened, resulting in folds of different asymmetry. Therefore, opposite fold asymmetries are not necessarily the result of high strains.

The fact that most folds are virtually perpendicular to the slickensides supports the inferred relationship between shear planes and fold formation. In this sense, the relative scattering of the fold axes results from the wide range in orientations of shear planes and slickensides. Thus, a definite relation of perpendicularity between cleavage folds and the transport direction does not necessarily exist, especially where shear planes show highly variable orientations or are grouped in several systems.

CONCLUSIONS

At the footwall of the Serres de Llevant thrusts in Mallorca deformed rocks show a composite planar fabric.

This thrust-related fabric results from a single deformation event and shows a progressive evolution away from the thrust.

Near the thrust, bulk strain corresponds to a simple shear strain and the extension direction is roughly parallel to thrust movement. Increasingly away from the thrust a significant component of coaxial strain contributes to the total deformation. Thus, either extension parallel and perpendicular to thrust movement, or in an almost radial arrangement on the cleavage plane, can result. In the latter case the usefulness of composite planar fabrics as shear criteria is limited and requires careful 3-D analysis.

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