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The kinematic interpretation of obliquely-transected porphyroblasts: an example from the Trois Seigneurs Massif, France

CEES W. PASSCHIER* and PATRICK J. H. R. SPECK

Faculty of Earth Sciences, Utrecht University, P.O. Box 80.021, 3508 TA Utrecht, The Netherlands

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Abstract—Obliquely-transected porphyroblasts (OTPs) contain a straight inclusion pattern that is continuous with the external foliation, but oblique in orientation. OTPs are interpreted to form by porphyroblast growth between two phases of deformation. The obliqueness of the inclusion pattern and external foliation is due to the second deformation phase and has been variously explained by porphyroblast rotation in the kinematic reference frame of bulk flow, or by foliation rotation around a stationary porphyroblast. The two models imply opposite sense-of-vorticity (also loosely referred to as sense of shear) to produce the same geometry and their relevance should be known if OTPs are to be used as sense-of-vorticity indicators. Andalusite-OTPs in the Trois Seigneurs Massif, French Pyrenees, have a spool-shape in three dimensions that is interpreted to result from passive overgrowth of andalusite on a spaced S_2 cleavage. Subsequent non-coaxial D_3 flow led to development of an S_3 crenulation cleavage and the OTP geometry. Although the porphyroblasts rotated, rotation of the foliation in the kinematic reference frame of bulk flow was mainly responsible for the OTP geometry. This example shows that OTPs can indeed develop by foliation rotation in non-coaxial flow. Similar looking OTPs can apparently develop in flows with opposite sense-of-vorticity depending on whether foliation or porphyroblast rotation is dominant; the dominance of either development mechanism depends on the importance of flow partitioning and solution transfer during progressive deformation.

INTRODUCTION

PORPHYROBLASTS are complex fabric elements in metamorphic rocks that can give information on deformation kinematics and on the relative age of mineral growth and deformation events. The central issue in the application of porphyroblast microstructures to tectonic analysis is the interpretation of inclusion patterns. Zwart (1962) and Spry (1963) provided a scheme to interpret such patterns which has been widely used in the past decades, but Bell and coworkers (e.g. Bell 1985, Bell *et al.* 1986, 1992, Bell & Johnson 1990, Bell & Hayward 1991) have suggested that these interpretations need revision. They claimed that porphyroblasts do not rotate during progressive deformation, but remain stationary in a deforming matrix with respect to geographical co-ordinates. They also suggested that foliations in the deformed matrix have rotated, whereas the orientation of inclusion patterns in porphyroblasts represent the original orientation of a foliation at the moment of its overgrowth by the porphyroblast. Bell & Johnson (1989) even presented a new model of orogenesis, based on the orientation of inclusion patterns in garnet and on the assumption of non-rotational behaviour of porphyroblasts.

Recently, however, Passchier *et al.* (1992) have reviewed present understanding of porphyroblast inclusion patterns and conclude that porphyroblast rotation is possible. Also, Busa & Gray (1992) reported porphyroblast rotation for staurolite from Connecticut, Visser & Mancktelow (1992) presented a flexural-flow fold model including rotation of garnet porphyroblasts for a single fold from the Central Alps and Miyake (1993) claims that biotite porphyroblasts from central Japan show evidence of rotation. Obviously, the interpretation of porphyroblast microstructures is a subject that warrants further investigation.

OBLIQUELY-TRANSECTED PORPHYROBLASTS

Many porphyroblasts have a straight inclusion pattern that is continuous with the external foliation, but inclined to it (Fig. 1a). We refer to these structures as *obliquely-transected porphyroblasts* (OTPs). Apparently, the porphyroblast grew over a straight foliation and the porphyroblast and/or the external foliation rotated subsequently with respect to the kinematic reference frame of bulk flow in the rock (e.g. Ramsay 1962, Zwart 1962, Spry 1963, 1969, Meneilly 1983, Ramsay & Huber 1987, p 633). In the case of bulk non-coaxial flow, the 'traditional' interpretation of OTPs is that porphyroblasts rotate with respect to the kinematic reference frame, while the foliation rotates less or is irrotational (Fig. 1b) (e.g. Zwart 1962, Spry 1963, 1969, Ramsay & Huber 1987, p 633). Ramsay (1962) suggested that similar structures can form around equidimensional porphyroblasts in coaxial flow if the foliation is inclined to the shortening direction; in that case, the foliation rotates while the porphyroblast is stationary. Meneilly (1983) and Bell and coworkers (*op. cit.*) went further and claimed that OTPs can also form in bulk non-coaxial flow. They suggested that bulk non-coaxial flow in a

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*Current address: Department of Geology, University of Mainz, 55099 Mainz, Germany.

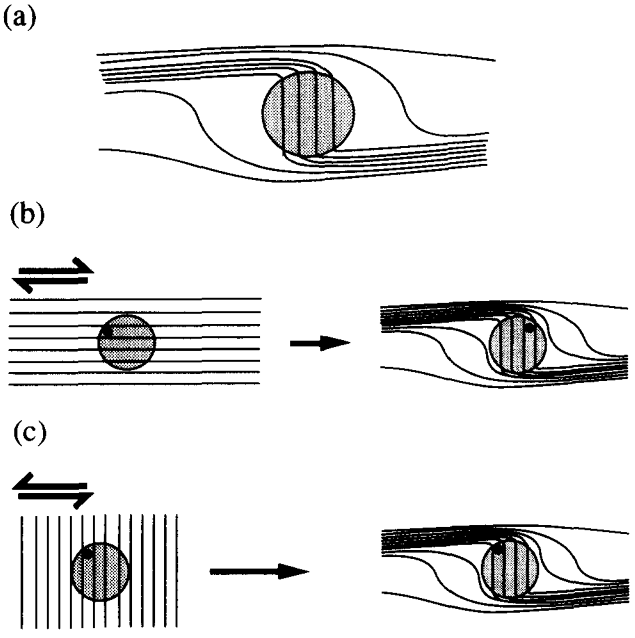

Fig. 1. (a) Obliquely-transected porphyroblast (OTP); a foliation (solid lines) is deflected through a porphyroblast (grey). There are two end-member models for development of this structure: (b) rapid dextral rotation of the porphyroblast with respect to slow or no rotation of the foliation, both in response to flow with dextral sense of vorticity; (c) sinistral rotation of the foliation in developing cleavage domains in response to flow with sinistral sense of vorticity. The porphyroblast remains stationary in the coaxially- or non-deforming microlithon. Dots in porphyroblasts are markers.

rock with porphyroblasts is strongly partitioned into approximately coaxial flow in microlithons, and non-coaxial flow in cleavage domains. They interpreted development of OTPs by relative rotation of the foliation in cleavage domains, while the porphyroblasts lie in microlithons and remain stationary with respect to the kinematic reference frame of bulk flow in the rock (Fig. 1c).

In the 'traditional' model (Zwart 1962) the rotation direction of the porphyroblasts is similar to sense-of-vorticity in the rock (also loosely referred to as sense of shear) while in the model of Meneilly (1983) and Bell (1985), the apparent rotation direction is opposite (Fig. 1). Since OTPs are amongst the commonest type of porphyroblasts in metamorphic rocks, it would be useful to know which interpretation is correct. Alternatively, *both* models may apply but at different conditions; in that case it is essential to find out what these conditions are, and how the geometry of the porphyroblast and its surroundings can be used to evaluate its evolutionary sequence and local kinematics. This paper describes complex OTPs from the Trois Seigneurs Massif, France, which may help further understanding of these structures.

REGIONAL GEOLOGY

The Trois Seigneurs Massif is an outlier of Palaeozoic rocks in Mesozoic limestones on the northern edge of the Pyrenean orogen at 42°50′N and 1°26′E (Fig. 2) (Allaart 1959, Wickham 1984, Wickham & Oxburgh 1985, 1986, 1987, Kriegsman 1989, Large 1989, 1991). The outlier is part of a N-directed Alpine thrust sheet which overrides the Mesozoic foreland of the Pyrenees (Choukroune *et al.* 1989). It is separated from the central part of the orogen by a major strike-slip structure, the North Pyrenean fault zone (Fig. 2). The massif mainly consists of a sequence of sediments of early Palaeozoic age which have undergone Variscan metamorphism and deformation. Pelitic sediments and minor calcsilicates of Cambrian and Ordovician age form the core of the Trois Seigneurs Massif and show a gradual increase in metamorphic grade from prehnite–pumpellyite to upper amphibolite grade over a horizontal distance of 5–7 km from northwest to southeast (Fig. 2) (Zwart 1979, Wickham & Oxburgh 1985, Large 1991). In the higher-grade zones, metamorphism led to widespread migmatization and genesis of biotite–granite and muscovite–leucogranite bodies (Wickham 1984, 1987, Bickle *et al.* 1988, Large 1991). Wickham & Oxburgh (1985, 1986, 1987) proposed that the Variscan low-pressure regional metamorphism occurred in a continental rift setting, possibly associated with strike-slip movement.

Three phases of deformation and two phases of mineral growth during metamorphism have been distinguished by previous workers in the early-Palaeozoic metapelites of the Trois Seigneurs Massif (Kriegsman 1989, Large 1989, 1991). Large (1989, 1991) proposed that mineral growth during peak metamorphic conditions is post-D_1/syn-D_2 and recognized a second phase of mineral growth during retrograde conditions syn-D_2/post-D_2. Kriegsman (1989) proposed a slightly different timing of peak metamorphism as post-D_2/pre-D_3 and a second metamorphic phase as post-D_3. This paper shows that the situation is probably more complex.

The central part of the early Palaeozoic pelitic sequence in the Jasse de Coumeders area (Fig. 3) consists of relatively homogeneous slate and micaschist with common psammitic layers and occasional calcsilicate bands defining bedding. Locally, grading is visible in the bedding. A NW–SE-striking and steeply-dipping main foliation is axial planar to asymmetric tight folds in bedding (Figs. 3, 4, 5 and 6a & b). This deformation phase has here been labelled D_3 because of observations of relict earlier structures in thin section and in the field. It corresponds to D_3 of Kriegsman (1989) and D_2 of Large (1989, 1991). On S_3 surfaces, a subhorizontal L_4 crenulation lineation is commonly present (Fig. 4d). The variation in orientation of S_3 visible in Figs. 3 and 4 is probably due to the presence of kilometre-scale upright open D_4 folds with NW-plunging fold axes. S_3 is a spaced cleavage with microlithons of 1–5 mm wide and relatively continuous cleavage domains (Figs. 6a & b). In the centre of the Jasse de Coumeders area, a 1 km wide band of micaschist occurs where andalusite porphyroblasts are visible in S_3 microlithons (Fig. 6b). We selected an outcrop of 30 m^2, referred to here as the Beulaygue outcrop, with relatively well developed porphyroblasts and bedding in order to investigate the local microstruc-

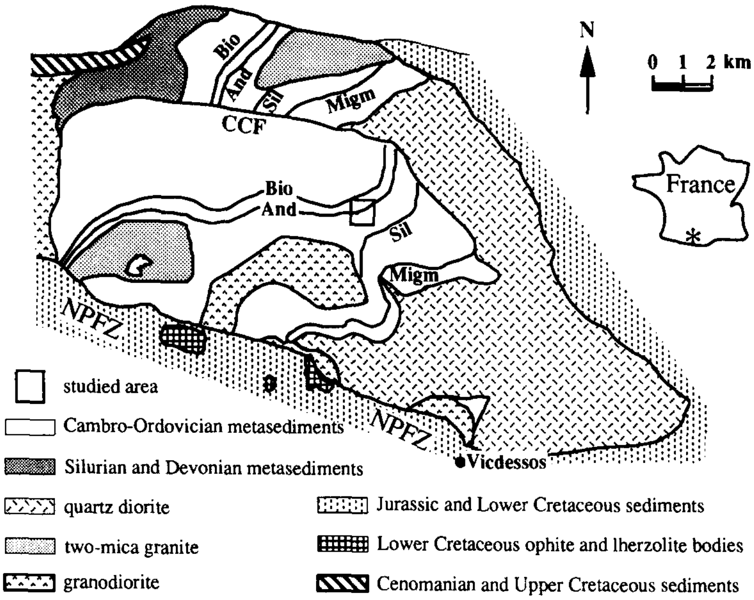

Fig. 2. Geological map of the Trois Seigneurs Massif, French Pyrenees. NPFZ—North Pyrenean Fault Zone. Bio—biotite in; And—andalusite in; Sil—sillimanite in; Migm—first appearance of partial melt veins. Square indicates position of Fig. 3.

tures (Fig. 5). The Beulaygue outcrop is a gently S-dipping glacier-polished rock at 1570 m altitude, 40 m above and 200 m northeast of a shed known as the Refuge de Beulaygue (Fig. 3).

MICROSTRUCTURE

We took 15 oriented samples in the Beulaygue outcrop from both limbs of 10 m-scale D_3 folds as shown in Fig. 5. Polished surfaces A parallel to S_3 (orientation 019–86) show elongate andalusite porphyroblasts with a preferred orientation that defines a weak, steeply SSE-plunging mineral lineation. Surfaces B (orientation 281–20; normal to S_3 and to the andalusite mineral lineation), show elongate andalusite-OTPs with variable orientation. Surfaces C (orientation 110–70, orthogonal to A and B) show disc-shaped cross-sections of the porphyroblasts around which the S_3 foliation wraps. Thin sections were cut in several orientations to investigate the three-dimensional microstructure of the porphyroblasts and their relation with other structures in the rock. OTPs are only visible on surfaces B.

In thin sections parallel to surfaces B (B-sections), the main foliation S_3 is visible as a well-developed asymmetric crenulation cleavage with cleavage domains of white mica and biotite, and microlithons rich in quartz and albite with relics of a folded earlier mica foliation (Figs. 6c and 7). The cleavage domains are relatively continuous and S_3 wraps around andalusite porphyroblasts and transformed porphyroblasts (Figs. 6c and 7). Transformed porphyroblasts are most common in thin section and consist of fine-grained aggregates of white mica, biotite, chlorite and albite. Relic fragments of the original mineral are locally preserved and are invariably andalusite. Inclusion patterns of elongate quartz and opaque grains occur in these andalusite relics and continue undisturbed into the surrounding transformed parts of the porphyroblasts. We therefore argue that the preferred orientation of elongate quartz and opaques in completely transformed porphyroblasts can also be interpreted as inclusion patterns.

Nearly all porphyroblasts in the A- and B-sections (Fig. 5) occur as *pairs* of oblong sectors separated by a quartz rich domain, which commonly contains isolated mica grains oblique to the porphyroblast sectors (Figs. 6c, 7, 8a & c and 9a). Single sectors or groups of three or four sectors in a porphyroblast have also been observed. The spacing between these elongate sectors in pairs or groups is remarkably constant at 0.7–1.2 mm. In many porphyroblasts, 'core-segments' of andalusite connect the sector pairs with an inclusion pattern at a high angle to that in the sectors (Figs. 6c, 7, 8c and 9a). This gives many of the porphyroblasts in the B-sections a typical 'H-shape' (Figs. 8c and 10). Investigation of the B-sections, in combination with A- and C-sections, shows that the three-dimensional shape of the porphyroblasts is a 'spool-shape' as shown in Fig. 11, in which parallel discs of andalusite are connected by core-segments of the same material.

The inclusion pattern in undeformed porphyroblast discs is invariably straight, with minor deflection near the tips of the discs (Figs. 6c, 7 and 8b & c). Most porphyroblasts show an unbroken connection between the inclusion pattern in the discs and the S_3 foliation outside as shown in Figs. 8(c) and 9(a), and schematically in Figs. 10 and 11. The vergence of the inclusion pattern and S_3 on the B-sections is as shown in Figs. 5, 10 and 11 for all samples, even from opposite limbs of D_3 folds. Typical are a sharp deflection on the northwest and southeast sides of the porphyroblasts, and isoclinal microfolds on the northeast and southwest sides (Figs. 5, 9b and 10). We named these rim-structures *connection folds*. The deflection of S_3 and the inclusion patterns in the porphyroblasts show that D_3

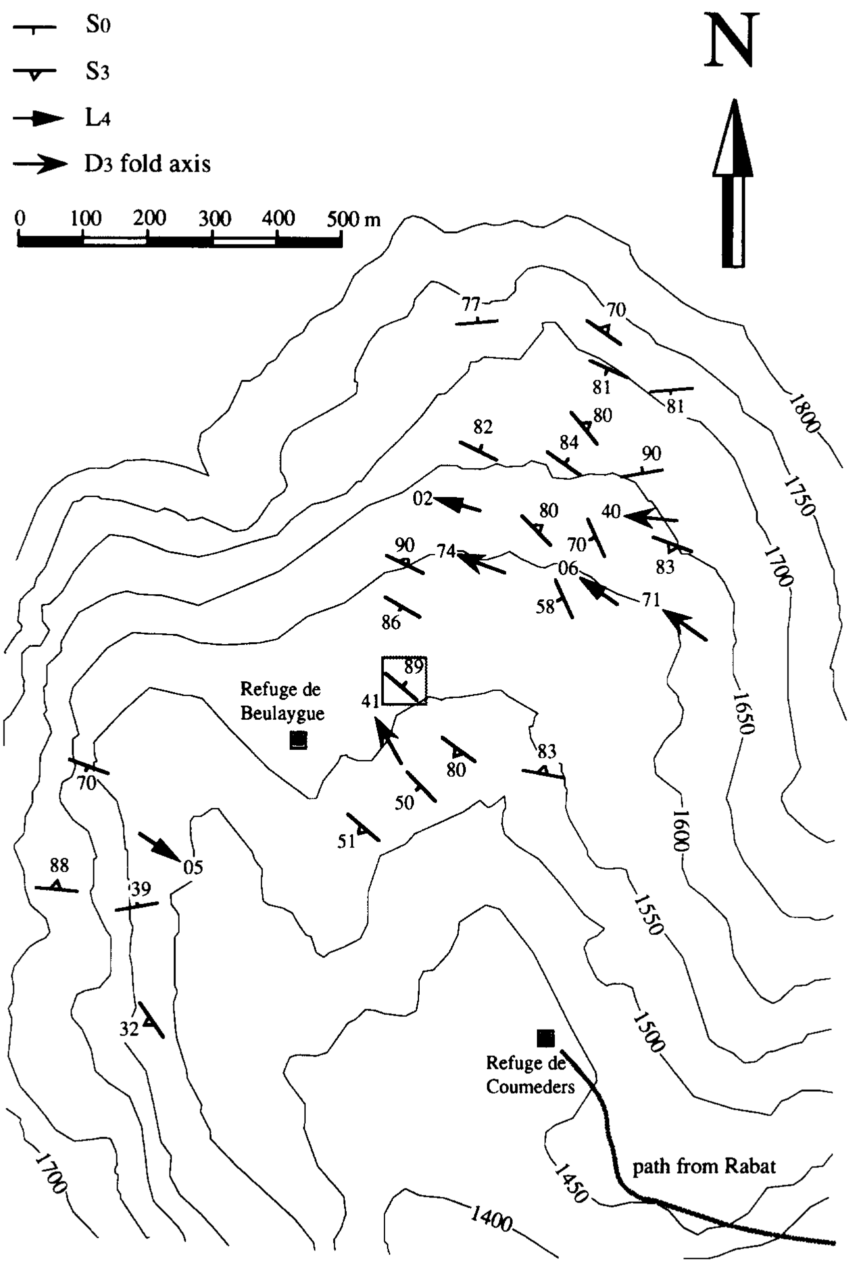

Fig. 3. Structural map of the Jasse de Coumeders area in the central Trois Seigneurs Massif. Location as indicated in Fig. 2. Square indicates position of the Beulaygue outcrop (Fig. 5). Contours are in metres.

largely post-dates andalusite growth in the Beulaygue outcrop.

Connection folds may be an asymmetric equivalent of 'millipede structures' around porphyroblasts as described by Bell & Rubenach (1980). Alternatively, some 'millipede structures' may be flattened and transposed connection folds where the microfolds have been partly erased by flattening or dissolution; around some of our porphyroblasts the connection folds are less clear, or the connection between internal and external foliation is broken, possibly by pressure solution.

Many porphyroblast discs in the B-sections are truncated by well-developed steeply-dipping late micro-shear zones. These occur only inside porphyroblasts and are overgrown by idiomorphic biotite crystals and/or white mica with a strong preferred orientation (Figs. 8c and 9c). Conjugate shear zones are common. In A- and C-sections micro-shear zones are less clear and do not show consistent displacement directions; we therefore conclude that the displacement direction on micro-shear zones is approximately parallel to the B-sections. Movement on the shear zones has caused considerable flattening of individual porphyroblasts in B-sections, and some crystals have been folded (Fig. 6c). Even in these deformed porphyroblasts, the initial orientation of the inclusion pattern was apparently straight. Figure 12(a) shows a plot of shear zone strike against strike of porphyroblast discs in the B-sections. Sinistral and dextral shear zones seem to be equally developed and are symmetrically arranged with respect to S_3, suggesting a pure shear flattening component in the microlithons during shear zone development. Since the orientation of the boundary between sinistral and dextral shear zones is independent of porphyroblast orientation (Fig. 12a),

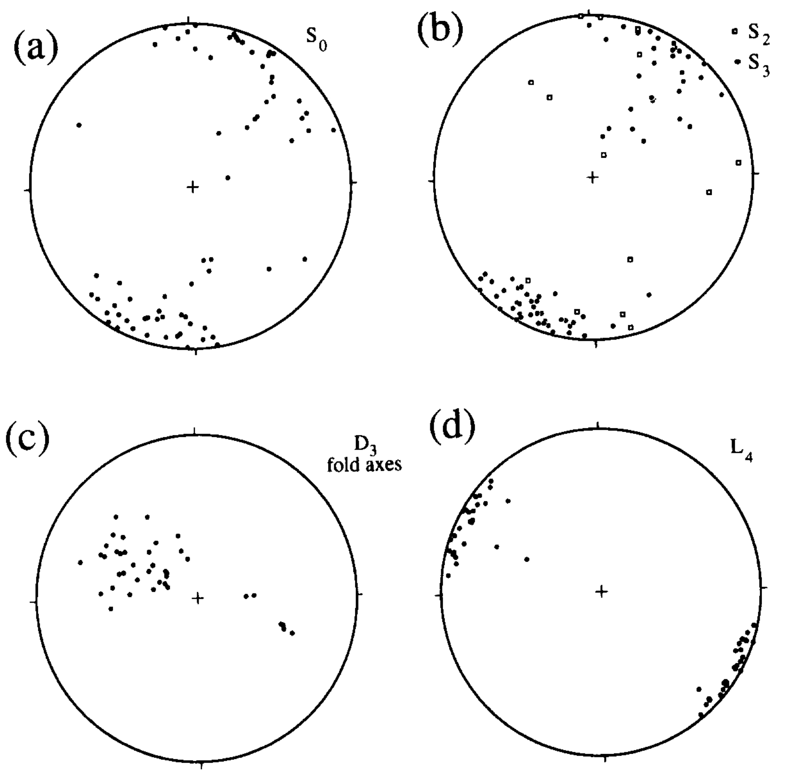

Fig. 4 (a)–(d). Orientation data of structures in the Jasse de Coumeders area. Equal-area projections.

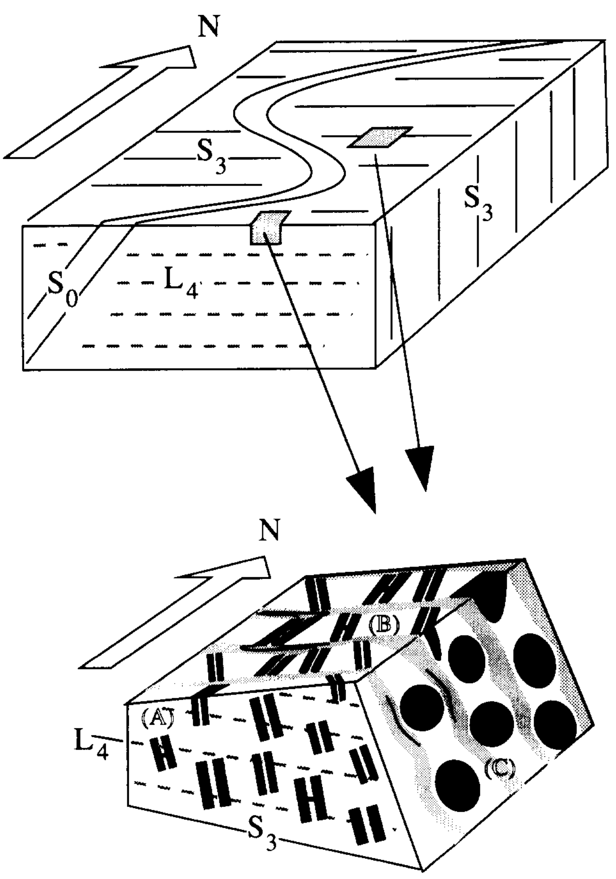

Fig. 5. Schematic representation of the structure in the Beulaygue outcrop, Jasse de Coumeders area. Inset shows the relation of porphyroblast orientation and microstructure on surfaces of different orientation in the samples. Samples from both limbs of D_3 folds have a similar orientation and vergence of structures. The geometry of foliation patterns on surfaces B and C is indicated for two porphyroblasts.

the porphyroblasts must have shown a scatter in orientation before shear zone development. There seems to be a weak connection between porphyroblast orientation and shear zone orientation (Fig. 12a); this may be due to local reorientation of the stress field around the porphyroblasts.

Porphyroblasts in the Beulaygue outcrop vary strongly in orientation in thin section and on outcrop surfaces (Figs. 6c, 7 and 12). Since two-dimensional observations on porphyroblast orientation are ambiguous and difficult to interpret, we have investigated the three-dimensional orientation of porphyroblasts by serial sectioning. An oriented rectangular sample of 4 cm^3 from the Beulaygue-outcrop was cut into slices of 2 mm thick with a 0.5 mm thick diamond saw. About 100 porphyroblasts were visible on these slices, and we cut a large number of these at right angles to the first sections. We then investigated individual porphyroblasts visible on both sections in reflected light to measure the apparent dip of inclusion patterns on the two orthogonal sections. Since the orientation of our saw cuts was known, and because inclusion patterns in the porphyroblasts are straight, we could reconstruct the orientation of the inclusion pattern of 72 porphyroblasts in the sample from the apparent dips (Fig. 13). Comparison with two-dimensional data from thin sections indicates that this is a fair representation of the range in orientation distribution of porphyroblasts in the Beulaygue outcrop. The poles to porphyroblasts form a slightly oblong maximum with a variation in the orientation of 82° in the plane of the great circle, and 70° at right angles to this.

The porphyroblast core-segments are in all cases oblique to the porphyroblast discs and we have tried to detect their orientation as well. Because of their small size this could unfortunately not be done in three dimensions. Figure 12(b) shows the orientation of 27 porphyroblast discs with associated core-segments, measured in the available B-sections. If the core-segments would all have had the same orientation at the onset of D_3 and would have passively rotated with the porphyroblast discs during D_3, they would all be on a diagonal line parallel to the one in Fig. 12(b). The distribution is more along a gently inclined line, however. This may imply that the core-segments had a variable orientation at the onset of D_3, or that they rotated with respect to porphyroblast discs during D_3 in response to shear-movement between the discs.

INTERPRETATION OF PORPHYROBLAST GEOMETRY

Our first impression of the curious spool-shaped porphyroblasts (Fig. 11) was that of boudinaged or broken crystals, although the regular spacing would be difficult to explain in that case. Microstructural evidence, however, suggests that the spool-shape formed by another mechanism. Many of our samples contain quartz veins which have been affected in a complex way by progressive deformation (Figs. 6c and 7). Some of these quartz veins have been folded into an S-shape (Fig. 7—arrows) and some of these folds were subsequently included in a porphyroblast (Fig. 7 arrows at top; Fig. 8a). The geometry of the fold in Fig. 8(a), shown schematically in Fig. 14(a), makes it highly unlikely that the spool-shaped porphyroblast formed by boudinage; the vein occurs in both discs of the porphyroblast and is not disrupted in the intervening space, as should have happened during boudinage. The same S-folds also occur isolated in microlithons (Fig. 7 arrow at right centre) and give the impression of refolded folds.

Our interpretation is that the spool-shaped porphyroblasts result from growth of andalusite over a spaced crenulation cleavage S_2, which contained folded quartz veins (Fig. 14b). The central core-segments in the spool-shaped porphyroblasts can be explained as pre-S_2 megacrystals that were preserved within the microlithons of S_2 in a similar way as complete porphyroblasts are now preserved in S_3 microlithons (Figs. 8c and 10). In fact, many porphyroblasts show deflection of the S_2 inclusion patterns in the discs adjacent to the core-segments (Figs. 8c and 10). The relatively central position of core-segments in porphyroblasts (Fig. 8c) can be explained by initiation of growth of andalusite discs on the central core, which may have been a mica or an older andalusite grain, and radial growth over the mica-rich cleavage domains of S_2 (Fig. 10). Some porphyroblasts show a weak preferred orientation of micas in the space between the discs, oblique to the inclusion pattern in the discs. This structure may represent a relic of S_1 in microlithons of the S_2 crenulation cleavage.

S_2 is likely to have been an asymmetric crenulation cleavage, as indicated by the asymmetry of relic D_2 folds, the oblique orientation of inclusion patterns in porphyroblast discs with respect to included quartz veins, the deflection of bedding through some of the porphyroblasts, and asymmetric microboudinage of quartz veins in the porphyroblast discs (Figs. 8b & c). Notice that in the sample of Figs. 7 and 8 the deflection vergence of quartz veins in porphyroblast discs (and therefore in S_2 cleavage domains) is dextral, while the relative deflection vergence over S_3 cleavage domains is sinistral. The vergence of relative S_3 deflection through OTPs is uniform over the entire Beulaygue outcrop, but the vergence of relative S_2 deflection in porphyroblast discs varies from sample to sample. We were not able to map vergence boundaries for S_2 with the limited set of samples available.

RELATIONSHIP OF PORPHYROBLASTS AND S_3

OTPs as shown in Fig. 1(a) have traditionally been interpreted as evidence for porphyroblast rotation (Fig. 1b) in the kinematic reference frame of bulk flow (Zwart 1962). However, Ramsay (1962) and Bell (1985) correctly pointed out that the asymmetry is only indicative of *relative* rotation of foliation and porphyroblasts. Instead of *dextral* rotation of the porphyroblast in Fig. 1(b), a similar structure could form by *sinistral* rotation of the foliation with respect to a stationary porphyroblast (Fig. 1c). The presence of bedding, deformed quartz veins, connection folds and micro-shear zones in and around OTPs from the Trois Seigneurs samples constrains the possible mechanisms by which these structures may have developed. One important aspect is that the poles to porphyroblasts in Fig. 13 form a slightly oblong maximum with a variation in orientation of up to 82°, while less-accurate two-dimensional data from other samples show variations up to 100°. This variation in orientation, together with the straight nature of S_2 inclusion patterns in porphyroblast discs suggest that the porphyroblasts rotated significantly with respect to each other (and therefore with respect to geographical coordinates) after they grew over a straight S_2. The role of micro-shear zones in porphyroblast rotation seems to be minor; shear zones apparently developed after porphyroblasts had already rotated over a significant angle.

The 'traditional' interpretation of OTPs (dextral rotation of OTPs with respect to a stable foliation) can explain the relative orientation of inclusion patterns and S_3 and even the connection folds in our samples; deflection of markers with a shape similar to connection folds has been obtained in flow experiments by Ghosh & Ramberg (1976) and in computer modelling by Masuda & Ando (1988) for deformation around a rotating rigid body. Despite this apparent fit, however, some critical fabric elements in the Trois Seigneurs example cannot be explained and we therefore think that the traditional interpretation of dextral porphyroblast rotation does not apply here. Several microstructures indicate a bulk *sinistral* D_3 sense-of-vorticity. These include displacement

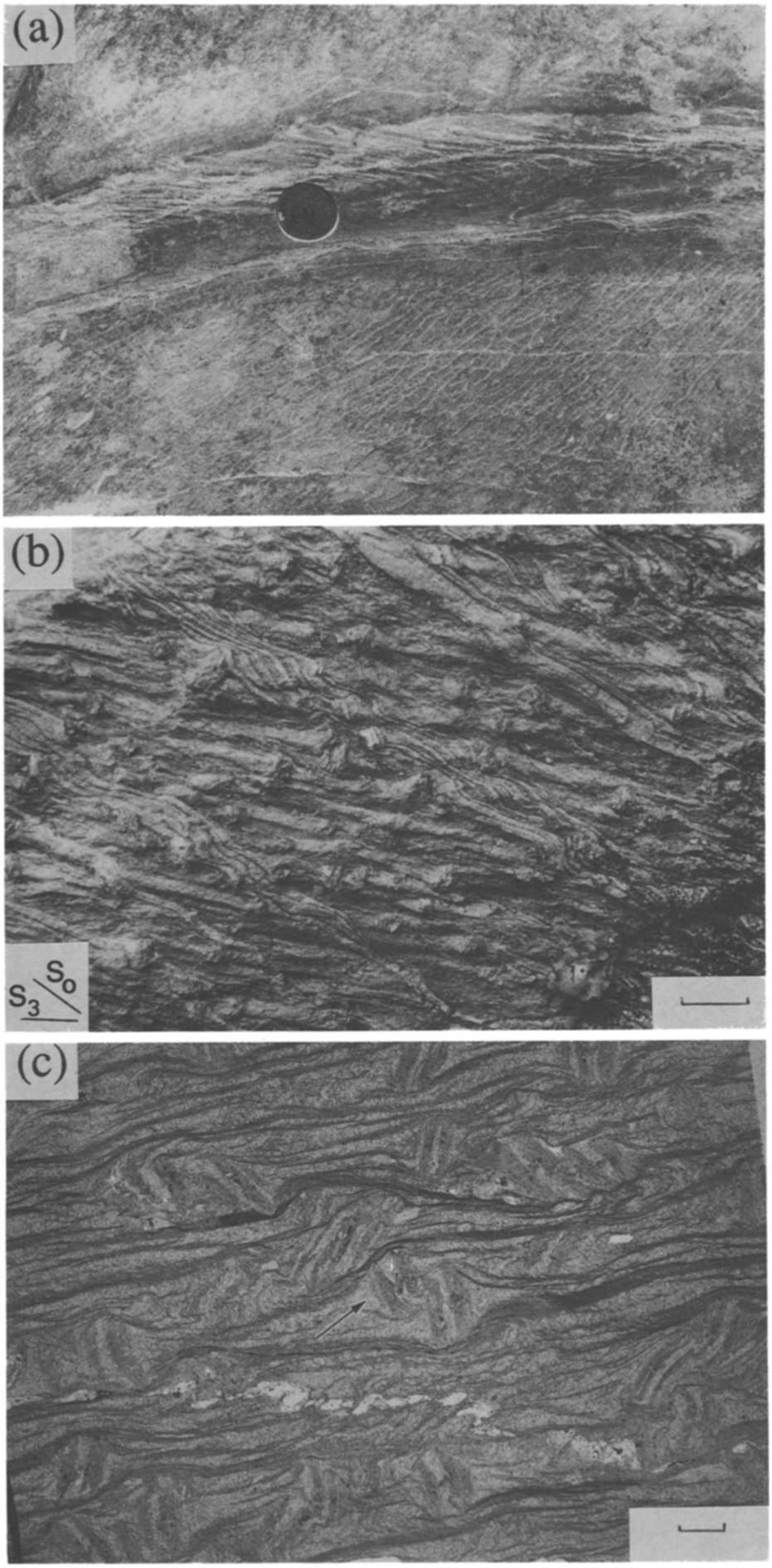

Fig. 6. (a) Field photograph (negative image) of psammitic layers with an S_2 spaced cleavage (lower half and top), overprinted in a pelitic layer (just above the coin) by an S_3 crenulation cleavage. Diameter of coin is 2 cm. (b) Field photograph of S_3 transecting bedding. Andalusite porphyroblasts are visible in S_3 microlithons. Bedding is steeper in S_3 microlithons than in cleavage domains. Scale bar is 1 cm. (c) Thin section of micaschist with andalusite porphyroblasts cut parallel to surface B (Fig. 5). Porphyroblasts occur as paired discs in microlithons of S_3 (horizontal). Some porphyroblasts (arrow) are H-shaped and have a core-segment. An early quartz vein has been transected by S_3. Notice up to 100° variation in porphyroblast orientation, and folded porphyroblasts (bottom right). Scale bar is 1 mm. North is up.

Fig. 7. Thin section parallel to surface B. Quartz veins are folded and displaced by S_3. Folds interpreted as D_2 occur in microlithons of s_3 (arrows) and one is overgrown by a porphyroblast (bottom right). Boxes indicate details in Fig. 8. Scale bar is 1 cm. North is up.

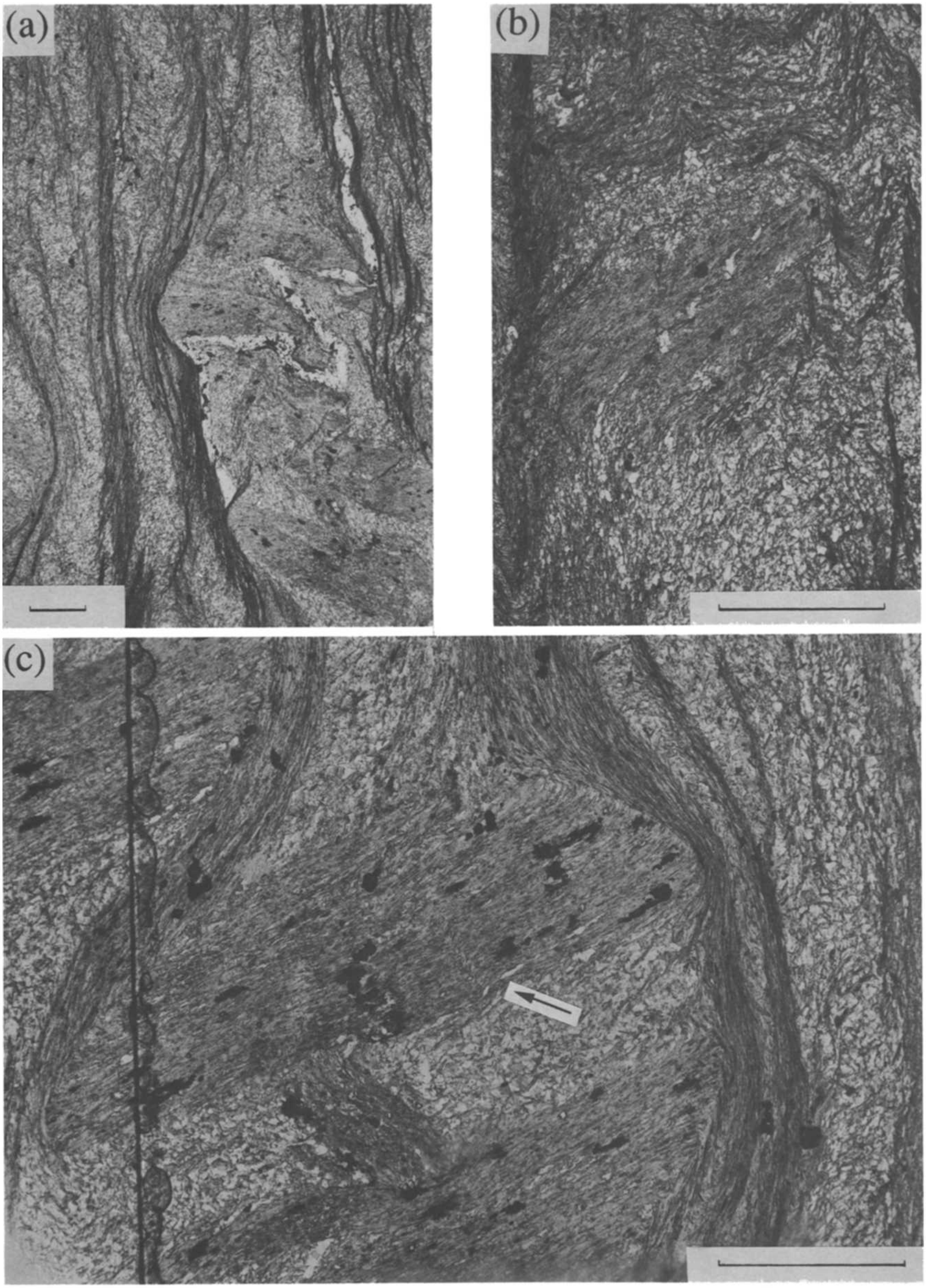

Fig. 8. Details of Fig. 7. (a) S-shaped D_2 fold of a quartz vein included in an andalusite porphyroblast in a microlithon of S_3. The vein is refolded by D_3. The porphyroblast consists of three discs with a core-segment between the lower and middle disc (see Fig. 14a). Scale bar is 1 mm. (b) D_2 asymmetric boudinage of a quartz vein included in an undeformed andalusite porphyroblast disc. The porphyroblast is interpreted to have overgrown an S_2 cleavage domain. Dextral sense of D_2 displacement agrees with shear sense indicated by the folded vein in (a). Scale bar is 1 mm. (c) Typical cross-section of a spool-shaped andalusite porphyroblast. The inclusion pattern in the two discs is interpreted as S_2; it is deflected around the central core-segment which contains a weak inclusion pattern, possibly S_1. The S_2 inclusion pattern is continuous with the external S_3 crenulation cleavage through connection folds as shown schematically in Fig. 10. The top disc is cut by a micro-shear zone (arrow) which transects a boudinaged quartz vein similar to that in (b). Scale bar is 1 mm.

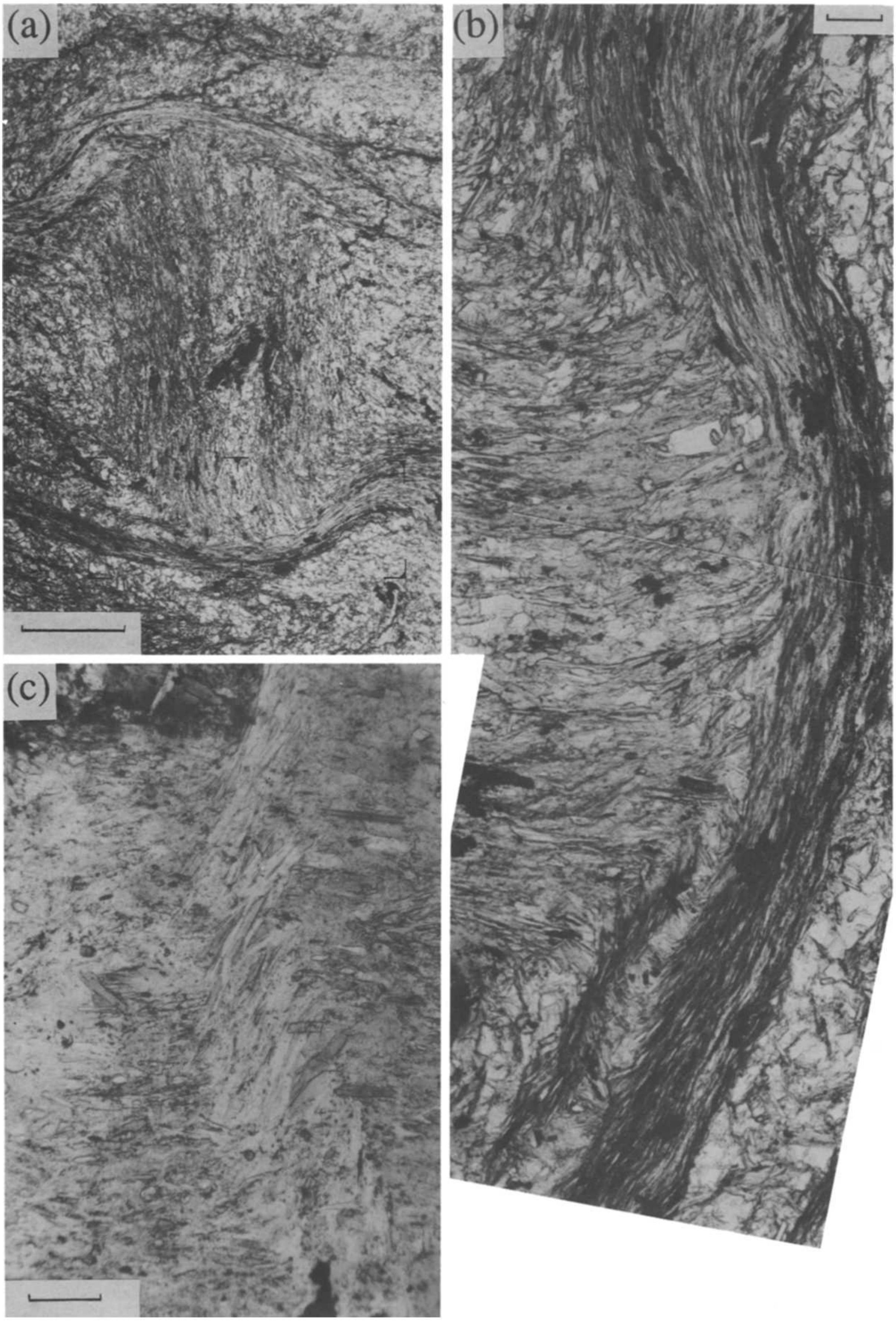

Fig. 9. (a) Spool-shaped andalusite porphyroblast with symmetric distribution of connection folds on both sides. (b) Enlargements of the lower half of (a) showing the connection folds. (c) Detail of a micro-shear zone in an andalusite porphyroblast, similar to the one in Fig. 8(c).

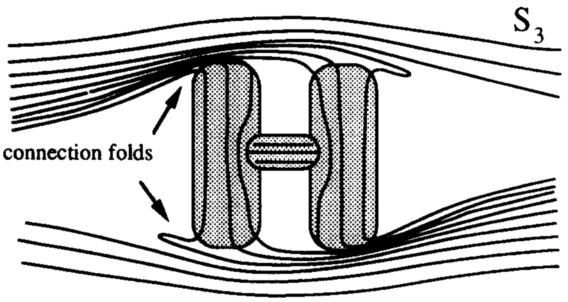

Fig. 10. Schematic representation of the microstructure of andalusite OTP on B surfaces in the Trois Seigneurs Massif. Porphyroblasts are H-shaped in thin section and show symmetrically disposed connection folds. The inclusion pattern in the core-segment is transected by the inclusion pattern in the paired sectors on both sides, which is deflected into S_3 by connection folds.

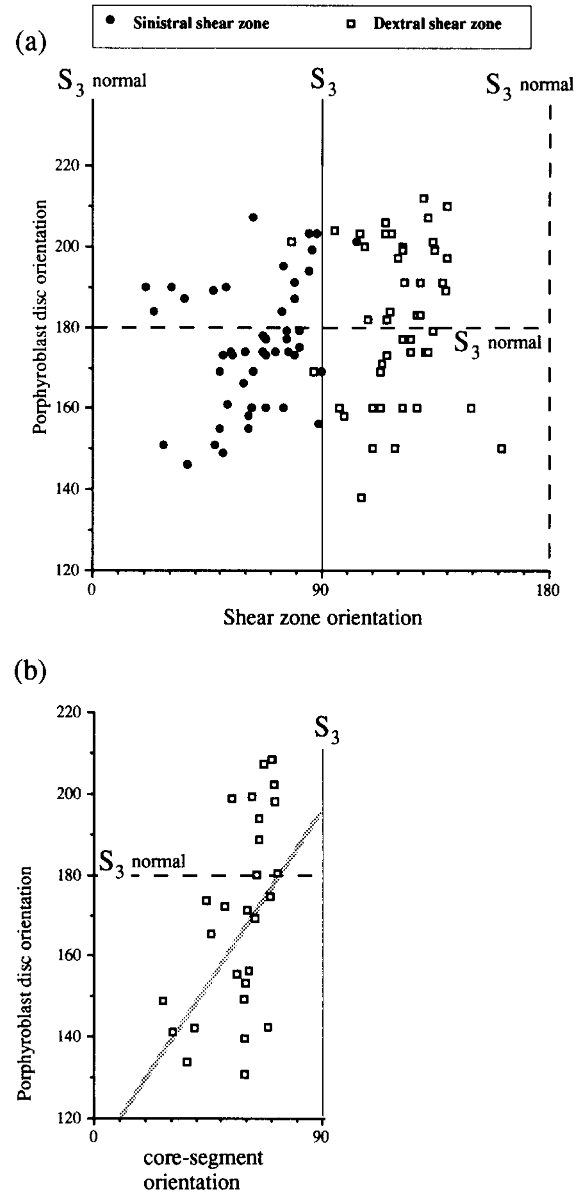

Fig. 12. (a) Plot of OTP disc trend against trend of micro-shear zones in the discs on B surfaces. The boundary between sinistral and dextral shear zones coincides with the S_3 trend irrespective of disc orientation. There is a weak correlation between disc orientation and shear zone orientation. (b) Plot of OTP disc trend against trend of core-segments. Grey diagonal line indicates theoretically-expected orientation of core segments if they would have had identical orientations before D_3. Further discussion in text.

of quartz veins and bedding along S_3 planes (Fig. 7); asymmetric boudinage of quartz veins; oblique mica-orientation in S_3 cleavage domains (Figs. 6c and 7); and sinistral displacement of porphyroblast fragments which are still partly linked across S_3 planes.

In our view, a model for development of OTPs in the Beulaygue outcrop during D_3 is constrained by the following observations: the S_3 cleavage domains have been enriched in micas relative to microlithons; strain values must have been higher in cleavage domains then in microlithons to cause the present fabric; bulk flow was probably a sinistral non-coaxial flow; and an originally spaced S_2 cleavage as mimicked in porphyroblasts must have degenerated in microlithons to form a homogeneous fabric. The last observation, and the evidence for internal deformation of porphyroblasts, implies that microlithons must have been deformed. If microlithons would have remained undeformed in sinistral non-coaxial flow as shown in Fig. 15(a), either very high shear strains or extreme volume loss in cleavage domains (and therefore bulk volume loss) would have been necessary to form the present fabric. Also, in the case of a bulk sinistral sense-of-vorticity the connection folds can only be explained by significant stretching of microlithons along S_3 (Fig. 15b). Thinning of microlithons is estimated at less than 30% since their width is constrained by the porphyroblast diameter. This suggests volume *increase* in the microlithons during S_3 development. In fact, the development of S_3 may be an approximately isochemical process with quartz migration from cleavage domains to microlithons (Fig. 15b). The symmetric orientation distribution of micro-shear zones in porphyroblasts (Fig. 12a) and the strong deflection of S_3 around some of the porphyroblasts with well-developed micro-shear zones suggest that at least late-stage D_3 flow in microlithons was coaxial. The scatter in the orientation of porphyroblasts may have developed at an early stage of D_3, before micro-shear zones started to form. Since porphyroblast orientation is distributed roughly symmetrically with respect to S_3, it is likely that flow in the microlithons has a significant component of pure shear during the entire development of S_3.

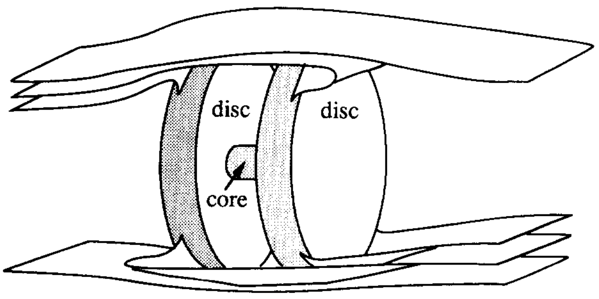

Fig. 11. Three-dimensional reconstruction of an OTP in the Trois Seigneurs Massif. Separate paired discs of andalusite are connected by a core-segment, leading to an overall spool-shape of the porphyroblast.

If our interpretation is correct, the porphyroblasts in the Trois Seigneurs Massif preserve a curious and com-

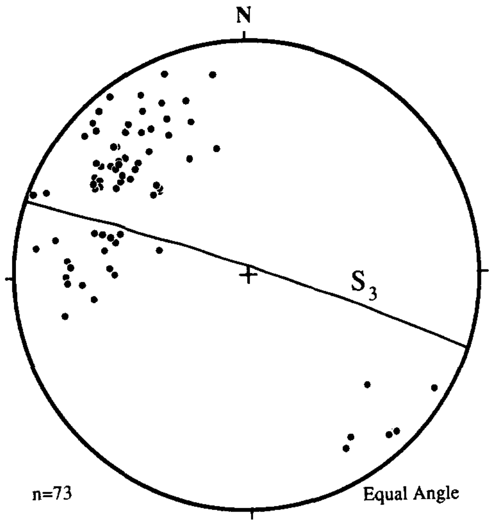

Fig. 13. Poles to porphyroblast discs in a sample from the Beulaygue outcrop, illustrating the orientation scatter of the porphyroblasts.

plex history (Fig. 16). A first cleavage (S_1) formed approximately parallel to bedding. This is possibly a diagenetic bedding-parallel cleavage (Borradaile *et al.* 1982). The present core-segments of porphyroblasts may have been detrital micas in a bedding parallel cleavage, or a first phase of andalusite or biotite porphyroblast growth (Fig. 16a). Quartz veins developed oblique to this cleavage. Subsequently, a phase of deformation shortened the existing fabric and led to folding of quartz veins and development of a spaced cleavage S_2 with relics of the older porphyroblasts in the microlithons (Fig. 16b). This was followed by porphyroblast growth over S_2 to form the present spool-shape (Fig. 16c). Since inclusion patterns are straight, this occurred mostly before intense later deformation. After growth, a new phase of deformation (D_3) shortened S_2 and caused development of S_3 and rotation of porphyroblasts (Fig. 16d). Micro-shear zones developed relatively late during D_3. Finally, D_4 caused a crenulation lineation on S_3 planes and large-scale open folding (Figs. 3, 4 and 5).

DISCUSSION AND CONCLUSIONS

The beautiful and highly informative microstructures of the Trois Seigneurs Massif are not only a structural curiosity, but they can give at least partial answers to some questions for which few reliable data are presently available. These questions are as follows.

(1) Do structures in microlithons represent undeformed relics of an earlier fabric?

(2) Do porphyroblasts rotate during subsequent phases of deformation with respect to geographical coordinates?

(3) Can porphyroblasts be used to determine the orientation of foliations which have been destroyed by later deformation?

(4) Do obliquely transected porphyroblasts with an orientation as in Fig. 1(a) indicate dextral rotation of the porphyroblast, or sinistral rotation of an older foliation?

(1) If our interpretation of the spool-shaped porphyroblasts in the Trois Seigneurs Massif as overgrowths on a spaced S_2 is correct, this has interesting consequences for the evolution of foliations in deformed rocks. The random positioning of porphyroblasts in the samples and the occurrence of porphyroblasts composed of three or four equidistant discs suggests that S_2 had a spaced nature throughout the samples before porphyroblast growth. Since the microfolded S_2 cleavage in S_3 microlithons is now rather homogeneous (Figs. 6c and 7), its spaced nature must have been destroyed during S_3 development. The proposed model for development of OTPs in the Trois Seigneurs Massif implies considerable deformation in microlithons; dissolution of quartz in cleavage domains may be compensated by redeposition in the microlithons where it destroyed the spaced nature of S_2. It is surprising, however, that S_2 survives the deformation process at all. If our reasoning is correct, structures in microlithons are not necessarily little deformed relics of an older fabric, even if they contain an undisturbed-looking homogeneous foliation.

(2) The variation in orientation of porphyroblasts described above, together with the straight nature of S_2

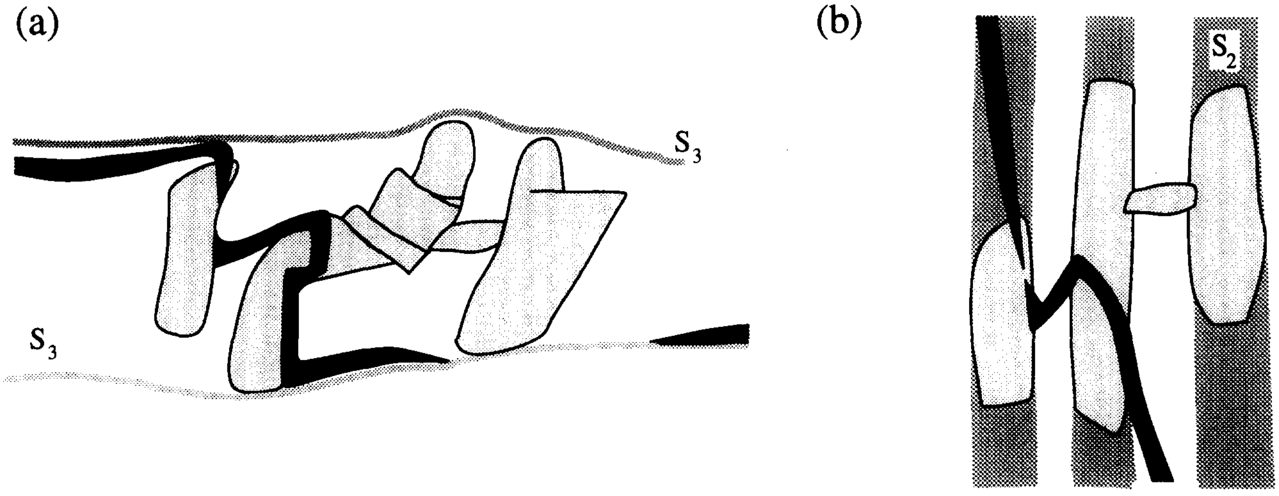

Fig. 14. (a) Schematic presentation of the geometry of the porphyroblast and folded quartz vein in Fig. 8(a). The porphyroblast is folded and cut by micro-shear zones. (b) Reconstruction of the same porphyroblast after D_2 and before D_3.

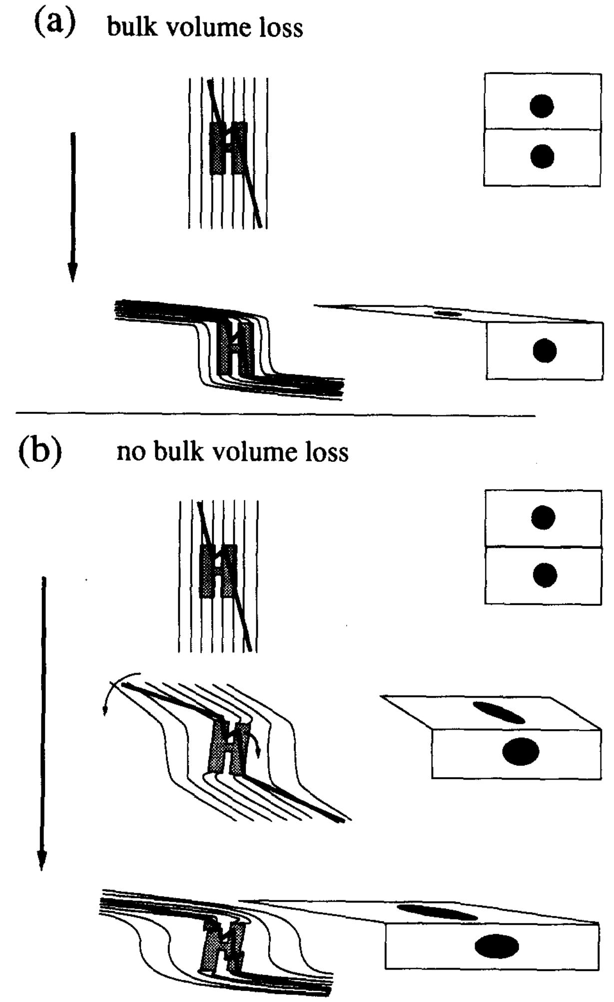

Fig. 15. Two models of progressive D_3 deformation around porphyroblasts. (a) No deformation or volume loss in S_3 microlithons and non-coaxial flow with volume loss in S_3 cleavage domains. (b) Deformation with non-coaxial flow and volume loss in S_3 cleavage domains, and volume increase in S_3 microlithons. Model (b) is probably applicable here since it can explain the development of connection folds and degeneration of S_2 spaced cleavage in S_3 microlithons.

inclusion patterns in porphyroblast discs suggests that the porphyroblasts rotated significantly with respect to geographical co-ordinates after they grew over a straight S_2.

(3) Because of the wide spread in orientation of porphyroblasts (Fig. 13), it seems impossible to determine an original orientation for S_2 with any degree of confidence. Figure 13 shows a maximum around direction 280–20, but with available data it is not possible to say whether the original orientation of S_2 coincided with this maximum, with any point in the observed orientation range, or was even outside this range. Since bulk flow is apparently non-coaxial during D_3, the original position of S_2 is likely to be modified.

(4) In our opinion, the OTPs in the Trois Seigneurs rocks with an S_3 foliation oblique to the inclusion pattern in the porphyroblasts are best explained by sinistral rotation of S_2 and sinistral or dextral rotation of individual porphyroblasts in the kinematic reference frame of bulk flow. A similar relation, but with opposite sense, can be inferred for S_1–S_2 in porphyroblasts (see above).

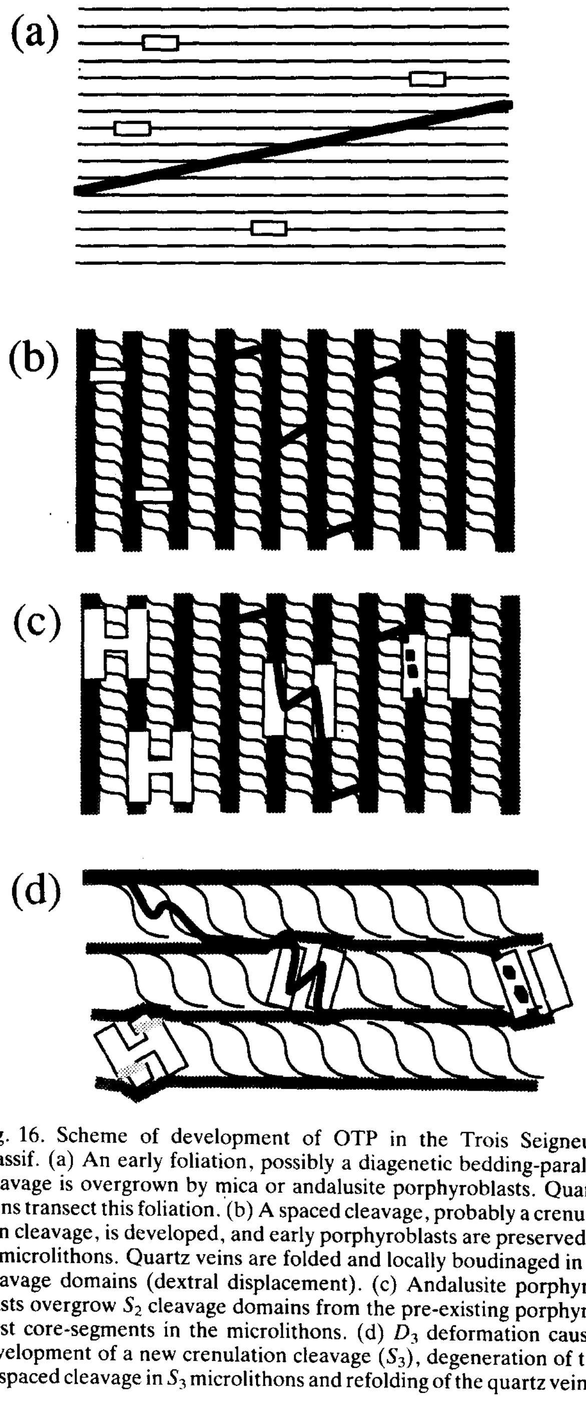

Fig. 16. Scheme of development of OTP in the Trois Seigneurs Massif. (a) An early foliation, possibly a diagenetic bedding-parallel cleavage is overgrown by mica or andalusite porphyroblasts. Quartz veins transect this foliation. (b) A spaced cleavage, probably a crenulation cleavage, is developed, and early porphyroblasts are preserved in S_2 microlithons. Quartz veins are folded and locally boudinaged in S_2 cleavage domains (dextral displacement). (c) Andalusite porphyroblasts overgrow S_2 cleavage domains from the pre-existing porphyroblast core-segments in the microlithons. (d) D_3 deformation causes development of a new crenulation cleavage (S_3), degeneration of the S_2 spaced cleavage in S_3 microlithons and refolding of the quartz veins.

This implies that the traditional interpretation of OTP structures as in Fig. 1(b) to represent dextral rotation of porphyroblasts in the kinematic reference frame of bulk flow does not apply in all cases; such structures can indeed form by sinistral rotation of the foliation as proposed by Ramsay (1962), Meneilly (1983) and Bell (1985). This may create serious havoc with the use of these structures as sense-of-vorticity markers (Hanmer & Passchier 1991). The fact that oblique trace-structures in the Trois Seigneurs Massif can be explained by foliation rotation does not necessarily imply that the 'traditional' interpretation (Fig 1b) of OTPs is always wrong. Presently available data indicate that rigid objects in mylonites and some other rocks with homogeneous foliations do rotate with respect to the kinematic reference frame of bulk flow (Passchier & Simpson 1986, Passchier & Sokoutis 1992). If porphyroblasts are to be used as sense-of-vorticity indicators in future, the subject will have to be investigated in further detail. The fact that the structures in the Trois Seigneurs massif are associated with significant solution transfer of quartz may imply that foliation rotation dominates where solution transfer gives rise to strong flow partitioning, while porphyroblast rotation occurs where crystal-plastic deformation is dominant and the flow pattern around rigid objects is perturbed without creation of flow partitioning domains (Passchier & Sokoutis 1993).

In conclusion, we find that the development of porphyroblasts in the Trois Seigneurs Massif agrees in many aspects with the flow-partitioning model proposed by Bell and coworkers (*op. cit.*). However, the available evidence strongly supports rotation of porphyroblasts with respect to each other, and therefore with respect to geographical co-ordinates. Our findings are therefore in agreement with the views on porphyroblast rotation expressed in Passchier *et al.* (1992).

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