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'V'-pull-apart microstructures: a new shear-sense indicator

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Abstract—Granitoids deformed in a low-grade shear zone show conspicuous development of asymmetric pull-apart microstructures in feldspars, characterized by 'V'-shaped gaps between the separated fragments ('V'-pull-aparts). They occur beside active shear planes and result from rigid-body rotation of one fragment relative to the other. The shear sense in the adjacent flow surface can be easily determined through the asymmetry normally shown by 'V'-pull-aparts, where the fracture wall at a lower angle to the shear plane indicates which fragment has rotated synthetically to the adjacent shearing. Another diagnostic feature is the foliation deflection that occurs adjacent to the rotated fragment.

The 'V'-shaped gaps are infilled by recrystallized quartz–mica aggregates, showing quartz *c*-axis patterns indicative of strong participation of crystal-plastic processes in these domains. Evidence of crack–seal by precipitation (*c*-axes parallel to the direction of separation) have also been found.

The rigid-body rotation indicated by these microstructures, worked as a mechanism of removal of protruding porphyroclast edges, enabling the smoothing of the shear planes. Rigid-body rotation should operate in circumstances where other mechanisms such as dissolution or crystal-plasticity did not succeed in eliminating undulations along the shear planes.

INTRODUCTION

QUARTZO-FELDSPATHIC rocks deformed at greenschist–amphibolite facies normally display microstructures indicative of deformation partitioning between crystal-plastic processes (operating in quartz) and brittle deformation of feldspars (e.g. Berthé *et al.* 1979, Tullis *et al.* 1982, White & White 1983, Simpson 1985, Takagi 1986, Gibson 1990, Paterson *et al.* 1990, Wenk & Pannetier 1990, Schandelmeier & Richter 1991, Tobisch *et al.* 1991, and many others). The relative movement along discontinuities such as cleavages and microfractures has been analysed in a number of papers (e.g. Stauffer 1970, Lister & Snoke 1984, Simpson 1985, Brunel 1986, Kanaori *et al.* 1991), and different models relating these movements to the overall shear sense have been proposed (e.g. Etchecopar 1977, Simpson & Schmid 1983). However, such a relationship is usually difficult to establish (Hanmer & Passchier 1991, Bell & Johnson 1992), because the orientation of microfractures relative to the kinematic framework exerts a decisive control on the movement of broken fragments (Simpson 1986). Indeed, opposite microshears are frequently found within a single thin section (e.g. Simpson 1985, 1986, Bell & Johnson 1992).

In this paper, I discuss a particular kind of pull-apart characterized by a wedge or 'V'-shaped gap between the separated feldspar fragments, which is well developed in a low-grade shear zone of southeastern Brazil. These microstructures are referred to as 'V'-pull-aparts. The local shear sense determined from 'V'-pull-aparts was always the same as the overall shear sense resolved by independent criteria (*S–C* foliations, mesoscale asymmetric pods, asymmetric *c*-axis fabrics). 'V'-pull-aparts are a common brittle deformation microstructure in shear zones, which can portray the bulk shear sense with more confidence than other, commonly ambiguous, pull-apart microstructures.

GEOLOGICAL SETTING

The Moeda–Bonfim shear zone (Hippertt *et al.* in press) is a 70 m-wide, low-grade shear zone that extends along the contact between the Proterozoic Bonfim diapir (Dorr 1969, Herz 1970) and its country rocks (Archaean greenstone schists and micaceous quartzites) in the western Quadrilátero Ferrífero granite–greenstone terrain, southeastern Brazil (Fig. 1) (see Dorr 1969 and Marshak & Alkmin 1989 for review). This dip-slip shear zone was produced during the solid-state ascent of the diapir and affected both the granite and the country rocks (Hippertt *et al.* in press). In the sheared granitoid, a deformation regime close to ideal simple shear has been inferred from *c*-axis fabrics (Hippertt & Borba 1992), and prism ⟨*a*⟩ has been recognized as the principal glide during quartz deformation, possibly reflecting intense fluid activity during the deformation history.

Most of the shear zone displays microstructures typical of low-strain, greenschist facies deformation, where feldspars show intense microfracturing associated with mica-producing retrograde reactions (softening-reactions, cf. White & Knipe 1978), while quartz deforms exclusively by intracrystalline plasticity. Microshears and pull-apart microstructures are very abundant in feldspars, except in local high-strain domains, where the feldspar content is drastically reduced due to high production of mica by retrograde reactions.

S–C foliations (cf. Berthé *et al.* 1979, Lister & Snoke

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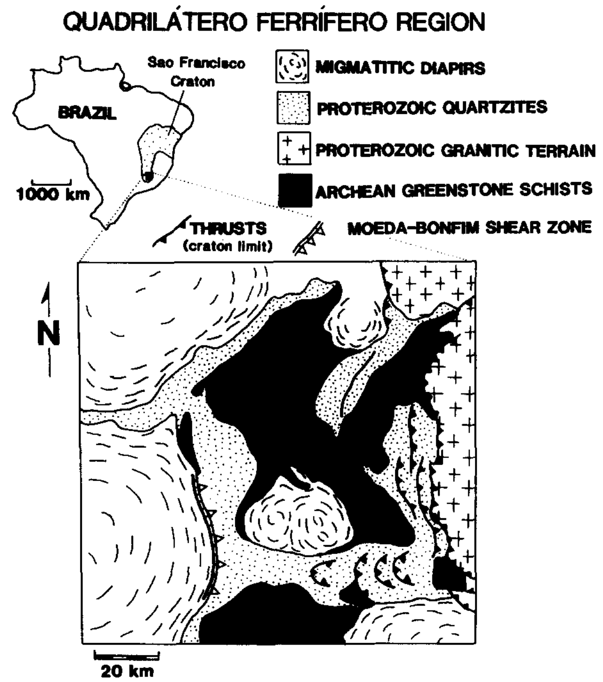

Fig. 1. Simplified geological map of the Quadrilátero Ferrífero region of Brazil.

1984) are pervasively developed within the shear zone, indicating a shear sense that corresponds to the vertical ascent of the granitoid relative to the host rocks. This shear sense is also consistent with the obliquity shown by the *c*-axis fabrics in Hippertt & Borba (1992). The shear direction is reflected by a dip-plunging stretching lineation characterized by the alignment of sericite flakes. Away from the sheared margins, the granitoid is isotropic, indicating that the two sets of foliations present in the shear zone are the product of a single deformation event (the diapiric ascent). This is an important aspect in studying shear sense indicators as it permits all deformation microstructures to be related to a single kinematic framework.

PARALLEL DISPLACEMENT OF BROKEN FRAGMENTS AS SHEAR-SENSE INDICATORS

The microstructures produced by displacement of rigid objects can be divided in two categories, parallel and non-parallel, with respect to style of relative movement between the fragments. In this section, I discuss briefly some limitations in the use of parallel displacements as kinematic indicators.

Parallel displacements are characterized by the maintenance of the parallelism between the fracture walls during the movement. They can be called microshears or pull-aparts depending on the direction of movement. Microshears refer to displacements occurring exclusively along the fracture plane, without separation between the fragments across the fracture. In contrast, parallel pull-aparts are formed when the direction of movement is oblique to the fracture plane, causing the development of gaps between the fragments. The development of gaps appears to depend on the geometry and orientation of the fragments (Mandal & Khan 1991), and is favoured when the fractures are oriented approximately perpendicular to the axis of maximum extension. Microshears and parallel pull-aparts have been correlated with the bulk shearing in a number of papers (e.g. Choukroune & Lagarde 1977, Simpson & Schmid 1983, Brunel 1986, Takagi 1986). However, the sense of movement of rigid objects along microfractures depends principally on the initial orientation of these fractures relative to the kinematic framework (Simpson & Schmid 1983, Simpson 1986), being usually difficult to determine what this orientation was. The geometry of the fragments and the nature of the deformation of embedding medium may also exert an important control on the sense of movement (N. Mandal written communication 1992).

The principal limitation is that these displacements only indicate with confidence the bulk shear sense when the precursor fractures lie at a low angle to the flow plane (Simpson 1986) (see Fig. 2a). On the other hand, relative movements along fractures initially oriented at high angles to the flow plane can be either synthetic or antithetic relative to bulk shearing. In these cases, the movement is synthetic relative to the overall shear sense when the fragments rotate antithetically (back-rotated pull-aparts) with respect to the flow plane (e.g. Hanmer 1984, 1986, Hanmer & Passchier 1991, Jordan 1991). Conversely, an antithetic microshear may be produced when the fragments move similarly to a set of 'dominoes' falling down (Etchecopar 1977, Simpson & Schmid 1983). The microstructures produced by both processes are identical, making them poor kinematic indicators (Hanmer & Passchier 1991). Moreover, similar microstructures can also form by superimposed cross-cutting shears where no rotation of the fragments has occurred (T. Bell personal communication 1991) (see Fig. 2b).

In summary, parallel displacements of rigid objects are frequently ambiguous and are not recommended as positive shear-sense indicators. A complete discussion on the limitations involved in utilizing these microstructures as kinematic indicators was given by Hanmer & Passchier (1991). On the other hand, the shear sense can be more easily resolved when there is a non-parallel gap between the fragments ('V'-pull-aparts) (Figs. 2a and 3), as discussed in the next section.

'V'-PULL-APART MICROSTRUCTURES

'V'-shaped gaps between mineral fragments only form when the rigid fragments separate through non-parallel movements, i.e. the originally parallel microfracture walls become oblique during the pull-apart development. A non-parallel relative movement necessarily occurs when there is a difference between the rate of rotation of the fragments. When both fragments move with identical rotational components (in magnitude and sense) or when no rotation is involved, a parallel pull apart should be formed. This rotational component is usually revealed by the different optical orientations of the separated fragments (Figs. 4 and 5). However, to ensure that the fragments came from a single grain, it is necessary to check the optical orientation relative to the separated fracture walls (it must be the same; see Fig. 6a). The non-parallelism between the twinning lamellae is particularly useful to detect relative rotation between separated feldspar fragments (Figs. 4c and 5c).

'V'-shaped gaps can be also caused by differential internal deformation of the fragments (T. Bell personal communication 1992) as sketched in Fig. 7(e) and exemplified in Fig. 4(b). However, in most cases documented in the Moeda–Bonfim shear zone, no significant differential internal deformation of the fragments has occurred (e.g. Figs. 4a & c and 5). 'V'-pull-aparts tend to form in porphyroclasts containing a set of irregularly spaced microfractures oriented at low angles to the *XY*-plane of the finite strain ellipsoid, i.e. at high angles to the shear plane. They normally occur when there is a marked contrast in size between the adjacent fragments

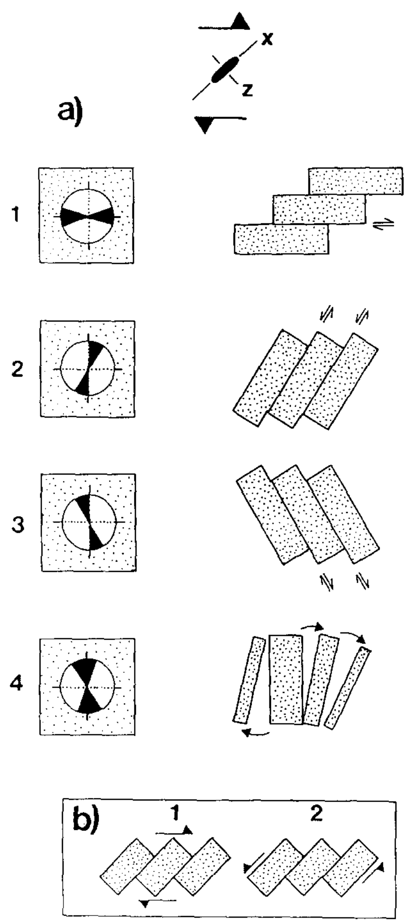

Fig. 2. (a) Sketch showing the development of parallel and non-parallel displacements of broken fragments as a function of the orientation of the precursor microfracture (left column). Case 1: synthetic microshears are produced along the microfractures (no body-rotation involved). Case 2: antithetic microshears are produced during synthetic rotation of the fragments (domino-like microstructure). Case 3: synthetic microshears are produced during back-rotation of the fragments. Note that the shear sense can not be resolved from the microstructures of cases 2 and 3. (b) Sketch showing how a identical geometries can be produced even by overall shearings of different shear directions. Note that rotation of the fragments has occurred only in case 1.

(e.g. Figs. 4a and 5b & c). A component of translation is commonly associated with the development of the 'V'-shaped gaps, provoking an opening of the bottom of 'V' (e.g. Figs. 4c and 5c).

In all cases documented, the precursor fractures of the 'V'-pull-aparts correspond to cleavage planes in K-feldspar oriented at high angles to the shear plane. The fracturing along the cleavages was enhanced by the preferential formation of sericite on these planes, because they permit easier access of H_2O-bearing fluids necessary to promote the transformation of feldspars via mica-producing softening reactions (White & Knipe 1978). Fractures oriented at angles lower than, say 50°, were found to be not suitable to develop 'V'-pull-aparts, possibly because they favour the accommodation of strain by means of parallel or oblique microshears (see Figs. 2 and 12). 'V'-pull-aparts were always found in sites of heterogeneous shear strain, where the opening of the 'V' lies beside an active shear plane while the closure of the 'V' tends to be within a microlithon. This indicates that the progressive shearing along the adjacent flow planes should have been the driving force that promoted the opening of the 'V'-shaped gaps. Thus, the principal problem in inferring the shear sense from 'V'-pull-aparts is to determine which fragment has rotated (or which one has rotated more).

The microstructures in Figs. 4 and 5 strongly suggest that the differently oriented, small fragments were broken from the principal porphyroclast body, but sometimes it is necessary to compare the outlines shown on thin sections parallel to lineation and perpendicular to foliation ('P' thin sections) to ensure that they came from the same grain (Fig. 8). Note that in some cases, small movements along directions oblique to the *XZ*-plane of the finite strain ellipsoid can produce significant differences in the outlines of the fragments shown on 'P' sections, impeding a perfect fit of the fragments (A. Forde personal communication 1992).

Inferring shear sense from 'V'-pull-aparts

'V'-shaped pull-aparts correspond to extensional voids created by non-parallel movement of broken fragments along directions oriented at low-angles with the *X*-axis of the finite strain ellipsoid. They can be opened either by opposite or synthetic (but unequal) rotation of the fragments as sketched in Fig. 7. However, the first hypothesis would not be realistic in non-coaxial regimes, because it is unlikely that two objects under the same local stress conditions (at a microscale) could have opposite spins. They can also form by rotation of only one fragment, while the other keeps its original position.

Figure 9 displays the orientation of fracture walls in 'V'-pull-aparts from the Moeda–Bonfim shear zone, relative to the nearest shear surfaces. Nearly all cases show fracture walls asymmetrically oriented relative to a plane perpendicular to the shear plane. Usually, the wall of the smaller fragment lies at a lower angle to the shear plane than the fracture of the bigger fragment. This relationship suggests that the smaller fragments have

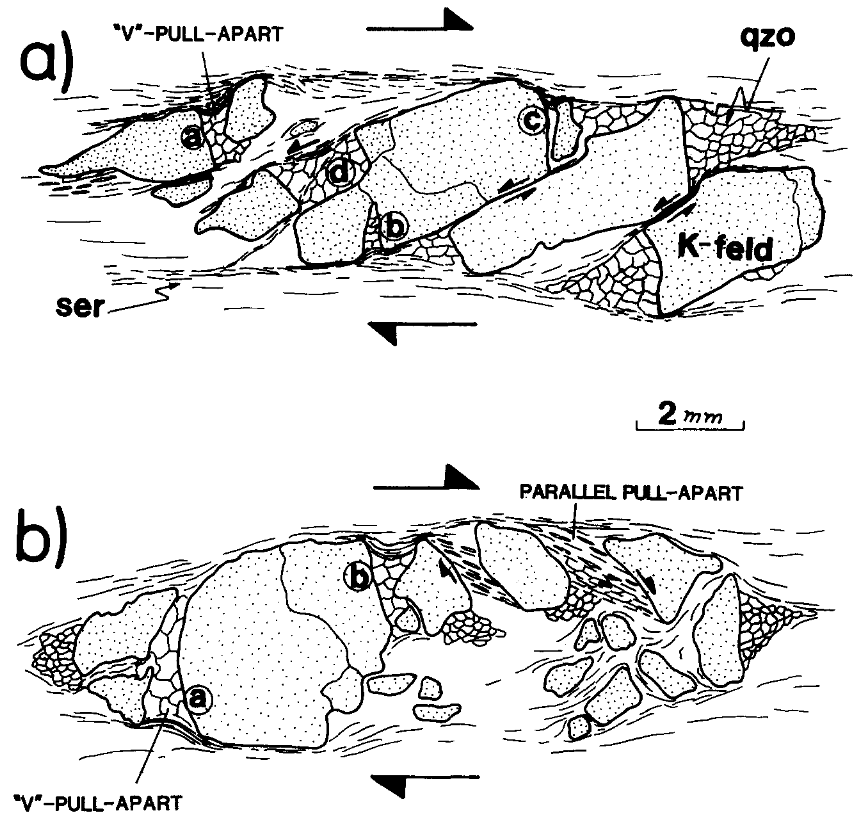

Fig. 3. Examples of parallel and non-parallel pull-aparts in a single 'P' thin section. (a) 'V'-pull-aparts associated with 'domino'-like microstructure in feldspar. The pull-aparts 'a', 'b' and 'c' were produced by shearing along the principal shear planes parallel to shear zone boundaries (bigger arrows) and, therefore, reflect the overall shear sense (dextral). The pull-apart 'd' was produced by microshear between the fragments of the 'domino'-like microstructure and indicates an antithetic shear sense relative to overall shearing. (b) 'V'-pull-aparts ('a' and 'b') and parallel (back-rotated?) pull-aparts in a K-feldspar megacrystal. Both 'V'-pull-aparts were produced by shearing along the principal shear surfaces (bigger arrows). Note that wide gaps exist between the fragments of the parallel pull-apart, contrasting with the 'domino'-like microstructure shown in 'a'.

moved away from the bigger ones, because their fracture walls have rotated into a more stable position of lower resolved shear stress (Fig. 10). The opposite rotation of the bigger fragments would certainly be unrealistic because it implies moving a fracture wall from an orientation of lower resolved stress (oblique to the shear plane) to one of higher (perpendicular to the shear plane; Fig. 10b), contradicting the natural tendency observed in evolving microstructures produced by shearing. This tendency is the same as that causing rectangular porphyroclasts in mylonites to be oriented with their straight boundaries oblique to the shear plane (see Passchier 1987 and Hanmer 1990, for detailed treatments and discussion). Furthermore, the preferential movement of the bigger fragments is obviously more difficult because it would require a higher kinematic energy and a more profound rearrangement of the adjacent matrix. Another possible controlling factor is the aspect ratio of the fragments, which, in most cases, was found to be higher in the smaller fragments than in the bigger ones. This suggests that the smaller fragments might have been more unstable and, therefore, preferentially rotated towards a position of less energy.

Thus, 'V'-shaped gaps should preferentially form by rotation of the smaller fragments, while the bigger ones tend to keep their original positions or rotate more slowly. When no internal strain occurs, this rotation is directly reflected in the angle between the separated fracture walls. However, if significant size contrast does not exist between the separated fragments, or if the fracture walls are symmetrically oriented relative to shear plane, it can be very difficult to recognize which

Fig. 4. 'V'-pull-apart microstructures in the Moeda–Bonfim shear zone. (a) Small broken fragments of K-feldspar have moved away the porphyroclast body (arrows) by sinistral shearing. Note that the separated fragments do not display the same optical orientation of the principal porphyroclast body, indicating that they have undergone rigid-body rotation. No internal deformation of the fragments has occurred as evidenced by the fit of the fragment outlines (see also Fig. 8). The microfracturing was favoured by intense sericitization of the perthitic plagioclase (ser). Observe how the sericite flakes produced by alteration of the feldspar contribute to form mica-rich folia. Note also that no significant difference exists between the mica–quartz aggregates outside and inside the gap (see also Fig. 11). (b) 'V'-pull-aparts (1, 2 and 3) in K-feldspar indicating dextral shearing along two principal shear surfaces. In '1' and '3', the small fragments were pulled away from the porphyroclast body, creating the 'V'-shaped gaps. Note that internal deformation of the fragment in the right part of the photograph has contributed to the formation of the 'V'-gap (compare with e). (c) 'V'-pull-apart in K-feldspar. The different orientation of the twin lamellae was produced by rigid-body rotation of the smaller fragment (S). The internal microfoliation is deflected near the fragment that has rotated, in the top of the 'V'. This microfoliation lies at a smaller angle with the fracture wall of the fragment that has moved away. All photographs taken on 'P' sections. Scale bar is 0.75 mm.

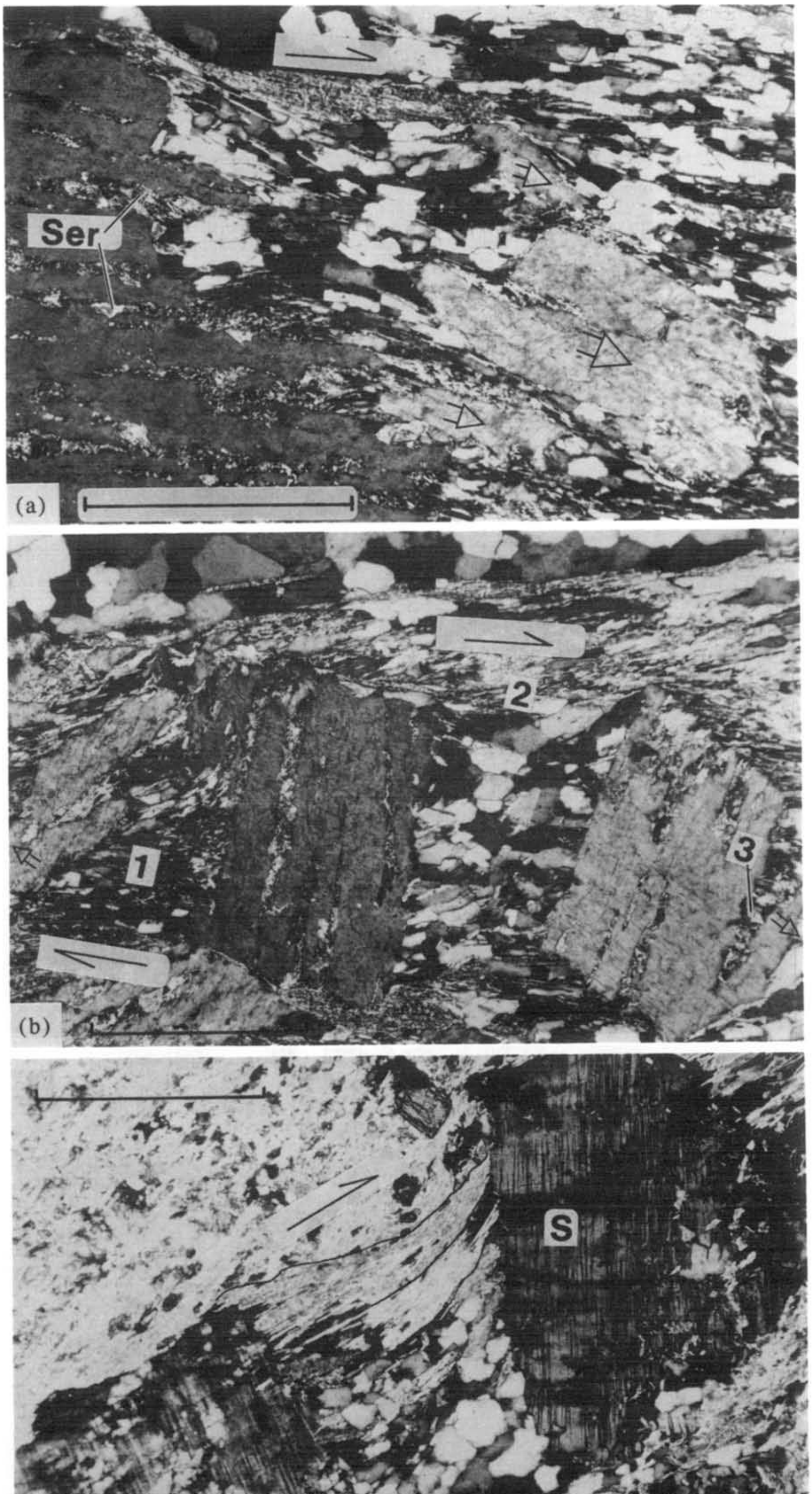

Fig. 4.

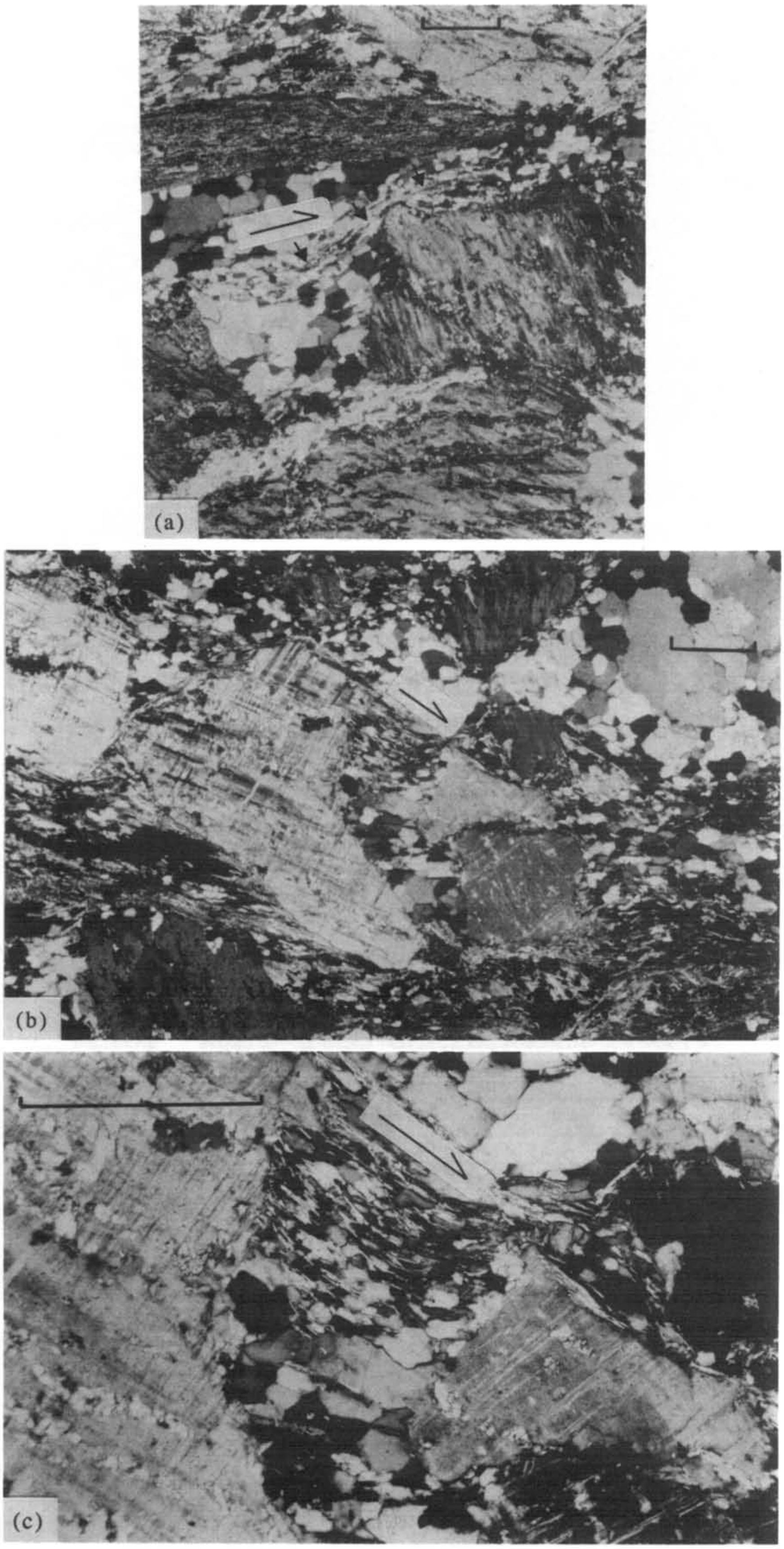

Fig. 5. (a) & (b) Two different materials infilling 'V'-gaps (produced by dextral shearing) between K-feldspar fragments. Coarse polygonal quartz grains occupy the bottom of 'V', while a fine-grained quartz–mica aggregate occurs in the top. Note that this quartz–mica aggregate passes continuously into a fine-grained mica-rich surface outside the gap (small arrows). Observe also that the internal microfoliation is convex towards the bottom of 'V' (see text). (c) Detail of 'b'. All photographs taken on 'P' sections. Scale bar is 0.75 mm.

fragment has rotated. In these cases, alternative criteria such as differences in grain size (the grain size tends to decrease near the fragment that has moved) or inflections of the microfoliation within the 'V'-shaped gaps can sometimes be used (see Fig. 6b).

It should be noted that 'V'-pull-aparts are tightly constrained by the movement along the surface adjacent to the open end of the 'V'. They can indicate the bulk shear sense as well as the sense of shear on secondary oblique microshears (e.g. along S-foliations, between rigid fragments, etc.), depending on which surface is adjacent to the open end of the 'V' (this is exemplified in Fig. 3a). Therefore, the determination of the bulk shearing must always be done on 'V'-pull-aparts adjacent to principal shear surfaces (i.e. parallel to the shear zone boundaries).

In summary, shear sense from 'V'-pull-aparts can be directly determined in 'P' thin sections through the orientation of the fracture walls, where the fracture wall at a lower angle to the shear plane indicates which fragment has rotated (usually the smaller one). In the Moeda–Bonfim shear zone, the shear sense resolved by utilizing this criterion was always in agreement with the overall shearing deduced from independent criteria.

INFILLING OF GAPS IN 'V'-PULL-APARTS

Gaps in pull-apart microstructures are commonly sites of deposition during solution-transfer. They are generally filled with quartz (sometimes fibre quartz) or fine-grained mica–quartz aggregates (Ramsay 1980, Cox & Etheridge 1983, 1989). However, some features of the 'V'-pull-aparts suggest that processes other then precipitation could contribute to the infilling of gaps in the Moeda–Bonfim shear zone.

In most cases, two different materials occupy the gap, with a sharp interface between them. Coarse-grained polygonal quartz occurs in the bottom of the 'V', while the upper part is frequently filled with fine-grained

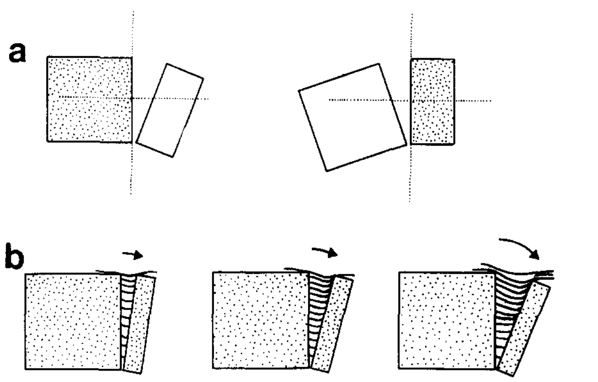

Fig. 6. (a) Sketch showing how to check the optical orientation of fragments in 'V'-pull-aparts. If no movement out of the XZ-plane of the strain ellipsoid occurs, the fragments must display the same optical orientation when the fracture walls have a same orientation on the microscope stage. (b) Sketch showing successive development of internal microfoliation in 'V'-gaps. Note that a deflection exists near the fragment that has rotated, in the top of 'V'. The microfoliation lies at a lower angle with the fracture wall of the fragment that has moved away (see Figs. 4b & c as well).

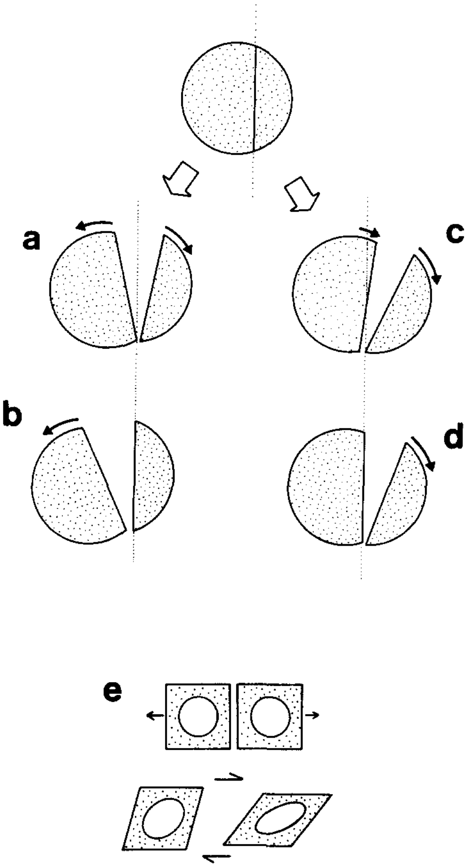

Fig. 7. Sketch showing different ways to form 'V'-pull-aparts. (a) The fragments rotate in different senses. (b) Only the bigger fragment rotates. (c) The fragments rotate in a same sense, but with different magnitudes. (d) Only the smaller fragment rotates. (e) Development of 'V'-pull-aparts by different magnitude of internal deformation of the fragments. Note that 'a' and 'b' should not be realistic in non-coaxial strain regimes (see text).

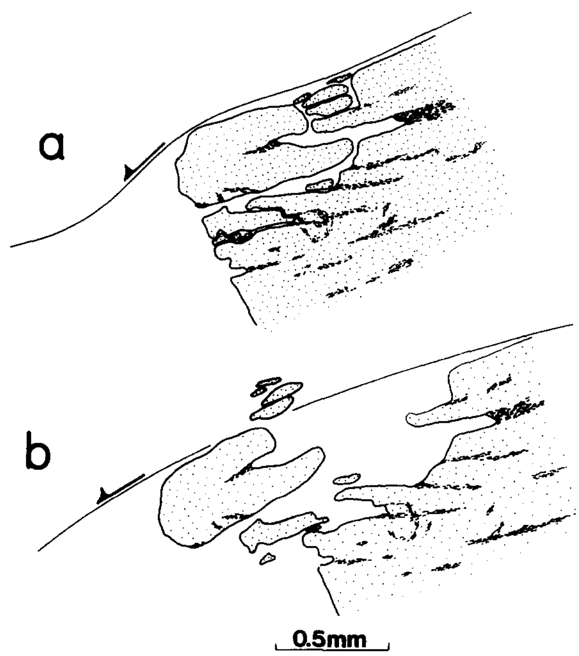

Fig. 8. Reconstruction of the original outline of the porphyroclast shown in Fig. 4(a). The minor differences observed in the outlines of the 'jigsaw pieces' are due to transformation of plagioclase in sericite (shaded) along the perthitic lamellae. Note how the adjacent shear foliation becomes smoother with the separation of the fragments.

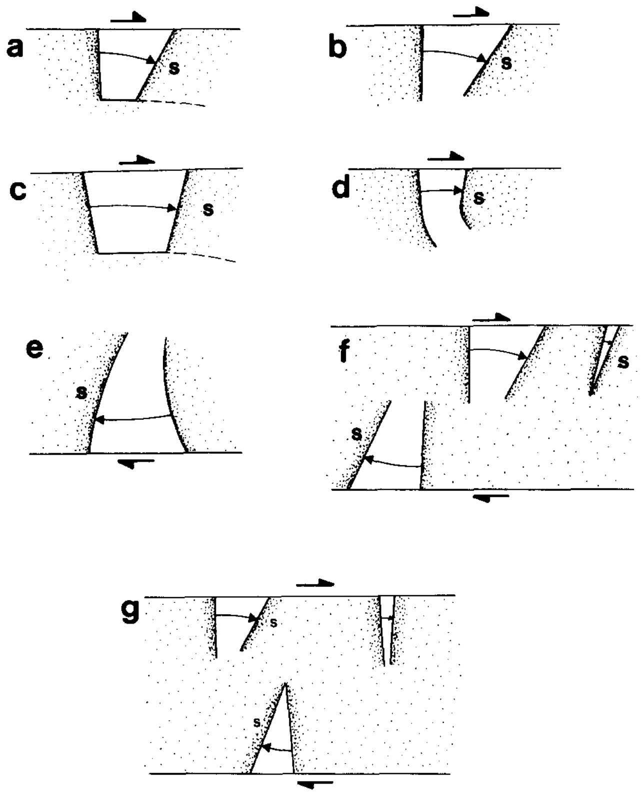

Fig. 9. Sketch illustrating the geometry of some 'V'-pull-aparts from the Moeda–Bonfim shear zone, relative to the adjacent shear surface. Note that in nearly all cases the fracture wall of the smaller fragment is oriented at a lower angle to the shear plane than the fracture wall of the bigger fragment (usually perpendicular to the shear plane). The smaller fragments separated from the bigger ones (arrows) creating the 'V'-shaped gaps. They have always rotated synthetically relative to shearing along the adjacent flow planes, permitting the use of these microstructures as shear sense indicators. Examples 'f' and 'g' correspond to the multiple 'V'-pull-aparts shown in Figs. 4(b) and 3(a), respectively.

aggregates of mica and elongated quartz (Fig. 5). This increasing grain size towards the closure of the 'V' (e.g. Figs. 4c and 5b), may reflect the fact that the fragments are separating at rates successively lower in this direction.

A microfoliation defined by the preferential orientation of sericite flakes is usually well developed in the top of the gap (Fig. 5), but much less conspicuous in the material occupying the bottom of the 'V'. The concentration of sericite flakes in the tops of the gaps suggests that this mineral was not produced by precipitation from a solution as there is no apparent reason for a domainal nucleation of sericite within the gaps. Part of the sericite content in these domains could have been introduced through the mechanical collapse of adjacent mica-rich folia as strongly suggested in Fig. 5(a). This microfoliation is generally convex towards the bottom of 'V' and does not track the opening trajectory of the fragments (see Urai *et al.* 1991 for discussion). Rather, it reflects the tendency of the external matrix to move into the opened void. Frequently, this microfoliation is deflected near the fragment that has rotated at higher rates (e.g. Fig. 4c; see also Fig. 6).

The materials that fill the gaps also display distinct *c*-axis patterns, where the coarse, polygonal quartz grains show *c*-axes concentrated in two planes (one parallel to and other perpendicular to the microfoliation), while the fine-grained, mica-associated quartz aggregates exhibit a peculiar fabric skeleton characterized by the concentration of *c*-axes at low angles to the internal microfoliation (Fig. 11b). Some coarse quartz grains are elongate perpendicular to the adjacent fracture walls and usually show *c*-axes at a low angle to the pull-apart direction (as indicated by gypsum plate analysis; see Fig. 11a, example 1), suggesting an origin by precipitation during crack-sealing (cf. Cox & Etheridge 1983). However, most of the grains in the bottom of 'V' are equidimensional and have *c*-axes oriented at high angles to the pull-apart direction, as normally occurs during crystal-plastic processes. This may suggest a mechanism of infilling by synkinematic plastic flow of the external matrix into the gaps. Alternatively, this *c*-axis pattern could reflect superimposed recrystallization of the infilling materials (perhaps originally formed by precipitation). This is particularly suggested in Fig. 4(a), where there is no significant difference (in microstructure or

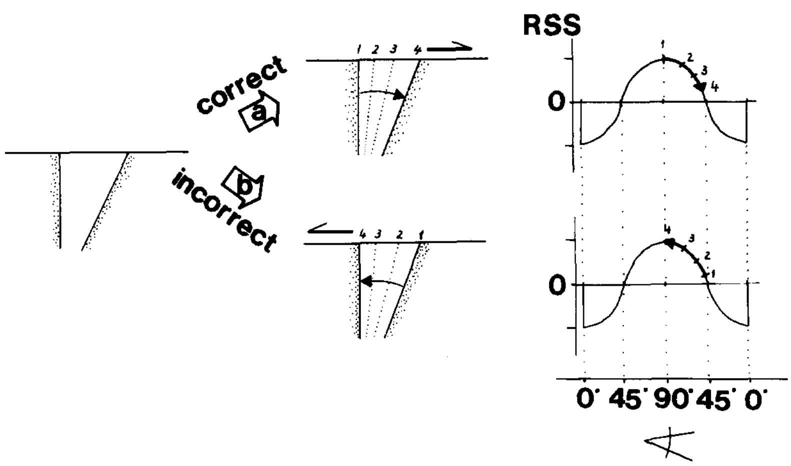

Fig. 10. Resolution of shear sense in 'V'-pull-aparts. (a) *Correct.* The fracture wall of the fragment that has rotated lies at a lower angle to the shear plane, depicting a movement (1–4) towards a more stable position of lower resolved shear stress (RSS, right column). (b) *Incorrect.* An opposite shear sense would not be realistic because it would imply moving a fracture wall from a stable position of lower RSS (oblique to the shear plane) to one of higher RSS (perpendicular to the shear plane).

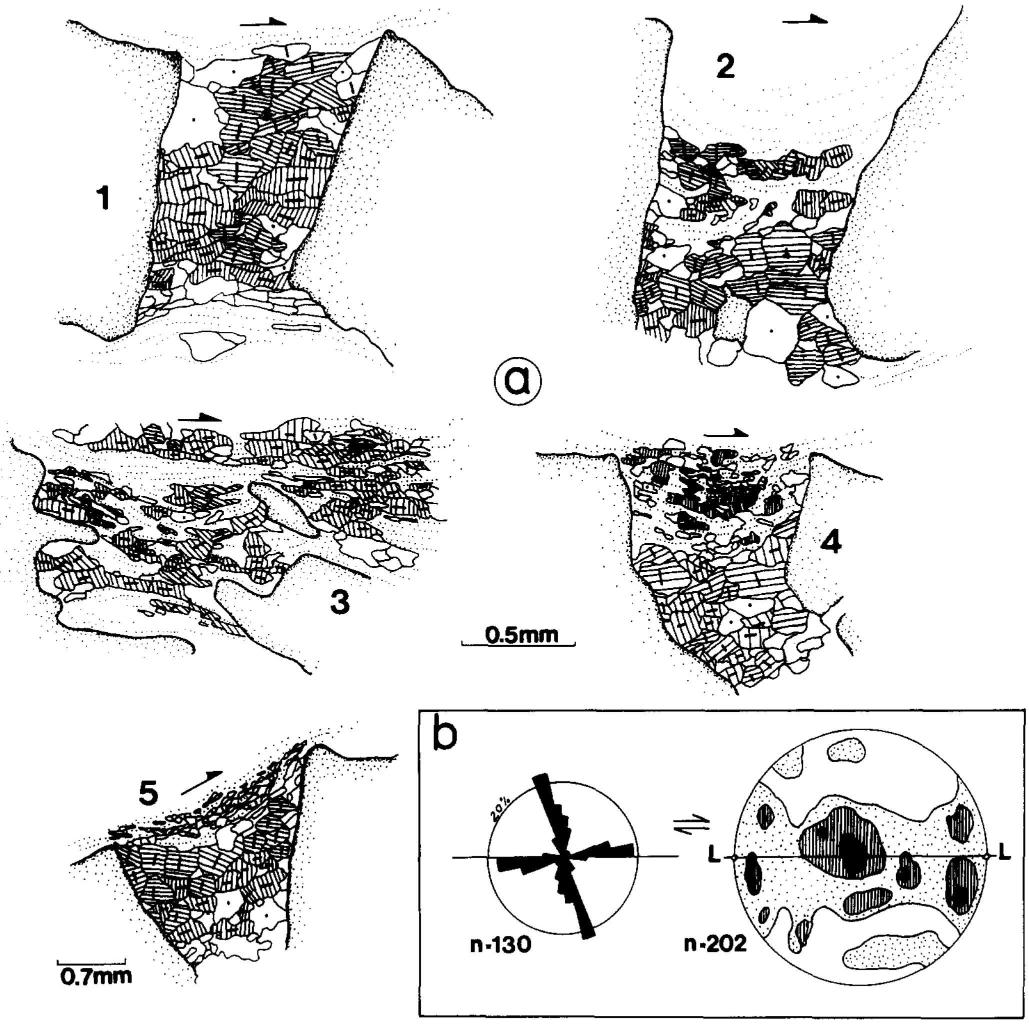

Fig. 11. (a) Internal microstructure of some 'V'-gaps shown in Figs. 4 and 5. Trace of *c*-axis and basal planes are indicated in most of quartz grains. A dot in the centre of some quartz grains indicates a *c*-axis oriented perpendicular to the thin section. Fine dotted lines represent alignment of sericite flakes. A mica-free quartz aggregate totally infills the gap in example '1'. Examples '2', '4' and '5' show gaps infilled by two different materials. Mica-free, coarse-grained quartz occupies the bottom of 'V', while mica-associated aggregates occur in the top of 'V'. The example '3' shows a gap totally infilled by a mica–quartz aggregate. (b) Rose diagram of *c*-axis traces shown in 'a'. Note that the *c*-axis are concentrated in two planes; one parallel and the other perpendicular to the internal microfoliation (E–W on diagram). *c*-axis stereoplot of mica-associated quartz grains similar to those shown in '3' and '4'. Contours 1, 2.5 and 4%. The microfoliation and the direction of separation of the fragments (L) are indicated.

crystallographic pattern) between the materials inside and outside the gaps.

Mechanical collapse of quartz grains from the matrix into the opening gaps (associated with some chemical rearrangement between the grain boundaries) may have been a significant process of infilling in some cases. Infilling of gaps by mechanical collapse should be favoured by high strain rates, where the fragments would separate relatively quickly. Conversely, when the rate of separation is lower, continuous grain growth by precipitation (or infilling by plastic flow) may seal the gap faster than the external grains can collapse into it.

On the other hand, the *c*-axis plot displayed by the fine-grained, mica-associated quartz in the tops of 'V's (Fig. 11b), shows a concentration of *c*-axes along the microfoliation defined by morphological alignment of sericite flakes and elongated quartz grains, with maxima near the direction of movement and in the centre of the plot. This fabric skeleton probably reflects quartz grain growth by precipitation, as there is a significant concentration of *c*-axes near the direction of separation as usually occur during crack-sealing. The maximum in the centre of the plot (around of the *Y*-axis of the strain ellipsoid) and the secondary concentration near the microfoliation pole, however, should reflect crystal-plastic processes rather than a crystallographic pattern produced by precipitation. *Y*-maxima have been normally attributed to prism ⟨*a*⟩ glide (e.g. Schmid & Casey 1986, Manckletow 1987, Fueten *et al.* 1991) and appear to be very common during deformation-recrystallization of mica-bearing materials (e.g. Berthé *et al.* 1979, Burg *et al.* 1984, Hippertt & Borba 1992). This control of mica on the development of *Y*-maxima was noted by Hoffman (1972, cited in Fueten *et al.* 1991) and was explained by Hippertt (in review) as consequence of a more intense fluid flow in these domains, which would favour prism ⟨*a*⟩ glide (Paterson 1989). It should be noted that at least a part of the mica flakes in these aggregates came from the matrix (previously discussed) or was produced by retrograde reactions in the feldspars fragments (e.g. Fig. 4a).

DISCUSSION

A rotational component has been unequivocally recognized to occur during separation of broken fragments of feldspar in the Moeda–Bonfim shear zone. This rotation can be directly inferred by the different optical orientations of the fragments and by the non-parallelism between the two separated fracture surfaces (creating the 'V'-shaped gaps), although, in some cases, internal deformation in the feldspar fragments contributes to this geometry. This rotational component (usually less than 40°) was more frequently recognized in small fragments separated from the main porphyroclast body, which does not show any indication of significant rotation (e.g. asymmetric strain shadows or curved recrystallized tails, cf. Passchier & Simpson 1986). This phenomenon was always identified in porphyroclasts adjacent to mica-rich shear surfaces. The low values of the rotational component may reflect the fact that rotation ceases when the fragment escapes from the influence of the adjacent shear surface (Fig. 8).

The local strain field appears to be the principal controlling factor on the development of 'V'-pull-aparts. These microstructures were found to correspond to sites of heterogeneous shear strain where, in most cases, the fragment that rotates is partially enclosed within a microlithon, having contact with a shear surface only on one side. 'V'-pull-aparts were rarely seen between fragments in contact with two adjacent shear surfaces where, in contrast, back-rotation and 'domino'-like microstructures are common. Initial fractures at high angles to the shear plane are also essential to the development of 'V'-pull-aparts as fractures at lower angles should preferentially favour the accommodation of strain via oblique microshears.

Rigid-body rotation of the feldspar fragments has probably occurred in this low-grade shear zone, because neither crystal-plastic processes nor dissolution (e.g. O'Hara 1990) were dominant deformation mechanisms (in feldspar) able to eliminate the protruding porphyroclast edges along the shear planes (see Fig. 12). Brittle deformation in these porphyroclasts was also favoured by the transformation (by softening reactions) of the perthitic plagioclase to sericite, permitting easy fracture of the porphyroclasts along the perthitic planes. Thus, rigid-body rotation can be understood as an alternative mechanism of removal of undulations along the shear planes, permitting a more efficient accommodation of strain during progressive shearing. Rigid-body rotation necessarily implies an energy-consuming rearrangement of the adjacent matrix and should not operate when an energetically more economic process (e.g. dissolution) can promote the smoothing of the shear planes.

Similarly to other microstructural kinematic indicators, 'V'-pull-aparts should be statistically analysed in a number of grains. The best results are obtained in porphyroblasts elongated parallel to the shear plane and with precursor fractures oriented at a high angle to the shear plane, so that the smaller fragment has its long dimension perpendicular to the shear plane as well. Principally, the kinematic analysis should be made in 'V'-pull-aparts adjacent to clearly defined principal shear surfaces (usually C planes), because inconsistent results can be obtained in 'V'-pull-aparts associated with secondary surfaces (e.g. S planes).

CONCLUSIONS

(1) The asymmetry of the 'V'-pull-aparts relative to the shear plane as well as the foliation deflection within the gaps can be used to evaluate the shear sense along the active shear surface adjacent to them. The evaluation of the sense of movement in 'V'-pull-aparts does not involve the ambiguities commonly associated with other kinematic indicators based on displacement of rigid fragments.

(2) The crystallographic preferential orientation of quartz grains within the 'V'-gaps indicates a significant operation of crystal-plastic processes in these domains, which partially obliterated the crystallographic patterns produced by precipitation. Synkinematic plastic flow of the matrix into the gaps may also have been a possible infilling mechanism.

(3) The microstructures investigated in this paper indicate that small-angle rigid-body rotation can be very common in broken fragments pulled away from porphyroclasts, in which deformation mechanisms such as dissolution or intracrystalline plasticity were not domi-

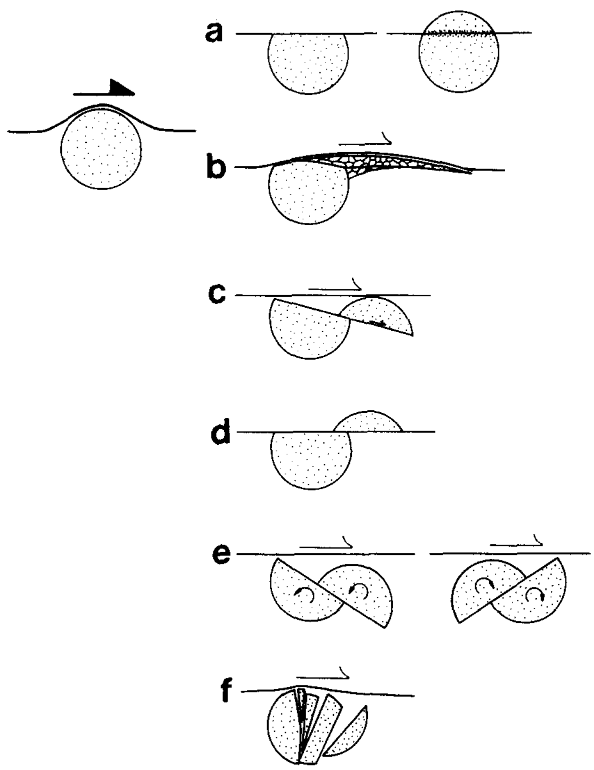

Fig. 12. Different ways to smooth shear foliations by removal of porphyroclast edges. (a) Sequential edge dissolution and cross-cutting dissolution zones. (b) Formation of recrystallized tails. (c) Non-rotational oblique microshears. (d) Cross-cutting microshears. (e) Microshears associated with antithetic and synthetic rotation of the fragments. (f) Non-parallel displacements ('V'-pull-aparts).

nant in eliminating protruding porphyroclast edges along the active shear planes.

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