Development of different types of pull-apart microstructures in mylonites: an experimental investigation

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Received 22 January 2001; revised 15 October 2001; accepted 16 October 2001

Abstract

Intragranular fracturing of feldspar porphyroclasts in granite mylonites of a ductile shear zone has led to development of diverse types of pull-apart and bookshelf structures. Porphyroclasts with centrally located fractures show pull-aparts with parallel walls (Type 1), whereas those with off-centered fractures display pull-aparts with both parallel (Type 1) and non-parallel (Type 2) geometry. Analog model experiments, performed by embedding segmented rigid elliptical objects within a viscous matrix, indicate that the orientation and location of the fracture and the aspect ratio of the porphyroclast are the principal parameters in controlling the development of bookshelf structures and pull-aparts. In the case of centrally located fractures, porphyroclasts of moderate aspect ratios develop either Type 1 pull-apart or bookshelf depending upon the fracture orientations, whereas those of large aspect ratios (>3) form only Type 1 pull-aparts irrespective of the fracture orientation. Off-centered fracturing of porphyroclasts gives rise to fragments of unequal size, which rotate independently at equal or contrasting velocities, forming Type 1 or Type 2 ('V'-) pull-aparts, respectively. In the latter case, depending upon the orientation of fracture, the smaller fragment rotates faster or slower than the larger fragment, showing relative tilt synthetic (Type 2a) or antithetic (Type 2b) to the bulk shear sense, respectively. Type 2b geometry generally develops when the fracture angle with respect to the short axis of porphyroclasts is low, antithetic to the shear direction, and the long axis of the porphyroclast is at a high angle to the shear plane.

Keywords: Pull-apart; Mylonite; Shear-sense indicator

1. Introduction

In many deformed rocks micro- to macro-scale brittle objects floating in a ductile matrix show a variety of fracture-related structures, such as intragranular joints (Ji et al., 1997), bookshelf structures (Etchecopar, 1977; Ramsay and Huber, 1987; Goldstein, 1988) and pull-apart structures (Simpson and Schmid, 1983; Hanmer, 1986; Jordan, 1991; Mandal and Khan, 1991; Hippertt, 1993; Michibayashi, 1996).

Brittle objects floating in a ductile matrix undergo fracturing in response to the traction exerted on them by the flowing matrix (Ramberg, 1955; Hobbs, 1967; Lloyd and Ferguson, 1981; Lloyd et al., 1982; Masuda and Kuriyama, 1988; Masuda et al., 1989; Ji and Zhao, 1993; Ji et al., 1997; Mandal et al., 2000, 2001). Subsequent to fracturing the derivative fragments of the object may move independently in the course of progressive deformation and, depending upon the nature of their relative movements, two types of structure may develop: (1) bookshelf, and (2) pull-apart (Fig. 1a; Ramsay and Huber, 1987). In pure shear deformation the orientation and spacing of the fractures appear to be the principal factors determining the mode of fragment displacement to result in either bookshelf or pull-apart structures (Mandal and Khan, 1991). Alternatively, in simple shear deformation the vergence of the fractures with respect to the shear direction seems to control the development of bookshelf and pull-apart structures (Simpson and Schmid, 1983; Jordan, 1991).

Recently, a new type of pull-apart structure has been reported from granite mylonites (Hippertt, 1993), that shows a V-shaped geometry. Hippertt (1993) has proposed that off-centered fracturing of a brittle object develops fragments of unequal sizes, which rotate with contrasting angular velocities, resulting in a V-shaped pull-apart at a finite stage of bulk deformation (Fig. 1b). According to his model, the tilt of the smaller fragment relative to the larger one in a V-shaped pull-apart indicates the movement direction along the surface adjacent to the open end of the 'V'.

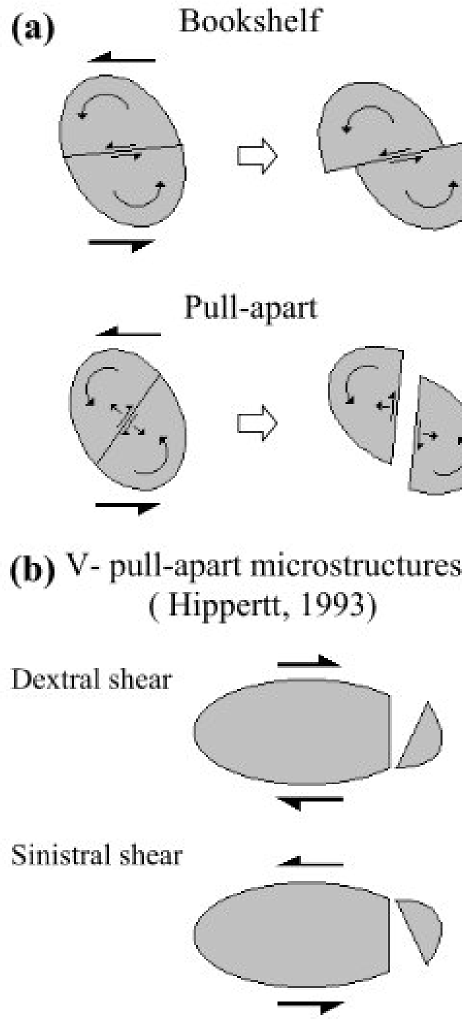

Fig. 1. Modes of movement of fragments after intragranular fracturing. (a) Rotation and offsetting of fragments without and with separation across the fractures, forming bookshelf and pull-apart structures, respectively. (b) Development of V-pull-aparts in dextral and sinistral shear (after Hippertt, 1993).

Thus, these structures can give the sense of bulk or local shear depending on the nature of the shear surface bounding the open end of the 'V'. It has been suggested that V-pull-aparts adjacent to the principal shear surfaces should be used for determination of bulk shear sense (Fig. 1b).

This paper describes different types of pull-apart structures from a shear zone and attempts to investigate experimentally their mode of development in relation to several geometrical factors, such as location (centred and off-centred) and orientation of intragranular fractures and aspect ratio of porphyroclasts. The results of the study lead to refinement of the use of V-pull-apart (Hippertt, 1993) in shear-sense determination.

2. Pull-apart geometry: natural observations

A variety of pull-apart microstructures occur in the granite mylonites of a shear zone within the Precambrian Peninsular Gneissic Complex, South India (Naqvi and Rogers, 1987). The shear zone is about 0.5 km long and 8–10 m wide, showing a clear transition from an apparently undeformed, coarse-grained massive granite at the wall, to fine-grained schistose mylonites at the central part of the shear zone. The vergence of the S foliation with respect to the principal shear plane (C foliation) indicates dominantly thrust movement in the shear zone. An overall simple shear is inferred, as the maximum angle between the C and S fabrics is around 45° (Ramsay and Huber, 1983). Mylonites consist mainly of quartz, mica and feldspar. Feldspar generally occurs as porphyroclasts floating in a fine-grained matrix of quartz and mica. Structural sections chosen for the microstructural study were parallel to the lineation and perpendicular to the foliation, and are interpreted as representing the *XZ* plane of finite strain in the shear zone.

Intragranular features indicate that quartz and feldspar in mylonites have deformed in contrasting ways, as also documented by several workers (e.g. Wakefield, 1977; Mitra, 1978; Hippertt, 1993; Michibayashi, 1996). Quartz has undergone crystal–plastic creep forming deformation bands and dynamically-recrystallized smaller grains. In contrast, feldspar has deformed cataclastically, showing intragranular fractures.

The microstructures produced by fracturing of feldspar porphyroclasts include: *bookshelf structure* where the fragments rotated and are offset (Fig. 2a), and *pull-apart structure* where the fragments rotated and are offset along with separation across the fracture (Fig. 2b–d). Pull-apart zones are generally filled with elongate quartz grains showing a preferred orientation. They mostly occur normal to the fracture walls suggesting face controlled fiber growth (Ramsay and Huber, 1987). The sense of offset in these structures is antithetic (Fig. 2b) as well as synthetic (Fig. 2c and d) to the bulk shear sense, as shown by earlier workers (Etchecopar, 1977; Simpson and Schmid, 1983; Jordan, 1991).

The fracture within a porphyroclast may be centered (Fig. 2) or off-centered (Fig. 3). The pull-apart structure associated with the centered fracture essentially shows parallel wall-disposition of the fragments (henceforth called *Type 1 pull-apart;* Fig. 2), whereas those associated with the off-centered fracture may be of Type 1 (Figs. 3a and 4a) or *Type 2*, characterized by non-parallel wall-disposition of the fragments (Figs. 3b and c and 4b and c). Type 2 is similar to the V-shaped pull-apart of Hippertt (1993). In Type 2 pull-aparts, the tilt of the smaller fragment relative to the larger one may be synthetic (Fig. 3b), as well as antithetic (Fig. 3c) to the bulk shear sense, and are referred to as *Type 2a* and *Type 2b*, respectively (Fig. 4) in the following sections.

3. Analog models

3.1. Experimental method

Experiments were conducted by embedding rigid objects

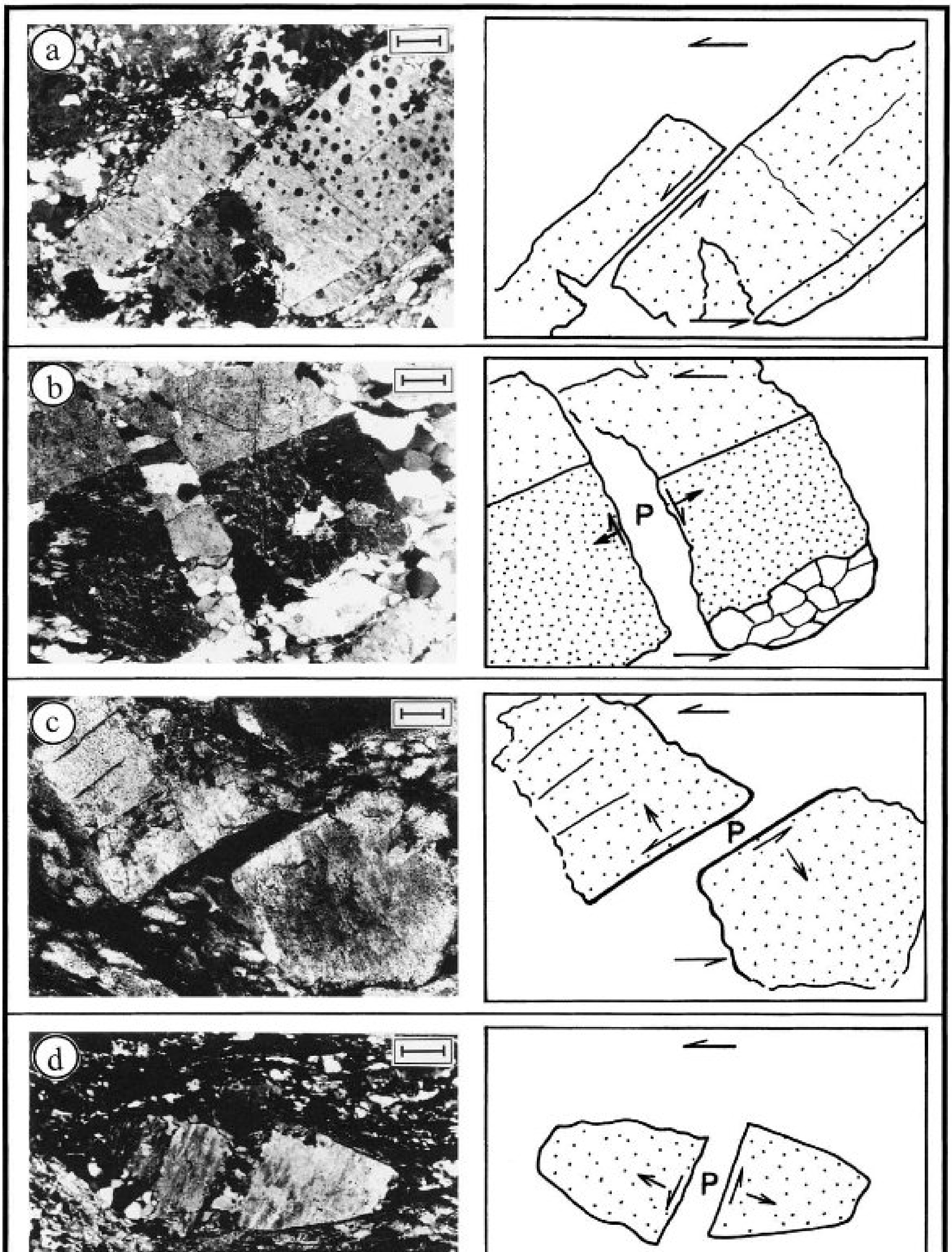

Fig. 2. Intragranular fracture-related structures within feldspar porphyroclasts in granite mylonites. (a) Bookshelf structure with synthetic slip. (b) Pull-apart structure with synthetically verging fracture walls and antithetic sense of offsetting. (c) and (d) Pull-apart structures with antithetically verging fracture walls and synthetic sense of offsetting. Corresponding sketches highlight the cataclastic structures. Single-headed arrows indicate shear senses. Scale bar: 0.25, 0.25, 0.10 and 0.25 mm in (a), (b) (c) and (d), respectively. XPL in all photomicrographs.

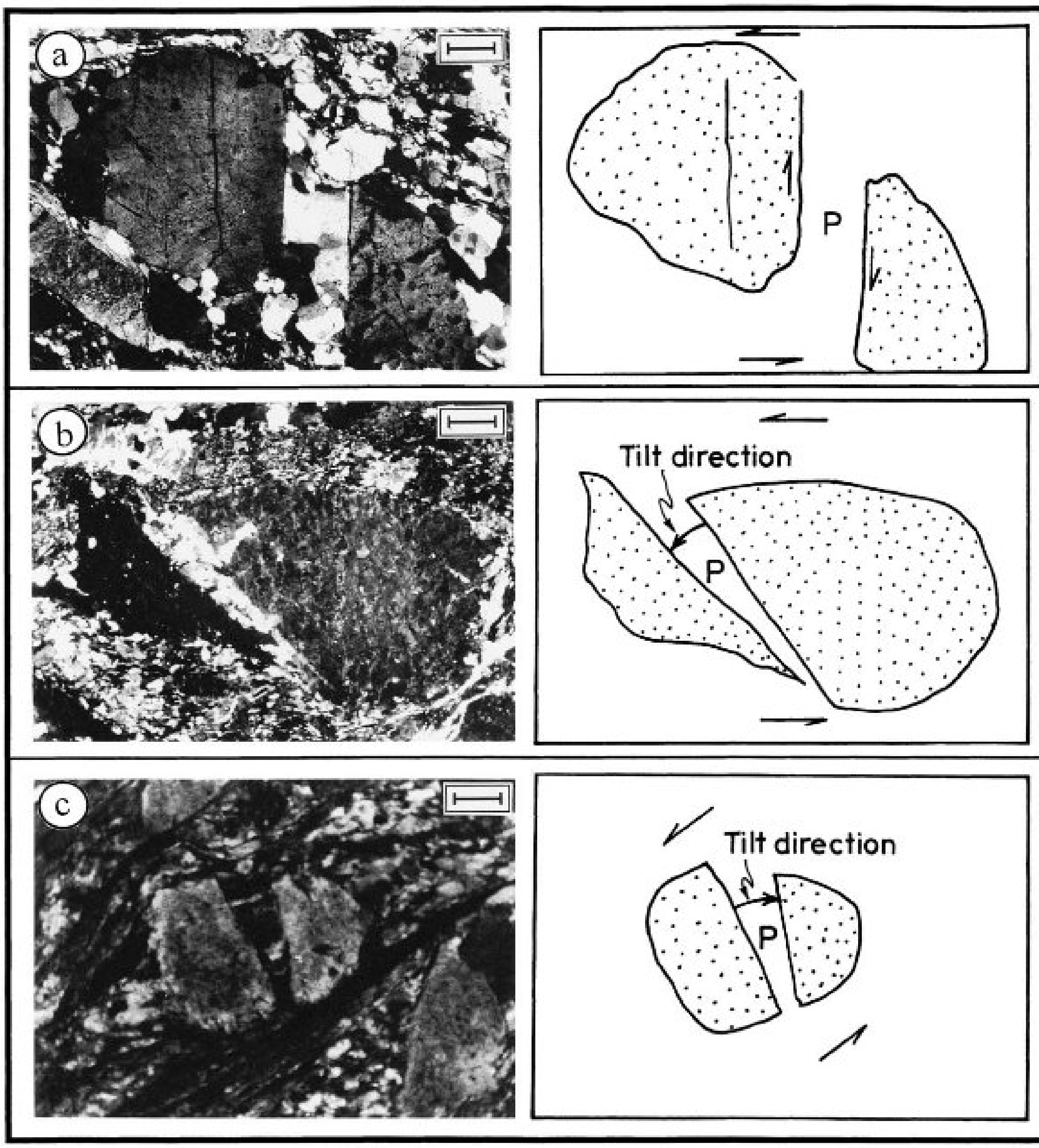

Fig. 3. Pull-apart structures in feldspar porphyroclasts with off-centered fractures. (a) Pull-apart with parallel walls (Type 1). (b) and (c) Non-parallel walls with synthetic (Type 2a) and antithetic (Type 2b) tilt of the smaller fragments relative to the larger one (as shown by arrows in the corresponding sketches). Scale bar: 0.25 mm. XPL in all photomicrographs.

(paraffin wax) within a viscous (pitch) slab (Fig. 5) at room temperature (30 °C). At this temperature the viscosity of pitch is about 5×10^5 Pa s. The model was prepared in the following manner: a volume of wax was melted in a tray with a flat, horizontal base, and allowed to solidify to form a uniform 1.2-cm-thick layer. An elliptical portion was cut out before the layer became rigid. A planar cut was also induced at a desired position in the elliptical part, simulating a fracture in the object. When the wax was hard enough, the elliptical part was taken out from the tray and embedded in the pitch block. The elliptical object got stuck firmly to pitch and there was no observable slip at its interface with pitch during the deformation.

The model was deformed in a simple-shear apparatus simulating plane strain. The overall shear rate in the model was about 1.5×10^{-3} s^{-1}. The model base was lubricated with liquid soap to minimize the basal friction. Marker lines were drawn parallel and perpendicular to the shear direction in order to measure the bulk shear in the model (Fig. 5). The top of the model was covered with a transparent glass plate to restrict the flow of pitch in the vertical direction and simulate plane strain. During progressive deformation the fragments of the elliptical objects underwent rotation and offsetting with or without separation, giving rise to either bookshelf or pull-apart structures. The viscous matrix had a tendency to flow into the separation

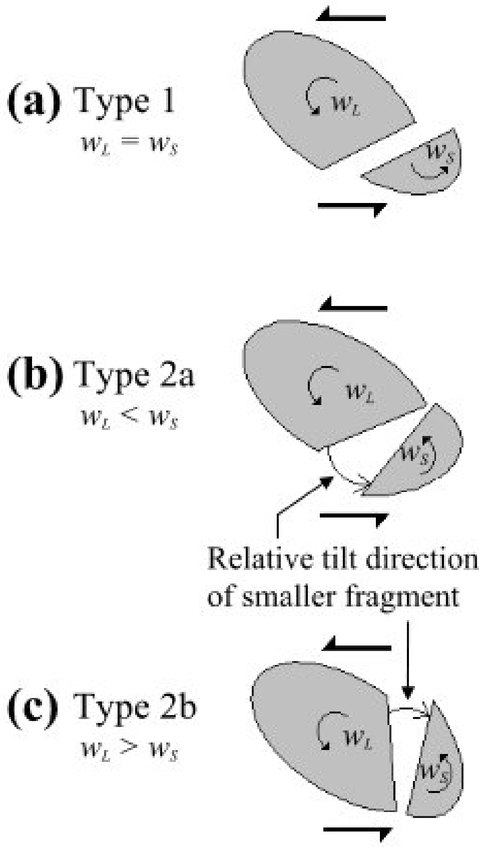

Fig. 4. Formation of different types of pull-apart structures in objects containing single, off-centered fractures. w_L and w_S are the instantaneous angular velocities of the larger and smaller fragments, respectively. (a) Pull-apart with parallel walls (Type 1) when $w_L = w_S$. (b) and (c) Pull-aparts with non-parallel walls showing tilt of smaller fragment synthetic to the shear direction (Type 2a) when $w_L < w_S$ and opposite to the shear direction (Type 2b) when $w_L > w_S$.

zone between the fragments as usually happens in natural boudinage processes. However, the flow was of limited extent, leaving the major part of the separation zone as a gap between the fragments. The progressive deformation of the model was observed and photographed through the top glass plate.

3.2. Experimental results

Experiments were performed to investigate the controls of the following geometrical parameters on the development of bookshelf and pull-apart structures: (1) the aspect ratio of the brittle object (R); (2) the position of the fracture (λ, expressed as the ratio l/a, where a is the major semi-axis of object and l is the distance of fracture from the object center); (3) the inclination of the long axis of object to the shear direction (ϕ); and (4) fracture-angle to the short axis of the object (θ) (Fig. 6a). The last two parameters together reflect the effect of the initial orientation of fractures relative to the shear direction, as it equals $\{90° + (\theta - \phi)\}$. In the description we follow a sign convention for the fracture angle θ, with positive and negative values implying the vergence of the fracture synthetic and antithetic to the shear direction, respectively (Fig. 6b).

We performed several sets of experiments for different combinations of the four geometrical parameters mentioned above. Experiments were run for two different orientations ($\phi = 45$ and $60°$) of inclusions with aspect ratios $R = 1.25$, 1.5 and 3, and fracture-angle θ varying between +40 and −30°. Under these conditions all the varieties of pull-apart and bookshelf structures described in the previous section developed within a moderate finite shear strain ($\gamma = 4$). The experimental results are summarized in Table 1. The following sections present the principal findings of the experiments.

3.3. Models with centrally located cuts ($\lambda = 0.01$)

To understand the influence of aspect ratio, we performed a set of experiments by varying R, but keeping ϕ and θ constant at 60 and +40°, respectively. The fragments of objects with $R = 1.25$ underwent separation during rotation, forming a narrow Type 1 pull-apart with a large antithetic offset (Fig. 7a). In contrast, when $R = 1.5$, the fragments did not separate at any stage of deformation; they only experienced rotation and antithetic offsetting, giving rise to a bookshelf structure (Fig. 7b). These contrasting movements perhaps resulted from the competition between the

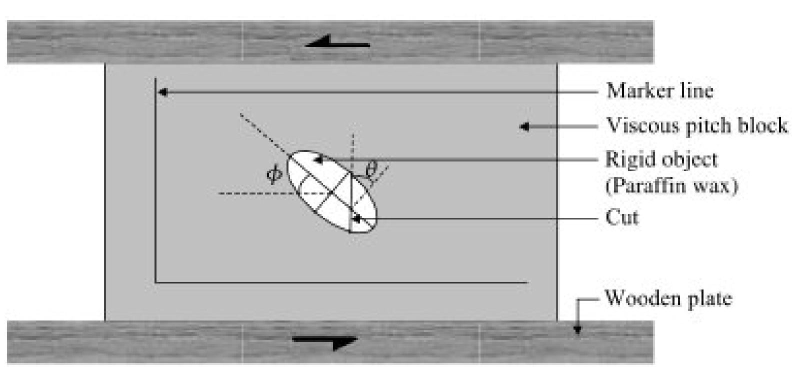

Fig. 5. Schematic plan view of the experimental set-up. The top of the model was covered with a transparent glass plate (not shown here).

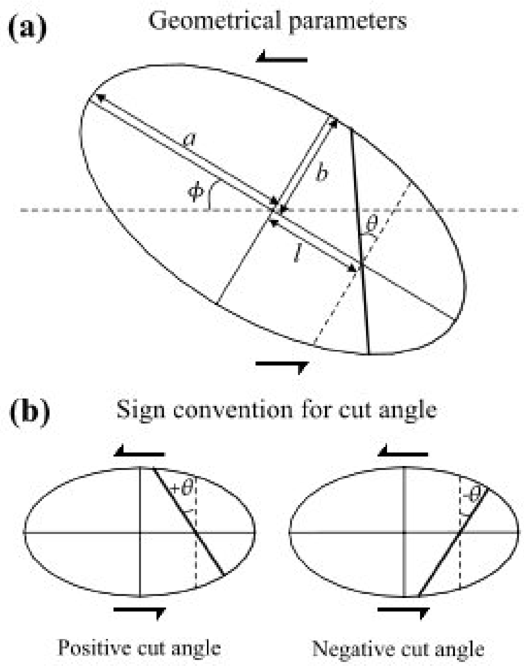

Fig. 6. (a) Geometrical parameters in physical model experiments. l: distance of cut from the object center; ϕ: inclination of the long axis of object to the shear direction. θ: inclination of cut with respect to the short axis of object. (b) Sign convention of cut angle θ; positive and negative signs imply the inclinations relative to the shear direction.

rotation and displacement rates of the fragments, which depend essentially on the shapes of the fragments. In the latter case ($R = 1.5$), pull-apart did not develop because the separation due to relative displacement of the fragments was counterbalanced by their rotational movement, inhibiting formation of a gap between them (Mandal and Khan, 1991). On the other hand, the object of $R = 1.25$ developed a pull-apart structure because the fragments derived from it did not rotate to an extent that could balance the separation, and thereby formed a gap between them. When the aspect ratio was even greater ($R = 3$), the separation of fragments was again much more pronounced than their rotation, and thereby produced a Type 1 pull-apart with a small antithetic offset (Fig. 7c). The experimental results imply that, for particular aspect ratios of the clast, pull-apart structures may not develop even if the fracture-normal lies initially in the extension field of the incremental strain ellipsoid (Table 1).

To understand the influence of the fracture angle, the experiments discussed above (run at a constant fracture angle of +40° and inclusion orientation of 60°) can be compared with experiments performed under similar conditions, but for different fracture angles. Objects with a low aspect ratio ($R = 1.25$) show Type 1 pull-aparts with antithetic offset for $\theta = +40°$ (Fig. 7a), but the sense of offset reverses and becomes synthetic as the cut angle is reduced to −30° (Fig. 7d). On the other hand, objects with a moderate aspect ratio ($R = 1.5$) form bookshelfs for $\theta = +40°$ (Fig. 7b), but pull-aparts at a cut-angle of +20°, both showing antithetic offset (Fig. 7e). With further decrease in θ the sense of offset in the pull-aparts reverses (Table 1). For large aspect ratios ($R > 3$), pull-apart formation is found to depend little on the cut angle. However, the sense of offset changed as the initial cut angle varied from +40 to −30° (Fig. 7c and f). Our experimental observations reveal that, in general, the development of bookshelf structures is favored when the inclusion is oriented at an angle of 45° (Table 1).

Table 1

Summary of the experimental results. λ—normalized position (l/a) of cut; ϕ—initial inclination of long axis of inclusion; BS—bookshelf structure; P(1), P(2a) and P(2b)—types of pull-apart structures, as shown in Fig. 4; (a) and (s)—antithetic and synthetic sense of offset, respectively; †—no experimental run

Inclusions with nearly centrally located cuts ($\lambda = 0.01$)

$\phi = 45°$				$\phi = 60°$			
Cut angle with the short axis (θ in degrees)	Aspect ratio (R)			Cut angle with the short axis (θ in degrees)	Aspect ratio (R)		
	1.25	1.5	3		1.25	1.5	3
+40	BS$_{(a)}$	BS$_{(a)}$	P(1)$_{(a)}$	+40	P(1)$_{(a)}$	BS$_{(a)}$	P(1)$_{(a)}$
+20	BS$_{(a)}$	BS$_{(a)}$	P(1)$_{(a)}$	+20	P(1)$_{(a)}$	P(1)$_{(a)}$	P(1)$_{(a)}$
−20	P(1)$_{(a)}$	P(1)$_{(a)}$	P(1)$_{(a)}$	−20	P(1)$_{(s)}$	P(1)$_{(s)}$	P(1)$_{(s)}$
−30	P(1)$_{(s)}$	P(1)$_{(s)}$	P(1)$_{(s)}$	−30	P(1)$_{(s)}$	P(1)$_{(s)}$	P(1)$_{(s)}$

Inclusions with off-centred cuts ($\lambda = 0.5$)

$\phi = 45°$				$\phi = 60°$			
Cut angle with the short axis (θ in degrees)	Aspect ratio (R)			Cut angle with the short axis (θ in degrees)	Aspect ratio (R)		
	1.25	1.5	3		1.25	1.5	3
+30	BS	BS	P(2a)	+30	P(2a)	P(2a)	P(1)
+20	P(2a)	P(2a)	P(2a)	+20	P(2a)	P(2a)	P(1)
−10	P(2a)	P(1)	†	−10	P(1)	P(1)	†
−20	P(1)	†	†	−20	P(2b)	P(2b)	P(2b)

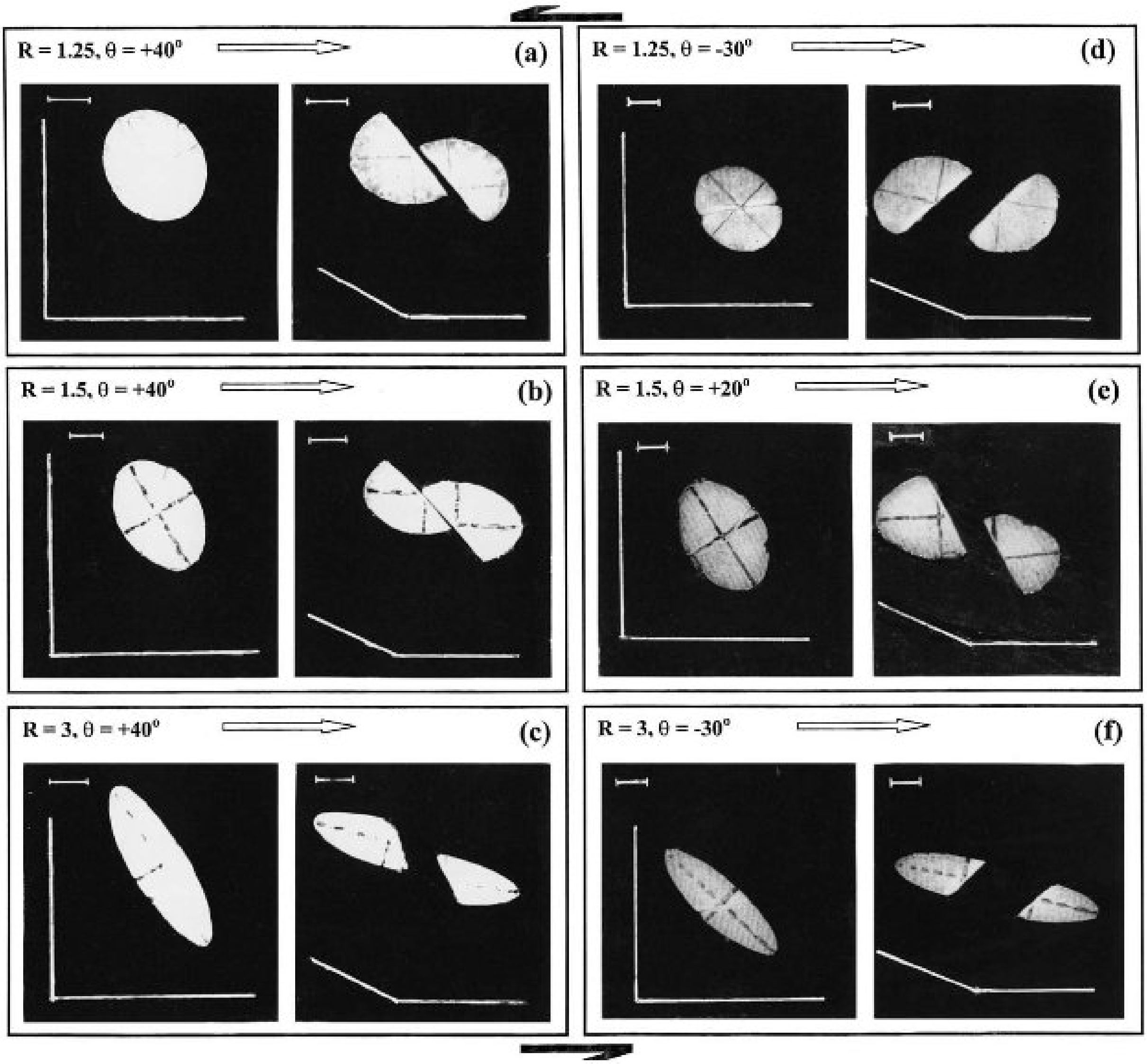

Fig. 7. Development of Type 1 pull-apart and bookshelf structures in test models containing objects with centrally located cuts. (a) and (b) bookshelf with antithetic slip; (c) pull-apart with antithetic offset; (d) and (e) Pull-aparts with synthetic and antithetic offset, respectively; (f) Pull-aparts with large separation relative to the offset. R: aspect ratio of object; θ: cut angle. The initial orientation ϕ of object was 60°. Scale bar: 1 cm.

3.4. Models with off-centered cuts ($\lambda = 0.5$)

Experiments were performed with objects containing single cuts located at a distance of $a/2$ from the center ($2a$ is the long dimension of the object). Similar to the earlier models, three geometrical parameters were taken into consideration: object orientation (ϕ), aspect ratio of object (R) and cut angle (θ) (Table 1). In a set of experiments the cut angle θ was varied, keeping the two other parameters constant ($R = 1.5$, $\phi = 60°$). When $\theta = +30°$, the fragments were separated, giving rise to a Type 2a pull-apart (Fig. 8a). At the initial stage the pull-apart did not show strong non-parallelism of the walls. This is probably due to the rotational interaction of the larger fragment with the smaller one, as they were close to each other. With increasing separation, the interaction became progressively less effective, and the smaller fragment thereby could rotate faster than the larger one, giving rise to Type 2a pull-apart structure (Fig. 8a). The tilt of cut-wall on the smaller fragment relative to that on the larger fragment was synthetic to the bulk shear direction as also suggested by Hippertt (1993). With decreasing cut angle, the contrast in rotational velocity between the fragments decreased, as revealed in the lower taper angle of the non-parallel pull-aparts (Fig. 8b). At a particular cut angle ($\theta = -10°$) the fragments rotated more or less equally in the course of progressive deformation, giving rise to a parallel pull-apart (Type 1) (Fig. 8c). With further decrease in θ, the smaller fragment rotated slower than the larger one forming a non-parallel pull-apart, but with Type 2b geometry (Fig. 8d).

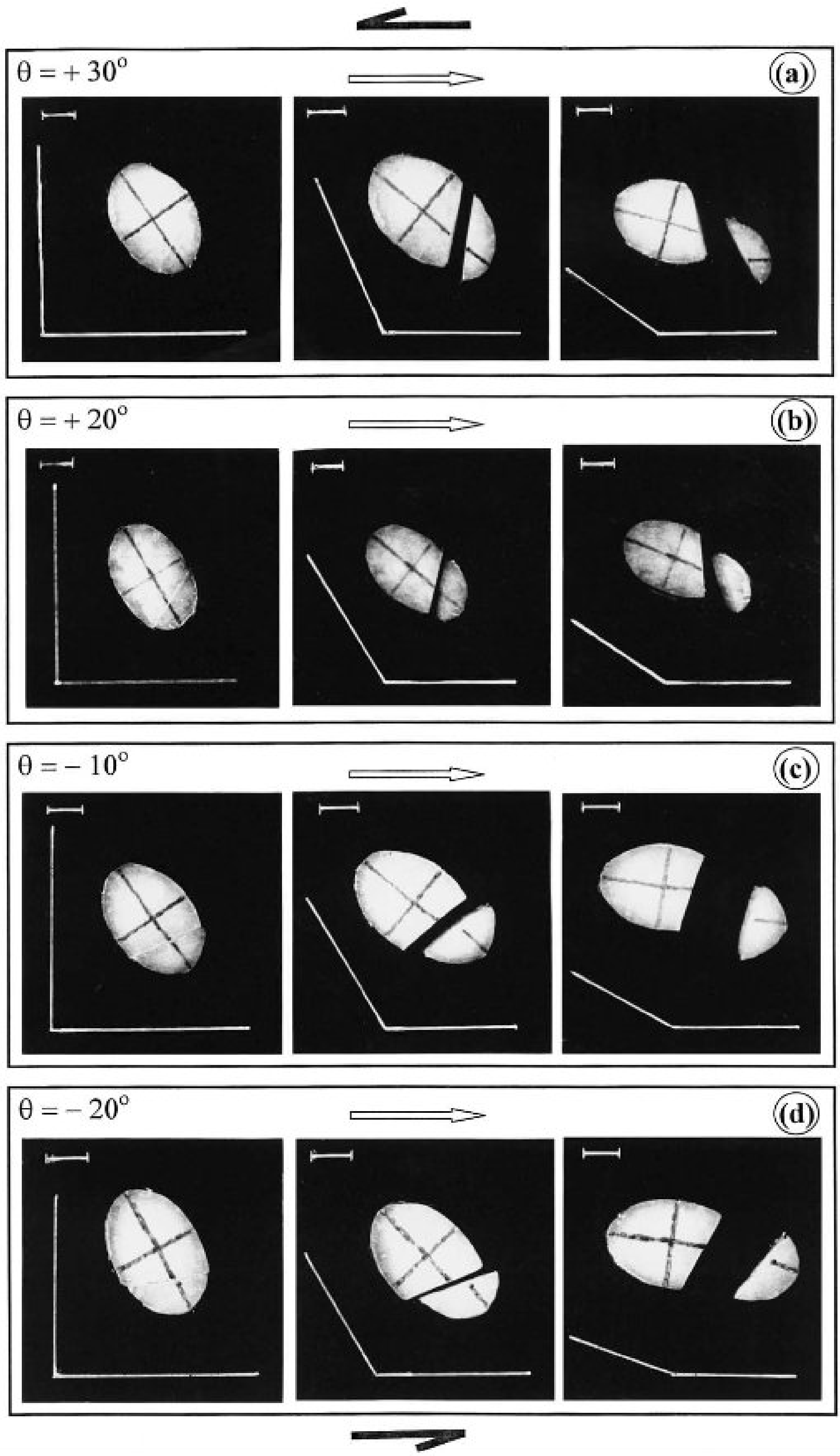

Fig. 8. Development of pull-aparts in objects with off-centered ($\lambda = 0.5$) cuts for different orientations of the cut (θ). (a) and (b) Type 2a; (c) Type 1 and (d) Type 2b pull-aparts. The aspect ratio (R) and initial orientation (ϕ) of the object were 1.5 and 60°, respectively. Scale bar: 1 cm.

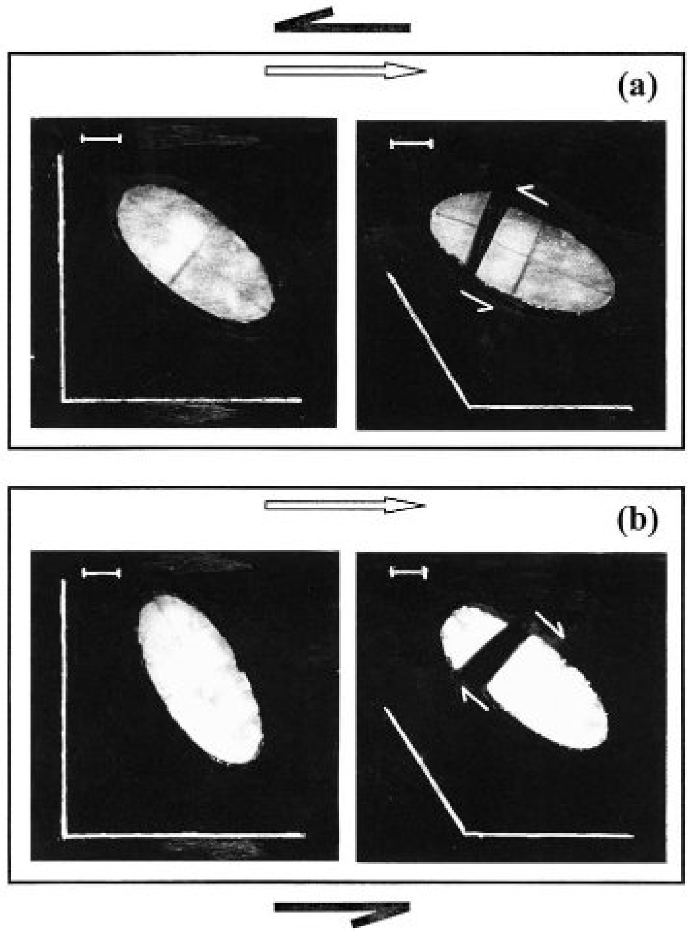

Fig. 9. Development of Type 2a (a) and Type 2b (b) V-pull-aparts in test models. In (a) the long axis of the object is initially at an angle of 40° (a) and 60° (b) to the bulk shear direction. The small arrows indicate the local shear on planes adjacent to the 'V'. Scale bar: 1 cm.

We conducted a few experiments with fractures at a right angle to the long axis of the object (cf. Hippertt, 1993). The objects were significantly elongate in shape ($R = 2.3$). In these experiments the fragments rotated unequally, giving rise to non-parallel (Type 2) pull-aparts. The initial orientation of the inclusion (ϕ) with the bulk shear direction governed the type of non-parallel pull-apart. When ϕ was less than 45°, the relative tilt of the smaller fragment was synthetic to the bulk shear (Type 2a; Fig. 9a). On the other hand, when ϕ was greater than 45°, the relative tilt was opposite to the bulk shear (Type 2b; Fig. 9b). In the Hippertt (1993) model, the tilt direction indicates the sense of movement on the shear plane against the opening end of the 'V'. In the present experiments, when the long axis of the inclusion is at an angle smaller than 45°, this plane becomes oriented closer to the principal shear plane, and thus the movement on this plane reflects the bulk shear sense. But, when $\phi > 45°$, the tilt direction is reverse, reflecting an opposite sense of shear on the plane adjacent to the opening of the "V". This reverse sense probably occurs because the plane is oriented at an angle greater than 45° to the bulk shear direction.

4. Discussion

The natural examples presented in this paper suggest that diverse types of pull-apart microstructures can form in simple shear deformation. Physical model experiments run under simple shear demonstrate that their development depends principally on the orientation and location of the fractures within the porphyroclast and its aspect ratio. In the case of centrally located fractures, porphyroclasts of moderate aspect ratios may show either bookshelf structures or parallel pull-aparts, which develop within specific ranges of fracture orientation (Table 1). Strongly elongate porphyroclasts, in contrast, develop parallel pull-aparts irrespective of the fracture orientation (Table 1). Porphyroclasts with off-centred fractures show V-pull-apart, in addition to bookshelf and parallel pull-aparts (Table 1). In such cases, pull-aparts (both "V" and parallel) develop within a specific range of fracture orientation and there is a unique fracture orientation for which the geometry of the pull-apart is parallel (Fig. 10). This critical fracture orientation divides the pull-apart field into two types of V-pull-aparts, where the relative tilt of the smaller fragment is synthetic (Type 2a) or antithetic (Type 2b) to the overall

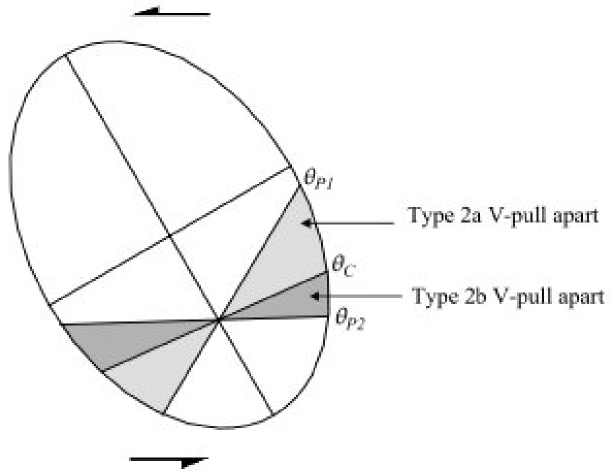

Fig. 10. Fields of pull-apart (shaded) and bookshelf (blank) structures defined by the orientations of fractures θ_{p1} and θ_{p2} within a porphyroclast with a particular initial shape and orientation. The critical fracture-angle θ_c separates the fields of Type 2a and 2b V-pull-aparts. At $\theta = \theta_c$, the fragments of the porphyroclast rotate equally giving rise to a parallel (Type 1) pull-apart.

shear sense (Fig. 10). Type 2b pull-aparts generally develop when the fracture angle with respect to the short axis of porphyroclasts is low, antithetic to the shear direction, and the long axis of the porphyroclasts is at a high angle to the shear plane.

The experiments show that the formation of pull-aparts and bookshelf structures is essentially controlled by the kinematics of the rigid fragments. Theoretical analyses suggest that the rotational motion of rigid objects depends on the nature of bulk deformation, in addition to their shapes and orientations (Jeffery, 1922; Ghosh and Ramberg, 1976; Passchier, 1987; Hanmer and Passchier, 1991). Thus, the geometrical conditions (fracture and porphyroclast orientations) for formation of bookshelf and pull-apart structures presented here may show significant departures if the shear zones were non-ideal, involving significant flattening components across them.

Off-centered intragranular fracturing leads to formation of fragments of contrasting shapes, which generally rotate unequally, forming non-parallel (Type 2) pull-aparts (cf. Hippertt, 1993). The relative rotation rates of the fragments govern their relative tilt in pull-apart structures. Experimental observations reveal that there are specific ranges of fracture orientation for which the smaller fragment rotates faster or slower than the bigger one, giving rise to Type 2a and 2b V-pull-apart structures. However, the fields of Type 2a and 2b pull-aparts outlined in this paper are strictly relative, and are likely to show departures in more general strain regimes.

The bulk shear strain in our experiments was generally smaller than five. Theoretical studies (Jeffery, 1922) indicate that the rotation rate of centro-symmetric, elongate objects varies systematically with progressive deformation. In the pull-apart structures the fragments did not have a center of symmetry, and their rotational behavior is thus likely to be much more complex. However, it appears that the relative rotation rates of the smaller and larger fragments may vary with progressive shear, and thereby change their relative tilt at very large finite shear strains. In summary, the experimental data outlined in this paper are, in a strict sense, valid for ideal shear zones with moderate finite shear strains.

The other limitations that adhere to our experimental study are as follows. (1) In natural conditions the development of pull-apart is associated with synkinematic infilling by minerals. However, pull-apart structures in our experiments remained as gaps during the deformation. (2) The matrix was mechanically isotropic and homogeneous, and there was no observable slip on the matrix–object interface, a condition which may not always prevail in naturally deformed rocks.

5. Conclusions

Feldspar porphyroclasts floating in a fine-grained ductile matrix can fracture and the derivative fragments may subsequently rotate and move independently in the course of progressive simple shear, forming either bookshelf or pull-apart structures. Centrally located fractures produce parallel (Type 1) pull-apart geometry, whereas off-centered fractures can develop both parallel (Type 1) and non-parallel (Type 2) pull-aparts. Depending upon the orientation of fracture, the smaller fragment may rotate faster or slower than the larger fragment, leading to development of Type 2a or Type 2b non-parallel pull-aparts. Type 2b pull-apart structures are more common when the porphyroclasts have large aspect ratios and high inclinations to the bulk shear direction, and the fracture is disposed at a low angle with respect to the short axis of porphyroclasts and opposite to the shear direction. Our findings suggest that Type 2a pull-aparts can be considered in analyzing the bulk shear sense (cf. Hippertt, 1993). However, this type of pull-apart structure is likely to be more common in specific conditions: (1) when intragranular fractures are oriented at high angles to the long axis of the porphyroclasts, and (2) when the long morphological axis of the porphyroclast is initially at an angle smaller than 45° to the shear direction (Fig. 9a).

Acknowledgements

We wish to thank Drs T. Masuda, S. Hanmer and an anonymous reviewer for their critical comments that greatly contributed to the improvements of the paper. We also thank Dr J. Hippertt for his constructive suggestions in revising the manuscript. The present work was supported by DST, India. SKS is grateful to CSIR, India for providing a fellowship in carrying out the work. CC acknowledges the infrastructural facilities provided by the Indian Statistical Institute, Calcutta.

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