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Are isolated stable rigid clasts in shear zones equivalent to voids?

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Abstract

Particles in shear enclose important information about a rock's past and can potentially be used to decipher the kinematic history and mechanical behavior of a certain outcrop or region. Isolated rigid clasts in shear zones often exhibit systematic inclinations with respect to the shear-plane at small angles, tending towards the instantaneous stretching direction of the shear zone. This shape preferred orientation cannot be easily explained by any of the analytical theories used in geology. It was recently recognized that a weak mantle surrounding the clast or a slipping clast–matrix interface might be responsible for the development of the observed inclinations. Physical considerations lead us to conjecture that such mantled, rigid clasts can be effectively treated as voids that are not allowed to change their shape. The resulting equivalent void conjecture agrees well with numerical and field data and has the following important geological implications. (i) Clasts in shear zones can have stable positions in simple shear without the requirement of an additional pure shear component. (ii) The stable orientation can be approached either syn- or antithetically; hence, the clast can rotate against the applied shear sense. (iii) The strain needed to develop a strong shape preferred orientation is small ($\gamma \approx 1$) and therefore evaluations based on other theories may overestimate strain by orders of magnitude. (iv) The reconstruction of far-field shear flow conditions and kinematic vorticity analysis must be modified to incorporate these new findings.

Keywords: Clasts; Inclusions; Shear zones; Stabilization

1. Introduction

Geological field observations sometimes deliver counterintuitive and seemingly coincidental patterns. Careful examination often resolves these paradoxes by correcting our intuition, which is usually based on oversimplified or non-direct analogies. The "strange coincidences" do not call for special physics; they call for more accurate evaluation of classical physics predictions compared to qualitative intuition-based reasoning. The ongoing active discussion on synchronous stabilization of apparently non-interacting rigid particles in shear zones tending towards instantaneous stretching directions instead of being continuously rotated, is an excellent example of such a paradox (Arbaret et al., 2001; Mancktelow et al., 2002; Marques and Cobbold, 1995; Marques and Coelho, 2001, 2003; Pennacchioni et al., 2001; Piazolo et al., 2002;

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Piazolo and Passchier, 2002; ten Grotenhuis et al., 2002, 2003).

Since Jeffery (1922), it is known that rigid ellipsoidal particles should rotate indefinitely with the applied simple shear in a shear zone. Conversely, if one considers a simple thought experiment in which a Swiss cheese is sheared, its holes will deform to ellipses, initially aligned towards the stretching direction at 45° to the shear-plane. Why do we see an almost identical picture for rigid particles in shear zones having substantial inclination angles to the shear zone, even after the surrounding matrix has accommodated enormous amounts of shear strain (Fig. 1)? A picture of an airfoil welded to something out of the observation plane, resisting the action of the gas flow that tries to turn and to lift it, comes to mind. What holds the clasts in mylonitic shear zones? Why do they all have similar inclination angles after being subject to thousands percent of strain? The resolution proposed here states that the presence of a seemingly unimportant thin and weak boundary layer, or imperfect welding of the clast to the matrix, turns the clast into a hybrid of quasi-rigid and quasi-void behaviors. This mantle allows the clast to back-rotate towards the stretching direction as a void would (the concept of non-rigid inclusion rotation is discussed later), yet the presence of the clast maintains the rigid particle-like overall shape of the hybrid.

The behavior of particles embedded in a matrix and subjected to boundary conditions remains a problem of fundamental interest for many branches of science (e.g., Furuhashi et al., 1992; Gao, 1995; Mura, 1987; Ru and Schiavone, 1997; Shen et al., 2001). The analytical theories used in geology go back to Jeffery (1922) who, based on Einstein (1906), developed a theory that explains the behavior of a rigid ellipsoid immersed in a viscous fluid subjected to far field simple shear flow. The most important addition was made by Ghosh and Ramberg (1976) who combined Jeffery's theory and Muskhelishvili's (1953) complex variable method to produce a two dimensional theory that explains the behavior of rigid elliptical particles embedded in a viscous fluid subjected to arbitrary combinations of pure and simple shear.

The focus of this study is on the kinematic behavior of isolated, rigid clasts in shear zones. The term rigid is used here to describe a phase that has a much higher resistance to flow than all other phases present, thus termed weak. A clast that only interacts with the homogenous surrounding matrix, and not with nearby clasts, is designated as an isolated clast. Ildefonse et al. (1992) have shown that, for equally sized particles, the interaction effects become significant if the distance between individual clasts is smaller than their length. This distance is assumed to be the limit of applicability of the present work.

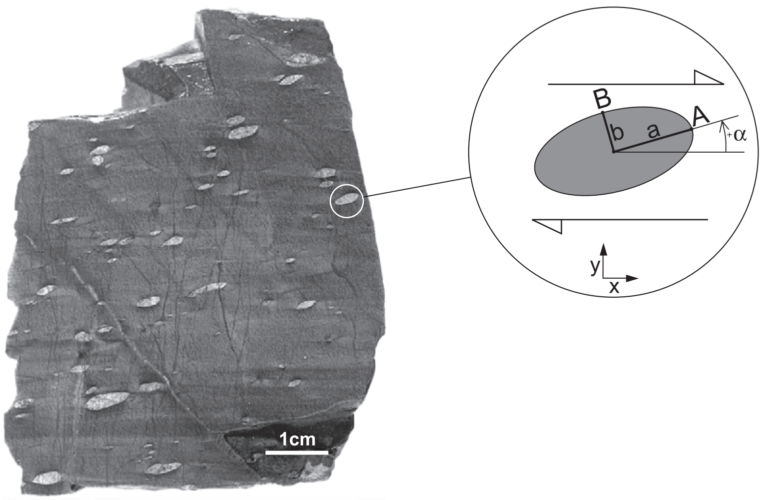


Fig. 1. Ultramafic mylonite showing a clear shape preferred orientation of olivine porphyroclasts inclined at a low angle to the shear-plane (horizontal). Shear sense is top to the right. Site location is near Finero in the Italian Western Alps. The conventions used in this paper are displayed in the insert. (Photo courtesy of G. Pennacchioni.)

Our motivation is the aforementioned observation that natural shear zones often exhibit systematic inclinations of porphyroclasts (e.g., Passchier and Trouw, 1996; Snoke et al., 1998). Analysis of natural data sets reveals that these inclinations are at shallow, positive angles with respect to the shear-plane (e.g., Mancktelow et al., 2002; ten Grotenhuis et al., 2002; see also Fig. 1) and that there is a general trend for more elongated clasts to be less inclined with respect to the shear-plane (Pennacchioni et al., 2001; ten Grotenhuis et al., 2002; cf. Fig. 4). If large numbers of clasts show these inclinations then they must be stable, or at least metastable with the clast rotation rates vanishing compared to the shear rate. Existing analytical theories used in structural geology fail to provide an explanation for the observed stable positions, either because no stable position exists (Jeffery, 1922) or because the location and trend of the stable position does not correspond to the field data (Ghosh and Ramberg, 1976; cf. Fig. 4). Metastable systematic orientations of rigid clasts in combined pure and simple shear may sometimes occur as a result of the pulsating patterns of order and disorder (Marques and Coelho, 2003; Masuda et al., 1995). However, there is evidence from field data and analogue modeling suggesting that the observed stable orientations are due to interfacial slip or a weak mantle (Ildefonse and Mancktelow, 1993; Mancktelow et al., 2002; Marques and Coelho, 2001). If this is indeed the reason for clast stabilization, then we need to rethink possible applications, such as deciphering the far-field flow conditions during deformation (Ghosh and Ramberg, 1976; Passchier, 1987) and strain determinations (for a review, see Arbaret et al., 2000).

2. Ignoring the clast to study the clast

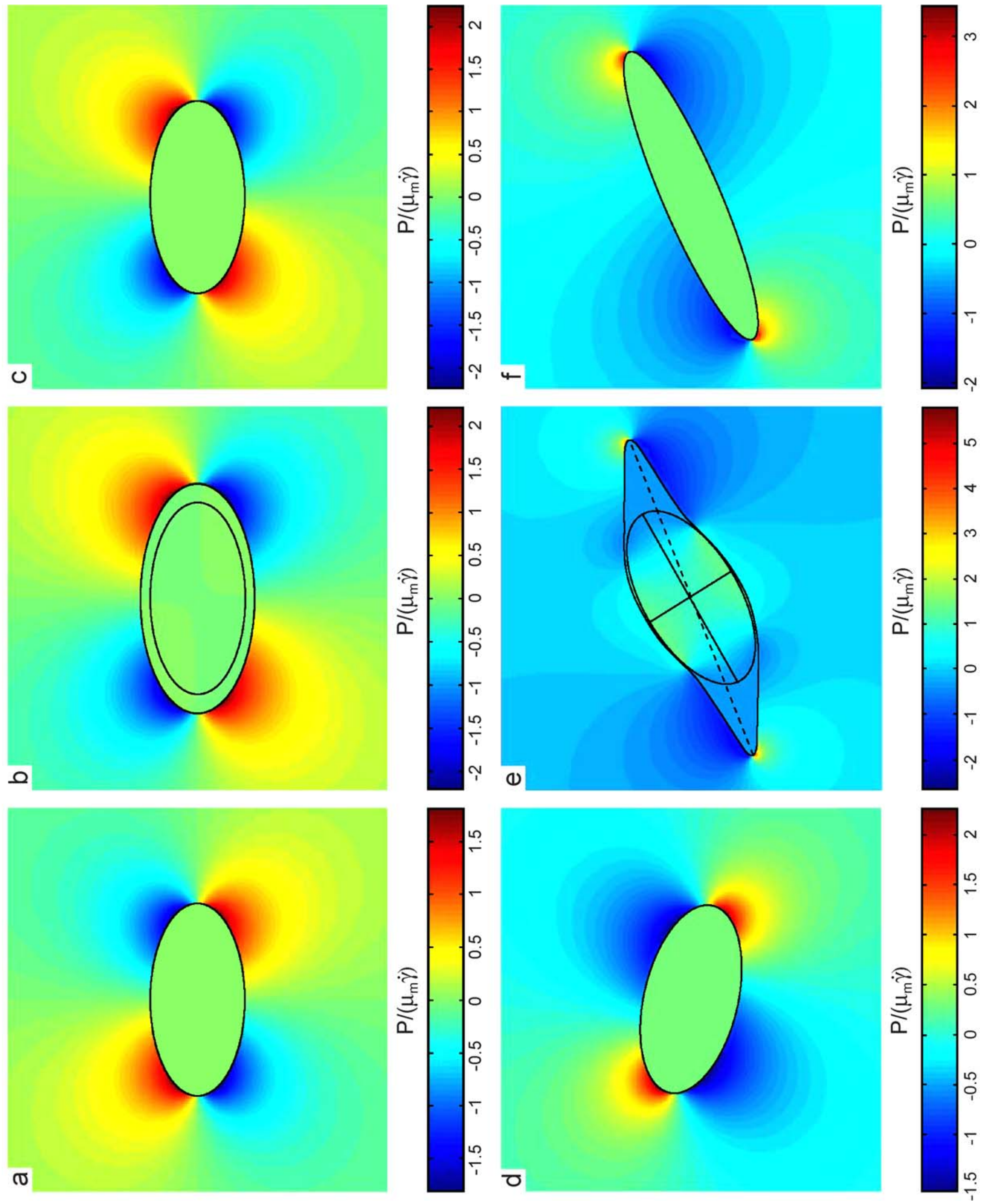
Mantled porphyroclasts exhibit the largest strains in the fine-grained mantle material. Therefore, it is reasonable to propose that the mantle material is weaker than the rigid clast. For the purpose of this study, we assume that the mantle material is even weaker than the surrounding matrix. An end-member case of this configuration is the clast where slip occurs at the clast–matrix interface, but no mantle is present. Here, both the viscosity and the thickness of the mantle material are zero and the shear tractions on the clast–matrix interface vanish. For a detailed account of the various conditions under which different types of slip and detachment occur at the clast matrix interface, see Samanta and Bhattacharyya (2003).

Since vanishing shear tractions cannot be responsible for the clast kinematics, the normal traction components should be analyzed. For example, the pressure distribution in the matrix can be used as a proxy to determine if the clast–mantle couple behaves effectively as a rigid clast or as a void. Void is used here and in the remainder of the paper to imply an inclusion that has vanishing viscosity compared to the matrix, but whose area is constant due to the mass conservation constraint of the employed models. It can be shown that if the weak mantle around a rigid clast is either sufficiently thick (compared to the clast size) or has a vanishing viscosity compared to the matrix, then the presence of the clast will be effectively masked by the mantle, e.g., the matrix does not "feel" the shear resistance of the clast. Practically speaking matrix-mantle viscosity contrasts of 100:1 are already enough to "hide" the clast (Schmid, 2002). Fig. 2a–c illustrates the masking of a rigid clast by a weak mantle. The combined rigid clast–weak mantle system (b) causes an almost identical pressure perturbation in the surrounding material as the weak inclusion scenario (c). Therefore, we conclude that in order to study the stabilization of clasts in shear zones it is more appropriate to look at the very weak inclusion (void) end-member than to reduce it to the usual rigid clast in a weak matrix situation.

It is tempting to use pressure or another stress component to explain clast rotation and stabilization based on the intuition that everything flows from high to low pressure and to argue that the high pressure zones adjacent to the clast push it towards the pressure lows. Yet, because inertial effects are negligible the net forces and torques acting on any particle are always zero, irrespective of the particle rotation, and do not indicate the rotation direction. We therefore need to find an admissible explanation for the rotation to a stable inclination.

3. Rotation direction of perfectly bonded inclusions

Stable clast inclinations are the result of vanishing rotation rates. The rotational behavior of differ-


a
b
c
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P/(μ_mγ̇)
-1.5 -1 -0.5 0 0.5 1 1.5
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
-1.5 -1 -0.5 0 0.5 1 1.5 2
-2 -1 0 1 2 3 4 5
-2 -1 0 1 2 3

ent kinds of clasts is of considerable complexity and is illustrated here by means of some model cases. The underlying assumptions are that we are dealing with a two-dimensional, plane strain system, containing incompressible Newtonian fluids, subject to simple shear far-field boundary conditions. Under these conditions, a rigid circular clast always rotates consistently with the applied shear sense, i.e., clockwise when subject to top to the right simple shear. Jeffery (1922) showed that this rotation rate is half of the applied shear rate. If the circular clast has the same viscosity as the matrix material, then the clast is just a passive recorder of the homogeneous finite simple shear strain. The initially circular clast shape will be instantaneously deformed into an ellipse with the long axis nearly perpendicular to the shear-plane. With increasing strain, this ellipse will become progressively elongated and the inclination will tend towards the shear-plane (Ramsay and Huber, 1983).

Like the passive recorder clast the circular void cannot maintain its shape during shear. Being pulled into the instantaneous stretching direction, the first elliptical appearance of the void is at almost 45° to the shear-plane, as described with the Swiss cheese example in the introduction. The finite strain behavior is again recorded in that the elliptical shape becomes more elongated and approaches the shear-plane asymptotically. Thus, for all cases considered, the rotation direction of an elliptical shape derived from an initially circular inclusion is synthetic with applied shear sense.

For initially non-circular inclusions, the corresponding observations are significantly different. The behavior of clasts that are elliptical depends on their inclination to the shear zone (and the clast aspect ratio). For now, we assume that the long axis is parallel to the shear-plane. If rigid, such a clast will rotate synthetically with the shear sense. However, due to its elliptical shape the rotational behavior is pulsating. If the particle is shear-plane parallel, the simple shear flow easily streams around the particle, which consequently rotates slowest in this position. On the other hand, if the particle is inclined at 90° to the shear-plane, it acts as a relatively large obstacle to the shear flow and consequently rotates fastest. The analytical expression describing this behavior was derived by Jeffery (1922) (cf. Fig. 3, $\tilde{\mu} = \infty$). If the elliptical clast in the shear-plane parallel position has the same viscosity as the matrix (passive marker), the ellipse will be passively deformed. Although the simple shear flow has only shear-plane parallel velocities, the ellipse will initially undergo apparent back-rotation, antithetically against the shear sense. This can easily be verified with any drawing program. For large shear strains, the passive ellipse is progressively stretched and becomes aligned with the shear-plane.

The passive ellipse is a case of no viscosity contrast between the clast and the matrix, whereas the rigid case represents an infinite viscosity contrast. Therefore, lowering the clast/matrix viscosity contrast from infinity to unity causes a change in the rotation direction from synthetic to antithetic. The last and most relevant example is the shear-plane parallel void, a case of infinitely small clast/matrix viscosity contrast, still subject to the condition of mass conservation. It may be speculated that the void's shape also shows back-rotation, extending the tendency of the passive ellipse due to a further drop in the clast–matrix viscosity contrast. The void is able to accommodate the pull towards the instantaneous stretching direction by deformation, adding an extra component to the back-rotation compared to the passive ellipse case.

In order to substantiate this intuitive reasoning concerning clast rotation, we developed the complete two-dimensional analytical solution for an elliptical clast subject to general shear, covering the entire span of possible viscosity contrasts between clast and matrix (Schmid and Podladchikov, 2003). However, to enable discussion about the rotation of non-rigid inclusions and infinitely weak inclusions, some

Fig. 2. Comparison of clast end-member cases, rigid (a, d) and weak (c, f), with a clast that is surrounded by a weak mantle (b, e). The viscosity of the matrix, μ_m, is in all cases equal to 1. The viscosities of the rigid and the weak phase are 1000 and 1/1000, respectively. The aspect ratio of the central clast is always 2:1. The initial thickness of the mantle material was 20% of the rigid clast radius. The first row displays the initial situation, the second row the same experiments after a total shear strain of $\gamma = 1.12$ that corresponds to an overall shear angle of 48°. Data plotted is the pressure perturbation (P) normalized by the shear stress in the matrix. The numerical method employed is a finite element model, briefly described in Appendix A.

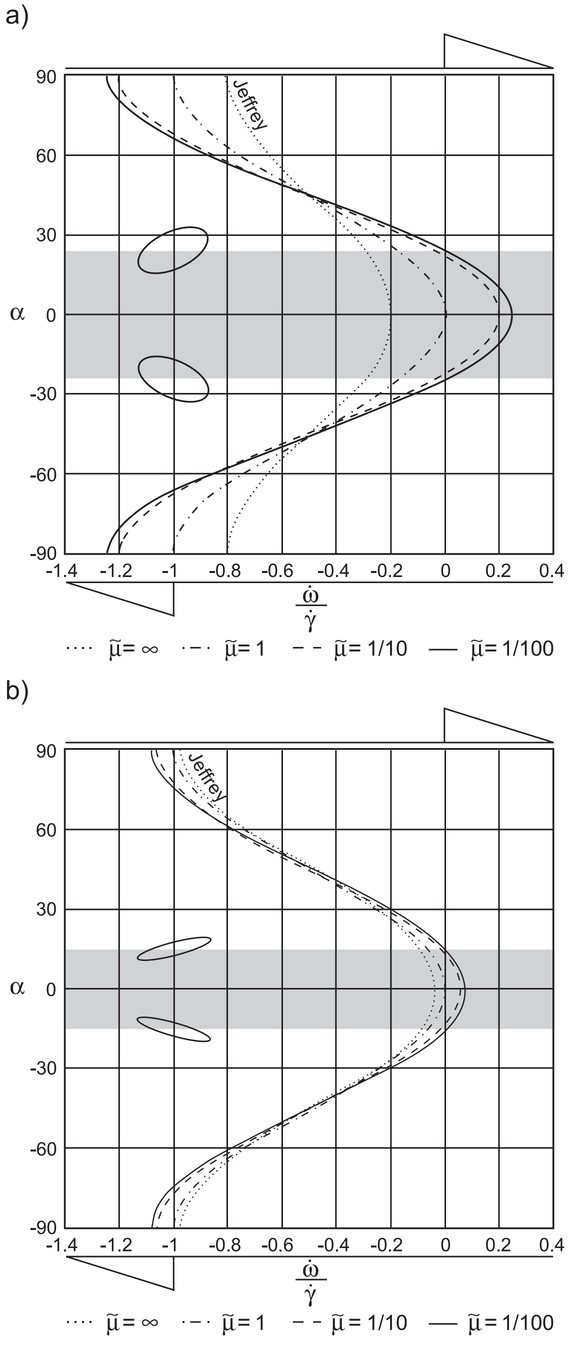

Fig. 3. Rotational behavior of elliptical inclusions according to Eq. (1). The field where weak inclusions rotate backwards/antithetically is highlighted in gray. (a) Aspect ratio $R=2$; (b) aspect ratio $R=6$.

explanation of the concept may be required. From Eshelby (1957) it is known that, if in direct contact to the matrix, the inside of an ellipsoid, or an ellipse in two-dimensions, shows the exceptional property of uniformity, i.e., under uniform, far-field loading (such as simple shear) all stress components inside the ellipsoid are constant and, hence, the strain rates are also constant (cf. Fig. 2a,c,d,f). Therefore, it is possible to derive a single rigid-body rotation component for the elliptical inclusion. Yet, for non-rigid inclusions, this expression is meaningless in the current context, since the apparent rotation of the shape is not only determined by the rigid-body rotation, but also must take into account the deformation of the inclusion. Like a water wave, the actual elliptical shape may move through the material points and this should be taken into account by the expression for the rotation rate. For this study, it can be shown that the tangential velocity in the ellipse tip (point A in Fig. 1) divided by the long axis radius is an accurate approximation of the shape rotation. The analytical expression for this rotation rate, $\dot{\omega}$, is

$$\frac{\dot{\omega}}{\dot{\gamma}} = \cos(2\alpha)\frac{\tilde{\mu}R^2 + 2R - \tilde{\mu} + 2}{2\tilde{\mu}R^2 + 2\tilde{\mu} + 4R} - \frac{1}{2} \qquad (1)$$

Here $\dot{\gamma}$ is the applied shear strain rate ($\dot{\gamma} = \partial v_x/\partial y$), x and y are Cartesian coordinates parallel and orthogonal to the shear-plane, respectively, v is the velocity vector, α the inclination of the ellipse to the simple shear flow, R the aspect ratio of the elliptical inclusion, and $\tilde{\mu}$ the viscosity contrast between clast and matrix. The sign convention used is that top to the right shearing is positive and all positive angular quantities designate counterclockwise.

The characteristic rotational behavior of elliptical inclusions according to Eq. (1) is depicted in Fig. 3. The rigid inclusion rotates according to Jeffery's theory, always in agreement with the applied shear sense. The distinctive effect of decreasing the inclusion viscosity is to amplify the behavior of the rigid inclusion, i.e., to accelerate the rotation where it is already fast and to slow it down where it is slow. If $\tilde{\mu} < 1$, the slow field even goes into back-rotation. The larger the aspect ratio, the smaller the size of the back-rotation field.

The rigid limit ($\tilde{\mu} \rightarrow \infty$) of Eq. (1) is identical to Jeffery's (1922) expression. However, our interest is in the infinitely weak inclusion, $\tilde{\mu} \rightarrow 0$, for which we obtain

$$\frac{\dot{\omega}}{\dot{\gamma}} = -\sin(\alpha)^2 \frac{R+1}{R} + \frac{1}{2R} \tag{2}$$

This expression has the interesting property that positive rotation rates result when

$$\sin(\alpha)^2 < \frac{1}{2R+2} \tag{3}$$

($\dot{\gamma}$ is always assumed to be positive). This means that the elliptical void indeed rotates backwards from a shear-plane parallel position. The maximum α for which back-rotation occurs is

$$\alpha = \arcsin\left(\frac{1}{\sqrt{2R+2}}\right) \tag{4}$$

This yields only 30° for $R \rightarrow 1$ as the maximum possible value for α, compared to the 45° that represent the direction of maximum instantaneous extension.

The existence of the maximum angle for which back-rotation occurs has a second significance: it represents metastable and stable clast inclinations. At the inclination angle described by Eq. (4), the rotation rate is zero and there is an equivalent angle mirrored with respect to the shear-plane that also has this property. This negative angle represents a metastable inclination since the rotation rate of the void vanishes once it is there, but even the smallest perturbation will cause it to move towards the positive zero-rotation inclination. In fact, voids from all possible inclinations will either rotate forward or backward towards the positive inclination, which is why the positive inclination is stable.

Fig. 3 also illustrates the simplification in the calculation of the rotation rate mentioned previously. The shear-plane parallel passive ($\tilde{\mu}=1$) ellipse is predicted to have a zero rotation rate, which is in opposition to the suggested drawing-program exercise. Nevertheless, the tangential tip velocity is an accurate proxy for the rotation velocity. In addition, the natural system with which we are dealing is the clast–weak mantle–matrix system that has only some of the characteristics of a void as explained below.

4. Equivalent void conjecture

Rigid clasts surrounded by a mantle that is weaker than the matrix, or exhibiting slip at the clast–matrix interface, can be reduced to equivalent voids. The equivalent void has an elliptical shape, approximating the size of the clast. The tangential tip velocity of real voids, i.e., inclusions where the viscosity contrast to the matrix goes to zero, determines the rotational behavior of the equivalent void. This velocity pulls the equivalent void into a stable inclination that is at shallow positive angles to the shear zone. In contrast to real voids, shear deformations of the equivalent void can be ignored because its shape is given and supported by the contained rigid clast. The rigid clast is assumed to follow the pull of the tips and to stabilize at approximately the angles predicted by the equivalent void conjecture.

5. Verification

To verify the validity of the assumptions underlying the equivalent void conjecture, we compare the equivalent void conjecture with the geometry resulting from a numerical finite strain experiment (Fig. 2e). The clast–mantle system has rotated backwards from the initially horizontal position (*b*) into the present inclination, which appears to be stable. The aspect ratio of the clast is 2:1 and its inclination is 30°. This is steeper than that predicted by the equivalent void conjecture for this aspect ratio (24°) and is characteristic for all finite strain experiments performed. However, the measured deviations were never large considering the simplifying assumptions made. It is noteworthy that if the inclination and aspect ratio are measured based on the weak mantle phase (cf. dashed line in Fig. 2e), we obtain 21° and 3.3:1 respectively, compared to the theoretically predicted 20° for this aspect ratio. The shear strain required to reach the stable orientation depicted in Fig. 2e is ≈ 1, equivalent to a total angle of the shear deformation of $\approx 45°$.

The most important test of any geological theory is the comparison with field data. ten Grotenhuis et al. (2002) collected an extensive data set (558 data points) of mica and tourmaline fish in shear zones from Brazil and California. Fig. 4 shows the compar-

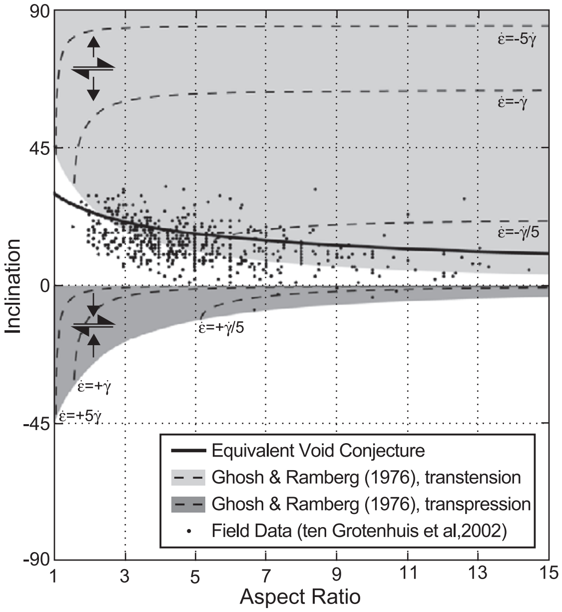

Fig. 4. Comparison of mica and tourmaline fish data collected by ten Grotenhuis et al. (2002) to the presented void conjecture (solid bold line). The gray fields indicate the location of possible stable inclinations according to Ghosh and Ramberg's (1976) combined pure and simple shear theory. Dashed lines display examples resulting from particular shear flow combinations. The "transpression" and "transtension" are explained via the schematic arrow diagrams.

ison of the equivalent void conjecture versus the field data set and the Ghosh and Ramberg (1976) theory. Ghosh and Ramberg derived their stable positions for a perfectly bonded clast in combined pure and simple shear. For any given relative intensity of these two shear components, the clast may have stable positions depending on the aspect ratio. However, for any given far-field flow, the stability curves lie in the gray areas and follow the trends indicated by the dashed lines. These trends conflict with the field data. In contrast, the equivalent void conjecture shows excellent agreement with the field data, both in trend and in absolute amplitudes of the angles.

The fact that neither the sigma shaped clast–mantle system in Fig. 2e nor the tourmaline and mica fish measured by ten Grotenhuis et al. (2002) exhibit the perfect elliptical geometry that our analytical solution requires, supports the hypothesis that the equivalent void conjecture is applicable to a broad variety of shapes. The same was demonstrated for Jeffery's (1922) solution by Arbaret et al. (2001).

6. Conclusions

The combination of field, analogue, numerical, and analytical results reduces the problem of the back-rotating and stabilizing competent clast in a shear zone to the one of a rotating, isolated void of fixed elliptical shape. We have derived a theoretical curve for stable clast inclination that agrees well with natural data. The characteristics of the stable positions are that they exist at shallow positive angles to the shear-plane and the stable inclination angle decreases with increasing clast aspect ratio. One prerequisite for the theory to be applicable is the presence of a weak phase (weaker than the matrix) between the rigid clast and the matrix or imperfect bonding between clast and matrix, both of which may be the case in natural shear zones.

The equivalent void conjecture has the following important geological implications. (i) Clasts in shear zones can have stable positions in simple shear without the requirement of an additional pure shear component. (ii) The stable orientation can be approached either syn- or antithetically; hence, the clast can rotate against the applied shear sense. (iii) The strain needed to develop a strong shape preferred orientation is small ($\gamma = 1$) and therefore evaluations based on other theories may overestimate strain by orders of magnitude. (iv) The reconstruction of far-field shear flow conditions and kinematic vorticity analysis must be modified to incorporate these new findings.

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Appendix A

The numerical model employed to produce Fig. 2 is a personally developed two-dimensional finite element method (FEM) code using the seven-node Crouzeix-Raviart triangle (Crouzeix and Raviart, 1973) to solve the Stokes equations for incompressible, viscous materials under plane strain assumption. A mixed method is employed, with linear interpolation of pressure, since this avoids spurious pressures usually due to the incompressibility constraint (Brezzi and Fortin, 1991). The code has been extensively tested from simple flow problems to mantle convection.

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