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SHORT NOTE

Flow mixing, object–matrix coherence, mantle growth and the development of porphyroclast tails

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Abstract—The kinematic 'stability fields' of common porphyroclast types have been defined using a computer program that simulates low Reynolds number Newtonian shearing flow in the vicinity of a rigid spherical object. The principal variables governing the geometry of porphyroclast tails at a given finite shear strain are: (1) porphyroclast–matrix coherence, and (2) mantle recrystallization history, both of which affect the extent to which mantle material becomes mixed with the matrix as deformation progresses.

INTRODUCTION

In applying the concept of flow mixing to the study of porphyroclast systems, Passchier (1994) has made another insightful contribution to the understanding of these useful kinematic indicators. Passchier has proposed that an important and previously overlooked factor governing the development of porphyroclast tails in bulk simple shear is the geometry of the 'separatrix'—the boundary between open and closed flow lines in the perturbed flow field surrounding a rigid porphyroclast. In particular, the extent to which the recrystallized mantle around a porphyroclast overlaps the area bounded by the separatrix may determine whether the porphyroclast eventually takes on a spiralling δ-shape, stair-stepping σ-shape (Passchier & Simpson 1986), symmetrical ϕ-shape (Passchier 1994) or wingless Θ-shape (Hooper & Hatcher 1988). In a kinematically passive matrix, the size of the separatrix-bounded area is proportional to the size of the rigid interior of the porphyroclast. The shape of this area is apparently governed by the rheology of the matrix; in Newtonian materials, it is eye-shaped, while in power law materials it is 'bow-tie'-shaped (Passchier *et al.* 1993, Passchier 1994).

Passchier (1994; his fig.3) proposes that wingless Θ- and spiraling δ-porphyroclasts can develop in either kind of flow perturbation, with Θ-types forming when the mantle lies entirely within the separatrix and δ-types developing when there is a partial overlap between mantle and separatrix. Stair-stepping σ-type and symmetric ϕ-type objects both occur when the mantle occupies all of the area bounded by the separatrix, but ϕ-types are thought to occur only for eye-shaped flow perturbations (Newtonian materials) and σ-types only for bow-tie-shaped perturbations (power-law materials).

These proposals have important implications for the interpretation of porphyroclast systems, including the possibility that matrix rheology might be read from their geometry. We have tested some of these inferences using a computer model we created to simulate the development of porphyroclast systems and other kinematic indicators (Zhang & Bjørnerud 1992, Bjørnerud & Zhang 1994). We concur that the nature of the separatrix is important in porphyroclast evolution, but caution that separatrix geometry is highly sensitive to factors other than matrix rheology, particularly (1) mantle recrystallization history (noted by Passchier 1994) and (2) the degree of coherence between porphyroclast and matrix.

COMPUTER SIMULATION OF PORPHYROCLAST SYSTEMS IN A NEWTONIAN MATRIX

Mathematical model

The simulation program is a kinematic model based on the analytical velocity field solution for low-Reynolds-number shearing flow of a Newtonian fluid around a rigid sphere (Lamb 1906). The total velocity field V has two distinct components, one (V_a) associated with deflection of matrix particles around the rigid object, the other (V_b) with the shear-induced rotation of the object (Lamb 1906, pp. 537–554, Lister & Williams 1983). If u, v and w are velocity components in the x, y and z Cartesian coordinate directions, r and Θ are polar coordinates centered on the object, a is the object radius, h is the half-width of the shear zone, and

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$U = U(y) = U_o(y/h)$ is the rate of displacement in the x (shear) direction, then the boundary conditions are:

$$V_a(u_a, v_a, w_a) = (0, 0, 0) \quad \text{for } r = a$$
$$V_a(u_a, v_a, w_a) = (U, 0, 0) \quad \text{for } r \rightarrow \infty$$
$$V_b(u_b, v_b, w_b) = (k\omega_o a \sin\Theta, k\omega_o a \cos\Theta, 0) \quad \text{for } r = a$$
$$V_b(u_b, v_b, w_b) = (0, 0, 0) \quad \text{for } r \rightarrow \infty \qquad (1)$$

where $k\omega_o$ is the angular velocity of the rigid object.

The components of the total velocity field V_a (u_a, v_a, w_a) + V_b (u_b, v_b, w_b) are:

$$u_a = (3Ua/4r^3)(1 - a^2/r^2)x^2 + U(1 - 3a/4r - a^3/4r^3)$$
$$v_a = (3Ua/4r^3)(1 - a^2/r^2)xy$$
$$w_a = (3Ua/4r^3)(1 - a^2/r^2)xz$$
$$u_b = k\omega_o ya^3/r^3 \quad v_b = -k\omega_o xa^3/r^3 \quad w_b = 0 \quad \text{for } r > a$$

and

$$u_b = k\omega_o y \quad v_b = -k\omega_o x \quad w_b = 0 \quad \text{for } r \leq a \qquad (2)$$

Although this analytical solution has been known for almost a century, visualization of its predictions for particle displacements at high finite strain would be impractical without computer simulations. Our program calculates and iteratively updates the analytical velocity field for user-specified values of variables including object radius, rate of change in radius, and bulk shear rate. Progressive deformation is simulated by continuously displacing points in the program domain through the velocity field. Porphyroclast systems can be simulated either by beginning with a pre-existing 'mantle' around the rigid object or by decreasing the radius of the rigid object in each time step to replicate dynamic recrystallization on the perimeter of the grain. In either case, the mantle is assumed to be rheologically identical to the matrix. As discussed below, the shape of the porphyroclast tail at any given value of the shear strain is very sensitive to the recrystallisation rate, consistent with the experimental findings of Passchier & Simpson (1986).

The parameter k in equation (2) is an index of coupling between the object and matrix (Bjørnerud & Zhang 1994). The value of k (always ≥ 0 but ≤ 1) determines the magnitude of the rotation-related part of the velocity field, V_b, and can be thought of as a measure of the efficiency with which the spin vorticity of the object (Lister & Williams 1983) is transmitted into the matrix. In all cases, the rotational part of the velocity field decays rapidly with radical distance (r) from the center of the object (velocity components u_b and v_b are proportional to k/r^3). A no-slip boundary between object and matrix, the usual continuum assumption, corresponds to the case $k = 1$. With this boundary condition, the object rotates at an angular velocity equal to half the bulk shear rate (Jeffrey 1922) and causes the largest possible flow perturbation in the matrix—that is, the region bounded by the separatrix (where flow lines define closed loops) has its maximum possible area. For k values between 0 and 1, the value of the rotational component of the velocity field at any point is k times the no-slip value. For $k = 0$, object and matrix are completely decoupled, the object does not rotate, and only the first part of the velocity field, V_a, has non-zero values. Because particles are simply deflected around the stationary object, there are no closed flow lines and the separatrix is non-existent (or could be considered to coincide with the perimeter of the object).

Although full decoupling is physically implausible, the possibility of partial decoupling ($0 < k < 1$) should not be discounted. As discussed by Ildefonse & Mancktelow (1993), some loss of cohesion seems likely at the interface between a rigid porphyroclast and its much weaker, dynamically recrystallized mantle. As shown below, the extent of particle–matrix decoupling profoundly affects the resultant geometry of porphyroclast systems.

Results of the model

Figure 1 shows kinematic 'stability fields' of various types of porphyroclasts in the recrystallization rate: shear rate vs. shear strain plane for systems with and without pre-existing mantles and for different values of the coupling factor k. The positions of the boundaries between these fields were determined by repeated experimental runs, using the visual criteria shown in Fig. 2. It should be emphasized that the model results were generated for the idealized case of a spherical object in bulk simple shear. The diagrams in Fig. 1 are meant only to show the qualitative effects of the various factors on porphyroclast geometry; quantitative application of the results to natural tectonites is not yet appropriate.

One of the most striking results of our computer simulations is the observation that δ-type porphyroclasts are produced only under a very restricted range of circumstances. In particular, their development requires not only: (1) relatively high finite shear strains; and (2) relatively low rates of radical attrition (recrystallization; da/dt), as shown experimentally by Passchier & Simpson (1986); but also (3) the pre-existence of a soft elliptical mantle; and (4) strong coupling between porphyroclast and matrix. In contrast, σ-type porphyroclasts develop under a much wider range of conditions. At moderate recrystallization rates and shear strains greater than 3, σ-shapes are always the result in this Newtonian system (Figs. 1 a–d). This is at odds with the suggestion by Passchier (1994) that σ-type porphyroclasts are characteristic only of non-Newtonian rheologies, with bow-tie-shaped separatrices. Although Passchier (1994) acknowledges that finite recrystallization rates would tend to favor σ-type tails, his proposed classification scheme (his fig. 3) applies to the rather restricted instances in which (1) no recrystallization occurs during shearing deformation but (2) a weak mantle has already formed around the porphyroclast during some earlier event. (These conditions are represented by a traverse along the x-axis in Fig. 1b.)

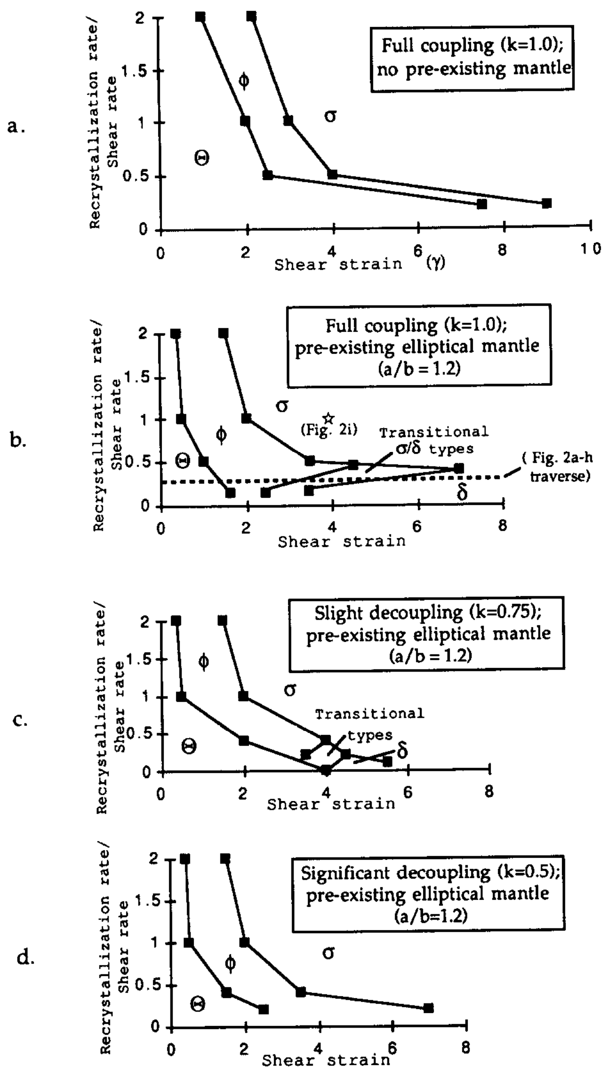

Fig. 1. Diagrams showing the 'stability fields' of common porphyroclast types, based on simulations by computer program described in text. Vertical axis is dimensionless ratio of recrystallization rate to shear rate (Passchier & Simpson 1986); horizontal axis is finite shear strain. Boundaries between fields were determined using the visual criteria shown in Fig. 2. (a) Stability fields for full porphyroclast–matrix coupling (k = 1.00 in equations 2) and no pre-existing mantle at onset of shearing deformation. Note absence of δ-type porphyroclasts under these circumstances. (b) Stability fields for full porphyroclast–matrix coupling and a pre-existing elliptical mantle with axial ratio (a/b) of 1.2, inclined 30° in the shear direction. Values for the ellipticity and orientation of the mantle were chosen to maximize the extent of the δ-type stability field. Exact positions of the field boundaries depend on the size and orientation of the pre-existing mantle. Geometries shown in Figs. 2(a)–(h) were generated along the traverse shown by the dotted line (recrystallization rate/shear rate ratio equal to 0.25). (c) Stability fields for slight decoupling (k = 0.75 in equations 2) and pre-existing mantle as in (b). Size of δ-type field is significantly smaller than in the case of full coupling. (d) Stability fields for significant decoupling (k = 0.50 in equations 2). Under these circumstances, δ-type are not stable at any shear strain because the magnitude of the spin-related component of the velocity field—and thus the size of the area bounded by the flow separatrix—are significantly reduced.

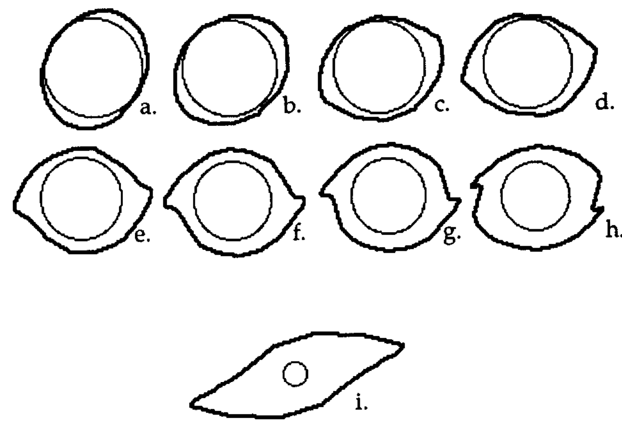

Fig. 2. Graphical program output showing porphyroclast geometries generated under conditions shown in Fig. 1(b). (a) through (h) correspond to points along dotted line, and (i) corresponds to point marked with star in Fig. 1(b). (a) Starting configuration (γ = 0). Θ porphyroclast (Hooper & Hatcher 1988). Maximum mantle width <10% of object diameter. (b) Θ porphyroclast. γ = 0.7. (c) & (d) ϕ porphyroclasts (Passchier 1994). γ = 1.5 and 2.4. Mantle width >10% of object diameter; mantle still symmetrical, but now lens-shaped rather than elliptical. (e)–(g) Transitional σ/δ porphyroclasts (Passchier & Simpson 1986). γ = 3.4, 4.4 and 5.3. Asymmetric mantle 'wings' have developed and extend in the down-shear direction in the manner of σ porphyroclasts, but are slightly inflected in the manner of δ porphyroclasts. These geometries would be difficult to interpret unambiguously in a natural tectonite. (h) δ porphyroclast (Passchier & Simpson 1986). γ = 6.9. Inflections in mantle wings now less than 90°. (i) σ porphyroclast (Passchier & Simpson 1986). γ = 4.0. Uninflected, stair-stepping wings.

Our simulations support earlier observations (Passchier & Simpson 1986, Passchier 1994) that development of δ-type porphyroclasts requires a pre-existing elliptical mantle (compare Fig. 1a with Figs. 1b & c). Although this has been recognized for some time, the geological implications have not been fully considered. In particular, it appears that most δ-type porphyroclasts begin as σ- or ϕ-types under conditions of rapid dynamic recrystallization but that recrystallization rates drop and/or shear rates increase during their subsequent development. The presence of δ-type grains in a mylonite may therefore reflect significant strain softening (and resultant increases in strain rate) or some other change that would prevent recrystallization from keeping pace with deformation. In the case of feldspar porphyroclasts, whose recrystallized mantles often consist of quartz and mica produced by hydration reactions with the host grain, a change to drier metamorphic conditions could cause recrystallization rates to drop and would favor the development of δ-shaped grains. Thus the relatively restricted 'stability field' in which δ-type porphyroclasts are stable gives insights into the specific geological circumstances under which they develop. The broad stability field of σ-type porphyroclasts makes them less promising as indicators of particular deformational conditions.

A second important factor governing the development of δ-type porphyroclasts is the extent to which the rigid grain and surrounding matrix are kinematically coupled. In analogue experiments designed to explore the effect of slip at particle–matrix boundaries, Ildefonse & Mancktelow (1993) found that δ-type tails formed in a non-Newtonian material around rigid particles only when particle–matrix coherence was high. Otherwise, σ-type or symmetrical (ϕ-type) porphyroclasts formed. Despite differences in model geometry, our results indicate that the same is true in Newtonian systems. In contrast to the model described here, the rigid objects in the scale models of Ildefonse & Mancktelow (1993) were rectangular, rather than circular, in cross-section. The amount of slip along the boundary of these objects was apparently sensitive to the resolved shear stresses at the boundaries, and these would vary continuously as the object rotated. For an object of circular cross-section, there is no such dependence on orientation.

Our computer experiments show that the stability field for δ-type porphyroclasts is largest in the case of full coupling with the matrix (Fig. 1b); significantly reduced in extent for slight decoupling ($k = 0.75$; Fig. 1c); and non-existent when decoupling is significant ($k \leq 0.5$; Fig. 1d). This reflects the fact that the rotational component of the velocity field, V_b (equation 2), essential in development of the spiraling arms of δ-type porphyroclasts, becomes less and less significant as the coherence between the object and matrix decreases. For a porphyroclast of a particular size, the area where flow lines close will be smaller for decoupled systems than it would be under conditions of full coupling. Decoupling can cause even a thin mantle to overlap the separatrix significantly, leading to the development of σ- or ϕ-type porphyroclasts at finite strains and recrystallization rates under which δ-types would otherwise form (compare Figs. 1b & d).

CONCLUSIONS

Porphyroclast systems of different types can be considered to form in well-defined 'stability fields' within a poly-dimensional kinematic phase space, and definition of these fields may allow quantitative inferences about the deformational conditions under which natural porphyroclasts developed. Porphyroclast geometries are particularly sensitive to (1) the extent, rate, and changes in rate of syn-deformational recrystallization and (2) the degree of coherence between porphyroclast and matrix. These factors significantly affect the size of the perturbation caused by a rigid object in shearing flow and therefore influence the extent of mantle–matrix mixing (Passchier 1994). Further studies are needed to explore quantitatively the effects of variables including irregular object shapes and matrix–mantle viscosity contrasts (Passchier & Sokoutis 1993) on porphyroclast geometry.

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