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## SHORT NOTES

# Mixing in flow perturbations: a model for development of mantled porphyroclasts in mylonites

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**Abstract**—The presence of a rigid object such as a porphyroclast in simple shear flow induces a flow perturbation with a relatively simple geometry. Domains of closed and open flow lines are bounded by a 'separatrix' that surrounds the porphyroclast. The concept of a separatrix to describe heterogeneous flow gives rise to some new insights in the development of porphyroclasts with a mantle of recrystallized material in mylonites. The final shape of the recrystallized mantle depends on separatrix shape, but also on the degree of intersection of the mantle and the separatrix, and therefore on relative mantle width. This model can explain the coexistence of several types of mantled porphyroclast in a single mylonite sample, the occurrence of porphyroclasts that lack wings at high strain values, and the presence of symmetric winged mantled porphyroclasts in ductile shear zones.

## MANTLED PORPHYROCLASTS

MYLONITES commonly contain mantled porphyroclasts, i.e. monomineralic aggregates composed of an equidimensional weakly- to undeformed core and a fine-grained mantle that can have a large variety of shapes (Fig. 1). Mantled porphyroclasts are usually surrounded by a fine-grained matrix of another mineral composition. They are interpreted to have formed by recrystallization in the outer zone of a large rigid single crystal and ductile deformation of the resulting mantle of recrystallized grains in response to ductile flow in the mylonitic matrix (Tullis & Yund 1985, 1991, Passchier & Simpson 1986, Dell' Angelo & Tullis 1989). Both ellipsoidal mantles without tails or wings (Θ-shaped mantles; Hooper & Hatcher 1988) and winged mantles (Simpson & Schmid 1983, Passchier & Simpson 1986) occur. The latter can have a $\delta$-, $\sigma$- or complex shape (Fig. 1) (Simpson & Schmid 1983, Passchier & Simpson 1986) or can even be symmetric ($\phi$-shape; Fig. 1). Some winged objects show *stair-stepping*, i.e. wings are not at equal level with respect to a marker line through the centre of the rigid object and parallel to the straight, far-field part of the wings (Fig. 1) (Passchier & Simpson 1986). $\delta$- and $\sigma$- shaped mantles are commonly used to determine sense of shear in mylonites (Passchier & Simpson 1986, Hanmer & Passchier 1991).

Studies on the development of mantled porphyroclasts have been largely empirical or experimental, without much reference to the flows pattern around such objects (Passchier & Simpson 1986, van den Driessche & Brun 1987, Hooper & Hatcher 1988). In fluid mechanics, much attention has recently been directed to the study of chaotic mixing (Ottino 1989, Meiburg & Newton 1991) and this concept can give some new insight in the development of mantled porphyroclasts. One particularly effective mixing regime is found in vortical flow perturbations at the boundary of two shearing fluids (Kundu 1990, pp. 373–395), or around rigid objects in non-coaxial flow (Jimenez 1980). By analogy, the development of $\delta$-, $\sigma$- or other types of mantles in non-coaxial flow can be modelled as an effect of the mixing of recrystallized mantle material and mylonitic matrix

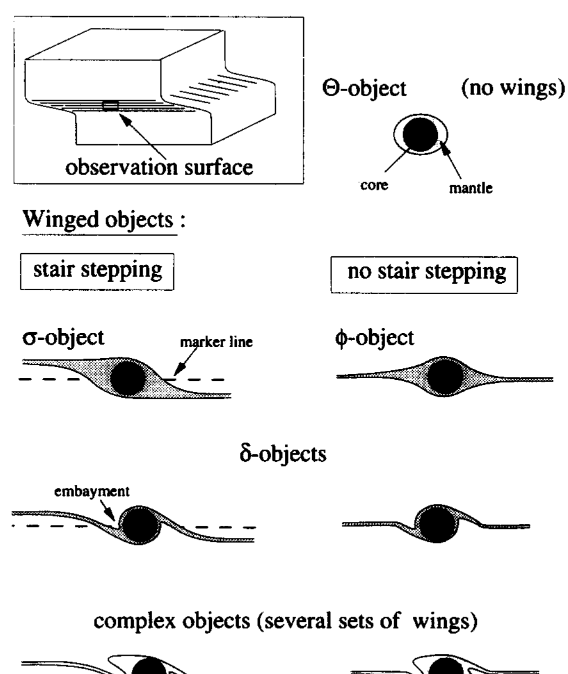


Fig. 1. Schematic representation of the most common types of deformed mantled porphyroclasts in mylonites, as seen in cross-sections parallel to the stretching lineation and normal to the mylonitic foliation. Objects on left show stair-stepping mantles.

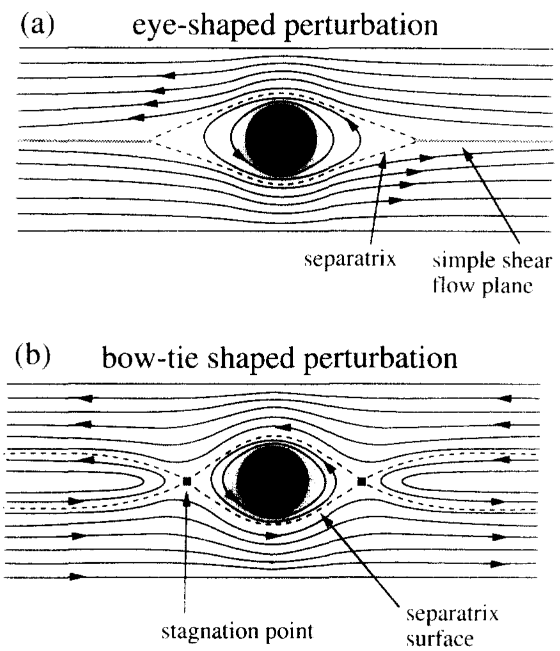


Fig. 2. Flow patterns around a spherical rigid object in simple shear flow, in a plane normal to the vorticity vector. Two types have been reported: (a) eye-shaped; and (b) bow-tie-shaped flow perturbations.

material in vortical flow perturbations around rigid porphyroclasts. For briefness, flow and flow perturbations are only treated in this paper for bulk plane strain and in a two-dimensional section normal to the vorticity vector of the far-field flow. This approach illustrates the concept sufficiently since this plane is usually also studied in thin section (Fig. 1).

## FLOW PERTURBATION AROUND PORPHYROCLASTS

Homogeneous simple shear flow, envisaged as a flow regime for ductile shear zones with relatively rigid wall rocks, can be visualized as a pattern of parallel flow lines and a plane of stationary points known as the flow plane (Fig. 2). The presence of a rigid object will cause a local perturbation in the flow pattern (Fig. 2a). If no secondary shear zones are induced, the rigid object will rotate in response to the rotational nature of simple shear flow. In association with this rotation, a field of elliptical flow lines is induced immediately adjacent to the rigid object (Passchier & Simpson 1986, Masuda & Ando 1988, Bjornerud 1989). If the object is spherical, these flow lines are completely closed (Fig. 2a) (Masuda & Ando 1988). Since far-field flow lines of simple shear are open, a boundary must exist somewhere in the flow between open and closed flow lines (Masuda & Ando 1988). Such a boundary is known as a *separatrix* (Fig. 2a) (Ottino 1989). This separatrix merges with the flow plane of simple shear where the perturbing effect of the rigid object of the bulk flow pattern vanishes laterally (Fig. 2a). The result is an 'eye-shaped' flow pattern similar to a Kelvin–Helmholtz instability in fluid mechanics (Kundu 1990, Meiburg & Newton 1991). Recently, experiments by ten Brink (Passchier 1993, ten Brink & Passchier 1992) have shown that, besides the 'eye-shaped' pattern, another 'bow-tie shaped' flow perturbation pattern is possible around a porphyroclast (Fig. 2b). In this pattern, separatrices terminate in two 'stagnation points' (Ottino 1989) that are immobile in the flow (Fig. 2b). Experimental data show that the shape of the flow perturbation pattern and associated separatrices (Fig. 2) depends on the rheology of the matrix material; in materials with Newtonian rheology eye-shaped patterns develop (Passchier & Sokoutis 1993), while in materials with non-Newtonian 'power-law' rheology, bow-tie-shaped patterns develop (Passchier *et al.* in press).

## MANTLE DEFORMATION IN A FLOW PERTURBATION

A deformable mantle around a rigid porphyroclast as discussed above deforms in response to the eye- or bow-tie-shaped flow pattern in the flow perturbation. Imagine a simple model where the mantle is a passive spherical shell with the same rheology as the surrounding matrix material, on a spherical rigid porphyroclast (Fig. 3). In this theoretical simple case, the separatrix coincides with the same material points throughout deformation history and a volume of deformable material is permanently 'locked' inside the separatrix. Three scenarios are possible.

(1) If the porphyroclast mantle is thin, it may lie entirely within the central separatrix (Figs. 3a & d). This implies that all mantle material is 'locked' inside the separatrix and an ellipsoidal mantle with stable or pulsating geometry will result, even at very high finite strain values; no wings can form. This behaviour has been observed in experiments by Passchier & Sokoutis (1993) and may be an explanation for the occurrence of apparently little deformed ellipsoidal mantles without wings around porphyroclasts in high-strain environments such as ultramylonites ($\Theta$-objects; Fig. 1).

(2) If the porphyroclast mantle is slightly wider, part of it will be outside the separatrix (Figs. 3b & e). This 'external' mantle segment is subject to open flow lines and can develop into wings. The space inside the separatrix contains both mantle and matrix material that will be mixed into a spiral shape; in combination with the external mantle segment, a $\delta$-object will form. The matrix material that was locked inside the separatrix forms the characteristic embayments of the $\delta$-object (Fig. 1), while the mantle material that was locked inside forms the inner part of the wings. If formed in a bow-tie shaped flow perturbation, $\delta$-objects will develop stair-stepping wings.

(3) If the porphyroclast mantle is so wide that it encloses the entire central separatrix, the external mantle segment develops into wings. Since the separatrix is completely filled with mantle material, matrix material cannot approach the porphyroclast. Consequently, a 'bow-tie-shaped' flow perturbation gives rise at high

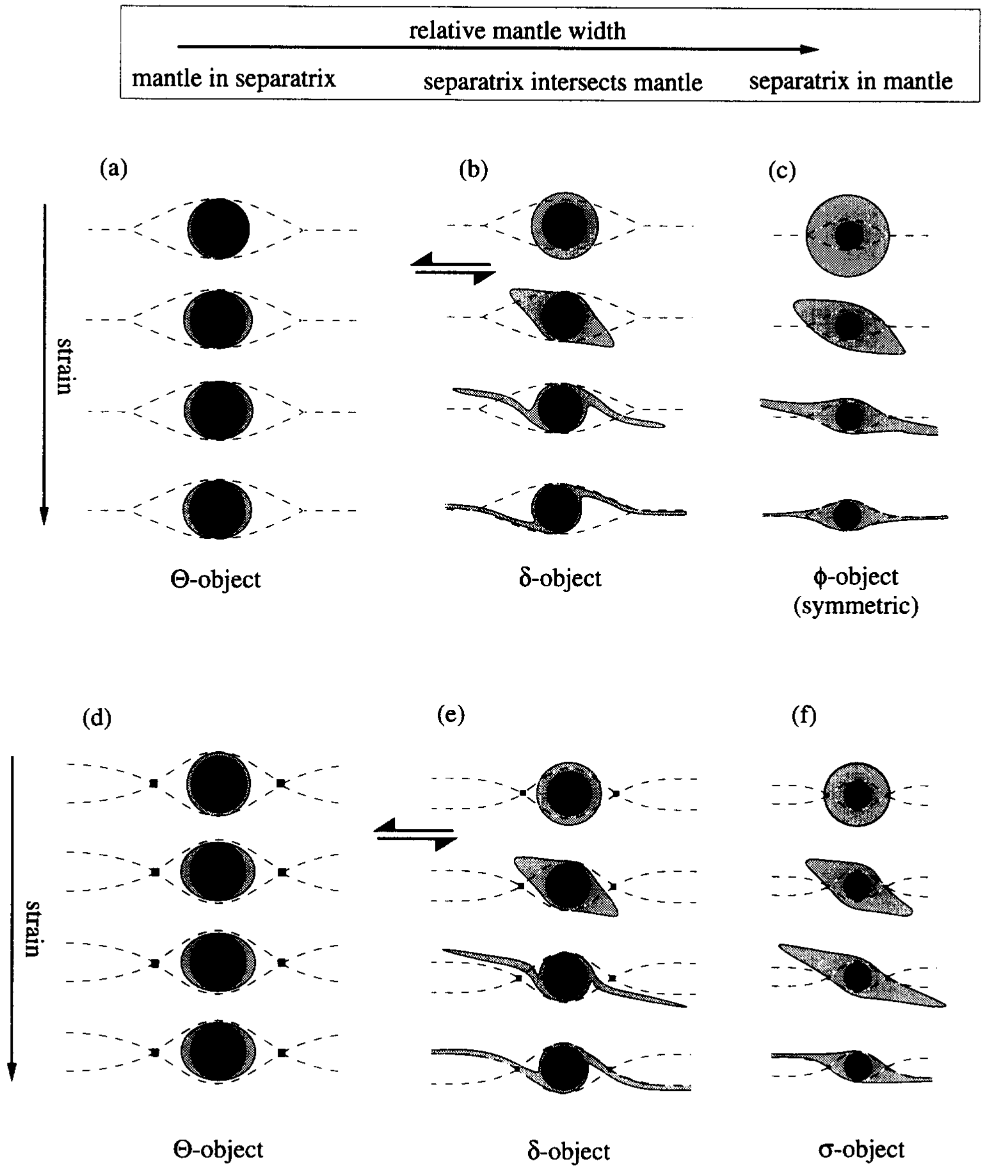


Fig. 3. Schematic diagram showing the three possible categories of mantle deformation around spherical rigid porphyroclasts in the two reported types of flow perturbation. (a–c) Eye-shaped flow perturbations. (e–f) Bow-tie-shaped flow perturbations. (a) & (d) Thin mantle lies inside the separatrix, no wings develop with progressive deformation. (Θ-objects); (b) & (e) mantle is transected by the separatrix. δ-objects develop. In the case of bow-tie-shaped perturbations, stair-stepping develops. (c) & (f) Wide mantle where separatrix lies inside the mantle. For eye-shaped perturbations approximately symmetric ϕ-objects form; for bow-tie-shaped perturbations, σ-objects form.

strain to σ-objects (Fig. 3f), while an 'eye-shaped' perturbation gives rise to approximately symmetric, spindle-shaped ϕ-objects (Fig. 3c). This may explain why mantled porphyroclasts in some ductile shear zones are symmetric despite the vortical flow to which they were subject. Mantled feldspar porphyroclasts in high-grade shear zones are commonly ϕ-objects, possibly due to strong dynamic recrystallization of feldspar and approximately Newtonian flow in the matrix at these conditions (Passchier *et al.* in press).

### *More complex situations*

Progressive deformation in natural mylonites is more complex than the simple geometrical model presented above, and deviations from the model should therefore be considered for practical purposes. Although the aim of this paper is to draw attention to the flow perturbation concept, it is useful to consider the possible effects of deviations from the basic model such as: (1) a shrinking porphyroclast adding material to the mantle; (2) a non-spherical porphyroclast; (3) a non-passive mantle; and (4) deviations from simple shear flow. However, much more experimental and numerical analysis is needed before the effects can be quantified.

(1) A rigid porphyroclast may be shrinking during natural deformation by recrystallization in its rim and add material to the mantle (Tullis & Yund 1985, 1991, Passchier & Simpson 1986). In this case the separatrix may shrink in size, and mantle and matrix material can 'leak' out of the separatrix into the far field flow (Meiburg & Newton 1991). If the shrinkage is fast, develop-

ment of $\sigma$-objects will be encouraged (Passchier & Simpson 1986). It is important to note that $\delta$-objects cannot be formed in the case of a shrinking core. Intuitively, it would seem possible that new material can flow out from the rigid object into the wing of the $\delta$-object but this is not the case; the segments of the wings inside the separatrix are continuously extending and any new material would accumulate in the corner opposite the existing wings and their connections with the rigid core. This would lead to development of secondary wings and complex objects (Fig. 1). Consequently, the material in the wing of a $\delta$-object was present in the wing before development of the $\delta$-geometry.

(2) If a porphyroclast deviates strongly from a spherical shape, the separatrix will move through the material and change shape in response to rotation of the rigid object. As a result, mantle material can 'leak' periodically out of the separatrix and complex objects (Fig. 1) will form.

(3) Since the composition of the mantle of a porphyroclast is different from the surrounding matrix, it is feasible that it will also have other rheological properties. Experiments with viscous fluids (Passchier & Sokoutis 1993) have given some indications of the effects of a non-passive mantle. If the effective viscosity of mantle material is relatively high, the separatrix will tends to occur further away from the rigid object, and $\delta$- or $\Theta$-objects rather than $\sigma$-objects tend to form (Passchier & Sokoutis 1993). In addition, wings will have a smaller aspect ratio than the bulk strain ellipsoid. If the effective viscosity of mantle material is relatively low, no change in geometry class results but wings tend to be much better developed than for passive mantles, and wings have a higher aspect ratio than the strain ellipsoid (Passchier & Sokoutis 1993).

(4) If a pure shear component is added to simple shear flow, i.e. if the kinematic vorticity number decreases from 1 to 0 (Passchier 1986), the geometry of a bow-tie-shaped flow perturbation evolves towards that of an eye-shaped one. Objects with geometries similar to that in Fig. 1 are formed, but their asymmetry will be less pronounced and stair-stepping will be less well developed. As a consequence, $\phi$-objects will be relatively common.

## CONCLUSIONS

The final shape of a deformed mantled porphyroclast depends on the relative volumes of mantle and rigid core and the shape of the flow-perturbation separatrix. If the porphyroclast and the separatrix do not change shape or size, the separatrix geometry and the initial mantle width determine what kind of object develops. Shifts from one geometry to another can occur if the porphyroclast is recrystallizing and adding to the volume of mantle material during the deformation, if changes occur in the rheology of mantle or matrix, or if the kinematic vorticity number of flow changes. Wings can only develop on porphyroclasts if part of the mantle has been outside the separatrix during the deformation history.

Apparently undeformed, ellipsoidal mantled porphyroclasts ($\Theta$-objects) can theoretically be stable up to high strain if the mantle remains relatively thin. Symmetric $\phi$-objects may form in pure-shear (coaxial) flow, but are not exclusively indicative for such flow. They can also form in simple shear or other non-coaxial flow if the mantle is relatively wide, and if the flow perturbation is eye-shaped. $\delta$-objects can only form around stable rigid objects with a mantle of intermediate relative thickness. Stair-stepping $\sigma$-objects can form both around stable rigid objects in bow-tie-shaped perturbations, and around shrinking porphyroclasts in eye-shaped perturbations. Complex objects form if the porphyroclast is non-spherical or shrinking.

The coexistence in a mylonite of mantled porphyroclasts of different types can be a consequence of different mantle width. If porphyroclasts are recrystallizing during progressive deformation, the speed of recrystallization (and associated speed of separatrix shrinkage) will determine what type of object will develop.

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