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#### Notes

# Porphyroblast rotation and strain localization: Debate settled!

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## ABSTRACT

This contribution shows unequivocally that porphyroblasts rotate relative to one another during ductile deformation. The porphyroblasts described here have special significance because they are from the original “millipede” rocks that led to the nonrotation hypothesis. Thus, the debate that has lasted for more than 20 years is settled. Despite this finding, porphyroblast microstructures continue to provide important evidence for deformation and metamorphic histories. Although porphyroblasts clearly rotate relative to one another during ductile deformation, there are several factors that contribute to relatively minor rotation in many instances, including (1) low strain during and after porphyroblast growth in comparison, for example, to mylonitic shear zones; (2) small axial ratios combined with relatively low internal vorticity during growth and post-growth deformation; and (3) strain localization at the porphyroblast-matrix interface. Thus, given the right circumstances, porphyroblasts may preserve the approximate orientations of deformation fabrics present at the time of their growth, but each case must be individually assessed.

## INTRODUCTION

Porphyroblasts are relatively large metamorphic minerals that commonly show chemical zonation and trap preexisting structural fabrics as inclusion trails during their growth (Fig. 1). For these reasons, they are centrally important

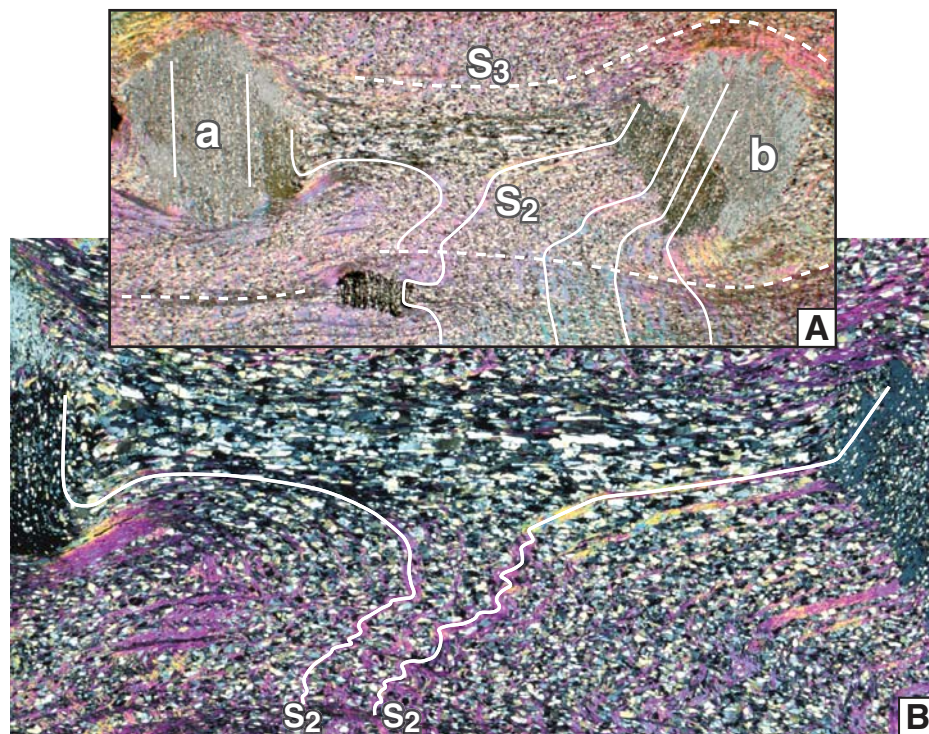
for a wide range of studies in deformed metamorphic rocks, including those that examine deformation and metamorphic histories, rates of diffusion and chemical reaction, deformation kinematics, finite strain, kinematic vorticity, pluton emplacement, and folding mechanisms

(reviewed by Johnson, 1999; Carlson, 2002; Johnson et al., 2006). The topic of whether porphyroblasts rotate relative to one another and a fixed reference frame during ductile deformation has attracted particularly energetic debate over the past two decades (reviewed by Johnson, 1999; cf. Fay et al., 2008; Bons et al., 2009). The debate gathered momentum when Bell (1985) questioned porphyroblast microstructures that had previously been used as evidence for rotation relative to an externally fixed kinematic reference frame, suggesting instead that they may form by growth, without rotation, during crenulation cleavage development. This hypothesis was based on a geometrical millipede microstructure preserved in and around plagioclase porphyroblasts described by Bell and Rubenach (1980). Much of the debate surrounding porphyroblast rotation can therefore be traced back to these plagioclase porphyroblast microstructures, so they figure centrally in the porphyroblast rotation debate. In this paper I show that these same plagioclase porphyroblasts have rotated relative to one another and to a developing crenulation cleavage, and discuss some implications for deformation histories and strain localization in rocks.

## BACKGROUND

Comprehensive theoretical (Jeffery, 1922) and experimental (Ghosh and Ramberg, 1976) studies provide a firm foundation for evaluating the rotational behavior of rigid objects embedded in a Newtonian viscous medium, but with rare exceptions (e.g., Holcombe and Little, 2001) these studies have been difficult to successfully apply to porphyroblasts. Some reasons for this are discussed herein, but in general, the kinematic history of porphyroblasts in regionally deformed metamorphic rocks is ambiguous compared to, for example, the kinematic history of porphyroclasts in mylonitic shear zones with well-defined boundaries (e.g., Passchier et al., 1992; Johnson and Vernon, 1995).

The primary evidence used to argue against porphyroblast rotation is the tight clustering of average inclusion-trail orientations over areas ranging in size from sample-scale and outcrop-scale folds to tens or hundreds of square kilometers (see Bell et al., 1992; references in Johnson et al., 2006). These data are impressive and give good reason to question the direct applicability of the above-mentioned theoretical and experimental results to deformed rocks. However, close examination of these data reveals a large



**Figure 1.** Examples of porphyroblast microstructures from rocks discussed in this paper and by Bell and Rubenach (1980). **A:** Thin section that cuts approximately through centers of porphyroblasts marked a and b. **B:** Magnification of region between porphyroblasts a and b illustrating continuity between inclusion trails and matrix  $S_2$  foliation. Two individual foliations in the matrix that are adjacent, and parallel, to one another diverge and can be traced into edges of the two different porphyroblasts. See text for discussion. Both images under cross-polarized light. Width of field in A is 32 mm, in B is 17 mm.

range of inclusion-trail orientations in individual samples, typically between  $40^\circ$  and  $80^\circ$ . This large variance in sample-scale orientations has generally been interpreted by proponents of nonrotation as preserving initial variation in foliation orientations prior to porphyroblast growth, possibly reflecting more than one porphyroblast growth episode (e.g., Bell et al., 1992; Bell and Bruce, 2007). Nevertheless, it can also be explained by variable rotation of porphyroblasts of different shape and orientation (e.g., Passchier et al., 1992; Jiang, 2001; Johnson et al., 2006).

In addition to measuring inclusion-trail orientations, a suite of more recent papers shows clustering of relative rotation axes (referred to as foliation intersection-inflexion axes) in porphyroblasts that contain sigmoidal, spiral-shaped, and other complex inclusion-trail geometries. These papers have consistently concluded that the data indicate a lack of porphyroblast rotation (see references in Fay et al., 2008). However, as with inclusion-trail measurements, measured foliation intersection-inflexion axes commonly span a large orientation range on the sample scale, and so also lend themselves to rotational explanations.

The fact that published data and observations can generally be interpreted either way has led to an impasse of sorts. One obvious way to resolve the issue of porphyroblast kinematics is to document examples in which the pre-deformation orientations of porphyroblast inclusion trails (or foliation intersection-inflexion axes) are known or can be confidently inferred. Ideally one would examine porphyroblasts collected across a well-characterized strain gradient that postdates their growth. The most convincing published example that I am aware of is in Johnson et al. (2006): we measured inclusion-trail orientations in staurolite porphyroblasts across a strain gradient that formed in response to pluton emplacement. The porphyroblasts typically preserve a straight

and consistently oriented regional foliation that predated pluton emplacement by  $\sim 30$  Ma. The spread of inclusion-trail orientations in the porphyroblasts increases nonlinearly from  $\sim 16^\circ$  to  $75^\circ$  with increasing strain in the aureole. These data provide strong evidence for rotation of the staurolite porphyroblasts relative to one another, the amount of relative rotation increasing with increasing strain. The Johnson et al. (2006) study will not convince some nonrotation supporters, so here I provide a different example in which the pre-deformation orientations of inclusion trails can be confidently inferred at the thin-section scale, thus eliminating any uncertainty associated with multiple-sample data sets.

## DESCRIPTION OF SAMPLE

A hand sample containing millipede microstructure, better described as oppositely concave microfolds (OCMs), was serially thin sectioned at  $\sim 1.5$  mm intervals and described in Johnson and Moore (1996). The sample contained the hinge and one limb of a small fold (Johnson and Moore, 1996, their figure 8). We prepared seven thin-section blocks from this sample and 75 serial sections were made from these blocks. The analyses here are based on observations in four identically oriented thin-section blocks from the hinge region of the fold. The OCMs in this rock occur in and around plagioclase porphyroblasts that grew over a matrix of quartz and muscovite (Fig. 1). The matrix has two well-developed foliations, referred to as  $S_2$  and  $S_3$  (Bell and Bruce, 2007). Both  $S_2$  and  $S_3$  are differentiated crenulation cleavages. All porphyroblasts examined are composed of a core in which inclusion trails are invariably straight, surrounded by a narrow rim in which inclusion trails curve into the matrix, forming the characteristic OCMs (Fig. 1). Of critical importance, the porphyroblast inclusion trails are continuous with matrix  $S_2$  (Fig. 1), which allowed us (Johnson and Moore, 1996) to reconstruct the

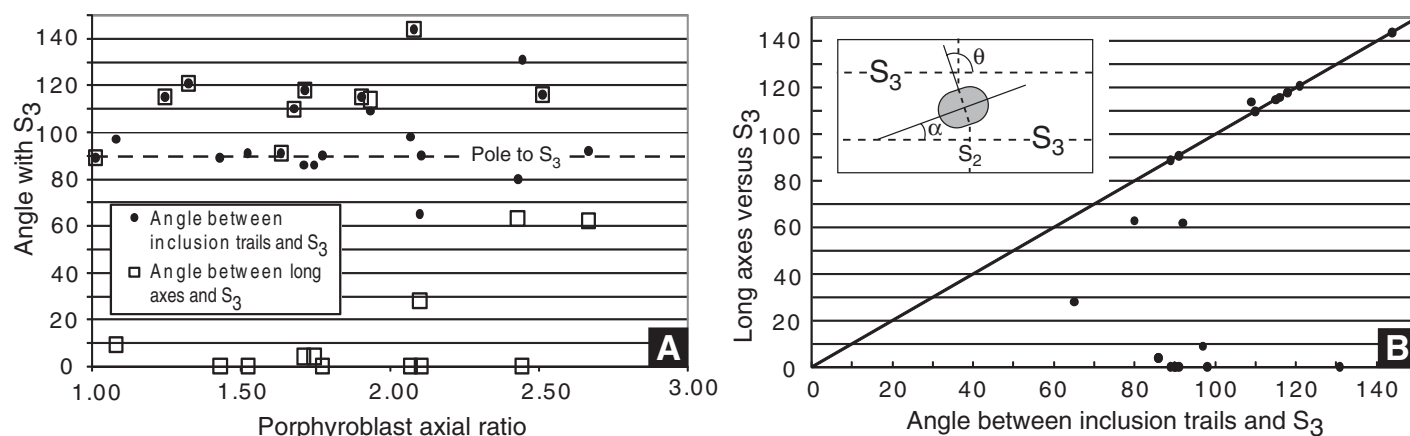
OCM geometry in three dimensions. We (Johnson and Williams, 1998) developed a new strain tool by comparing the spacing between  $S_2$  surfaces inside and outside of the porphyroblasts, calculating an elongation of 172% during the development of  $S_3$ .

## PORPHYROBLAST, FOLIATION, AND INCLUSION-TRAIL ORIENTATION RELATIONS

### Orientation Data For All Sections

I intersected 22 complete porphyroblasts in 42 thin sections from the four serial thin-section blocks. Figures 2A and 2B show the same orientation data from these porphyroblasts plotted in two different ways to clarify the relationships. All data in these plots were measured in sections that pass approximately through the center of each porphyroblast.

Figure 2A shows porphyroblast axial ratios plotted against both the angle between the inclusion trails and porphyroblast long axes (open squares), and the angle between the inclusion trails and  $S_3$  (filled circles). Also shown is the pole to  $S_3$ , which is approximately parallel to long segments of  $S_2$  across entire thin sections. Figure 2B shows the angle between the long axes of the porphyroblasts and  $S_3$ , plotted against the angle between inclusion trails and  $S_3$ . The following observations are important for this analysis. (1) The total spread of inclusion-trail orientations is  $79^\circ$ . This contrasts markedly with the average trend of  $S_2$  across entire thin sections, which varies around the pole of  $S_3$ , shown in Figure 2A, by  $\pm 10^\circ$  depending on local disturbances caused by the presence of porphyroblasts in or out of the section plane. (2) Nine porphyroblasts are elongate approximately parallel to  $S_3$ . Eight of these porphyroblasts have inclusion trails perpendicular to their long axes. (3) There are 10 porphyroblasts elongate approximately paral-



**Figure 2. A, B:** Orientation data collected in central cuts through 22 porphyroblasts. Inset sketch in B shows how angles between inclusion trails and  $S_3$  ( $\theta$ ), and porphyroblast long axes and  $S_3$  ( $\alpha$ ), were measured. See text for discussion.



lel to their inclusion trails (solid line in Fig. 2B), and these porphyroblasts show a trend in orientation as a function of axial ratio (dots inside squares; Fig. 2A). (4) Only three of 22 porphyroblasts are more than  $10^\circ$  outside of the populations in observations 2 and 3.

From the rotation perspective, these observations would be interpreted as indicating that, at the time of porphyroblast growth,  $S_2$  and the inclusion trails were locally parallel to one another and approximately perpendicular to incipient  $S_3$ . Those porphyroblasts with long axes parallel to the developing  $S_3$  did not rotate, and those with long axes oblique to  $S_3$  did rotate, broadly as a function of their axial ratios. From the nonrotation perspective, the observations above would be explained by original heterogeneity in  $S_2$  orientation at the time of porphyroblast growth, possibly in combination with multiple phases of porphyroblast growth (Bell and Bruce, 2007). In the absence of unequivocal evidence it is difficult to eliminate one or the other interpretation. I provide here the unequivocal evidence required to resolve the debate.

#### Orientations of $S_2$ and Inclusion Trails Around Individual Porphyroblasts

Owing to limitations in the length of this contribution, I show only a single example that demonstrates rotation of two porphyroblasts relative to one another during the formation of the  $S_3$  crenulation cleavage. Figure 1A shows a photomicrograph of most of a thin section containing two large porphyroblasts (marked a and b). This section is 1.5 mm away from what we (Johnson and Moore, 1996) interpreted as the central section through these two porphyroblasts. In the central section, porphyroblast a has a maximum aspect ratio of  $\sim 1.01$ , and therefore is effectively circular. Porphyroblast b has a maximum aspect ratio of  $\sim 1.32$ , and its long axis is approximately parallel to  $S_2$ . The two porphyroblasts contain inclusion trails that differ in orientation by  $\sim 32^\circ$ . General trends of  $S_2$  (solid white lines) and  $S_3$  (dashed white lines) are shown. Figure 1B is a magnification of the edges of these porphyroblasts and the extended region between them. The solid white lines trace the positions of two  $S_2$  foliations. The critical observation is that the inclusion trails at the edges of the two porphyroblasts can be tracked into the matrix where they are closely spaced and parallel to one another.

There is only one way to interpret these microstructural relationships: both porphyroblasts grew at approximately the same time, adjacent to one another, over parallel  $S_2$  foliations. During the development of  $S_3$ , they were separated by heterogeneous stretching parallel to  $S_3$ , leaving a quartz-rich dilatational region between them. During stretching and porphyroblast separation, porphyroblast b rotated  $\sim 32^\circ$

relative to porphyroblast a and the  $S_3$  crenulation cleavage. It is not possible in this instance to argue that the different inclusion-trail orientations reflect porphyroblast growth over a region of variably oriented  $S_2$ , because the original orientation of  $S_2$  is preserved in the matrix. It is not possible to argue that porphyroblasts a and b grew at different times. They clearly grew at the same time over parallel  $S_2$  foliations, and then were separated by approximately equal amounts from a center line during  $S_3$ -parallel extension.

#### NUMERICAL EXPERIMENTS

Numerical experiments (Fig. 3) illustrate how the angular variance between the inclusion trails in porphyroblasts a and b arose, and provide a contrast to the experiments by Fay et al. (2008), who used symmetrical, deformable objects. The three-dimensional (3-D) reconstruction (Johnson and Moore, 1996) revealed that porphyroblast b has an irregular, nonsymmetrical shape, with a true axial ratio  $>2.0$  and a long axis at a high angle to the thin-section plane of Figure 1. Thus, precise analysis of the rotation becomes a 3-D problem. Nevertheless, development of the geometry in Figure 1 can be explored by using a 2-D projection, resulting in the starting geometry in Figure 3A. A finite difference formulation (Itasca Consulting Group, 2006) was employed to solve the coupled motion and stress equations using velocity boundary conditions to define a coaxial deformation, as argued by Bell and Bruce (2007) and Fay et al. (2008) for these rocks. A viscoelastic (Maxwell) rheological description was used for the matrix, and an elastic description for the porphyroblasts. Applied velocities resulted in a nondimensional Deborah number well below 1.0 so that the matrix deformation was dominated by viscous behavior. The experiment was run to a total extension of only 100% so that the (deliberately coarse) Lagrangian grid could be easily compared to the deformed  $S_2$  geometry in Figure 1. As expected, the nonsymmetrical porphyroblast in the model rotated clockwise by an amount consistent with its shape and axial ratio, and the overall geo-

metry provides a good match to that in Figure 1. An effectively identical kinematic result is obtained using Mohr-Coulomb rheology (cf. Fay et al., 2008).

#### DISCUSSION AND CONCLUSIONS

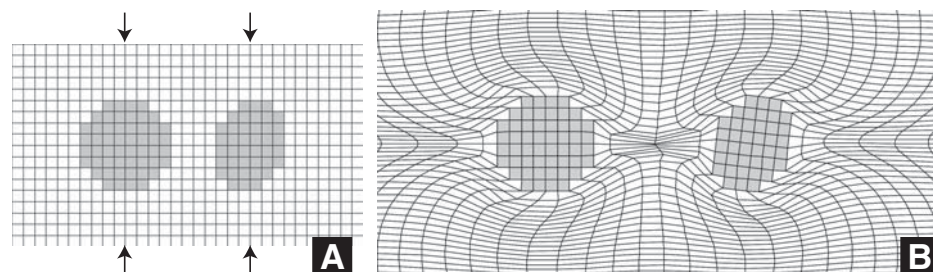
Although the debate over whether porphyroblasts rotate relative to an externally fixed reference frame has continued for more than 20 years, the fortuitous microstructural evidence presented here shows that the millipede plagioclase porphyroblasts of Bell and Rubenach (1980) rotated relative to one another during crenulation cleavage development. A different but similarly convincing example was presented by Johnson et al. (2006), and based on these two examples, I suggest that the debate about porphyroblast rotation is settled.

Apart from the external kinematic reference frame being poorly defined in many, or most, regionally deformed metamorphic rocks, some additional reasons why porphyroblast rotation is so difficult to demonstrate are worth reviewing.

1. Porphyroblasts are typically collected from folded rocks that presumably underwent deformation with relatively low bulk internal vorticity and finite strain compared to mylonitic shear zones. Given the typically small axial ratios of most porphyroblasts in a given sample, the total variation in inclusion-trail orientations under these conditions is expected to be relatively small (e.g., Fig. 3B).

2. Given that many or most porphyroblasts grow during folding events, the balance between external spin of the fold limb and shear-induced vorticity within the limb can also lead to little porphyroblast rotation relative to an external reference frame (Jiang, 2001; Evins, 2005).

3. Localization of shear strain at matrix-porphyroblast interfaces and elsewhere in the rock volume can profoundly affect porphyroblast kinematics, as shown in analog and numerical experiments (e.g., ten Grotenhuis et al., 2002; Ceriani et al., 2003; Schmid and Podladchikov, 2005; Marques et al., 2007; Johnson, 2008). In fact, partitioning of shearing and shortening



**Figure 3. A, B: Result of numerical experiment designed to illustrate rotation of porphyroblast b in Figure 1 during development of  $S_3$ . In B, bulk coaxial shortening is 50% (100% extension), and total rotation of porphyroblast b is  $7^\circ$  relative to flattening plane ( $S_3$  in Fig. 1). See text for discussion.**

strain in deforming rocks has, for more than 20 years, been used to explain nonrotation of porphyroblasts (Bell, 1985; Fay et al., 2008), and under certain circumstances such partitioning can lead to zero angular velocity of a porphyroblast (Johnson, 2008). However, there is no reason to expect that zero angular velocity relative to a fixed external reference frame should be a typical outcome (e.g., Jiang and Williams, 2004).

Although porphyroblasts clearly rotate relative to one another by difficult to predict amounts during ductile deformation, this does not diminish their multifaceted usefulness (noted in the Introduction). Their value as recorders of structural and metamorphic history has been firmly established. Given points 1–3 above, there should be instances in which porphyroblast inclusion trails preserve the approximate orientations of foliations and lineations present at the time of porphyroblast growth. But there should also be instances in which they do not, so each case must be individually assessed.

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