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The effect of microstructural and rheological heterogeneity on porphyroblast kinematics and bulk strength in porphyroblastic schists

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ABSTRACT

The kinematic record and bulk viscous strength of polyphase rocks depend in part upon the relative strengths and distributions of rheologically distinct fabric elements. Here, we explore the effects of microstructural and rheological heterogeneity in porphyroblastic schists. Electron backscatter diffraction and petrographic analyses reveal asymmetric microboudinage of staurolite, indicating relative rotation of staurolite porphyroblasts synchronous with bulk non-coaxial strain. Boudinage and relative rotation both require porphyroblast–matrix shear coupling. Based on 2D optical observations, the extent of the coupling appears related to the initial and boudinaged staurolite grain shape and orientation as well as the geometry of heterogeneities such as mica domains or shear bands.

We designed 2D finite element numerical models to assess the role of microstructural variation and rheological heterogeneity on the degree of porphyroblast–matrix shear coupling and bulk viscous strength. Model results indicate that the bulk strength of a three-phase system comprising inclusion, weak domain, and matrix is sensitive to the relative proximity of weak and strong domains, particularly at high viscosity contrasts (i.e. $\eta_{matrix}/\eta_{weak} > 10$). The threshold for bulk weakening below the matrix strength occurs over a narrow range of weak domain viscosities ($\eta_{matrix}/\eta_{weak} = 2.6$–$5.5$), regardless of the relative abundance and spatial distribution of weak domains. Kinematic decoupling of porphyroblasts occurs at low viscosity contrasts when weak domains are proximal ($\eta_{matrix}/\eta_{weak} = 2$–$5$), but for all other spatial distributions and modal abundances investigated, kinematic decoupling occurs at viscosity contrasts of $\eta_{matrix}/\eta_{weak} = 15$–$20$. These data indicate that bulk weakening due to rheological heterogeneity is not necessarily coincident with kinematic decoupling.

1. Introduction

To unravel the kinematics and dynamics of orogens, we rely in large part on the microstructural record. Tim Bell has made seminal contributions to our understanding of porphyroblast microstructures in the orogenic context, and we take the opportunity of this special volume to address the issue of porphyroblast kinematics and the use of microstructural modeling to infer the bulk strength of rocks. Due to their ability to preserve multiple deformation events and metamorphic conditions, porphyroblastic schists provide rich opportunities for reconstructions of past and changing deformation environments. However, one challenge associated with these rocks is that mineral-scale information, such as phase distribution and porphyroblast inclusion trail geometry, does not always predictably relate to macroscale kinematics and bulk properties such as strength (e.g., Fossen and Tikoff, 1993; Jiang, 1994a,b; Jiang and Williams, 2004; Johnson, 2008; Johnson et al., 2009a,b; Lister and Williams, 1983). For example, due to strain partitioning, the kinematic vorticity number as recorded by a population of porphyroblasts may not reflect the bulk strain field (e.g., Bailey and Eyster, 2003; Jessup et al., 2006; Johnson et al., 2009a,b; Klepeis et al., 1999; Law et al., 2004; Thigpen et al., 2010; Wallis et al., 1993; Xypolias and Koukouvelas, 2001). Comparatively, growth of effectively rigid porphyroblasts can strengthen a rock (e.g., Groome and Johnson, 2006), but well lubricated porphyroblast boundaries may counteract that effect and allow for bulk weakening (e.g., Johnson et al., 2009b). In this contribution, we focus on how the distribution and strength contrast of matrix domains (e.g., mica-rich and mica-poor) can affect porphyroblast rotation and bulk viscous strength. This work serves in part as further evidence that porphyroblasts rotate relative to each other, but more importantly to identify the conditions under which (1) interpretations of parameters such as kinematic vorticity number derived from grain or inclusion-trail orientations are valid and (2) porphyroblast growth strengthens a rock. Both the bulk strength and the relationship between porphyroblast kinematics and bulk kinematics depend strongly on the distribution and strength contrast of rheologically distinct matrix

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elements. To demonstrate this, we use a well-preserved kinematic record of microboudinaged staurolite porphyroblasts in a schistose matrix and finite element numerical modeling of analogous synthetic microstructures.

2. Kinematic vorticity measurements and controls on bulk strength

Many methods exist for evaluating the rotational component of strain, including the crystallographic or shape preferred orientations of rigid objects and their internal inclusion fabrics (e.g., Holcombe and Little, 2001; Johnson et al., 2009a,b; Masuda et al., 1995; Passchier, 1987; Simpson and DePaor, 1993, 1997; Wallis et al., 1993), crystallographic and shape preferred orientations in the matrix (Johnson et al., 2009a,b; Law, 2010; Passchier, 1987; Sullivan, 2008; Vissers, 1989; Wallis, 1993, 1995; Wenk et al., 1987; Xypolias and Koukouvelas, 2001), and deformed veins or dykes (Kuiper and Jiang, 2010; Passchier and Urai, 1988; Short and Johnson, 2006; Wallis, 1992). Application of the rigid clast method requires several assumptions, including measurements from a plane orthogonal to the rotation axis of the clast, ideal clast–matrix shear stress coupling, Newtonian viscous matrix behavior, clast shapes approximated as ellipsoids, clast shapes which do not change during deformation due to recrystallization or fracturing, sufficiently large strains such that clasts attain stable sink positions, no mechanical interaction among clasts, lack of strain partitioning at clast–matrix interfaces due to lubrication by a low viscosity material, and steady state, homogeneous bulk flow conditions at the scale of measurement (Jeffery, 1922; Johnson et al., 2009a,b; Means et al., 1980; Passchier, 1987; Passchier and Trouw, 2005; Xypolias, 2010 and reference therein). Because all these assumptions are rarely satisfied, the rigid clast method can substantially underestimate the kinematic vorticity number (e.g., Bailey and Eyster, 2003; Jessup et al., 2006; Johnson et al., 2009a,b; Klepeis et al., 1999; Law et al., 2004; Thigpen et al., 2010; Wallis et al., 1993; Xypolias and Koukouvelas, 2001).

In direct contrast to the interpretation of clast rotation, some workers, citing partitioning of kinematic parameters, have asserted that porphyroblasts (i.e. rigid clasts) remain confined to zones of pure shear and therefore do not rotate relative to one another or an external reference frame during non-coaxial deformation events (Bell, 1985; Bell and Hayward, 1991; Bell et al., 1992). In this interpretation porphyroblasts and their internal inclusion fabrics can be used to reconstruct the geometric evolution of complexly deformed metamorphic terranes (e.g., Bell and Newman, 2006; Bell et al., 1995; Cihan et al., 2006; Sanislav and Bell, 2011; Yeh, 2007). The primary difference between these two end-member applications of porphyroblasts is the degree of porphyroblast–matrix coupling, which is affected by strain partitioning and the distribution of weak and strong minerals (e.g., Bell, 1981, 1985).

To assess the relevancy of these end-member applications it is first necessary to establish porphyroblast–matrix shear coupling relationships. This may be done by constraining porphyroblast rotation synchronous with grain growth (e.g., Busa and Gray, 2005) or by constraining differential rotation of whole grains or grain fragments during shear that postdates porphyroblast growth (e.g., Hippertt, 1993; Johnson et al., 2006; Mezger, 2010; this study). Therefore, the timing of grain growth is less pertinent than the rheological and microstructural configuration that is coeval with non-coaxial deformation, which can significantly influence the partitioning of strain, degree of porphyroblast–matrix shear coupling, and thus the rotational behavior of rigid porphyroblasts.

The bulk strength of a polycrystalline material depends on three main factors: the strength contrast among the constituent phases, their modal abundance, and their spatial distribution. At the extreme, isolated spherical weak phases in a strong matrix provide an upper strength bound for a given mode and strength contrast (cf. Voigt, 1928), whereas layered weak phases provide a lower strength bound (cf. Reuss, 1929). Geological materials do not approach these bounds, but the distribution and degree of weak phase interconnection can exert significant control on the bulk strength (e.g., Gerbi, 2012; Handy, 1994; Holyoke and Tullis, 2006). Little is known about how rheological heterogeneities that affect bulk strength relate to those that affect porphyroblast–matrix coupling.

3. Geologic setting

The samples presented in this study are from the Appleton Ridge Formation, located in south-central Maine, USA (UTM: 0479400E 4904700N, 19T). This region experienced a protracted history of Silurian–Devonian orogenesis coincident with extensive plutonism, ductile deformation, and metamorphism (Bradley et al., 2000; Guidotti, 1989; Stewart et al., 1995; Tucker et al., 2001) due to the collision of multiple island arc systems, microcontinents, and proximal sedimentary basins with differing tectonic affinities (Fig. 1; see Murphy and Keppie, 2005; Tucker et al., 2001; van Staal et al., 1998; van Staal et al., 2007 for detailed tectonic syntheses).

Regional deformation resulted in a series of overprinting structural fabrics including a poorly recognized D_1 event associated with recumbent isoclinal folds and inferred overturned stratigraphy as well as a strong D_2 fabric that is characterized by upright to overturned tight and open folds that locally display a well developed axial planar cleavage and control general map patterns in the region (Fig. 1B; Hussey, 1988). The present dominant fabric (S_3) is a reactivated foliation that is subparallel to the earlier formed axial planar foliation (S_2) and is associated with the development of dextral asymmetric folds. The study area exhibits ubiquitous outcrop to microscale asymmetric dextral shear structures including asymmetric boudinage, north trending asymmetric folds (F_3), and shear bands (Gerbi and West, 2007; West and Hubbard, 1997). The structures are heterogeneously distributed and consistently display a dextral shear sense across a wide zone (>25 km perpendicular to orogen strike) that affect all lithologies in the study region (Fig. 1B; West and Hubbard, 1997; West et al., 2003). This phase of deformation is inferred, from regional structural analysis and thermochronology, to be the result of diffuse dextral ductile transpression in the middle crust associated with plate reorganization prior to localization associated with the development of the subvertical, right-lateral Norumbega Fault system (West and Hubbard, 1997). Due to this protracted history and across-strike strain partitioning, regional estimates of the mean kinematic vorticity number (W_m) range from $W_m = 0.67$ to 0.97 (Johnson et al., 2009a; Short and Johnson, 2006; respectively), reflecting deformation in a long lived zone of oblique convergence.

Peak metamorphic conditions reached low to intermediate amphibolite facies and spanned the andalusite and sillimanite stability fields (Bickel, 1976; Guidotti, 1989). Regional work indicates multiple discrete and/or overlapping Late Silurian–Devonian amphibolite facies metamorphic events occurred (Gerbi and West, 2007; Guidotti, 1989; West et al., 1995, 2003).

4. Microstructural analysis

4.1. Sample descriptions

At the study locality (star in Fig. 1B), the Appleton Ridge Formation is a staurolite–andalusite schist interbedded with micaceous quartzites. Beds are typically 5–60 cm and 3–8 cm thick, respectively, and where the quartzite is absent the schist is either bedded or massive (Bickel, 1976; this study). Outcrop-scale dextral shear structures consistent with regional deformation are ubiquitous and include asymmetric boudinage of more competent layers such as pegmatite pods (Fig. 2B) or quartz veins/pods (Fig. 2C,D), asymmetric folds with north trending axial traces (Fig. 2C), and shear bands which deflect the foliation at a low angle and strike 060-080 (Price et al.,