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Microstructural map of a thin-section scale fold pair; implications for folding mechanism in a fine-grained garnet

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Abstract: Detailed microstructural mapping of thin section-scale folds in a garnet bearing micaschist sample from the RIF Mountains (Morocco), including analysis of inclusion trails in 62 small garnets, reveals interesting details about the folding mechanism. A number of classic fold mechanisms capable of producing axial-plane cleavage are reviewed and shown to insufficiently explain the mapped microstructural patterns including cleavage fanning, wedge-shaped microlithons, and detailed crenulation geometries associated with different stages of compositional differentiation (S2). A new model is proposed in which crenulation cleavage evolves from initial conjugate kink bands to sets of closely spaced micro-shear zones with major shortening components.

Keywords: inclusion trails, folding mechanism, crenulation cleavage, cleavage fan, porphyroblast.

A detailed microstructural map (Fig. 1) was produced of a single thin section of microfolded garnet schist from the RIF Mountains (NE Morocco). The thin-section contains an anticline-syncline pair with well developed axial-plane crenulation cleavage (S2). This fabric exhibits typical cleavage fanning across the folds, and overprints an older main schistosity (S1). Amplitude and interlimb angle of the anticline-syncline pair are of the order of 2 cm and 50°, respectively. About eighty small garnet porphyroblasts are present throughout these structures and preserve a straight to weakly sigmoidal, to weakly crenulated S1 inclusion trails (mostly opaque minerals plus quartz). The trails are continuous with a more intensely crenulated S1 schistosity in the matrix.

Early fold geometry preserved by inclusion trails

Although inclusion trails (S1) maintain relatively constant orientations across the main anticline-syncline pair (Fig. 1) they define an open (subdued) fold with interlimb angles of about 150°, and developed "in phase" with the much tighter folding in the matrix. Axial planes of incipient crenulations are preserved inside many of the garnet porphyroblast and are subparallel to the axial planes of the main matrix folds. Thus, the porphy-
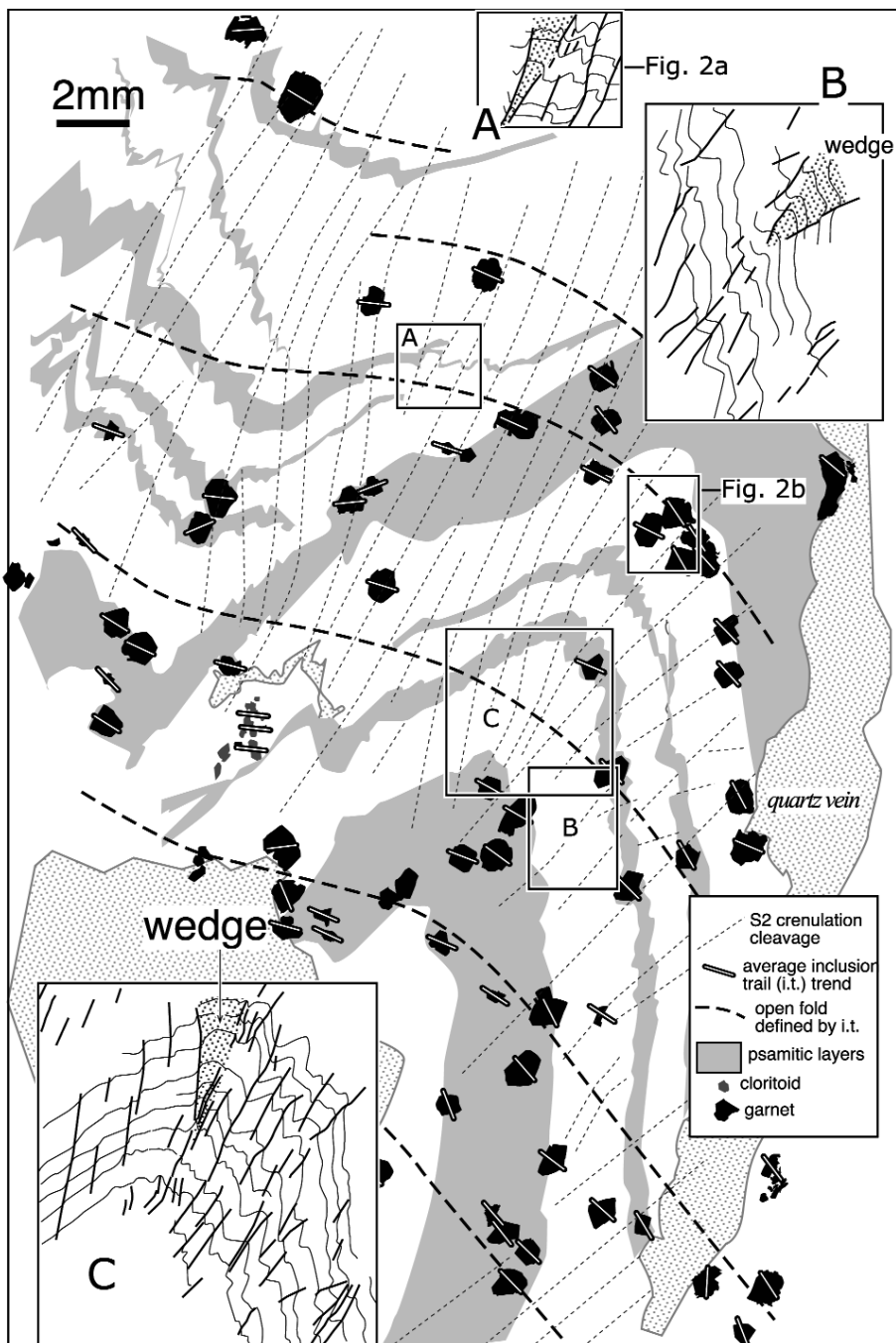
Figure 1. Accurate microstructural map of single thin section cut normal to fold axes in graphitic garnet schist from the RIF (NE Morocco). Insets A, B, and C showing wedge-shaped microlithons domains whose significance is discussed in text.

roblasts maintained relatively stable orientations and "fixed" an early fold-development stage. Nevertheless, some porphyroblasts have anomalous inclusion trail orientations which indicate more significant porphyroblast rotation, probably due to matrix-porphyroblast detachment and pressure-fringe formation (Fig. 2). However, the general inclusion-trail pattern demonstrates that the F2 folds developed by shortening parallel to the pre-existing S1 schistosity, which makes the sample well suited for assessing different folding mechanisms corresponding to layer-parallel shortening described in the literature.

Significance of axial-plane cleavage fanning

Cleavage fanning at the scale of the entire thin-section (Fig. 1) is closely related to wedge-shaped microlithons that appear concentrated in the main fold-hinge regions (Figs. 1 and 2b) but also in minor
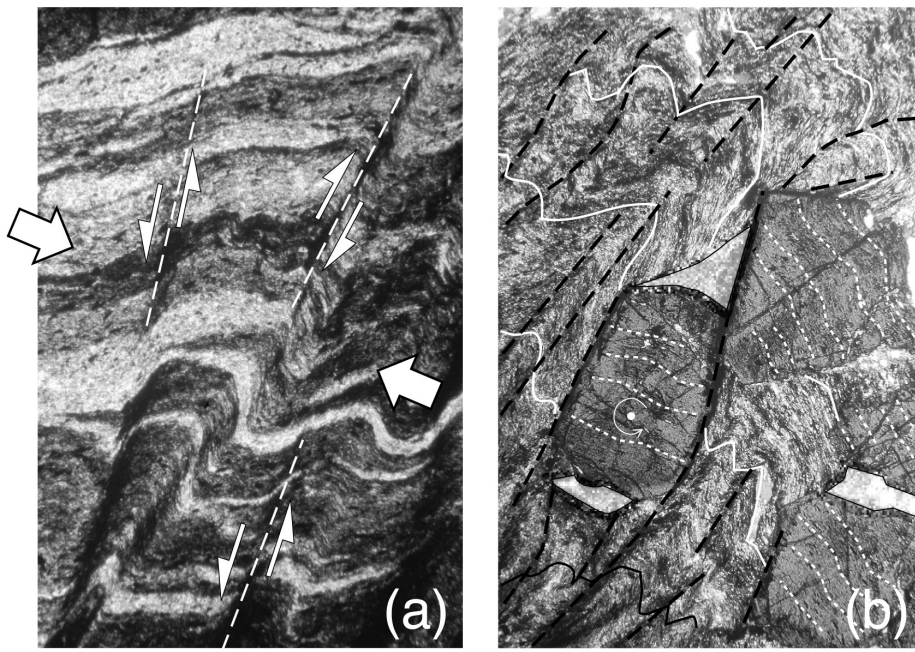
Figure 2. (a) Photomicrograph corresponding to inset "A" in figure 1, (b) group of garnets (location indicated in figure 1) with constant inclusion trails, except one that may have rotated in relation to matrix-porphyroblast detachment and pressure-fringe formation.

quantities in fold limbs. These wedges are bound by individual S2-cleavage septae making angles of 20° to 40° and causing opposite offsets of the deformed main schistosity (S1). These geometries are suggestive of extrusion of wedge-shaped domains during inhomogeneous shortening, which in turn implies minor shearing components along S2 cleavage planes (Bell, 1981; Hobbs *et al.*, 1982; Williams, 1990; Price and Cosgrove, 1990) rather than shortening and dissolution only (Gray and Durney, 1979; Treagus, 1983; Wright and Henderson, 1992). The quite different angle of S2 in opposite fold limbs suggests opposite shearing components. Thus we infer that bulk shortening was oriented perpendicular to the axial planes
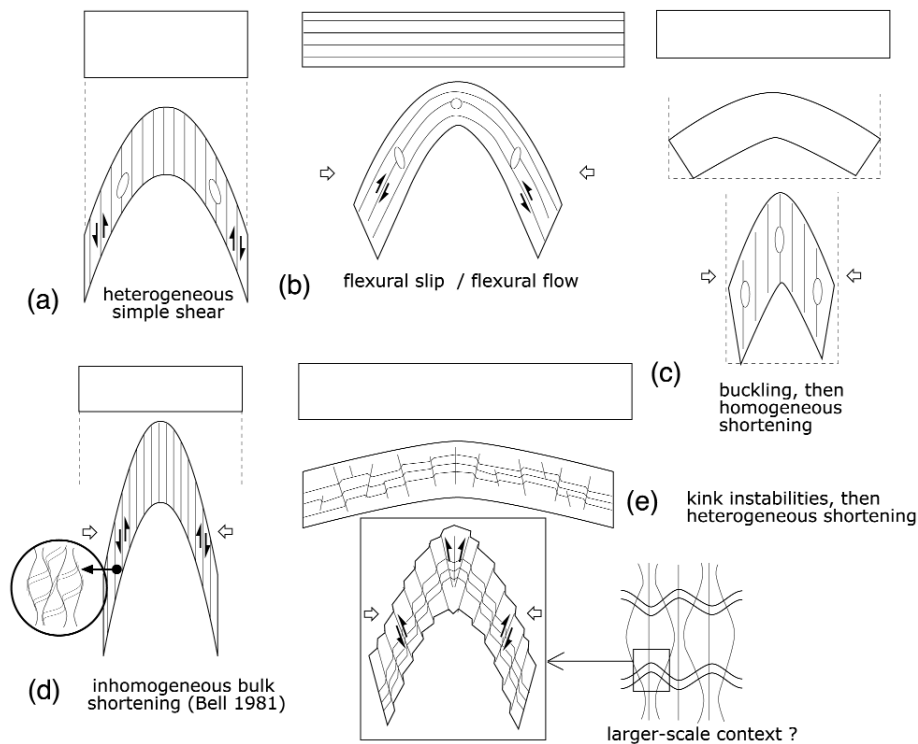

Figure 3. Schematic representation of different folding mechanisms discussed in text.

of the folds but partitioned into zones (fold-limbs) with opposite shearing components, apart from major shortening components. Various degrees of compositional differentiation along S2 cleavage zones are recognized preserved in the sample ranging from chevron-style microfolds of S1 showing no compositional differentiation, to intermediate-strain types showing some mica enrichment in crenulation long-limb domains, to discrete S2 cleavage seams marked by high concentrations of opaque minerals and mica.

Folding mechanism

Previous folding models fail to account for all of the described geometric features, which include cleavage-fanning, presence of wedge-shaped microlithons and conjugate systems of S2 cleavages showing opposite shear senses. For example, the classic card-deck model (heterogeneous simple shear) (Fig. 3a) does not account for shortening perpendicular to S2, or the fanning of cleavage. Flexural-slip or -flow (Fig. 3b) potentially predicts cleavage fanning as a result of differently oriented bulk-strain ellipsoids on opposite fold limbs. However, it does not explain the spaced nature of S2 with discrete cleavage septae cutting across S1, or the presence of wedge-shaped microlithons. Buckling followed by homogeneous shortening and cleavage development (Fig. 3c) fails to

explain the typical cleavage fanning. The "inhomogeneous bulk shortening" (Fig. 3d) for crenulation cleavage is affine to the mechanism we propose further, but still fails to explain cleavage fanning. Neither does it explain what causes shear senses along foliations to regularly switch in order to produce folds. The folding mechanism we propose (Fig. 3e) envisages that folding starts with the development of conjugate systems of kink bands (buckling instabilities in multilayer). As the larger-scale folds start to nucleate, one of both kink systems becomes dominant on a particular fold limbs. The kink bands then narrow due to strain-induced pressure dissolution, recrystallization and mechanical rotation of the mechanical anisotropy (S1 in this case). Thus, cleavage septae represent zones of general non-coaxial strain (not simple shear) in our model. Hinge regions are characterized by symmetrical microfolding and wedge-shaped domains bound by conjugate micro-shear zones. At a larger scale of observation, we speculate that the position of anticlines and synclines should be related to anastomosing cleavage patterns (Fig. 3e).

Acknowledgements

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