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Fracturing of garnet crystals in anisotropic metamorphic rocks during uplift: Reply

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I thank Jiang for his interest in our work on garnet fractures. I appreciate this opportunity to reply to his comments regarding stereological microstructures, the shear-lag model and its applicability to polyphase rocks deformed at high grade conditions.

MICROSTRUCTURES

Garnet crystals in granulite-facies mylonites and gneisses from the Morin shear zone are approximately *oblate* ellipsoids with their major axes in the XY plane and minor axes parallel to the Z direction (Ji and Martignole, 1994). Every section parallel to the XZ plane through such an oblate ellipsoid, produces an elliptical profile with a constant axial ratio or aspect ratio (X/Z). For the same reason, any section parallel to the Z direction (e.g. the XZ sections) is sufficient to determine the characteristic parameters for garnet size. Thus, Jiang's criticism against our methods of measuring aspect-ratio and grain size of garnet is baseless and unfair.

Both field and laboratory observations demonstrate that the fractures in the studied garnet crystals are dominantly perpendicular to the XZ plane. This is a fact rather than "a point taken for granted". It is thus the best choice to measure fracture spacing and orientation on the XZ sections. Yet, Jiang wrongly speculates that "the total fracture length cannot be a useful parameter unless it is measured on sections through the center of garnet crystals". It has long been realized that the total area of fractures in a given volume has a close relationship with the total length of fracture traces in any observed section, and both parameters depend on the mean fracture spacing (Underwood, 1970).

Whether it is possible to determine the true 3-D size distribution from 1-D or 2-D size data depends greatly on the variations in shape and in volume of the grains. If all grains approximate equi-sized spheres or cubes, the relationship between the 3-D size and the mean linear intercept is simple (Underwood, 1970). For ellipsoidal grains with varying volume and axial ratio, however, the conversion from the measured sectional area (or intercept length) distribution to the 3D size distribution has not been possible (Underwood, 1970).

The X-ray CT (Carlson and Denison, 1992) was not used to characterize the microstructure of the mylonites from the Morin shear zone mainly for the following reasons: (1) This technique is complicated, expensive, and, for many geologists like myself, it was inaccessible. (2) As shown by Denison *et al.* (1997), the practical limit of resolution for the X-ray CT is on the order of 0.1–0.2 mm. Thus, grains smaller than this limit cannot be measured. (3) Three-dimensional data from which one can extract the size and shape of individual crystals are actually obtained by stacking a series of two-dimensional CT images of slabs through the specimen. The thickness of each such slab is as large as 0.25–0.50 mm (Carlson and Denison, 1992). Each slab is then idealized as a flat cylinder. Sufficiently large numbers of slabs are needed in an individual grain in order to allow reconstruction of the true grain shape. In other words, the shapes of garnet crystals smaller than 3.0 mm (most garnet grains are smaller than 2 mm in the studied rocks) cannot be determined precisely using the technique. Moreover, multiple overlaps of grains within a slab in the transmission direction are difficult to separate.

SHEAR-LAG MODEL

I welcome any discussion that sheds light on the shear-lag model and its applications to structural geology, because this subject is of great interest to me (Ji and Zhao, 1993; Ji and Zhao, 1994; Ji *et al.*, 1997; Zhao and Ji, 1997). However, the author of this Discussion does not appear to understand completely the mechanical principles of the model (Ji *et al.*, 1997 and references cited therein). My responses to his comments are as follows.

(1) There is no such a restriction that "the shear-lag model requires an axial symmetry". Shear-lag analyses of planar symmetry were given by Hobbs (1967) and Lloyd *et al.* (1982).

(2) An objective of our paper was to answer qualitatively why tensile fracturing takes place

preferentially in strong garnet rather than in soft quartz and feldspar. We did not intend to obtain an exact numerical solution for the distributions of stress and strain in each real garnet crystal and the surrounding anisotropic matrix. To do so, one would need to perform numerical calculations. For simplicity, we approximated the system to a *rotational body* embedded in an elastically-*isotropic* matrix. Either of these treatments results in underestimating the magnitude of the tensile stress to some extent within the garnet crystals in the XZ plane, and particularly in the X direction. Thus, the simplification does not change our fundamental conclusions.

(3) Jiang wrongly states that the fiber can be fractured only if the interface strength is stronger than the fiber strength. Let me take a simple example to address this point. For a cylindrical fiber in a matrix, the largest tensile stress (σ_{max}) in the fiber occurs at the center while the largest interfacial shear stress (τ_{max}) appears at the ends of the fiber. If τ_{max} is equal to the *shear strength* of the interface (τ_o), slip will occur over a certain length at both ends of the fiber. Once the slip takes place, the interfacial shear stress for the slipping parts is constant and equal to τ_o. For the central part of the fiber, however, there is no interfacial slip since the interfacial shear stress is still lower than τ_o, and controlled by the shear-lag effect. Thus, the fiber end and center regions should be treated separately (Piggott, 1980). The mechanical analysis of interfacial slip is much more complex than Jiang suggested. Moreover, the ratio of σ_{max} to τ_{max} can be calculated according to Kelly and Macmillan (1986, equation 6.50). The value of σ_{max} is always larger and commonly much larger than that of τ_{max}. Thus, it is much easier for σ_{max} to reach the tensile strength of the fiber (C_o) than for τ_{max} to reach τ_o. This explains why the garnet crystals in the studied rocks are pervasively fractured while no interfacial fractures occurs between the garnet and its matrix (Ji *et al.*, 1997). Furthermore, Jiang erroneously declares that crystals should be always "much stronger than the interfaces". We know that failure strength of polycrystalline aggregates increases considerably with decreasing grain size or increasing the density of grain interfaces. This so-called "Hall–Petch relation" implies that the interfaces are stronger than the crystals in a fine-grained aggregate. If Jiang's declaration were correct, one would hardly observe intragranular and transgranular fractures and grain size reduction in metals, ceramics and rocks (Lloyd and Knipe, 1992).

(4) Like most analyses in composite mechanics (Cox, 1952; Kelly and Macmillan, 1986) and structural geology (Hobbs, 1967; Lloyd *et al.*, 1982; Ji and Zhao, 1993), the shear-lag model presented in Ji *et al.* (1997) assumes no slip on the phase interfaces. This assumption is likely to be correct in the studied rocks and is supported by the following points. First, microstructural evidence shows no relative motion between garnet and matrix in the studied rocks. Second, grain-boundary slip is unlikely in solids which have low-porosity and deform elastically. Third, although laboratory experiments (e.g. Schmid *et al.*, 1977) have demonstrated that interfacial slip may operate in *ultrafine-grained* polycrystalline aggregates being deformed at *high temperature* and *low strain rates*, unambiguous evidence for prevalence of this mechanism in natural mylonites are still rare (Fliervoet and White, 1995).

(5) Jiang misunderstands our points, concerning the closely-spaced fractures in garnet crystals. These were discussed in our original paper and are briefly summarized as follows. (a) According to the shear-lag theory (Lloyd *et al.*, 1982), the fracture spacing (f) is directly proportional to the ratio of the tensile strength of the fiber (C_o) to the shear strength of the interface between the fiber and matrix (τ_o). In a homogeneous, cylindrical fiber, for instance, the fracture spacing (f) ranges between $(C_o d)/(4\tau_o)$ and $(C_o d)/(2\tau_o)$, where d is the diameter of fiber's circular cross-section. The aspect-ratio of fractured segment (f/d) can be smaller than 0.25 if $C_o < \tau_o$. (b) The fracture density in a real fiber is significantly larger than that predicted by the shear-lag model from the tensile stress distribution because of the complexities inherent in fracture propagation (e.g. bifurcation, branching and deflection). For example, two cracks originate simultaneously at each side boundary of a garnet crystal and propagate inward, forming two overlapping cracks rather than a single transgranular crack. These two overlapping cracks then grow and form two parallel cracks (Ji *et al.*, 1997). (c) Garnet has a variable cross-sectional area: more closely-spaced fractures form at locations with smaller cross-sectional area (Ji and Zhao, 1993; Ji *et al.*, 1997). (d) In the garnet clusters, which are found in the pelitic and mafic gneisses (figs 3e and 4a–d, Ji *et al.*, 1997), garnet crystals are in contact with each other or very close together. Mechanical interactions between these garnets result in local stress concentrations and thus intensive fracturing (Ji *et al.*, 1997). (e) Inhomogeneous distribution of preexisting microflaws results in inhomogeneous distribution of fracture density in garnet crystals (Ji *et al.*, 1997). Higher fracture densities are found near the interfaces of garnet with the matrix and near the quartz inclusions (figs 3 and 4, Ji *et al.*, 1997).

FRACTURING TEMPERATURE

In the original paper, we concluded that the fractures in the garnet crystals from the Morin shear zone formed at low temperatures ($<300°C$) where plastic flow of quartz and formation of retrograde materials (e.g. amphibole, biotite, muscovite and chlorite) were impossible. Jiang agrees with us in this point.

According to the shear-lag theory, in a deforming composite the stress always tends to be concentrated in the strong inclusions embedded in the weak matrix. Cracks will form in the inclusions at weak points where the concentrated tensile stress has reached the tensile strength. The phenomenon occurs regardless of whether the matrix is deforming elastically or plastically. This contention was clearly presented in our original paper. One should also keep in mind that the mechanical behavior of the matrix depends not only on temperature but also on strain rate. The matrix can be elastic or even brittle at high temperature when the strain rate is sufficiently high. Such a high strain rate may occur temporarily in natural shear zones.

The fractured segments cannot be separated in the elastic matrix, and accordingly, the time relationship of the fractures cannot be determined in a given grain (Ji *et al.*, 1997). In the flowing matrix, however, the segments have to be separated and filled with matrix materials (Ji and Zhao, 1993). The cracks serve then as paths of fluids and mass transport and/or as locations for nucleation and growth of retrograde minerals which depend on both chemical composition of rock and metamorphic conditions. For example, a finer-grained symplectite of orthopyroxene–plagioclase–spinel is developed along the foliation-perpendicular tensile fractures of garnets in the mafic granulites from Sostrene Island, East Antarctica (Thost *et al.*, 1991). The 'elongate' garnets in the anorthosite–charnockite suite of the Adirondacks (New York State) developed two generations of foliation–perpendicular tensile fractures (Ji, unpublished data). The first generation of fractures took place at high temperature, making the garnet crystals boudined. The gaps between boudins are filled first with biotite and then with opaque minerals. The second generation of fractures, which occur in the garnet boudins, is similar to those in the Morin shear zone, and is interpreted to be formed at low temperature. Therefore, the shear-lag process is a viable mechanism for the development of the tensile fractures of stiff inclusions in the soft matrix under all metamorphic conditions.

From my knowledge of field geology, structures, microstructures, petrofabrics and seismic properties of the granulite facies mylonites in the East Athabasca mylonite triangle (Hanmer *et al.*, 1991; Ji and Salisbury, 1993; Ji *et al.*, 1993), and my own microscopic observation of 61 garnet-bearing mylonites, the garnet crystals in 44 samples have inclusion-free fractures and in 17 samples have fractures filled with retrograde minerals such as chlorite, white mica, biotite and occasionally amphibole. Therefore, I am doubtful about the validity of Jiang's assertion that "*more commonly* they may be filled with retrograde assemblages such as cordierite–anthophyllite–quartz $\pm$ biotite".

CONCLUSIONS

I maintain that the shear-lag model remains a viable model for the tensile fracturing of garnet crystals in the metamorphic rocks from the Morin shear zone. Jiang has not developed his own model for garnet fractures and, in my view, his discussion is inadequate and potentially misleading because it includes misconceptions about stereological microstructures and the shear-lag theory.

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