Pergamon

Journal of Structural Geology, Vol. 19, No. 11, pp. 1429 to 1431, 1997

PII: S0191-8141(97)00085-0
0191-8141/97 $17.00 + 0.00

Brevia

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

DAZHI JIANG

Department of Geology, University of New Brunswick, Fredericton, New Brunswick, Canada, E3B 5A3

(*Received* 3 *July* 1997; *accepted in revised form* 8 *September* 1997)

INTRODUCTION

Ji *et al.* (1997) proposed a shear-lag model for the development of the ordered fractures in garnet crystals from the Morin shear zone in the Grenville Province (Québec). Such fractures are also very commonly observed but poorly understood elsewhere such as in the East Athabasca mylonite triangle of the Snowbird tectonic zone (Hanmer *et al.*, 1994; Snoeyenbos *et al.*, 1995; Jiang, 1996; Hanmer and Williams, unpublished data). Major points of their argument may be summarized as follows.

(1) The fractures formed in the elastic–brittle regime when the rock was mechanically anisotropic due to the presence of an earlier mylonitic fabric.

(2) The fractures formed in a stress environment resulting from uplift without any influence of tectonic stress. The uplift was large enough to make horizontal stresses tensile. Had the rocks uplifted been elastically isotropic, the stress ellipse on a horizontal plane would have been circular (the stress state being: σ_1 subvertical and compressive, $\sigma_2 \approx \sigma_3 = \sigma_H$ (their equation 5), subhorizontal and tensile). Because of elastic anisotropy, the foliation-normal extension is easily accommodated and results in relaxation of σ_2, whereas the lineation parallel extension σ_3 remains high.

(3) Differential elastic response between the matrix (quartz/feldspar) and the garnet crystals induces shear stress at their interface, which in turn promotes an axial tensile stress within the garnet crystal that eventually fractures it. Successive fracturing of a garnet crystal forms the observed closely-spaced fractures.

Careful scrutiny of their paper reveals erroneous interpretations of the data and flaws in their arguments. This discussion points out these problems and concludes that the model proposed by Ji *et al.* (1997) cannot explain the observed phenomena.

STATISTICS

It has long been realized that quantitative textural analysis based on observations and measurements made in thin section has crippling drawbacks, particularly the inherent corruption of data that results from examining isolated two-dimensional sections within a three-dimensional system (e.g. Smith and Guttman, 1953; Kretz, 1966, 1969; Carlson and Denison, 1992; Denison *et al.*, 1997a,b). As a result, painstaking efforts have been made to obtain 3-D data from 2-D observations by either serial sectioning or by crystal-by-crystal dissection (Kretz, 1966, 1993; Christie and Ord, 1980). These approaches are unsatisfactory (Carlson and Denison, 1992; Denison *et al.*, 1997a,b). The recently-developed high-resolution computed X-ray tomography technique provides a better solution to the problem (Carlson and Denison, 1992; Denison *et al.*, 1997a,b). All statistical measurements by Ji *et al.* were carried out only in sections parallel to the lineation and perpendicular to the foliation. Measurements were converted to 'grain size' of garnet (d), aspect ratio (s), mean fracture spacing (m), and the aspect ratio of fractured segments (s_f) (equations 1–4, Ji *et al.*, 1997). Without any qualification, the data are presented (their figs 6–10) and interpreted to show the variation in the rock of garnet grain size, aspect ratio, etc. A small garnet in Ji *et al.*'s sense could well be a result of sectioning near the rim of a large garnet. Without first characterizing the 3-D shape distribution of the garnet crystals, it is not even possible to define a sound measure of 'grain-size'. Similar arguments apply to the aspect ratio of fractured segments, although perhaps to a lesser extent. The total fracturing length (y) cannot be a useful parameter unless it is measured on sections through the center of garnet crystals. Therefore the presented statistical results represent a mixture of real variation of a parameter (e.g. grain size), sectioning effect and biased observation (on one oriented section). Fracture spacing (m) and angular (ω) data may remain valid if the fractures are straight planes and their intersection with the foliation is perpendicular to the lineation (a point taken for granted but not demonstrated in the paper). With the possible exception of their fig. 7(b&c), figs 6–10 are not rigorously interpretable.

THE SHEAR-LAG MODEL

The application of the shear-lag model to the development of microboudinage of fibre-like rigid minerals such as piedmontite (Masuda and Kuriyama, 1988) and tourmaline (Ji and Zhao, 1993) embedded in a relatively incompetent matrix has been rather convincing. The deformation process of the matrix was considered to be either viscoelastic (Masuda and Kuriyama, 1988) or in flow (Ji and Zhao, 1993). Ji *et al.* (1997) consider the elastic deformation of the matrix. The shear-lag model predicts that the fibre will first fracture at the mid-point where the tensile stress is maximum (there are complications depending on the shape of the fibre, see Ji and Zhao, 1993; Ji *et al.*, 1997). The 'mid-point' fracturing process will continue until the fibre is reduced to 'stable' segments with aspect ratios equal to or less than the critical value for the stress condition. However, this model is unlikely to be applicable for the observed fractures in garnet because of the following arguments.

(1) Possibly because the shear-lag model requires an axial symmetry, Ji *et al.* (1997) (appendix) treat the garnet crystals as short fibres approaching rotational bodies surrounded by an elastically-isotropic matrix. This is not even nearly approximating the real geometry. First, the 3-D shapes of the garnet crystals are highly oblate with a Flinn shape parameter of 0.126 according to Ji and Martignole (1994). Second, the matrix has a symmetry no higher than orthorhombic. Strictly, the rocks considered have a monoclinic symmetry resulting from an earlier non-coaxial deformation with the section parallel to lineation and perpendicular to foliation being the symmetrical plane (see Ji and Martignole, 1994, fig. 2 for microstructures). Because of large strain, it remains a good approximation to treat them as elastically orthorhombic with the three mutually perpendicular diad axes being (i) the lineation, (ii) the line perpendicular to the foliation, and (iii) the line in the foliation perpendicular to the lineation. For an elastic material of orthorhombic symmetry, nine elastic constants are needed to describe its elastic behavior (Love, 1944 p. 159).

(2) A second problem for the applicability of the shear-lag model is concerned with the strength of the interface between the matrix and the garnet crystals. According to the shear-lag model, the smaller the aspect ratio of the inclusion, the harder it is to further break it. Ji *et al.* do not evaluate the stress conditions and estimate the critical aspect ratio below which garnet fracturing stops. The photomicrographs in their fig. 4 (Ji *et al.*, 1997) show that garnet crystals with an initial aspect ratio around or less than 2 (fig. 6c) have been sequentially fractured to segment aspect ratios (s_f) $\ll 1$ (figs 3, 4 and 7d). This translates into a very high shear-lag stress at the garnet/matrix interface. One must ask the question: can the interface support such a high shear stress before fracture develops and hence slip occurs along it? This critical point is not discussed by Ji *et al.* (1997).

In the elastic–brittle field, the shear strength of the interface can be described by the Coulomb law, $\tau = C + \mu\sigma_n$ (τ, the shear strength; C, the cohesion; μ, the internal friction; σ_n, the normal stress). In the stress environment proposed by Ji *et al.* and combining the orientation data of the interface (fig. 2), σ_n is tensile (negative). In such an environment, the shear strength of the interface would be particularly limited. Although the lack of data regarding the tensile strength of the garnet and the shear strength of the interface between the garnet and the matrix under natural deformation conditions precludes a quantitative analysis of the problem, our experience is that a garnet crystal is much stronger than the interface. It is conceptually impossible for the interface to remain coherent and transfer a shear-lag stress sufficiently high to fracture a garnet crystal or segment with an aspect ratio not much greater than unity (e.g. ~ 2). Since the fractures in garnet crystals are closely-spaced ($s_f \ll 1$) (Ji *et al.*, 1997, fig. 3 and fig. 4), the phenomena cannot adequately be explained by the proposed model.

Although Ji *et al.* claim that the fracturing process is sequential, as required by the shear-lag model, no evidence is provided to suggest this.

LOW TEMPERATURE FRACTURING?

From the photomicrographs presented in Ji *et al.* (1997), one might reasonably interpret the fractures as having formed in low temperature (< 300°C) conditions. However garnet fractures identical to those in Ji *et al.* (1997) are commonly observed in the granulite facies mylonites from the East Athabasca mylonite triangle (Hanmer *et al.*, 1991; Jiang, 1996). Ji is aware of the microstructures of these garnet crystals (oral communication by D. Jiang and J. C. White, 1995 Canadian Tectonics Group Workshop, Rawdon, Québec). The fractures can be inclusion-free, like those in Ji *et al.*, or more commonly they may be filled with retrograde assemblages such as cordierite–anthophyllite–quartz ± biotite (Hanmer and Williams, unpublished data). The matrix deformation temperature and pressure are estimated to be 850 ± 50°C and 9–11 kbar (Jiang, 1996); the retrograde assemblages in the fractures consistently yield 700–750°C, 4–5 kbar (Hanmer and Williams, unpublished data). Therefore the fractures must have formed at temperatures and pressures intermediate between the peak and retrograde metamorphism. This suggests that the fractures are high temperature (> 700°C) phenomena. The small change in temperature but drastic change in pressure between the peak and the retrograde metamorphism do suggest a rapid uplift following the peak metamorphism. If the garnet fractures from the Morin shear zone are equivalent to the inclusion-free fractures in the Snowbird tectonic zone, which coexist with fractures filled with retrograde assemblages, then they are high temperature fractures. In this case, a mechanism for the fracture development must consider the crystalline plastic flow of the quartz/feldspar matrix. If the garnet fractures from the Morin shear zone *is* low temperature, then such garnet fractures can form at both high (>700°C) and low (<300°C) temperature conditions. A viable mechanism for their development must be applicable for both temperature conditions.

CONCLUSIONS

(1) The statistical results in Ji *et al.* (1997), based on 2-D observations and measurements, are not rigorously interpretable and therefore do not quantitatively characterize the texture.

(2) The shear-lag model is unlikely to be applicable because (a) the model requires axial symmetry while the rocks have at most orthorhombic symmetry, (b) the garnet crystals are highly oblate as opposed to short 'fibres' approximating rotational bodies as required by the model, and (c) the interface between garnet and the matrix cannot support a shear stress sufficiently high to produce closely-spaced fractures ($s_f \ll 1$) in garnet crystals, particularly under the stress environment proposed.

(3) Identical garnet fractures have been observed by the present author and others in the Snowbird tectonic zone, Canada, where the temperature for fracture formation can be constrained between 700–800°C. It is possible that the garnet fractures from the Morin shear zone formed at temperature conditions similar to the Snowbird garnet. Whether the garnet fractures from the Morin shear zone are low or high temperature phenomena, a viable model for such garnet fractures should be applicable to both localities.

Acknowledgements—I am grateful to Simon Hanmer and Michael Williams for providing thermobarometric data of the retrograde assemblages in garnet fractures from the Snowbird tectonic zone. I thank J. C. White and P. F. Williams for discussion, Peter Stringer and Ron Pickerill for reading the text and suggesting improvements.

REFERENCES

Carlson, W. D. and Denison, C. (1992) Mechanisms of porphyroblast crystallization: results from high-resolution computed X-ray tomography. *Science* **257**, 1236–1239.

Christie, J. M. and Ord, A. (1980) Flow stress from microstructures of mylonites: example and current assessment. *Journal of Geophysical Research* **85**, 6253–6262.

Denison, C., Carlson, W. D. and Ketcham, R. A. (1997a) Three-dimensional quantitative textural analysis of metamorphic rocks using high-resolution computed X-ray tomography: Part I. Methods and techniques. *Journal of Metamorphic Geology* **15**, 29–44.

Denison, C., Carlson, W. D. and Ketcham, R. A. (1997b) Three-dimensional quantitative textural analysis of metamorphic rocks using high-resolution computed X-ray tomography: Part II. Application to natural samples. *Journal of Metamorphic Geology* **15**, 45–57.

Hanmer, S., Ji, S., Darrach, M. and Kopf, C. (1991) Tantato domain, northern Saskatchewan: a segment of the Snowbird tectonic zone. *Geological Survey of Canada Paper* **91-C**, 121–133.

Hanmer, S., Williams, M. and Kopf, C. (1994) Modest movement, spectacular fabrics in an intracontinental deep-crustal strike-slip fault: Striding-Athabasca mylonite zone, NW Canadian Shield. *Journal of Structural Geology* **17**, 493–507.

Ji, S. and Martignole, J. (1994) Ductility of garnet as an indicator of extremely high temperature deformation. *Journal of Structural Geology* **16**, 985–996.

Ji, S. and Zhao, P. (1993) Location of tensile fracture within rigid-brittle inclusions in ductilely flowing matrix. *Tectonophysics* **220**, 23–31.

Ji, S., Zhao, P. and Saruwatari, K. (1997) Fracturing of garnet crystals in anisotropic rocks during uplift. *Journal of Structural Geology* **19**, 603–620.

Jiang, D. (1996) *Kinematics and Mechanisms of Rock Deformation, with Reference to the East Athabasca Mylonite Triangle, Saskatchewan, Canada.* Unpublished Ph.D. thesis, the University of New Brunswick, Fredericton, Canada.

Kretz, R. (1966) Grain-size distribution for certain metamorphic minerals in relation to nucleation and growth. *Journal of Geology* **74**, 147–173.

Kretz, R. (1969) On the spatial distribution of crystals in rocks. *Lithos* **2**, 39–66.

Kretz, R (1993) A garnet population in Yellowknife Schist, Canada. *Journal of Metamorphic Geology* **11**, 101–120.

Love, A. E. H. (1944) *A Treatise on the Mathematical Theory of Elasticity.* Dover Publications, New York.

Masuda, T. and Kuriyama, M. (1988) Successive 'mid-point' fracturing during microboudinage: an estimate of the stress–strain relation during a natural deformation. *Tectonophysics* **147**, 171–177.

Smith, C. S. and Guttman, L. (1953) Measurement of internal boundaries in three-dimensional structures by random sectioning. *Transaction AIME* **197**, 81–87.

Snoeyenbos, D. R., Williams, M. L. and Hanmer, S. (1995) Archean high-pressure metamorphism in the western Canadian Shield. *European Journal of Mineralogy* **7**, 1251–1272.