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Comment on "Crystallographic orientation, chemical composition and three-dimensional geometry of sigmoidal garnet: evidence for rotation" by T. Ikeda, N. Shimobayashi, S. Wallis and A. Tsuchiyama☆

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1. Introduction

The origin of spiral-shaped inclusion trails is an important and intensively studied topic, yet there exists a lack of readily applied diagnostic criteria to distinguish the rotation and non-rotation end-member models in rocks (Johnson, 1993; Stallard et al., 2003).

In a recent study, Ikeda et al. (2002) analysed two spiral garnets and concluded a rotation origin based upon three criteria: spiral geometry, garnet compositional zoning, and the shape of chemical contours within the porphyroblasts. The aim of this comment is to illustrate the ambiguity of these three criteria, suggest alternative interpretations, and highlight additional evidence that may contribute to our understanding of spiral origin in similar rocks.

2. Review of Ikeda et al.'s evidence for a rotation interpretation

2.1. 3D geometry as a criterion

Ikeda et al. state that "Rotational and non-rotational models make different predictions about the 3-D shape of the inclusion trails in sigmoidal garnet.". This premise is the basis for distinguishing the two models based on 3D spiral geometry, but is it true? The authors do not provide evidence or references to support their claim, although examples exist in the literature of studies that both support (Williams and Jiang, 1999) and refute (Johnson 1993, 1999; Stallard et al., 2003) the above statement. If 3D spiral geometry is to be used as a criterion, the first step is to accurately describe the 3D spiral geometry, or more importantly the range of 3D spiral geometries, that might reasonably be produced by the end-member models. Ikeda et al. cite the spiral models of Powell and Treagus (1970) and Schoneveld (1977) as examples of spirals produced by the rotation model, but this assumption is flawed. These studies describe only the *relative* rotation of porphyroblast and matrix. Powell and Treagus state quite clearly that their model represents the geometry expected whether "…the crystals rotate in a static matrix or a matrix fabric rotates about them.". Similarly, Schoneveld's model can be considered to represent the non-rotation model if the rotating brass rings are fixed in place, and the table rotated about them (see fig. 1 of Williams and Jiang, 1999). Williams and Jiang (1999) also argued for contrasting 3D geometry between the rotation and non-rotation models, but their representations of the end-member models are both subjective and selective (see Johnson, 1999), and the authors failed to explicitly identify diagnostic geometric differences between the two models or compare their model geometries with examples from rocks. Williams and Jiang's conclusions have been challenged in subsequent studies (Johnson, 1999; Stallard et al., 2003).

The numerical modelling studies of Masuda and Mochizuki (1989), Gray and Busa (1994) and Stallard et al. (2002, 2003) probably represent realistic approximations of 3D spiral geometry according to the rotation model, while Stallard et al. (2002, 2003) have also simulated the 3D geometry of a spiral formed according to the non-rotation model. Stallard et al. (2003) found that 3D spiral geometries resulting from rotation and non-rotation simulations do not contain diagnostic differences, although differences exist in matrix microstructures adjacent to the porphyroblasts.

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2.2. Rotation of the long axis of chemical contours

Ikeda et al. attempt to demonstrate that the orientation of the long axes of spessartine contours within one of the analysed garnet is consistent with the rotation model of spiral development (Ikeda et al.'s fig. 6). This claim is based on the assumption that the non-rotating garnet should "undergo a series of roughly orthogonal shape changes" during the course of its growth, although their reason why the garnet should feel compelled to behave in this manner is not convincing. Ikeda et al. are not sure of their data, however, and initially state that the orientation of the chemical contours is "…a puzzling feature not readily explained by either the rotational or non-rotation models.". However, later in the same paragraph, the authors have changed their minds and claim that the non-rotation model is "inconsistent with the observed features in the present work" and that the chemical contour data is "…compatible with a rotation model…". It requires some special pleading (Ikeda et al.'s fig. 8) to explain how approximately 350° of inclusion trail curvature (and hence rotation of the garnet) might be consistent with an apparent rotation of the spessartine contours of only 40°. An alternative explanation is that the 2, 4, 6 and 8% contours represent garnet growth, without rotation, within a developing foliation that was oriented top right to bottom left with respect to fig. 5, and that the garnet core grew, without rotation, within a foliation oriented top left to bottom right with respect to the figure.

2.3. Continuous and discontinuous garnet growth

The third piece of evidence that Ikeda et al. present in favour of a rotation interpretation is chemical zoning patterns within the garnet porphyroblasts. The authors state that "Chemical zoning patterns perhaps represent one of the best ways to test the non-rotational models. To our knowledge, however, this aspect of sigmoidal garnets has not before been explicitly studied.". Such studies do in fact exist, and these include the works of Powell and Vernon (1979), Spiess and Bell (1996), Bell and Johnson (1989) and Stallard and Hickey (2002), all of whom document zoning anomalies within spiral garnets.

Ikeda et al. suggest that continuous garnet zoning disproves the non-rotation model, but this assumption is flawed. Bell et al. (1992) argued that continuously zoned, smoothly curving spirals are consistent with a non-rotation model of spiral formation. In a more recent study, Bell et al. (1998) state that the microstructures within garnet porphyroblasts imply either multiple generations of garnet growth or *continuous growth* over rapidly changing microstructures. Bell et al. (1998) prefer a discontinuous growth model, but their conclusions regarding porphyroblast non-rotation do not hinge on whether garnet growth was continuous or not. There is no reason why a spiral cannot form by the smooth, continuous and irrotational growth of garnet during the progressive development of overprinting fold and foliation events (Bell et al., 1992, p. 62).

3. Discussion

3.1. Folding vs. shear zone environment

The rotation model is generally described as involving non-coaxial shear within a shear zone (e.g. Williams and Jiang, 1999), while the non-rotation model involves multiple generations of folding and crenulation (e.g. Bell and Johnson, 1989). It is important to recognise that garnet growth during overprinting fold events will result in patterns of porphyroblast rotation and inclusion trail curvature different to those produced in a shear zone, regardless of whether the garnet behaves according to the rotation or non-rotation models (Williams and Jiang, 1999; Jiang, 2001; Stallard and Hickey, 2001a,b). Accordingly, the first step in any analysis of spiral formation is to determine the deformation environment, recorded in the matrix, in which the spiral formed. The two samples analysed by Ikeda et al. appear to be sourced from areas with contrasting deformation environments. Sample #MS95 is from a shear zone in the Austroalpine Alps, while sample #80904 is from polydeformed Dalradian rocks in the Loch Leven area, Scotland. Treagus (1974) identified five stages of folding and foliation development in the Loch Leven area (see also Bailey and Maufe, 1960; Ikeda, 1996). The dominant matrix foliations are horizontal and vertical, and the intersection lineation of these foliations is parallel to the rotation axis of the spiral garnet (Ikeda et al., 2002). Ikeda (1996) recognised three foliations in the small (3.5 km^2) portion of the Dalradian rocks that he studied north of Loch Levin. Ikeda correlated these foliations with S_1, S_3 and S_5 of Treagus (1974), but Ikeda et al. (2002) present a more simple structural interpretation consisting of just two foliations, S_1 and S_2. Given the multiple generations of folding and foliation recorded in the Dalradian rocks, it is possible that the spirals represent the accumulated curvature of overprinting crenulation cleavages consistent with the non-rotation model. Alternatively, the spirals may have resulted from a combination of the rotation and non-rotation models within a folding environment, with little net porphyroblast rotation relative to local geographic coordinates (e.g. Stallard and Hickey, 2001b). A third interpretation, and that adopted by Ikeda et al., is for spiral formation within a shear zone environment, but the available structural data suggests that this is the least likely hypothesis.

4. Summary and conclusions

1. The criteria on which Ikeda et al. base their conclusions are ambiguous and equally well explained by both the rotation and non-rotation models of spiral development.

2. Much of the evidence presented in previous publications is equally well explained by either model of spiral development. Consequently, conclusions from previous studies are commonly interpretative and model-driven, and therefore fail to progress the debate concerning spiral origin. The current priority for research in this area is to develop better methods of analysing spiral garnets (e.g. absolute dating and high resolution microtomography) and develop diagnostic and reproducible tests of hypotheses in order to reduce the subjective and interpretative component of conclusions.
3. Focus on the end-member models places artificial constraints on the research that we carry out and the interpretations that we make. The rocks themselves have no appreciation for the end-member models and may in fact follow an intermediate path of spiral formation (e.g. Stallard and Hickey, 2001b).
4. The quest to quantify porphyroblast rotation is almost impossible and does not necessarily reveal the mode of spiral origin. There may be more benefit to our understanding of spiral formation to answer the following questions: in what kind of deformation environment did the porphyroblast grow? What was the relative timing of garnet growth and matrix structures? Do the inclusion trails represent more than one foliation? What is the relative contribution of the following processes to total inclusion trail curvature: overgrowth of matrix crenulations, porphyroblast rotation within a static matrix, some combination of the two within a folding environment?
5. Although Bell and co-workers have produced the only detailed non-rotation model of spiral formation, they do not own the rights to the concept of porphyroblast non-rotation. Accordingly, attacks on specific aspects of the Bell model do not necessarily refute a non-rotation origin for spirals.
6. Johnson (1999) summarises some of the above concerns in the following passage: "Owing to the controversial nature of porphyroblast microstructures, it seems important that each new paper make an attempt to clarify the assumptions on which interpretations are based, and illustrate ambiguities or inherent difficulties encountered.".

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