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Discussion

Comment on “Reference frame, angular momentum, and porphyroblast rotation” by Dazhi Jiang and Paul F. Williams

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1. Introduction

Modeling of ductile rock deformation has been largely based on fluid dynamics or continuum mechanics. This approach simplifies rocks to perfectly homogeneous isotropic media, whereas in fact, rocks are composed of (discontinuous) mineral grains with contrasting mechanical properties. Detailed microstructural studies have shown that this heterogeneity leads to intense partitioning of deformation with major consequences for the cinematic significance of so-called ‘rotated porphyroblasts’ (Bell, 1985). As shown in Fig. 1a–c, these microstructures were reinterpreted to have formed by vorticity-induced matrix rotation relative to stable porphyroblasts. The feasibility of this process has been confirmed by modeling of strain-partitioning in heterogeneous media (e.g. Takeda, 2001; ten Grotenhuis et al., 2002), and a vast number of inclusion-trail orientation data have furnished empirical evidence for lack of porphyroblast rotation in metamorphic regions (Aerden, 2004 and references cited therein). In spite of this evidence, Jiang and Williams (2004) recently argued that the concept of ‘non-rotating’ porphyroblasts is cinematically and physically unsound. They claimed further that spiral-shaped inclusion trails (SSIT) defined by a single, continuously curving foliation refute an origin via the ‘non-rotation’ model of Bell and Johnson (1989). This comment discusses this criticism and confronts its authors with the principle evidence for ‘non-rotation’, ignored in their recent article and previous work.

2. Stating the porphyroblast controversy

Jiang and Williams state the porphyroblast-rotation controversy in terms of the ‘Schmidt–Schoneveld’ model versus the ‘strain-partitioning model’ of Bell and Johnson (1989). This terminology requires some clarification. Schoneveld (1979) did not model a mechanism, but only the geometry of spiral garnets by rotating a plasticine cylinder (porphyroblast) relative to a set of strings (foliation). Although Jiang and Williams (2004) recognize the mechanism-independent nature of the model, they give the false impression that Schoneveld supported the analogy assumed by Schmidt (1918) of a rigid sphere rotating without slippage between two plates. Rosenfeld (1970) later adopted the alternative model of a rigid sphere surrounded by a homogeneous fluid undergoing simple-shear flow. Although Schoneveld (1979, p. 54) shared the, at the time, unquestioned idea of vorticity-induced porphyroblast rotation, he recognized speculative character of the mechanisms of Schmidt (1918) and Rosenfeld (1970), because both ignore the influence of mechanical anisotropy, diffusional deformation mechanisms, and pure-shear components. Fifteen years later, consideration of these factors led to the unexpected reinterpretation of curved inclusion trails in terms of deformation partitioning and ‘non-rotation’ (Bell, 1985; Bell and Johnson, 1989). Williams and Jiang (1999, p. 369) acknowledged that strain-partitioning effects (or matrix–matrix slippage) can significantly reduce vorticity-induced porphyroblast rotation rates, but maintain their

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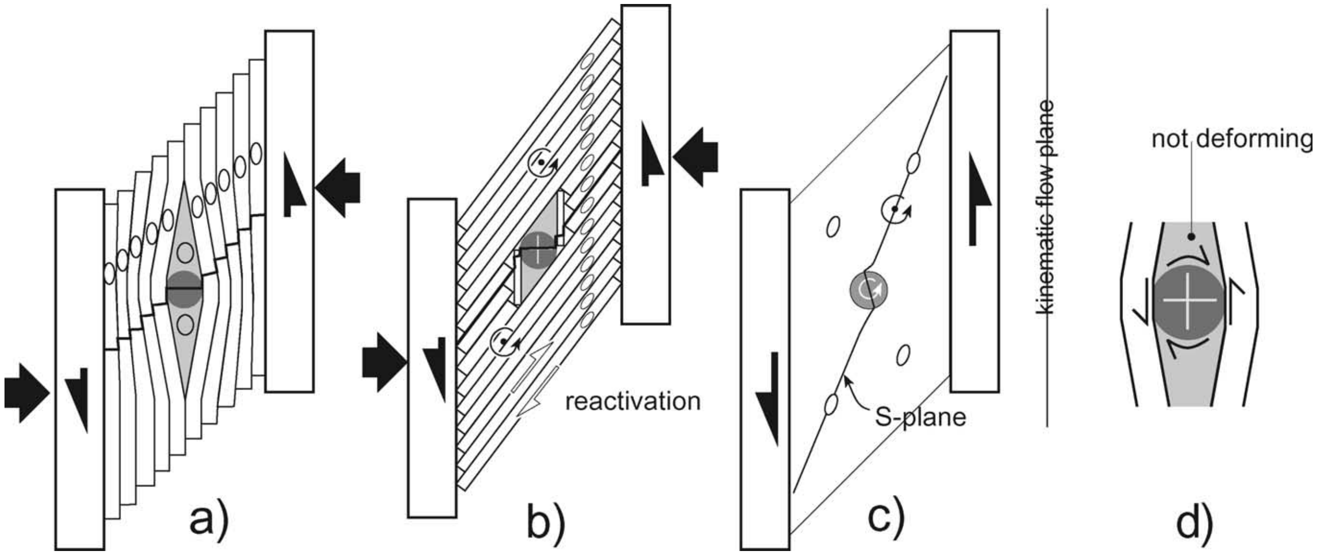

Fig. 1. Conceptual sketches of strain-partitioning around porphyroblasts in (a) zones of progressive crenulation-cleavage development (Bell, 1985), and (b) zones of foliation reactivation (Aerden, 1995). (c) Conventional model of vorticity-induced porphyroblast rotation followed by Jiang and Williams (2004). (d) Torque transmitted by foliation septae on porphyroblast edges balanced by reaction torques exerted by the strain shadow region (gray).

belief that SSIT form by porphyroblast rotation based on arguments discussed in Section 3.

3. Arguments against a 'non-rotation' origin of spirals

The first part of Jiang and Williams' (2004) article describes a numerical experiment simulating the development of inclusion trails in elliptical porphyroblasts rotating in a homogeneous simple-shear flow. The model predicts a large variation of uninterpretable inclusion-trail geometries. The authors do not test this prediction against data from real rocks and ignore data that directly contradict it (e.g. Aerden, 1995; Hickey and Bell, 1999). Therefore, this aspect of their article contributes in no way to resolving the porphyroblast-rotation controversy. In the second part of the article, the following four arguments are developed against an origin of spiral garnets via the 'non-rotation' mechanism of Bell and Johnson (1989).

(1) Bell and Johnson's (1989) model envisages multiple foliations being successively included in a porphyroblast, but many spirals are defined by a single continuously curving foliation.
(2) Rotating a foliation around a fixed garnet to form a spiral is only possible in a special vortex, where flow vorticity is exactly balanced by an opposite spin in an Earth-fixed reference frame. This is an unlikely general condition in the Earth's crust.
(3) Inclusion trails represent 'S'- or 'C'-planes, in line with Williams and Jiang's (1999) experience that spirals are exclusively found in shear zones.
(4) Lack of porphyroblast rotation violates the law of conservation of angular momentum. These points will now be discussed further.

3.1. Single-foliation spirals incompatible with Bell and Johnson's (1989) model

The origin of continuously or 'smoothly curving' spirals defined by a single foliation was discussed earlier by Bell et al. (1992) and in subsequent comments and replies. Although Jiang and Williams (2004) cite Bell et al. (1992), they do not address the arguments presented therein for a common origin of truncational and smoothly curving spirals via multiple phases of deformation. Bell et al. (1992) based their interpretation on the coexistence of smoothly curving and truncational spirals with near-horizontal and near-vertical attitudes in the same rocks. They attributed the development of relatively 'smoothly curving' trails to (1) a higher degree of protuberance of porphyroblast edges relative to newly developing crenulation cleavages, and (2) early cessation of porphyroblast growth during a crenulation-cleavage forming event. In their reply to Wallis (1992) they also discussed the role of foliation reactivation, in producing sigmoidal inclusion trails continuous with a single, straight matrix foliation (Fig. 1b). Repeated reactivation of a foliation by successive deformations could therefore be considered as a third factor favoring the development of continuously curving spirals. Consequently, the geometry of these microstructures considered in isolation cannot discriminate between the two opposed genetic mechanisms as was concluded earlier by Johnson (1993) and Stallard et al. (2003). Discrimination becomes possible, when inclusion trails from different porphyroblasts and samples are compared in an external reference frame (see Section 4).

3.2. Rotating a foliation around a porphyroblast only possible in a special vortex

The requirement of a special vortex in which flow-vorticity is balanced by an opposite spin in an Earth-fixed reference frame only considers steady-state deformation, and ignores the cumulative effect multiple deformations might have on the rotation history of a foliation (Section 3.1). Bell and Johnson (1989) showed that alternating contraction and gravitational collapse in orogens can produce circular paths of matrix particles around porphyroblasts in a step-wise fashion. They conceptualized how specific combinations of shear-senses associated with subhorizontal and subvertical foliations may relate to the location in an orogen, and suggested that spirals would only form in the lower half. Aerden and Malavieille (1999) built further on this model to include a mechanism for the exhumation of deep rocks by subvertical extrusion followed by nappe emplacement by gravitational spreading. Fig. 2a shows how such a model predicts roughly circular paths of rocks in orogens, which could be reflected in the geometry of SSIT. It should be realized though that strain intensification against porphyroblast edges will lead to significantly greater (or even opposed) rotation (i.e. deflection) of a preexisting foliation than elsewhere in the matrix (Fig. 3). Thus, inclusion-trail curvature will generally be greater than the average amount of matrix rotation in a rock, contrary to what is suggested in fig. 6 of Jiang and Williams (2004).

3.3. Spirals only occur in shear zones

Jiang and Williams (2004) reaffirm the idea of Williams and Jiang (1999) of spirals developing during progressive shearing, but leave unclear whether they interpret inclusion trails as ‘S’-planes (suggested on p. 2215), ‘C’-planes (suggested on p. 2223), or both. Numerous workers, including Schoneveld (1979), Hayward (1992), Stallard and Hickey (2001) and Bell and Chen (2002) have demonstrated complex, polyphase deformation histories in spiral-containing rocks, and discussed the genetic implications. No microstructural evidence has ever been presented demonstrating that SSIT represent ‘S’ and/or ‘C’ planes or formed during a single phase of progressive shearing.

3.4. Violation of the law of balance of angular momentum

Obviously, the net torque acting on an object is proportional to its angular velocity in a viscous medium. Jiang and Williams (2004) calculate this torque for a spherical particle surrounded by a homogeneous viscous fluid undergoing simple shear flow (equation 36 of Jeffery, 1922). They further consider the effects of a spherical low-viscosity envelope, which reduces the rotation rate of a particle. Again, extrapolating this theory to porphyroblasts depends critically on the assumption that metamorphic rocks behave analogous to viscous fluids. Microstructural observations and orientation data (Section 4) suggests that this assumption is not valid and that the torque exerted on a porphyroblast edge by a surrounding foliation is sufficiently small to be resisted by a reaction torque exerted by the strain

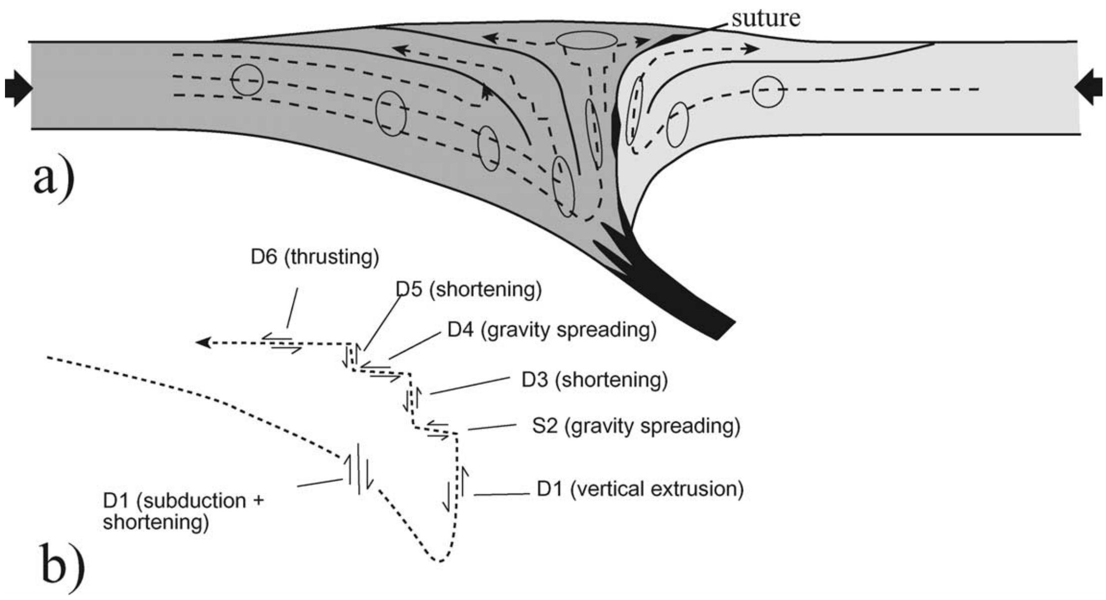

Fig. 2. (a) Conceptual model of an orogen in which rocks follow circular paths due to progressive shortening and burial, exhumation in steeply dipping root zones, and gravitational spreading. (b) Magnified view of path followed by a rock with hypothetic deformation phases and possible significance.

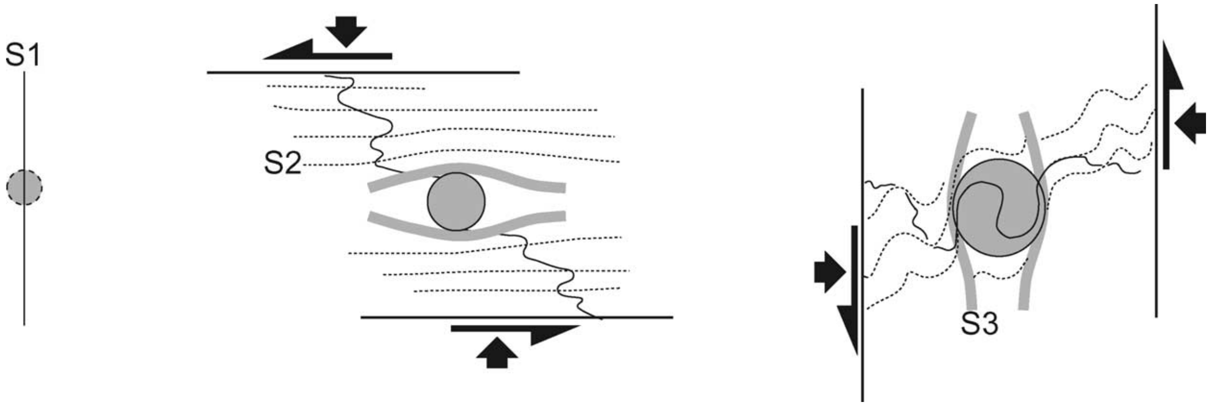

Fig. 3. Sketch showing how a foliation (S_1) may wrap 180° around a porphyroblast while elsewhere in the rock, the same foliation only experiences an average of 90° rotation.

shadow region (Fig. 1d). This implies a yield strength of the strain-shadow material, and hence, that a viscoplastic rheology may be a better starting point for modeling than purely viscous behavior.

4. Evidence for a 'non-rotation' origin of spirals

A complete range of spiral geometries between continuously curving and sharply truncational have been observed in the same rocks (e.g. Hayward, 1992), so that a common origin of both end-member types is generally not disputed. Jiang and Williams (2004), following Passchier et al. (1992), state that truncations do not necessarily reflect polyphase deformation, but rather variations in porphyroblast growth-rate during progressive deformation. However, this interpretation fails to account for well-developed preferred orientations of truncation surfaces quantitatively established in a number of orogens. Bell and Johnson (1989) were the first to notice that truncation surfaces in spiral-shaped and other types of complex inclusion-trails commonly align along vertical and horizontal axes. Subsequently, Hayward (1992) demonstrated similar preferred orientation to be spectacularly developed in the classic 'snowball garnet' area of Rosenfeld (1970), and comparable discoveries have been made in other regions since then (Bell and Chen, 2002 and references cited therein). The orthogonal orientation patterns are matched in the horizontal plane by pronounced single, bimodal, or multi-modal preferred trends of inclusion trails (e.g. Bell and Chen, 2002; Aerden, 2004). The different modal peaks have been shown to correspond to successive porphyroblast growth stages, which exhibit consistent core–rim relationships in thin sections, and yield consistent radiometric ages (Bell and Welch, 2002). This data has been generally attributed to repeated stages of (transient) gravitational collapse during continuous plate convergence, with changes in crustal shortening direction possibly indicated by distinctive inclusion-trail trends. Alternative mechanism potentially capable of generating succession of subhorizontal and subvertical foliations in the crust were considered by Johnson (1999), who even speculated about the possibility of periodic increments of 90° porphyroblast rotation.

Jiang and Williams (2004), however, simply ignore this data and only consider a (hypothetical) sketch of a continuously curving spiral (fig. 5) after Johnson (1993, fig. 9). The same author published high-quality photographs of what Jiang and Williams (2004) consider some of the best examples of continuously curving trails. Detailed geometric analysis of these microstructures reveals important differences with respect to Schoneveld's model (Fig. 4a), which have not yet been sufficiently pointed out in the previous literature. Accurate line diagrams (Fig. 4b–d) show how inclusion-trail curvature is produced as a series of relatively straight segments separated by inflexion points. Truncations are also present even though these are the most continuously curving spirals Johnson (1993) found in his samples (Johnson, 2005, personal communication). Careful tracing of inclusion trails, inflexion points and truncation surfaces reveals their subtle, yet distinctly orthogonal character and tendency to align with the Earth's surface. This evidence matches data presented in fig. 12 of Johnson (1993) where he plots the total amount of inclusion-trail curvature as measured in 28 spirals from the same sample. The measured values cluster about multiples of 90°. Thus, even the most continuously curving natural spirals contain geometric elements that witness their common origin with sharply truncational spirals with more explicit subvertical and subhorizontal preferred orientations.

Wegener's theory of continental drift was long opposed by geophysicists who relied on invalid assumptions and gave insufficient weight to new geological evidence. Jiang and Williams (2004) make a similar mistake with respect to porphyroblast 'non-rotation'. They should critically reconsider the assumption of fluid-flow behavior, and explore new models capable of explaining all existing porphyroblast data.

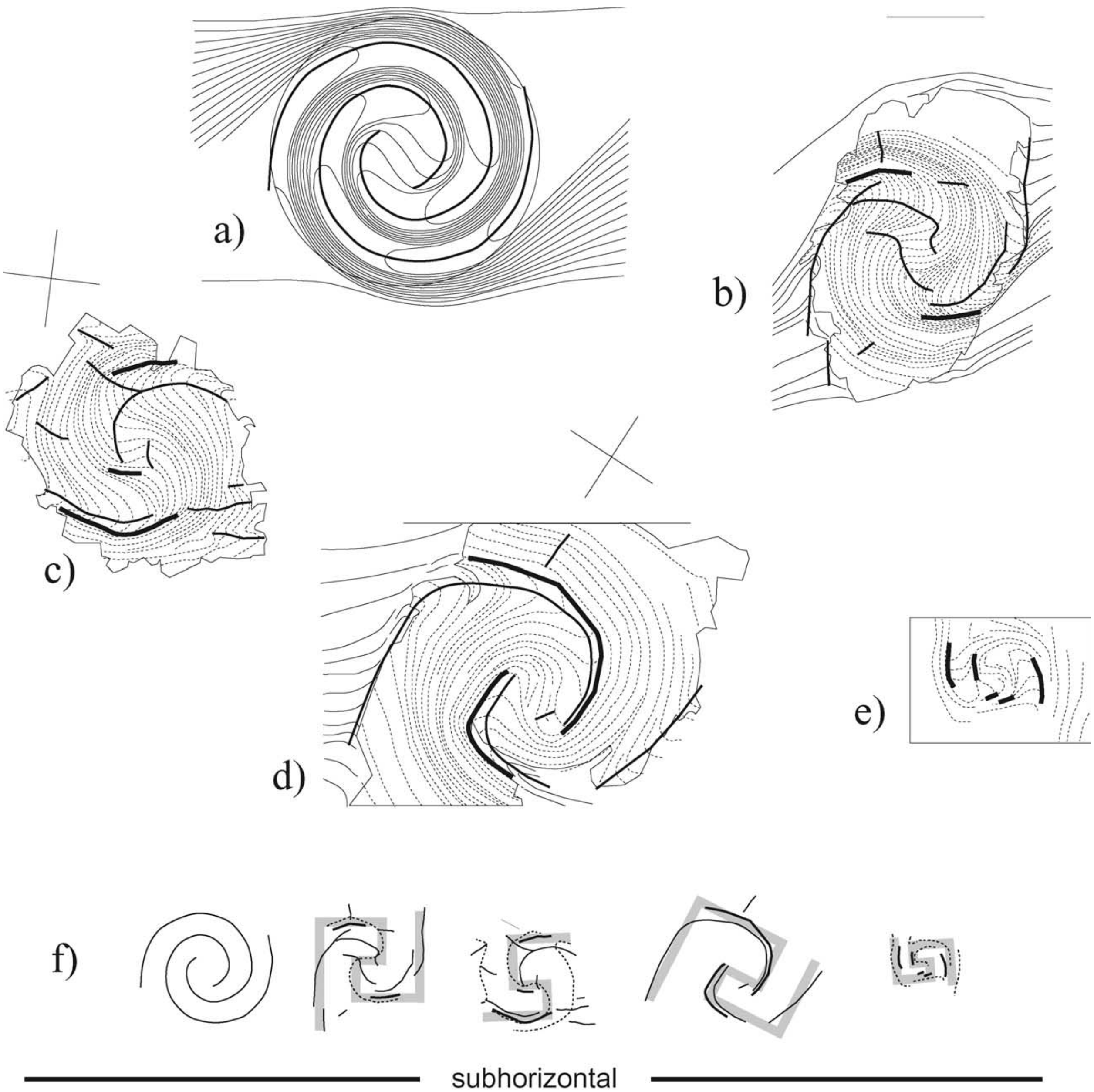

Fig. 4. (a) Spiral geometry produced by Schoneveld (1979). Inflexion points (solid lines) define perfect spirals. (b)–(d) Line tracings of SSIT of Johnson (1993, figs. 6b, 8 and 10), in which inflexion-points (solid continuous lines) and truncations (extra solid lines) define orthogonal elements aligned with the Earth's surface (subhorizontal). (e) Same exercise for a spiral in Ikeda et al. (2002) interpreted to have rotated by these authors. (f) Summary sketches with solid gray lines highlighting the orthogonal character of these inclusion trails.

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