A new spin on 'non-rotating' porphyroblasts: implications of cleavage refraction and reference frames

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Abstract

It has been claimed that rigid porphyroblasts which grow before or during folding and concurrent cleavage development do not rotate with respect to the geographical reference frame (GRF), even if the straining is non-coaxial (Bell 1985; Bell and Johnson 1990). The explanation offered is based on strain partitioning. It is argued that the initial orientations of early fabrics included as internal foliations (S_i) in the porphyroblasts have been preserved after polyphase deformation, and even after successive orogenies. According to the strain partitioning model, the porphyroblasts are fixed in domains of coaxial straining (microlithons) and are isolated from the non-coaxial straining associated with the enveloping septa (S_e). This hypothesis, and also its discussions both pro and contra, suffer from insufficient attention to reference frames. We therefore attempt to demonstrate: (a) the need for rigorous treatment of reference frames in geological interpretations; (b) that, in a folding situation, grains that do *not* rotate with respect to their immediate matrix generally rotate with respect to the GRF; (c) that lack of porphyroblast rotation with respect to the GRF demands a rare folding mechanism (slip fold model); and (d) that the non-rotation hypothesis is in conflict with heterogeneous deformation (cleavage refraction). Finally, we question the validity of the evidence in a study by Fyson (1980), cited in support of non-rotation with respect to the GRF during folding. Fyson reported orientations of S_i that are constant, after folding, over a large area; this scenario is a product of selective data acquisition. In summary, our investigation shows that the lack of porphyroblast rotation with respect to a GRF during folding, while possible, is not universal. The development of microstructures (e.g. curved S_i) is only related to the local deformation path, the characterisation of which does not rely on the GRF. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The analysis of textures in porphyroblasts has proven very useful in elucidating the tectonometamorphic evolution of various areas, particularly in rocks in which matrix fabrics have been transposed into composite foliations during multiple deformation and/or obscured by coarsening or dissolution. In such rocks, internal foliations in porphyroblasts (S_i) are commonly the only evidence of earlier fabrics. Sigmoidal S_i may provide information on certain developmental stages of an external fabric (S_e), for example a crenulation cleavage, and variations of S_i geometries in different porphyroblast phases may permit the correlation of the growth sequence of metamorphic assemblages with the corresponding increments of small-scale deformation (e.g. Zwart, 1960, 1962; Spry, 1969; Vernon, 1977, 1978; Bell and Rubenach, 1983). Criteria for the interpretation of

porphyroblast–matrix relationships have been established (e.g. Zwart, 1960, 1962; Spry, 1969; Vernon, 1977, 1978). Ambiguities may remain, however, where S_i and S_e are discontinuous (e.g. Ferguson and Harte, 1975; Williams, 1985; Visser and Mancktelow, 1992; Johnson and Vernon, 1995; Bell et al., 1997).

Based on a graphical strain partitioning model (Bell, 1981, 1985, fig. 1, 1986), it has been argued that porphyroblasts do not rotate with respect to the geographical reference frame (GRF) during non-coaxial heterogeneous ductile deformation (e.g. Bell, 1985, 1986; Bell and Johnson, 1989, 1990, 1992; Steinhardt, 1989; Hayward, 1990; Johnson, 1990, 1992; Bell et al., 1992c; Aerden, 1994, 1995; Bell and Forde, 1995; Bell and Hickey, 1997; Hickey and Bell, 1999). If the non-rotation hypothesis was correct, then oriented hand specimens would be sufficient for deciphering the sequence of tectonometamorphic events in a spatial context (Bell et al., 1995, 1997). Hence, complex S_i would permit the reconstruction of the original orientation of fold axes, and even of orogenic events and plate movements (Bell and Johnson, 1989; Hayward, 1990; Bell et al., 1995).

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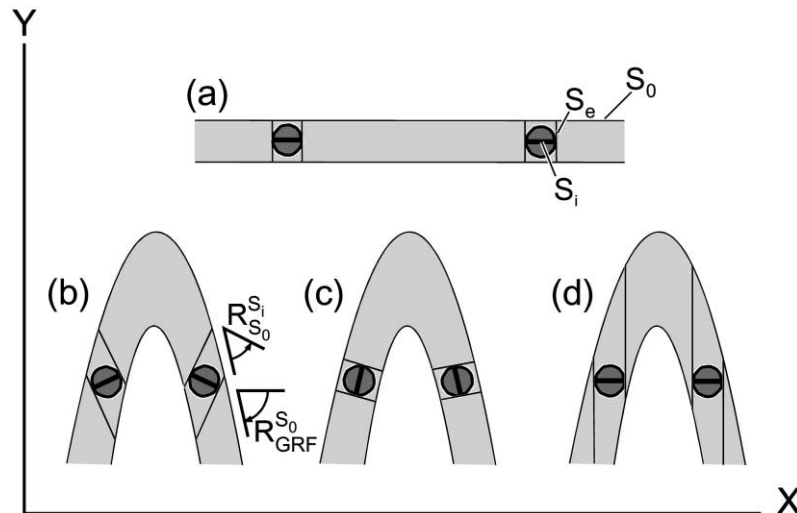*E-mail address:* jkraus@sem.gov.sk.ca (J. Kraus).

Fig. 1. Theoretical porphyroblast–bedding–cleavage relationships during folding without relative rotation between S_i and S_e. Reference frame is pinned to geographical coordinates (X, Y). Fold shapes are schematic. (a) Porphyroblasts overgrow a bedding-parallel fabric (S_0); an enveloping cleavage (S_e) is initiated during layer-parallel shortening that precedes folding. Three distinct further developments: (b) either, porphyroblasts rotate with respect to the GRF and with respect to S_0; (c) or porphyroblasts rotate with respect to the GRF but remain fixed with respect to S_0; (d) or porphyroblasts rotate with respect to S_0, but not with respect to the GRF.

In our opinion, there are major defects in the non-rotation hypothesis of Bell (1985, 1986), which have not been conclusively refuted by previous writers, who argued in favour of porphyroblast rotation (with respect to the GRF) (Passchier et al., 1992; Wallis, 1992; Lister, 1993; Henderson, 1997). Therefore, in this paper we rigorously investigate the roots of the problem inherent in the non-rotation hypothesis and adherent to the discussion of porphyroblast–matrix relationships in general; we discuss ambiguous data presentation and inconsistent use of reference frames. Although it has long been known that rotation is relative and hence reference-frame dependent, this axiom, as noted by Means (1994), is commonly neglected. The fact that such oversight flaws structural interpretations and models makes the present discussion necessary. In detail, we demonstrate both in theory and in a natural example that rotation of rigid objects with respect to the GRF during non-coaxial heterogeneous ductile deformation *does* exist and is *independent* of the strain partitioning model of Bell (1985, 1986). We also question the interpretations by others of the study by Fyson (1980), which has been frequently cited in support of porphyroblast non-rotation with respect to the GRF.

2. Structural settings considered

Porphyroblast–matrix ($= S_i – S_e$) relationships are generally discussed for two structural environments: shear zones and folds that formed outside of shear zones, in which the porphyroblasts grew either pre- or synkinematically (we distinguish both environments because of their different deformation histories, and reference to folds is to such folds throughout the paper). In a shear zone, the c-planes, which are (sub-)parallel to the shear-zone boundaries are usually referred to as S_e, relative to which porphyroblasts rotate. In a fold environment, a domainal axial-plane foliation is commonly referred to as S_e (unless no axial-plane cleavage develops, in which case bedding or a bedding-parallel fabric is taken as S_e). The amount of strain, and hence the magnitude of slip on S_e and the resulting rotation with respect to S_e, are expected to be much larger in the shear zone than in a fold. Consequently, genuine spiralling of S_i *sensu* Bailey (1923), Rosenfeld (1970) and Schoneveld (1977, 1979) (i.e. angles greater than 90°) occurs only in a shear zone. In a fold, smoothly curved (sigmoidal) S_i (i.e. angles smaller than 90°) in synkinematic porphyroblasts may constitute former matrix crenulations and thus preserves increments of axial-plane cleavage (S_e) development. In most reported shear zone cases and in folds without an axial-plane cleavage, S_i represents the same foliation as S_e, but S_e is transposed, whereas in folds with an axial-plane cleavage S_i and S_e represent two distinct generations of fabric. Another marked difference is that, in so far as S_e is fixed in orientation with respect to the shear zone boundary, S_e is also fixed with respect to the GRF during shear zone deformation, because, in general, a shear zone as a whole does not rotate with respect to the GRF. In contrast, on a fold limb during fold amplification, the axial-plane cleavage is commonly rotated with respect to S_0, so that the cleavage is refracted from layer to layer (e.g. Hobbs et al., 1976, p. 216; Williams, 1979; Henderson et al., 1986; Kraus and Williams, 1998), and the whole fold limb (S_0) rotates with respect to the GRF.

The discussion of porphyroblast rotation with respect to the GRF is commonly reduced to the question of whether the porphyroblast has rotated with respect to its immediate matrix, and thus centres upon the interpretation of local
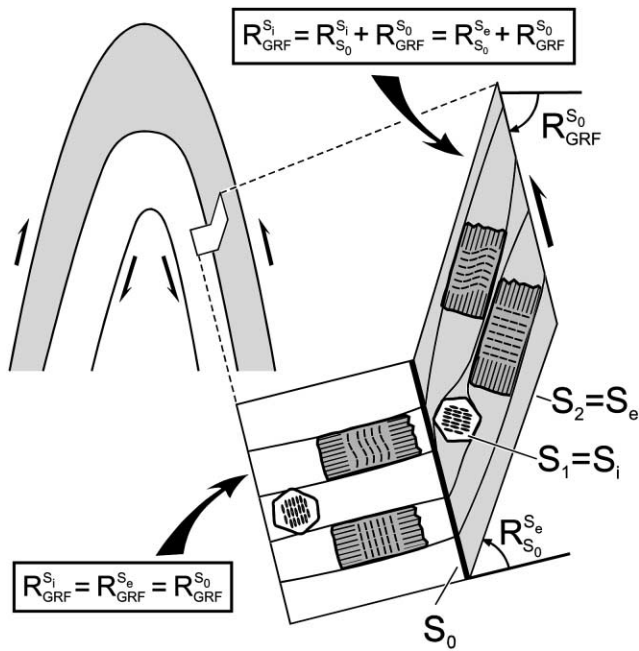
$$R_{GRF}^{S_i} = R_{S_0}^{S_i} + R_{GRF}^{S_0} = R_{S_0}^{S_e} + R_{GRF}^{S_0}$$

$$R_{GRF}^{S_i} = R_{GRF}^{S_e} = R_{GRF}^{S_0}$$

Fig. 2. Schematic bedding–cleavage–porphyroblast relationships during F_2 folding in metaturbidites at Snow Lake, Manitoba, Canada. Garnet and biotite porphyroblasts overgrew an S_0-parallel S_1 early and thus contain straight to smoothly sigmoidal S_i. During fold amplification, the porphyroblasts retained their orientation with respect to S_e ($= S_2$), but, depending on layer competency, rotated through different angles with respect to the GRF; in incompetent mudstone (stippled), the porphyroblasts have rotated with respect to S_0, but not in competent greywacke (white). Within an individual thin bed, at thin-section scale, S_i in neighbouring porphyroblasts has similar orientations.

deformation paths. Such local deformation paths are inferred from inclusion trail geometries and porphyroblast–matrix relationships. For example, porphyroblasts, which have overgrown crenulations on a fold limb, are generally considered not to have rotated with respect to the GRF (e.g. Bell, 1985, 1986; Vernon, 1988; Johnson, 1990; Bell et al., 1992a; Barker, 1994; Bjørnerud and Zhang, 1994; Williams, 1994). This conclusion is invalid because, if both cleavage refraction and rigid body rotation of any small domain on a fold limb during fold amplification are taken into account, the characterisation of these local deformation paths does not rely on the GRF. In other words, inclusion trail geometries and porphyroblast–matrix relationships, when taken out of context with the fold, constitute no evidence of porphyroblast rotation (or lack thereof) with respect to the GRF.

If evaluating porphyroblast rotation with respect to the GRF, it is necessary: (1) to distinguish between the structural environments a priori and the basis for the distinction must be given, (2) to specify S_e and its relationship to the associated large structure, and (3) to carefully correlate the local and the larger-scale deformation path(s). This is missing in many published accounts.

In this paper, we consider folds with straight to sigmoidal S_i in porphyroblasts. The porphyroblasts grow early in the

history of a folding event, while a domainal axial-plane cleavage (S_e) gradually develops, so that S_i predates S_e. These are the relationships found in most published examples discussing the lack of porphyroblast rotation with respect to the GRF (e.g. Fyson, 1975, 1980; Bell, 1985, 1986; Vernon 1988; Reinhardt and Rubenach, 1989; Steinhardt, 1989; Johnson, 1990; Bell and Forde, 1995; Henderson, 1997; Williams and Jiang, 1999). Further, in all our examples, S_i and S_e have not rotated relative to each other (Fig. 1). This is far from true in general (for a detailed discussion of the relative rotation of S_i and S_e, see Williams and Schoneveld, 1981, and references therein).

3. Rotation and reference frames—general remarks

Rotation is defined here to be a finite change of orientation relative to an arbitrary, but specified, reference frame (e.g. Sander, 1930, pp. 9–13, 1948, pp. 63–66; Hobbs et al., 1976, pp. 31–32; Passchier, 1987; Means, 1994; Passchier and Trouw, 1996, p. 176). The choice of reference frames is subjective (Sander, 1948, p. 63; Means, 1994). Failure to specify a reference frame, and to refer to it consistently, has been recognised as a major problem in the argument about porphyroblast rotation (Visser and Mancktelow, 1992; Wallis, 1992; Lister, 1993; Mancktelow and Visser, 1993; Means, 1994; Kraus and Williams, 1995; Williams and Jiang, 1999). Many writers do not specify a reference frame and may imply rotation with respect to the GRF, while others do not distinguish between rotations occurring with respect to different reference frames.

In folding, rotation is commonly referred to as one or more of six distinct reference frames. One of them (GRF) can be regarded as fixed on Earth. The other five reference frames, attached to S_0, S_e, S_i in neighbouring porphyroblasts, the fold's axial plane, and to the directions of maximum and minimum stretching *at any instant* (instantaneous stretching axes), are local and may be *non-fixed* (i.e. they may, over a time interval, have rotated) with respect to: (a) each other, and (b) the GRF.

A porphyroblast containing an S_i may have rotated on a fold limb with respect to the enveloping axial-plane cleavage (S_e) by $R_{S_e}^{S_i}$ (R denotes the magnitude of rotation; the subscript and superscript denote the reference frame and the rotating object, respectively). If S_e has also rotated with respect to layering (S_0), then the magnitude of rotation of S_i with respect to S_0 is:

$$R_{S_0}^{S_i} = -R_{S_i}^{S_0} = R_{S_e}^{S_i} + R_{S_0}^{S_e} \quad (1)$$

As the fold limb (S_0) itself rotates with respect to the GRF, the rotation of S_i with respect to the GRF can be written:

$$R_{GRF}^{S_i} = R_{S_e}^{S_i} + R_{S_0}^{S_e} + R_{GRF}^{S_0} \quad (2)$$

Eqs. (1) and (2) are valid for both rotation rates (angular velocities) and finite rotations in three dimensions. If the
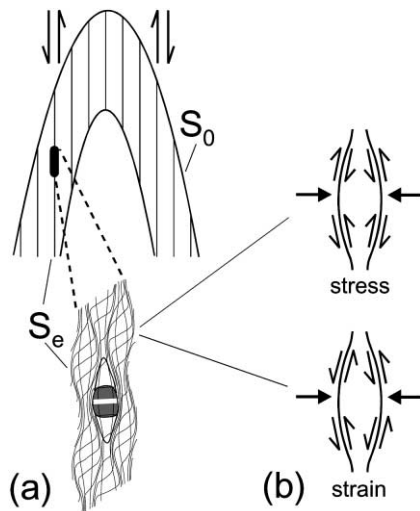
Fig. 3. Shearing on an axial-plane cleavage as a hypothetical folding mechanism that allows porphyroblasts not to rotate with respect to the GRF ($S_0 = S_i$ remains horizontal). (a) Note the opposite shear sense along S_e on the two fold limbs. Schematic after Steinhardt (1989). (b) The resolved shear stresses on the cleavage segments locally oppose the inferred shears and therefore this scenario is mechanically impossible.

sum of the relative rotations is zero, then $R_{GRF}^{S_i} = 0$. Obviously, any two reference frames are *mutually incongruent* so that the different relative rotations are not kinematically equivalent. Further, rotation is independent of scale so long as a reference frame is specified.

4. An example of porphyroblast rotation with respect to the GRF—the implications of cleavage refraction

Owing to the fact that rocks preserve finite strains, it is impossible to unambiguously reconstruct the orientations of primary layering and rigid porphyroblasts prior to a given folding event. The first folds (F_1) constitute an exception, because they generally deform originally horizontal layers. We are not aware of a reported case in which the first folding affected rocks at medium-grade regional metamorphism that allowed porphyroblast growth. Although it may be impossible to reconstruct spatial strain and rotation paths, it can sometimes be unambiguously shown that at least some porphyroblasts have rotated with respect to the GRF during a folding event subsequent to F_1. Such a case arises when S_i in neighbouring porphyroblasts were parallel prior to folding, and the porphyroblasts have rotated relative to each other during folding (Fig. 2). On the other hand, parallelism of S_i in neighbouring porphyroblasts prior to and after folding does not eliminate the possibility that these porphyroblasts have rotated with respect to the GRF.

Our example comes from a metamorphosed well-bedded greywacke–mudstone turbidite sequence in the internal Trans-Hudson Orogen at Snow Lake, Manitoba, Canada (Kraus and Williams, 1998, 1999). The metaturbidites form a large refolded F_2 fold limb and they contain an S_2

domainal cleavage that is strongly refracted in heterogeneously deformed beds. Garnet and biotite occupy the microlithons and enclose straight to weakly curved (sigmoidal) S_i ($= S_1$) that is, independent of S_0/S_2 dihedral angles, at a high angle to the enveloping S_2 septa ($= S_e$). Hence, S_i everywhere varies in orientation from layer to layer, but is consistent in orientation in neighbouring grains (Fig. 2). The porphyroblasts overgrew a bedding-parallel S_1 before S_2 existed and during the early stages in the formation of the F_2 fold. S_2 was originally at a high angle to S_0 ($= S_i$) (Fig. 1a). During folding, the bulk deformation was partitioned so that, depending on layer competency, S_2 rotated differentially with respect to S_0 between 0 and 80° (Figs. 1b,c and 2). Thus, at the thin-section scale, neighbouring garnet and biotite grains in the same fine layer did not rotate noticeably either relative to one another or with respect to S_2. Locally, where S_2 was subsequently crenulated by F_3, S_i remained sub-orthogonal to the enveloping S_2 septa around the F_3 crenulations. As expected, most of these porphyroblasts have rotated with respect to the GRF during F_2 and F_3. Nonetheless, the magnitude of rotation of the individual porphyroblasts with respect to the GRF cannot be quantified because the geographical orientation of bedding prior to F_2 folding cannot be reconstructed. Hence, the GRF is of limited use for small-scale kinematic analysis in folds unless the porphyroblasts did not rotate with respect to the GRF.

5. The non-rotation hypothesis of Bell

Bell (1985, 1986) and some subsequent writers (e.g. Bell and Johnson, 1989, 1990; Johnson, 1990; Bell et al., 1992a,b,c; Bell and Forde, 1995; Hickey and Bell, 1999) have claimed that non-deformable, synkinematic porphyroblasts never rotate with respect to either the GRF or S_e (enveloping cleavage septa) during bulk non-coaxial heterogeneous ductile deformation, associated with the development of a domainal cleavage (Fig. 1a,d). According to Bell (1985, fig. 1), non-rotation of porphyroblasts with respect to cleavage septa arises from deformation partitioning; cleavage septa (S_e) alone accommodate the non-coaxial part of deformation, whereas the microlithons are domains of coaxial deformation (see also Williams and Schoneveld, 1981, p. 312). Non-rotation with respect to S_e is indicated by the parallelism of the axial planes of curved S_i with S_e and by the parallelism of S_i in neighbouring porphyroblasts of the same phase (cf. Bell, 1985, fig. 3b). From this, it has been concluded that porphyroblasts never rotate with respect to the GRF and thus preserve orientations of earlier foliations (e.g. Bell, 1985, p. 115, 1986; Bell and Johnson, 1989, 1990; Hayward, 1990; Bell et al., 1992a,b,c, 1995). This conclusion is based on the assumption that the axial-plane cleavage (S_e) does not rotate relative to the GRF during folding, implicitly requiring that folds form according to the slip fold model or variations thereof
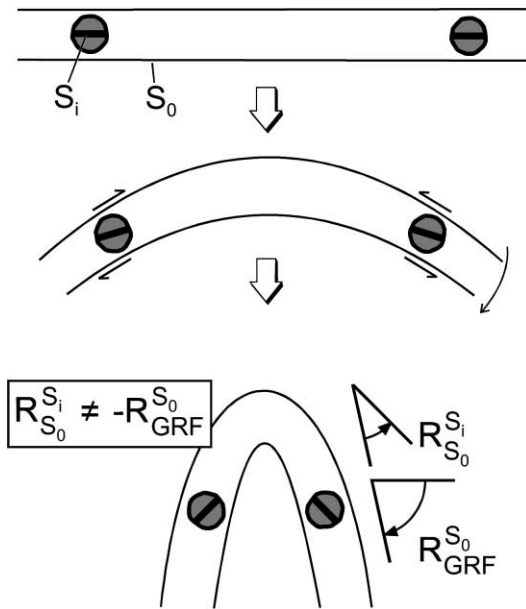
Fig. 4. Lack of balancing of bed rotation (with respect to the GRF) and the relative rotation between porphyroblast and bedding in a flexural-flow fold (see Williams and Jiang, 1999). The porphyroblasts enclose the fossil S_0 as S_i. Modified from Bell and Forde (1995).

(Fig. 3) (Schmidt, 1932, p. 84; de Sitter, 1956, p. 168; Turner and Weiss, 1963, p. 480; Bell, 1981; Steinhardt, 1989, fig. 10b; Bell and Johnson, 1992, fig. 13; Hayward, 1992, fig.16a; Bell and Hickey, 1997, fig. 11), or according to a special case of the flexural-flow fold model (Fig. 4) (Turner and Weiss, 1963, p. 473; Donath and Parker, 1964) that requires exact balancing of the relative rotations ($R_{S_0}^{S_i} = R_{S_0}^{S_e} = -R_{GRF}^{S_0}$) (Steinhardt, 1989, fig. 10a; Johnson, 1990; Hayward, 1992, fig. 16a; Bell and Forde, 1995, fig. 1; Bell and Hickey, 1997, fig.10).

According to the slip fold model ('Gleitbrettfaltung' of Schmidt, 1932), folds form by heterogeneous simple shear along cleavage planes that are parallel to the fold's axial plane while bedding is mechanically inactive. A variation of

the model allows shortening across the "Gleitbretter" as they move past one another (de Sitter, 1956). In yet another variation (the progressive bulk inhomogeneous shortening model of Bell, 1981), the slip planes are anastomosing (Fig. 3). The resulting folds are similar folds in each case. The slip fold model has been questioned on mechanical grounds (Hobbs et al., 1976, pp. 193–195) and we extend these doubts to the variations of the model. In particular, the systematic reversals of shear sense along (perfectly or statistically) parallel cleavage planes on opposite fold limbs, required to produce fold trains, are difficult to account for (see shear arrows in Fig. 3a). In fact, in the Schmidt and de Sitter models, there should not be any slip on the cleavage planes, because the latter are orthogonal to the direction of the maximum principal stress. Similarly, in the progressive bulk inhomogeneous shortening model, shear opposes shear stress on alternate segments of the anastomosing cleavage planes (Fig. 3b). Moreover, slip folds do not accommodate much crustal shortening, although, even if the models were applicable, the near-ubiquity of cleavage refraction, albeit small in some cases, indicates that slip folds are rare.

The other way by which porphyroblasts need not to rotate with respect to the GRF is in response to S_0-parallel shear during formation of parallel folds. Such a situation is given where folding approximates the flexural-flow fold model, shear is homogeneously distributed throughout the fold limb, and $R_{S_0}^{S_i} = -R_{GRF}^{S_0}$ (Williams and Schoneveld, 1981; Johnson, 1990; Bell and Forde, 1995; Bell and Hickey, 1997), and therefore $R_{GRF}^{S_i} = 0$. The latter would be a special case incompatible with cleavage refraction, which proves heterogeneity of any S_0-parallel shear. Further, Williams and Jiang (1999) have demonstrated that, in any small domain on the limb of a flexural-flow fold, $R_{S_0}^{S_i}$ and $R_{GRF}^{S_0}$, although opposite in sign, are unlikely to be equal in magnitude, and therefore $R_{GRF}^{S_i}$ is unlikely to be zero (Fig. 4). Thus, even if Bell's strain partitioning model were correct, porphyroblasts should still, in general, and in the Snow Lake example described here (Figs. 2 and 5), in particular, rotate with respect to the GRF. To avoid this logical
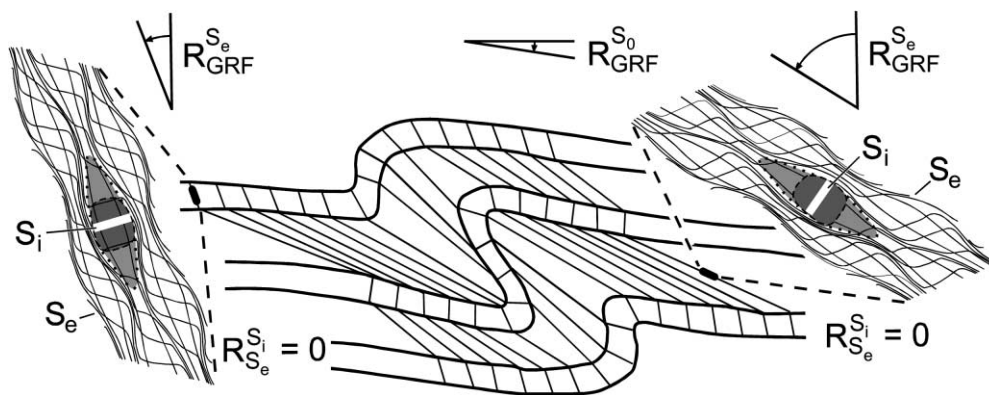

Fig. 5. A strain field diagram as in Bell (1985, 1986), but drawn for an asymmetrical fold with refracted axial-plane cleavage, shows that $R_{S_e}^{S_i}$ and $R_{GRF}^{S_i}$ are unrelated. Bedding ($S_0 = S_i$) assumed to have been horizontal prior to folding.
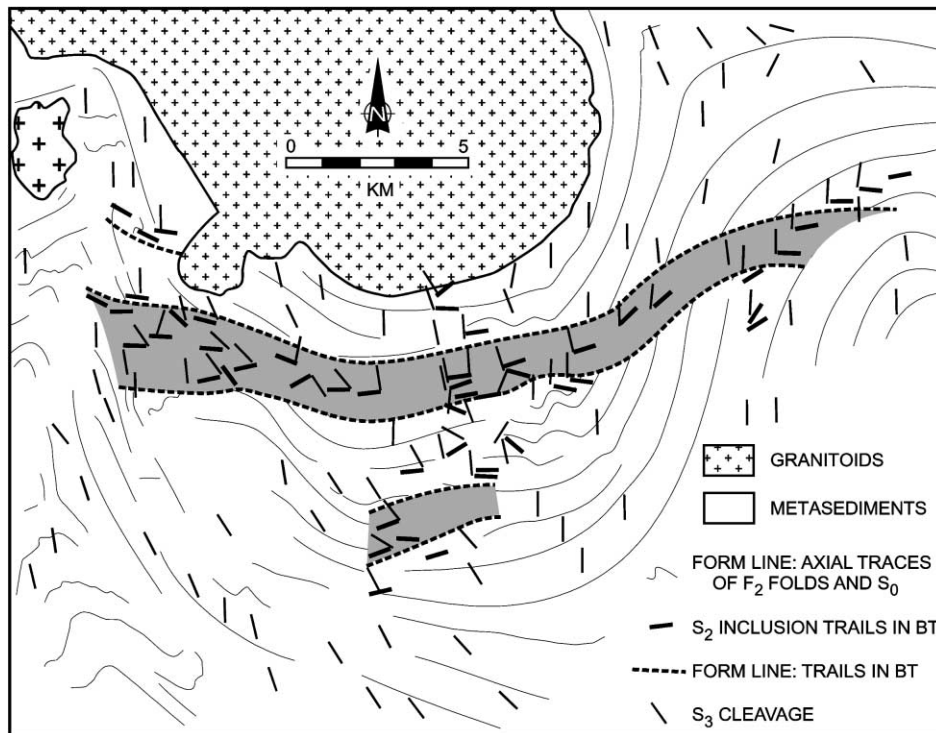
Fig. 6. Form surface map, Cleft Lake area, Northwest Territories, Canada, illustrating the relationships of the regional S_2 foliation, S_3 cleavage, and trend of S_i in biotites. Note S_i–S_e relationships. Shaded areas highlight zones of relatively high sample density. Modified from Fyson (1980).

problem, proponents of non-rotation with respect to the GRF generally consider the porphyroblasts out of context. Commonly, their discussion concentrates upon one or a few particular thin sections or hand specimens, and only the relationship of the porphyroblast to the cleavage is taken into account, not that of the cleavage to the fold, except perhaps by a statement or implication that the cleavage parallels the fold's axial plane (e.g. Bell, 1985, 1986; Bell and Johnson, 1989, 1990, 1992; Johnson, 1990; Bell et al., 1992a,b; Hayward, 1992; Aerden, 1995; Bell and Forde, 1995; Bell and Hickey, 1997; Hickey and Bell, 1999).

6. Fyson's inclusion trail form surface lines—an argument for lack of porphyroblast rotation with respect to the GRF?

Fyson (1980) is commonly quoted as an example of porphyroblasts that have not rotated relative to the GRF. Therein, S_i orientations in biotite in a greywacke–mudstone sequence were connected between grains and plotted as "form lines"; these form lines trend east–west for some 20 km in a 5-km-wide corridor across the axial plane of a large-scale subvertical, symmetrical F_3 fold (Fig. 6). Cleavage morphologies and refraction patterns, dimensional and crystallographic preferred orientation of biotite parallel to the cleavage, sub-orthogonal S_i–S_e relationships, and the relative timing between cleavage development and

porphyroblast growth are identical to the relationships at Snow Lake. The biotite porphyroblasts overgrew a straight to slightly curved S_2 during the early stages of an S_3 crenulation cleavage development and thus developed early during large-scale F_3 folding (cf. Hobbs et al., 1976; Williams, 1979; Kraus and Williams, 1998). At the thin-section scale, S_i is approximately parallel from one biotite to the next. Fyson (1980) concluded that the porphyroblasts did not rotate noticeably relative to one another and that S_i records the fossil orientation of an S_2.

Fyson's S_i form lines have been regarded as both an example of, and a general proof of, porphyroblast non-rotation with respect to the GRF (e.g. Jamieson and Vernon, 1987; Vernon, 1988, 1989; Reinhardt and Rubenach, 1989; Bell and Johnson, 1990; Gibson, 1992; Hayward, 1992; Phillips and Key, 1992; Williams, 1994; Bell and Forde, 1995; Stewart, 1997; Ilg and Karlstrom, 2000). We disagree with these interpretations for the following reasons: (1) S_i in biotite is not always parallel across the fold at Cleft Lake, but locally varies in orientation by up to 90° (Fig. 6) (see Passchier et al., 1992; Visser and Mancktelow, 1992), and (2) the shape of the form lines reflects consideration of selective data.

Visser and Mancktelow (1992) recognised a consistent pattern of S_i across Fyson's F_3 fold (cf. Fig. 7), which corresponds to the pattern in garnets across a minor fold at Lukmanier pass, Central Alps (Visser and Mancktelow, 1992, fig. 7). In both cases, S_i form lines are not straight
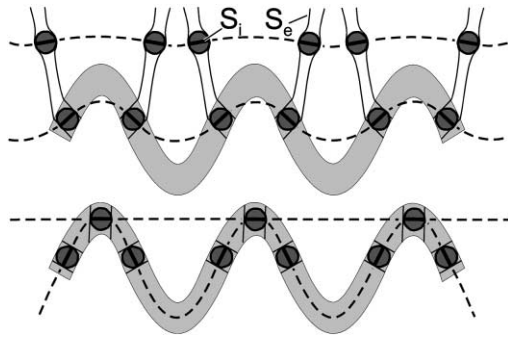
Fig. 7. Two-layer model demonstrating that the geometries of inclusion trail form lines (dashed) are a function of the layers' rheology. It is inferred that the porphyroblasts overgrew a bedding-parallel fabric prior to folding and no relative rotation of S_i and S_e has occurred. On the fold limbs the more competent beds (shaded) record lower non-coaxial strain and thus smaller amounts of porphyroblast rotation with respect to S_0 than the more incompetent beds (unshaded). Form lines become straighter with decreasing rock competency. The intersecting form lines in the lower half of the diagram demonstrate the general subjectivity of such lines.

but describe 'folds' which are more open than the related major fold. Visser and Mancktelow (1992) believed that these patterns arose from counteracting relative rotations. It is apparent that the opening angle of a 'form line fold' systematically decreases with increasing $R_{S_0}^{S_i}$ as a function of shear strain on the fold limbs and the form lines theoretically become straight, if the counteracting relative rotations balance (Fig. 7). Therefore, high layer-parallel shear strains (and subsequent fold flattening) may give rise to little porphyroblast net-rotation with respect to the fold's axial plane.

Fyson's (1980) openly curved form lines are not objective, because sampling was restricted to pelitic beds (Fyson, personal communication 1997), where, on the fold limbs, non-coaxial deformation, and therefore $R_{S_0}^{S_e}$, was maximised (cf. Figs. 2 and 5). There are no inclusion-trail data reported for the competent beds. Fyson (1980), however, reported a strong cleavage refraction between greywacke and mudstone layers. Two situations are possible in the less strained competent layers: (1) Most likely, and in analogy to the incompetent beds, $R_{S_e}^{S_i} = 0$ *sensu* Bell, and thus $R_{GRF}^{S_i} \neq 0$ (as in Fig. 1b). Under these circumstances, the form lines would display more complex geometries (Fig. 7); (2) $R_{GRF}^{S_i} = 0$, and hence, taking into account cleavage refraction, $R_{S_e}^{S_i} \neq 0$. This second possibility could justify Fyson's form lines (if $R_{S_e}^{S_i} + R_{S_0}^{S_e} \approx -R_{GRF}^{S_0}$); however, the latter would invalidate Bell's strain partitioning model and the argument for non-rotation. In order to obviate this problem and use Fyson's observations in support of their argument, Bell and Johnson (1990; fig. 1) incorrectly reproduced Fyson's fold as a slip fold with a cleavage truly parallel to the axial plane (as in Fig. 3). In summary, Fyson's (1980) form lines and interpretations are not valid evidence of porphyroblast non-rotation with respect to the GRF, either in his particular, or in the general, case.

7. Concluding remarks

In geological interpretations, reference frames must be treated rigorously: (1) rotation is always relative to and dependent on reference frames; thus, any statement that a porphyroblast is either 'rotated' or 'non-rotated' is pointless without specifying the reference frame; (2) different reference frames are mutually incongruent, so that rotation (or none) with respect to one frame does not imply rotation (or none) with respect to another; hence, the proposal by Bell and coworkers is invalid: that porphyroblasts never rotate with respect to the geographical reference frame (GRF) during deformation and that S_i can therefore be used for the spatial reconstruction of polyphase orogenic events; and (3) local deformation paths inferred from oriented hand specimens and thin sections (using inclusion trail geometries and porphyroblast–matrix relationships), without their larger scale context, are insufficient for such a reconstruction.

A study by Fyson (1980) in which S_i appears to be approximately constant in orientation over a large area after folding, is explained because rotation of the fold limbs with respect to the GRF was approximately equal and opposite to rotation of the porphyroblasts with respect to bedding (i.e. $R_{GRF}^{S_0} \approx -R_{S_0}^{S_i}$). Fyson's S_i-form lines are not representative of the whole sequence because S_i was only considered in incompetent rock units.

Few workers were concerned with geographical coordinates as a reference frame before Bell wrote his papers in 1985 and 1986. The GRF is important for the present discussion, because Bell and coworkers claim that original S_i orientations are preserved throughout several orogenic events. Yet, rigid objects generally change their orientation with respect to the GRF during deformation, but by amounts that in most cases cannot be determined. The development of microstructures is only related to the local deformation path, the characterisation of which does not rely on the GRF.

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