

## The rotation of garnet porphyroblasts around a single fold, Lukmanier Pass, Central Alps: Reply

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THE discussion by Forde and Bell reflects a fundamental difference of opinion on an important principle: can rigid inclusions (such as garnet porphyroblasts) rotate or are they fixed markers which preserve the geographical orientation of the internal foliation at the time of growth? This question has recently been the subject of two papers summarizing the opposing viewpoints (Bell *et al.* 1992, Passchier *et al.* 1992). If porphyroblasts can rotate, the variation in orientation of the internal foliation can be used, for example, to infer possible mechanisms of folding—the aim of our paper (Visser & Mancktelow 1992). If porphyroblasts cannot rotate, they should preserve the original orientation of the internal foliation and any consistent variation in orientation across a fold must be explained by porphyroblast growth at different times during fold amplification—the view of Forde and Bell. It is thus important to consider the basic principle before considering more specific comments raised in the discussion.

There is no such thing as an absolute rotation. Rotation can only be determined relative to some reference axes. Forde and Bell argue for the non-rotation of porphyroblasts but do not explicitly state the reference frame considered. However, previous publications from the same research group cited by Forde and Bell (e.g. Bell & Johnson 1990, Bell *et al.* 1992) consistently claim non-rotation relative to geographical co-ordinates, which forms the basis for their interpretation of inclusion fabrics within porphyroblasts. The question immediately arises as to how the porphyroblasts can determine and maintain their orientation relative to these co-ordinates. Inertial effects can be discounted in slow geological flows and the potential for determining orientation relative to geographical co-ordinates only lies with the magnetic and gravitational fields. Neither field is liable to have a significant influence on the cm-sized isotropic garnet crystals considered in the present study. It follows that the rotation or non-rotation of the inclusions can only be determined by the flow in the surrounding matrix. There is a great body of both theoretical and experimental work (e.g. Einstein 1906, Jeffrey 1922, Burgers 1938, Bretherton 1962, Gay 1968, Cox 1971, Ghosh & Sengupta

1973, Reed & Tryggvason 1974, Ghosh & Ramberg 1976, Ferguson 1979, Fernandez *et al.* 1983, Freeman 1985, Fernandez 1987, Passchier 1987, Van den Driessche & Brun 1987, Ildefonse & Fernandez 1988, Ildefonse *et al.* 1992a,b) which has established that the rotational behaviour of a rigid particle is a function of the flow in the matrix, the elongation and orientation of the rigid particle, and the particle concentration. For the simplest case, an isolated equant rigid inclusion will rotate with the vorticity of the flow in the surrounding matrix, where this vorticity is determined relative to specific reference axes.

Any relative rotation (or non-rotation) established in one reference system can only be transformed into another reference system if the relative rotation between the two reference systems is known independently. Measurements of rigid inclusion rotation relative to the shear direction in an analogue simple shear rig cannot tell us if the rig itself is rotating relative to some other co-ordinates (e.g. the rotation around the Earth's axis). In the field example considered in Visser & Mancktelow (1992), the rotation of garnet porphyroblasts is measured relative to axes fixed to the fold axis and axial plane. These measurements might tell us something about the mechanism of fold formation. They cannot tell us if the fold as a whole has been rotated (or translated) relative to geographical co-ordinates, either by refolding or due to larger-scale block rotations. Major translation and rotation of more or less rigid plates is a fundamental principle of plate tectonics, but rigid body rotations (or 'spin' in the terminology of Means *et al.* 1980) are important on all scales. For example, Neogene relative rotation of more than 50° between kilometre-sized blocks in southern California is well established by palaeomagnetic data (Luyendyk *et al.* 1980, Ross *et al.* 1989). At a smaller scale, spinning coaxial deformation is involved in the development of buckle folds (Lister & Williams 1983, fig. 4), to produce a tangential longitudinal strain distribution in the more competent layer (Ramsay 1967, fig. 7-63). Any porphyroblast within a more competent buckled layer will 'spin' or rigidly rotate, together with the layer. Our paper demonstrates that, for folding by flexural flow, the shear component in the limbs can produce a reverse

rotation which partially counteracts the 'spin' of the limbs. As a result, the preserved internal foliation orientation defines a more open fold, with the opening angle dependent on the elongation of the porphyroblasts. Such internal foliation geometries, which have been cited as evidence for non-rotation (e.g. Bell & Johnson 1990, after Fyson 1980) can therefore also be explained by a flattened flexural flow model for folding in schistose rocks (e.g. Ramsay 1967, pp. 391–393). The observation by Forde and Bell that our paper continues a tradition of similar studies on fold mechanisms derived from porphyroblast rotation underscores the whole point—this is a fruitful field of research which should not be neglected in favour of models which implicitly assume non-rotation.

We will now consider some of the more specific comments of Forde and Bell on the contents of the original paper. As Forde and Bell point out, it is difficult unequivocally to establish that the cores of all the garnet porphyroblasts grew before fold initiation. However, fig. 8 of Visser & Mancktelow (1992) does show that the measured zoning in spessartine content appears to be more closely related to the orientation of the  $S_i$  foliation relative to the  $S_e$  orientation in the core (fig. 8b) than to its geographical orientation (fig. 8a; all four garnet porphyroblasts were measured in a single polished thin section with a constant orientation to the external foliation; the external foliation therefore represents a consistent geographical reference frame). If the compositional variation reflects a change in metamorphic conditions with time, then the consistent composition of the garnet cores (despite the difference in  $S_i$  orientation) indicates that these cores all grew more or less contemporaneously under similar conditions, rather than representing a temporal sequence of garnet nucleation and growth over a progressively folded foliation. Whether growth of the narrow rims was continuous or involved a growth hiatus (i.e. a two-stage process) is not critical to the arguments. Indeed, cation diffusion would tend to eliminate any discrete step in the original composition (e.g. Chakraborty & Ganguly 1990).

Forde and Bell comment that "close examination of the data" presented in fig. 6 of Visser & Mancktelow (1992) does not support our conclusion that the more elongate garnet porphyroblasts (i.e. those with a higher aspect ratio) rotated more than less elongate porphyroblasts. To emphasize the strong dependence of the relative rotation on shape, we have replotted the original data as the dip of the internal foliation vs porphyroblast aspect ratio in Fig. 1. The increase in the dip of  $S_i$  with increasing aspect ratio is very clear, particularly on the limbs of the fold (dip of external foliation  $\geq 45^\circ$ ) where the external foliation is relatively planar—in the fold hinge region smaller-scale parasitic M folds introduce an additional inaccuracy to the determination of the  $S_e$  orientation (Visser & Mancktelow 1992, fig. 4). The dependence of the internal foliation orientation on porphyroblast aspect ratio is consistent with the shape control on rotation behaviour expected from earlier theoretical and experimental studies (e.g. Ghosh &

Ramberg 1976). Forde and Bell propose that the shape of the garnet porphyroblasts is determined by their orientation relative to the "anastomosing pattern of deformation partitioning parallel to the axial plane of the fold". However, a pervasive axial plane foliation comparable to Forde and Bell's fig. 3 is not developed throughout the fold in question; a new crenulation cleavage is only moderately developed in the core of the fold (Visser & Mancktelow 1992, figs. 2, 3 and 4). On the limbs of the fold, where the relationship between porphyroblast shape and  $S_i$  orientation is most clearly established (Figs. 1a . . . f), the overprinting crenulation cleavage is weak or absent.

Forde and Bell's observation that the theoretical curves on fig. 6 in Visser & Mancktelow (1992) vary from plot to plot is correct and reflects a misunderstanding. Each theoretical curve depends on the ellipticity of the particles considered (e.g. fig. 9b, Visser & Mancktelow 1992) and therefore is different for each plot from 6(a), with average ellipticity 1.2, through to 6(e), with average ellipticity of 2. Overlaying the "accurate trend surface" of Forde and Bell's fig. 2a on the trends of Visser & Mancktelow (1992) reveals that the two are identical where there are sufficient data. Although Forde and Bell state that their trend analysis is only for the garnets with ellipticities in the range 1.3–1.7 (i.e. their fig. 2a), their trend lines show a curious steepening in the lower left limb of the fold, in a region where there are no data (only more steeply dipping  $S_i$  values for the ellipticities 1.7–2.1 of fig. 2b, which should not have influenced the analysis). Disregarding this region, superposition of the trend surface lines on their fig. 2(b) still supports, at least to our eyes, the contention that the  $S_i$  foliation of the more elongate porphyroblasts generally dips more steeply than the trend of  $S_i$  in the less elongate porphyroblasts.

In conclusion, despite the limitations in measurement accuracy imposed by natural field examples, the orientation of the internal foliation in the garnet porphyroblasts shows a very consistent pattern dependent on position in the fold (i.e. the orientation of  $S_e$ ) and aspect ratio of the porphyroblasts. As the discussion by Forde and Bell highlights, the interpretation of this data is model dependent. In our opinion, there is sufficient theoretical and experimental evidence for rotation of rigid inclusions controlled by the flow in the matrix, the inclusion shape and the orientation. This model includes the possibility that for some combinations of the parameters an inclusion may not rotate relative to a specific reference frame—a classic example is an equant particle in a pure shear flow relative to a co-ordinate system fixed to the stretching axes. Forde and Bell, however, support a model of general non-rotation (e.g. Bell *et al.* 1992), which requires that the internal foliation included within a porphyroblast should always maintain the same geographical orientation. Considering that a porphyroblast has no way to determine its current orientation relative to this external co-ordinate system, nor does it possess the means to fix its orientation even if it were aware of the geographical co-ordinate system, it has no alterna-

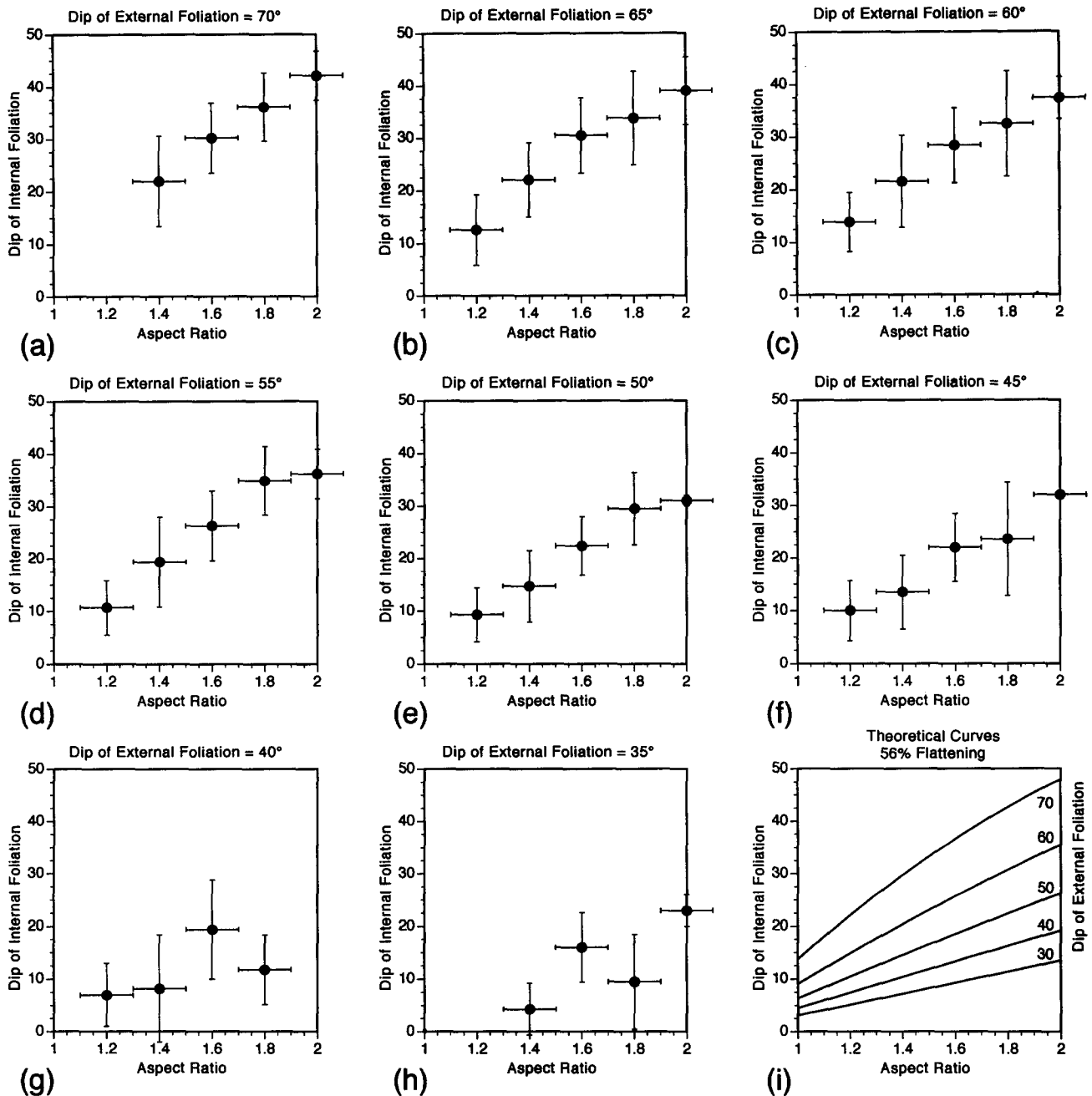


Fig. 1. Plots of dip of the internal foliation  $S_i$  vs the aspect ratio of garnet porphyroblasts for different values of dip of the external foliation  $S_e$ . The data is the same as in fig. 6 of Visser & Mancktelow (1992). Plot (i) shows the theoretical curves for a flexural flow fold flattened 56%, again the same values as for the theoretical curves on the original fig. 6.

tive but to react to the flow in the surrounding matrix. Since deformation involves major translations and rotations of blocks on a range of scales (plates, terrains, nappes, folds, etc.), it is unlikely that many porphyroblasts could have maintained their original geographical orientation during continued orogenesis, although on a chosen scale they may maintain quite constant relative orientations.

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