

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

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VISSER & MANCKTELOW (1992) have attempted to prove rotation of porphyroblasts during non-coaxial deformation by showing an apparent rotation of inclusion trails in garnet porphyroblasts relative to a folded foliation. However, any such fold-porphyroblast geometry, where there is a systematic non-parallelism of inclusion trails that is symmetrical about the fold axial plane, could be explained by overgrowth of the folded foliation during the folding. This creates a problem in interpretation that needs other evidence to resolve it. It is necessary to ascertain that the porphyroblasts pre-date the fold before any apparent rotation can be ascribed to folding. Evidence to show that the porphyroblasts completely predate the fold development is an essential prerequisite for studies of this type.

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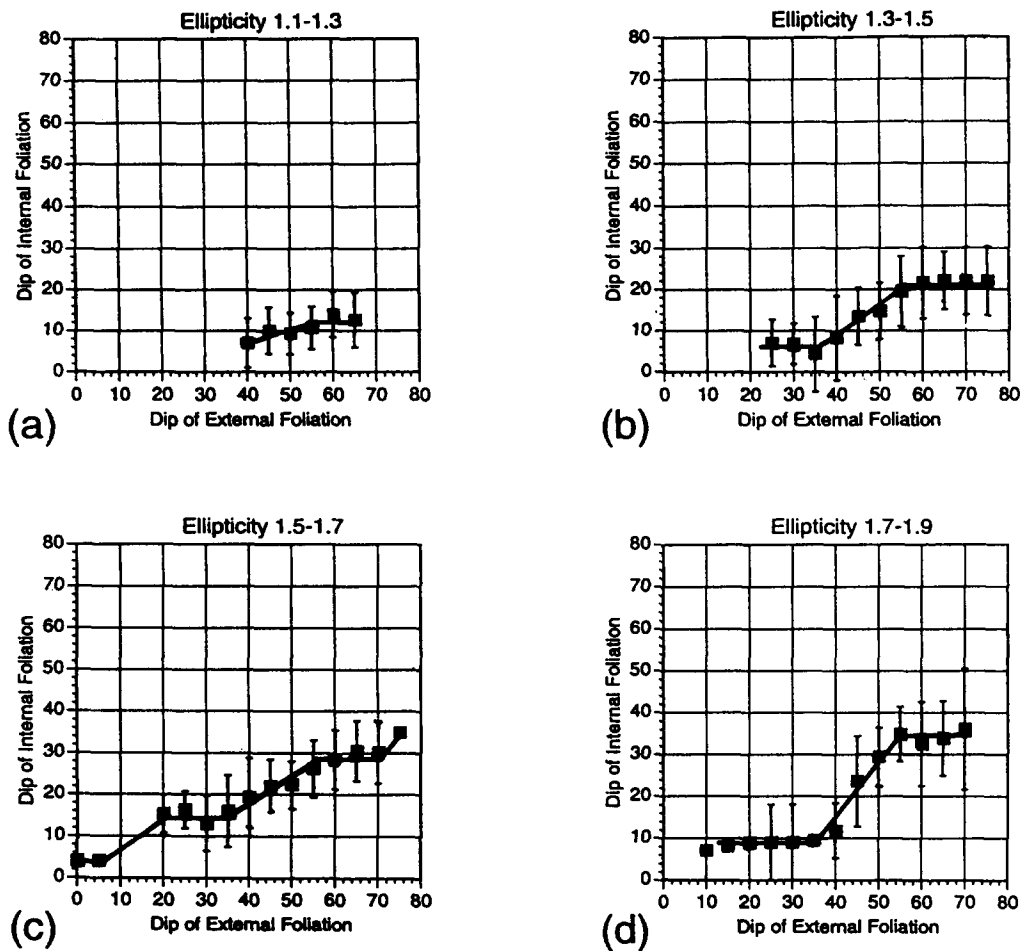


Fig. 1. Graphs of the dip of the inclusion trails vs the dip of the adjacent matrix foliation for porphyroblasts of different ellipticity modified from Visser & Mancktelow (1992). Note the plateaux indicating lack of rotation of the porphyroblasts with increasing rotation of the fold limb between 20° and 35° and between 55° and 70°. The explanation for this distribution is provided within the text.

blast rims. However, their photographs show no hiatus in the microstructural development from the core to the rim of the porphyroblasts. In our experience, some form of heterogeneity (e.g. a change in density, composition or shape of the inclusion trails) is always present along the zone of curvature of the inclusion trails, if the porphyroblast has undergone two stages of growth (Bell & Hayward 1991), even when the inclusion trails are very smoothly curving (Bell *et al.* 1992). Consequently, since the inclusion trails curve on the rims and the axial plane foliation intensifies in the immediately adjacent matrix, there are no criteria to suggest that any portion of the porphyroblasts pre-date the fold (e.g. Bell *et al.* 1986, Bell & Hayward 1991). Similarly, the chemical analyses of four of the garnets show very weak but continuous zoning in spessartine content from core to rim (fig. 8 in Visser & Mancktelow 1992) and no evidence for two stages of growth. The change in spessartine content simply indicates isolation of the zone of progressive shortening containing the garnet porphyroblast from further microfracturing and material access (Bell & Hayward 1991). Because of these flaws in their arguments, Visser & Mancktelow (1992) have not pro-

vided the necessary evidence that the porphyroblasts pre-date the fold.

Visser & Mancktelow (1992) argued that garnets with higher ellipticity have been rotated more than those with less ellipticity. Close examination of their data does not support this conclusion. They tried to fit a curve, corresponding to the best-fit theoretical results for a flexural flow fold 'flattened' 56%, to each ellipticity grouping plot of dip of the internal vs dip of the external foliation. *This curve differs markedly from their data* as well as from plot to plot. Our analysis suggests that rather than matching this curve, their plots indicate a very different distribution involving little or no change in the angle of the internal foliation as the external foliation rotates between 20° and 40° as well as between 55° and 75° (Fig. 1). This is strongly confirmed by the accurate trend surface analysis of the inclusion trails of ellipticity between 1.3 and 1.7 shown in Fig. 2(a). The resulting trend surface, when superimposed on the same fold showing the orientation of inclusion trails in porphyroblasts with ellipticity between 1.7 and 2.1 (Fig. 2b), matches this distribution far more precisely than the crude analysis done by Visser & Mancktelow (1992). It clearly

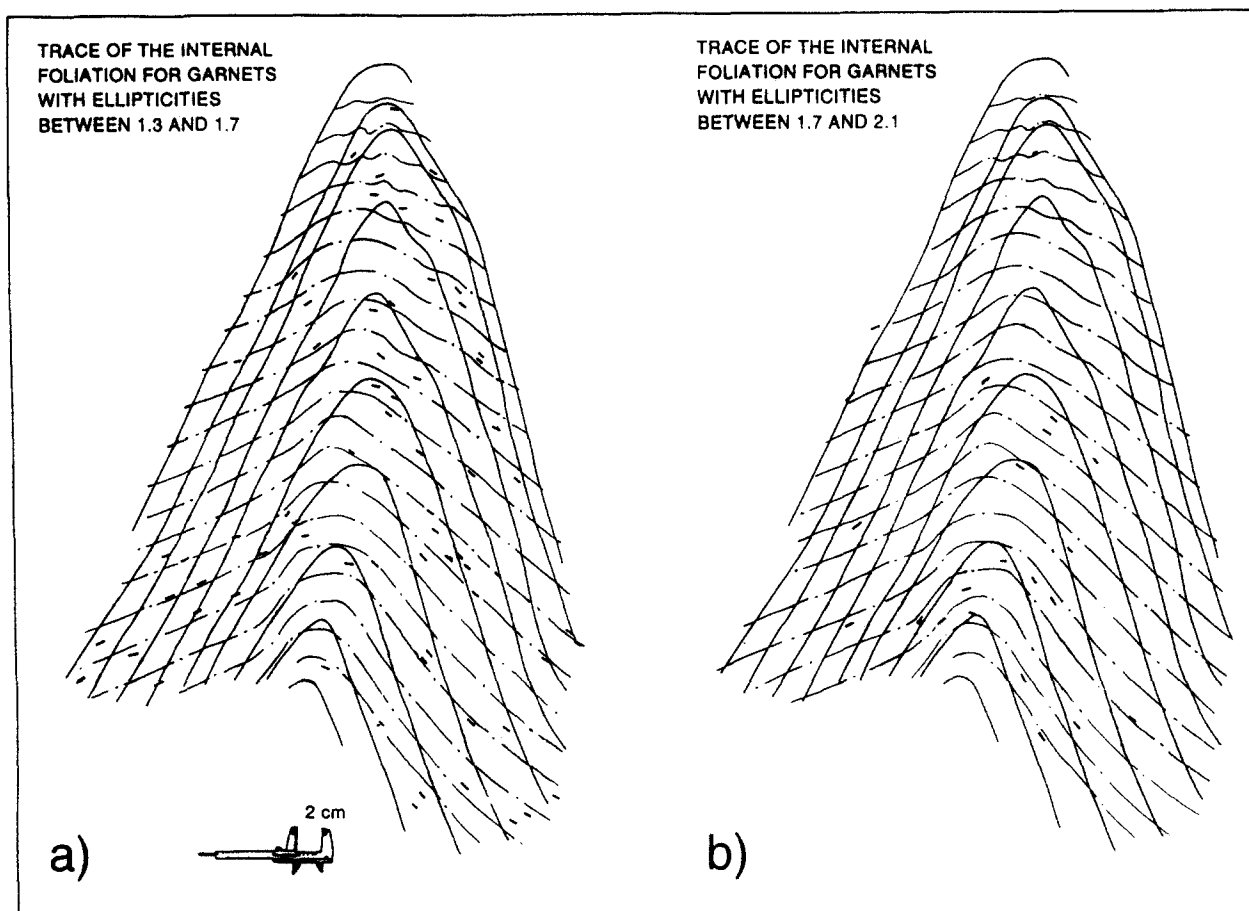


Fig. 2. (a) Accurate trend surface analysis of the inclusion trails in porphyroblasts with ellipticity between 1.3 and 1.7. Note how they define a more open fold than the matrix. Note also that the fold hinge defined by the inclusion trails does not align with that in the matrix. (b) The trend surface analysis for porphyroblasts with ellipticity between 1.3 and 1.7 shown in (a) has been superimposed on the same fold showing the orientation of the inclusion trails with ellipticity between 1.7 and 2.1. Note that the trend surface matches these trails also. That is, the porphyroblasts with greater ellipticity have not been more rotated than those with less ellipticity. This totally conflicts with the interpretation of this same data presented by Visser & Mancktelow (1992).

indicates that the apparent rotation of trails in the porphyroblasts with greater ellipticity is identical to that in porphyroblasts with lesser ellipticity. That is, it categorically opposes Visser & Mancktelow's (1992) assertion that the more elliptical porphyroblasts have been rotated a greater amount than the less elliptical ones.

We suggest these data are better explained by nucleation of porphyroblasts, after folding has commenced. The step-like character of the graphs of inclusion trail dip vs matrix foliation dip (shown in Fig. 1) is readily explained in terms of overgrowth by the porphyroblasts, after folding had commenced, over a fold with relatively straight but differently dipping limbs. Subsequent intensification of the deformation has tightened the fold in the matrix but not rotated the porphyroblasts. The bulk of porphyroblasts have internal inclusion trails with dips ranging between 9° and 38° . The plateaux of inclusion trail dip, for different ellipticities, at 9° – 14° , 21° – 28° and 34° – 38° simply reflect the hinge region, and the left and right limbs, respectively. The transitions between plateaux reflect the curving region between the hinge and limbs. It is noteworthy that the fold shape preserved by the inclusion trails would be tighter than that at the time of nucleation because of subsequent deformation and associated cleavage development, reactivation of the folded foliation (Bell 1986) and volume loss (Bell & Cuff 1989).

Significantly, if the porphyroblasts grew after folding had commenced and yet had not rotated, *there should be a strong tendency for those containing the most rotated internal inclusion trails to show the greatest ellipticity*. This is shown in Fig. 3 where it can be seen that microfracture along the foliation, which controls nucleation and growth of the porphyroblast (see Bell *et al.* 1986), extends across the length of the zone of progressive shortening. For any anastomosing pattern of deformation partitioning parallel to the axial plane of a fold, the greatest length of foliation preserved in zones of progressive shortening will always be that which is most rotated away from perpendicular to the axial plane (Fig. 3). This explains fig. 6(e) in Visser & Mancktelow (1992) which has a near linear relationship between the dip of internal trails and the external matrix.

The lack of proof of the rotation of the porphyroblasts around the fold described by Visser & Mancktelow (1992) means that their subsequent investigation of fold development, based on this rotational model, is not only misleading, but provides no advance on similar conclusions reached by Zwart (1960), Peacy (1961), Rosenfeld (1968) and Kennan (1971). Ramsay (1962) accepted the necessity of establishing age relationships in his investigation of the effects of flattening on similar folds in porphyroblastic rocks. In particular, Visser & Mancktelow (1992) have provided no evidence for homogeneous flattening for the later part of fold development. Indeed the microstructural relationships of the matrix outside the rims of the porphyroblasts suggest that the deformation after porphyroblast growth was non-coaxial on the fold limbs. This is particularly apparent from the geometry of the axial plane foliation both in the

strain shadows as well as further along the axial plane from the porphyroblasts. For example, their fig. 3(b) shows the early stages of differentiation preserved at some distance from the porphyroblast rims (e.g. Bell & Johnson 1992). The geometry of the foliation in the shortening zone remains very similar to that in the porphyroblast for a distance of at least four porphyroblast widths. This cannot be rationalized as a product of the porphyroblast rotation and provides a clear demonstration that sinistral (in this case) shear has generated a zone of greater shearing strain sub-parallel to the axial plane of the fold. We suggest that future attempts to investigate fold mechanisms determine unequivocally both the relative age of the porphyroblasts and fold, and using this information, whether or not the porphyroblasts have rotated during folding.

Variation in the orientation of inclusion trails in porphyroblasts around a fold is exactly what structural geologists expect to see if buckling has played a role during folding (e.g. Peacy 1961, Rosenfeld 1968, Kennan 1971, Visser & Mancktelow 1992). However, when porphyroblasts nucleate and grow during folding, their inclusion trails commonly show exactly the same pattern of variation. Alternatively, there may be no variation in the orientation of the inclusion trails around the folds (Steinhardt 1989, Johnson 1990, 1992, Hayward

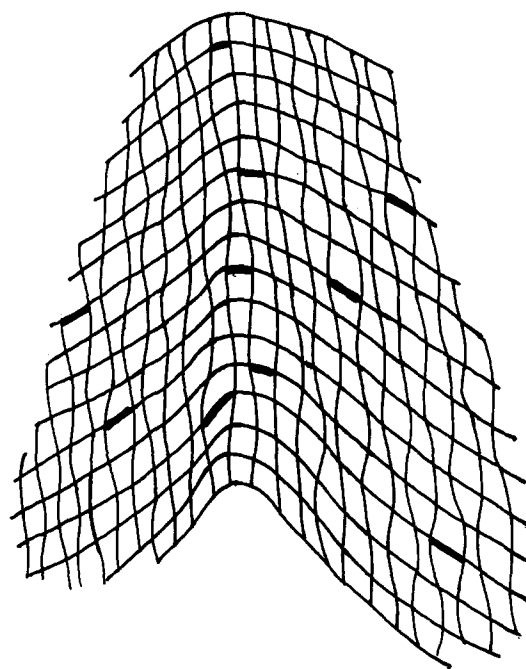


Fig. 3. Sketch of fold defined by inclusion trails in Fig. 2(a). The pattern of deformation partitioning is shown in a schematic fashion by anastomosing lines which represent zones of progressive shearing. The maximum length of folded foliation within zones of progressive shortening lies in those where the folded foliation has been most rotated (compare the thick short black lines from hinge to limb). Bell *et al.* (1986) have shown that porphyroblasts nucleate on microfractures which occur along phyllosilicates defining the folded foliation in the zone of progressive shortening; their shape is also controlled by this geometry. Consequently, for any particular scale of deformation partitioning, those porphyroblasts which grow on the fold limbs will tend to be the most elliptical. However, since the scale of deformation partitioning will vary, a range of ellipticities will eventuate, as demonstrated by Visser & Mancktelow (1992).

1992). Indeed, in the same fold sample, an earlier phase of porphyroblasts may show no variation around a fold while a later phase that formed during the development of this structure may vary in the manner recorded by Visser & Mancktelow (1992) (Bell & Forde unpublished data). For there to be progress in this debate on the role of porphyroblasts during folding, variations or lack thereof in the orientation of inclusion trails around folds must be critically examined in terms of both possibilities, as only then will data be sought that will resolve this issue.

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