Porphyroblast rotation: *eppur si muove*?

Institute of Earth Sciences, PO Box 80.021, Budapestlaan 4, Utrecht 3508 TA, The Netherlands
¹Departamento de Geologia, Universidade Federal do Rio de Janeiro, CEP 21910 Rio de Janeiro, Brazil

ABSTRACT In a number of recent papers, the theory has been postulated that porphyroblasts as a rule do not rotate with respect to geographical coordinates, and can be used to determine the original orientation of older foliations. Complex inclusion patterns in spiral garnets have even been used to advocate a new model of orogenesis, involving several alternating phases of horizontal shortening and extension. Critical assessment of the assumptions and data used to support the theory of irrotational porphyroblasts reveals numerous flaws. Millipede structures, used as proof for flow partitioning, can also form by other flow geometries. Evidence quoted to support irrotational behaviour of porphyroblasts is unsound. Porphyroblasts do occur in sets with a preferred orientation of the internal foliation trace, but these cannot be shown to represent original orientations. Microstructures which resemble truncation planes in spiral garnets are used as evidence that these structures developed by several phases of deformation and as proof for periodic extension and horizontal shortening in orogenesis. They can, however, also be explained by intermittent growth of a rotating porphyroblast during a single phase of deformation. Finally, porphyroblast sets in which orientation is a function of aspect ratio indicate that porphyroblast rotation with respect to kinematic axes does occur in at least some situations.

Key words: millipede structure; porphyroblast rotation; spiral garnet.

INTRODUCTION

A basic problem in geology is that rocks are commonly the only available data source from which a sequence of events is to be reconstructed; only an end-product can be studied, without access to intermediate stages. This applies especially to structural geology, where deformation mechanisms, flow and strain patterns, and deformation histories have to be inferred from finite geometries in rocks. The situation is comparable to that of reconstructing the sequence in which this manuscript was written and modified from the completed paper as it now stands. The best possible way to come to reliable conclusions is by experimental work and careful study of simple geometrical situations, in which as many parameters as possible have been fixed. Even then, we may have overlooked an aspect of the geometry considered to be insignificant, which may prove to be crucial for correct interpretation. Structural geology proceeds by small steps, through reinterpretation of geometries as our understanding of rheology and of progressive deformation in crystalline materials grows, and new data become available.

In a group of recent papers, established concepts of the interpretation of microstructural porphyroblast geometries in metamorphic rocks have been criticized (Bell, 1985, 1986; Bell et al., 1986; Bell & Johnson, 1989, 1990; Steinhardt, 1989; Johnson, 1990a,b; Hayward, 1990). These papers have made the useful contribution of calling attention to the fact that many apparently rotational fabrics can also be explained as non-rotational. However, they advocate the statement that porphyroblasts as a rule do not rotate with respect to geographical coordinates. If this statement is correct, inclusion patterns preserved within porphyroblasts could be used to deduce the original orientation of early foliations. On the basis of these statements, Bell & Johnson (1989) and Johnson (1990a) reinterpreted spiral-shaped inclusion patterns in garnets as being the result of progressive overgrowth over folds of up to eight deformation phases. They claim that these phases reflect periodic shortening and gravitational collapse of an orogen and that porphyroblasts can be used in this way as keys in the reconstruction of orogenesis. Because of the inherent problems with the interpretation of geometries in deformed rocks outlined above, it seems that such a radical reinterpretation of basic concepts in orogenesis justifies a critical analysis of the underlying assumptions, methods and data. In this paper, we proceed to assess the validity of the most important statements used by several of the aforementioned authors. We use the following terminology (Fig. 1):

- $S_i$ (i for internal)—pattern of elongate inclusions, reflecting an overgrown foliation within a porphyroblast as observed in thin section;
- $S_e$ (e for external)—trace of a foliation in the matrix around porphyroblasts as observed in thin section.

*Italian: 'but she moves nonetheless', the words reportedly spoken by Galileo Galilei on 22 June 1633 at the offices of the Holy Inquisition in Rome, after having been forced to renounce the idea that the Earth rotates around the Sun.
mica cap—a mica-rich domain adjacent to an object such as a porphyroblast;
strain shadow—a domain with low mica content adjoining an object such as a porphyroblast (also known as a pressure shadow);
cleavage lamella(e)—the domain of a spaced cleavage or crenulation cleavage which is rich in elongate grains of minerals such as micas or amphiboles;
microlithon—the domain of a spaced cleavage or crenulation cleavage which is rich in equidimensional grains of minerals such as quartz, feldspar or carbonates; this domain may contain relic fold closures;
truncation plane—surface in a porphyroblast which forms a sharp boundary between domains in which \( S_1 \) have different orientations; \( S_1 \) is discontinuous over a truncation plane;
deflection plane—plane in a porphyroblast where \( S_1 \) shows a sharp change in orientation; this structure resembles a truncation plane but \( S_1 \) is not discontinuous;
kinematic frame—set of characteristic directions in a deforming rock, such as the bulk instantaneous shortening and extension directions and the flow plane in the case of progressive simple shear deformation;
syntectonic growth—growth in an actively deforming rock: also known as synkinematic growth.

**COMMENTS TO STATEMENTS ON PORPHYROBLAST ROTATION**

**Statement (1)—porphyroblasts do not rotate because they are mechanically fixed in the rock by strain shadows** (Bell, 1985, 1986; Bell et al., 1986; Bell & Johnson, 1989; Bell & Cuff, 1989; Steinhardt, 1989; Johnson, 1990a, b; Hayward, 1990)

Rigid objects in a linear or non-linear viscous fluid will rotate with respect to the kinematic frame of the flow if the fluid deforms by a homogeneous non-coaxial flow type such as simple shear (Jeffery, 1922; Bretherton, 1962; Ghosh & Ramberg, 1976; Gierszewski & Chaffey, 1977). The angular velocity of the object depends on the vorticity of the bulk flow and, for non-spherical objects, on object orientation and aspect ratio. In simple shear flow, maximum and minimum angular velocities are reached when the long axis of the object lies normal or parallel to the simple shear flow plane (Ghosh & Ramberg, 1976; Passchier, 1987). If the foliation is parallel to this flow plane, the object can rotate with respect to a fixed foliation.

Porphyroblast geometries where \( S_1 \) is oblique to \( S_e \) and where \( S_1 \) and \( S_e \) constitute one continuous foliation (Fig. 2a) have traditionally been interpreted along these lines as rigid objects which rotated with respect to a foliation fixed to the flow plane of simple shear (Fig. 2b; Clough, 1897; Flett, 1912; Turner, 1948; Ramsay & Huber, 1987, p. 633). However, if the foliation is not fixed with respect to the kinematic frame, both the foliation and the porphyroblast can rotate and porphyroblasts with \( S_1 \), oblique to \( S_e \), can form in other ways. Ramsay (1962) pointed out that such porphyroblast geometries can even form by rotation of a foliation with respect to a stationary spherical object in coaxial (pure shear) progressive deformation (Fig. 2c). Bell (1985) and Bell et al. (1986) have suggested that the situation is even more complex. They state that spherical objects can also be stationary in non-coaxial progressive deformation if flow is partitioned around the object. If a rigid strain shadow is present adjacent to a porphyroblast, the strain shadow and porphyroblast may act mechanically as a single elongate rigid object (Bell, 1985; Bell et al., 1986). Such a combined porphyroblast–strain shadow aggregate will rotate at a very slow rate in non-coaxial flow in some orientations, leading to oblique \( S_1/S_e \) patterns (Fig. 2d; Passchier, 1987). Possible natural examples of such a situation have been reported by Fyson (1975, 1980). The local occurrence of such 'protected' porphyroblasts does not imply, however, that rotation of equidimensional porphyroblasts does not occur, although this is claimed by Bell (1985, 1986), Bell et al. (1986), Bell & Johnson (1989), Bell & Cuff (1989), Steinhardt (1989), Johnson (1990a, b) and Hayward (1990).

Flow partitioning as described above is commonly referred to in the literature as 'deformation partitioning'; although this is not strictly correct we will adhere to this use here in order to avoid confusion.

If a porphyroblast overgrows a straight foliation, some strain is needed for the development of a strain shadow, and until this strain has accumulated, the porphyroblast is unprotected and may therefore rotate. Bell & Rubenach
Porphyroblast rotation

Fig. 2. (a) Schematic diagram of a porphyroblast with S, oblique to S, in the surrounding matrix. Such a structure can form by a large number of progressive deformation paths including: (b) rotation of the porphyroblast with respect to a stationary foliation in simple shear flow; (c) rotation of the foliation around a stationary porphyroblast in pure shear flow; (d) rotation of the foliation around a stationary porphyroblast protected by a strain shadow in simple shear flow. Strain shadow in grey.

Bell et al. (1986) and Bell & Johnson (1989) address this problem by suggesting that the porphyroblast grows in an existing microlithon, which remains undeformed. In this case, S, in the porphyroblast should be exactly mimicked in the adjacent strain shadow, which is rarely the case in nature. The statement that the foliation trace in the strain shadow was destroyed by ongoing or subsequent deformation can be countered by the argument that, in that case, the porphyroblast would no longer be protected by the strain shadow, and may thus have rotated.

We conclude that it is rarely possible to determine from a superficial investigation of porphyroblasts with oblique S,/S, relationships whether the porphyroblast or the external foliation has rotated, or both (compare Fig. 2a, b, c & d); careful investigation of the structure is needed, and in a number of cases no solution may be possible. In all cases, it is safe to refer to the structure as being due to relative rotation of S, and S,.

Statement (2)—millipede microstructures are evidence for deformation partitioning into domains of coaxial and non-coaxial progressive deformation (Bell & Rubenach, 1980; Bell, 1985, 1986; Bell & Johnson, 1989). However, experiments by Ghosh & Ramberg (1976) and computer modelling by Masuda & Mochizuki (1989) show that asymmetric millipede-type structures can also form around objects that rotate with respect to the kinematic frame of progressive deformation (Fig. 3b). Millipede structures seem to result from deflection of foliation planes around rigid objects in general, and are not necessarily indicative of deformation partitioning of the type envisaged by Bell & Rubenach (1980).

Millipede-like structures can also result from sectioning. Schoneveld (1979) has shown that millipede-like structures may occur in thin sections of porphyroblasts with spiral-shaped inclusion trails, if these are cut parallel to what he interpreted as the rotation axis. Some of the examples in Bell & Johnson (1989) may be of this kind. Only serial sectioning can show the true nature of these patterns. We would like to stress, however, that not all millipede structures can be explained as a sectioning effect.

Statement (3)—porphyroblasts have not rotated with respect to each other because they show identical orientation of S, over a large area, despite later deformation (Bell, 1985; Bell et al., 1986; Bell & Johnson, 1989, 1990; Steinhardt, 1989; Johnson, 1990a, b; Hayward, 1990)

One of the main advances in the study of porphyroblasts in the last decade has been the discovery by Fyson (1975, 1980), Bell (1985) and Bell et al. (1986) that S, in different porphyroblasts can have a remarkably similar orientation within an outcrop, or even over a larger area, despite
The papers by Fyson (1975, 1980) show a striking preferred orientation of $S_i$ in biotite porphyroblasts over an area with a folded foliation. However, close inspection shows up to $45^\circ$ variation in orientation of $S_i$ in porphyroblasts over the investigated area, which may be due to porphyroblast rotation.

Johnson (1990b) claims to observe irrotational behaviour of porphyroblasts in the Otago schists. He does not present the full three-dimensional orientation of $S_i$ patterns, however. The rose diagrams in Johnson (1990b) are plots of the strike of steeply dipping $S_i$ which show a consistent orientation of the mean values; close inspection, however, shows that the spread in orientation of the strike in each diagram is considerable, up to $60^\circ$; in addition, the dip of $S_i$ in porphyroblasts is totally unconstrained. Clearly, these kinds of data cannot be used as proof for constant orientation of $S_i$. In fact, the same type of relatively constant orientation of $S_i$ strike would be expected from a population of rotated porphyroblasts with spiral inclusion patterns, with subparallel rotation axes. In that case, stretching lineations should lie approximately perpendicular to the strike direction of $S_i$. Inspection of the map fig. 9(b) in Johnson (1990a) shows that locally the lineations are indeed approximately perpendicular to $S_i$ traces in the rose diagrams.

Steinhardt (1989) gives evidence for constant orientation of $S_i$ in porphyroblasts in schists in South Australia. His fig. 4 shows the large-scale distribution of traces of $S_i$ in the plane of thin sections, plotted in a stereogram. However, because his thin sections are not randomly orientated, their orientation influences the $S_i$ distribution in the diagram and the significance of this plot is therefore doubtful. Only his fig. 5 shows the full orientation of planar $S_i$ in six porphyroblasts for a double fold which post-dates the porphyroblast growth. Of the six $S_i$ planes, five are of similar orientation, but these are all from porphyroblasts which lie in the same fold limb; the only $S_i$ plane in a porphyroblast on another limb has a different orientation. Clearly, the value of this material as evidence for non-rotation of porphyroblasts is highly questionable.

Besides the fact that presently published evidence for non-rotation of porphyroblasts is dubious, the papers dealing with the subject (Fyson, 1975, 1980; Bell, 1985; Steinhardt, 1989; Bell & Johnson, 1989, 1990; Johnson, 1990a, b; Hayward, 1990) commonly apply unsound argumentation, based on statements which cannot be tested. On the one hand, the authors claim that porphyroblasts do not rotate, since $S_i$ in porphyroblasts has the same orientation over large areas, in spite of intense later deformation (Fyson, 1975, 1980; Steinhardt, 1989; Bell & Johnson, 1989, 1990; Johnson, 1990a, b; Hayward, 1990). On the other hand, if porphyroblasts are discussed which do have a variable orientation of $S_i$ over an area, this is interpreted as an effect of folding of the foliation prior to porphyroblast growth or to deformation of the porphyroblasts, but not to rotation of porphyroblasts (Bell, 1985; Johnson, 1990b). By this interpretation, the basic statement of the theory of irrotational porphyroblasts cannot be tested.
Fig. 4. Effect of deformation on the orientation of porphyroblast populations. Schematic map views show porphyroblasts (rectangles) with $S_1$ parallel to their long axes (inset top right) in strain shadows (white) flanked by cleavage lamellae (solid lines). Shape of strain shadows and cleavage lamellae is indicated schematically. $S_1$ and the porphyroblasts have a strong preferred orientation with respect to geographical coordinates indicated by orientation distribution graphs under the maps; $n =$ number of measurements. (a) Simple shear of the material by slip on cleavage lamellae while the strain shadows remain undeformed may cause rotation of the whole set of porphyroblasts and the main foliation ($S_e$) into a new geographical orientation; (b) when a similar set of porphyroblasts is deformed by non-coaxial flow throughout the specimen, porphyroblasts are reorientated with respect to the cleavage lamellae. In both cases, the rotation of $S_1$ with respect to geographical coordinates cannot be deduced from the finite fabric in the rock.

**Statement (4)—porphyroblasts are fixed to geographical coordinates** (Steinhardt, 1989; Bell & Johnson, 1989, 1990; Johnson, 1990a; Hayward, 1990)

From the discussion of statement (3) it will be clear that the orientation of $S_1$ in porphyroblasts in a volume of rock may have a distinct mean orientation, but that the spread in orientation of $S_1$ in different porphyroblasts can be rather high. It is difficult in such situations to decide which orientation of $S_1$ is the ‘original’ orientation of the foliation over which the porphyroblasts grew. The mean value could be taken as such, but one can never be sure that subsequent deformation did not modify or shift the orientation distribution of $S_1$ while a clear mean value is still preserved (Fig. 4). Non-coaxial flow in cleavage lamellae without internal deformation in strain shadows as envisaged by Bell (1985, 1986), Bell *et al.* (1986) and Bell & Johnson (1980) could cause rotation of all porphyroblasts without changing their orientation with respect to each other (Fig. 4a). Penetrative non-coaxial flow after porphyroblast growth can also cause a shift in porphyroblast orientation, without affecting the shape of the orientation curve of $S_1$ (Fig. 4b). Besides this influence of deformation on porphyroblast orientation, any large-scale rigid body rotation of volumes of rock will cause rotation of the included porphyroblast population with respect to geographical coordinates. Reconstructions of the original orientation of foliations from porphyroblast populations are therefore unreliable.

**Statement (5)—porphyroblasts can remain irrotational with respect to geographical coordinates through several phases of deformation** (Bell & Johnson, 1989, 1990; Johnson, 1990a; Hayward, 1990)

Natural examples show that porphyroblasts can remain relatively stationary with respect to each other during one phase of foliation development after growth if the
Fig. 5. Porphyroblasts with rigid strain shadows can be protected from rotation by these strain shadows (a); however, when they are affected by later shortening oblique to the foliation, the porphyroblasts may lose the protection of these strain shadows (b) until new strain shadows are developed related to the newly developed foliation (c). In stage (b) porphyroblasts are unprotected and are free to rotate. Strain shadows—grey ornamentation, $S_i$ in porphyroblasts—striped ornamentation.

Porphyroblasts are equidimensional and progressive deformation is coaxial or, in other cases, if the porphyroblasts lie in elongate strain shadows (statement 1; Fyson 1975, 1980). It seems unlikely, however, that porphyroblasts can remain irrotational with respect to geographical coordinates through several phases of deformation which form overprinting foliations in oblique directions. The main problem is that shortening at a high angle to the strain shadows around a porphyroblast will tend to destroy this shadow, thereby destabilizing the porphyroblast which is then free to rotate until a new strain shadow has been established (Fig. 5). Bell & Johnson (1989, 1990), Johnson (1990a, b) and Hayward (1990) did not address this problem.

Fig. 6. Schematic diagram of the development of deflection planes in a porphyroblast which is periodically growing while it rotates in a non-coaxial flow: (a) porphyroblast core which has grown over a planar foliation is rotated and mica caps develop at upper left and lower right; (b) when these mica caps are sufficiently developed, they are overgrown by the porphyroblast mineral; (c) deflection planes are produced in the process. Further rotation of the porphyroblast can cause development of new mica caps and a repetition of the process.

Fig. 7. A garnet porphyroblast in which $S_i$ is clearly continuous with $S_1$ at top left and bottom right, but with two wings at top and bottom where $S_1$ has a different orientation from $S_i$ in the core; deflection planes partly separate the core and the wings. These could be mistaken as truncation planes. Development of this porphyroblast may correspond to the sequence in Fig. 6. Bafios, Equador. Scale bar = 1 mm.

Fig. 8. Staurolite crystal synkinematic with respect to the crenulation cleavage, the lower part of which overgrew a cleavage lamella, showing that the model proposed by Bell et al. (1986) restricting porphyroblast growth to microlithons is not valid in this case. Lukmanier Pass, Switzerland. Scale bar = 0.5 mm.

Fig. 9. Garnet porphyroblasts in mica schist that overgrew cleavage lamellae and part of a microlithon. São Felix do Araguaia, Goias, Brazil. Scale bar = 0.5 mm.

Fig. 10. Detail of a garnet porphyroblast as in Fig. 9 which overgrew two cleavage lamellae and part of microlithons. The garnet shows a relative rotation of 45° with respect to the crenulation cleavage. São Felix do Araguaia, Goias, Brazil. Scale bar = 0.5 mm.
Statement (6)—porphyroblasts in pelitic rocks nucleate during progressive deformation in microlithons, grow until they impinge on developing cleavage lamellae, and stop growing there (Bell & Rubenach, 1983; Bell et al., 1986; Bell & Johnson, 1989)

The idea that porphyroblast growth is syntectonic and limited to microlithons which correspond to domains of coaxial progressive deformation (statement 2) is of crucial importance for the development of the non-rotational model proposed by Bell and co-workers. On theoretical grounds, Bell & Rubenach (1983), Bell et al. (1986) and Bell & Johnson (1989) have rejected the possibility of growth of a porphyroblast over cleavage lamellae or mica caps. They claim that pressure solution during deformation will inhibit such growth. However, examples of syntectonic porphyroblasts which have indeed at least partially overgrown cleavage lamellae (Figs 8–10) or even complete developing crenulation cleavages including numerous lamellae (Fig. 11) are not uncommon in nature.

Statement (7)—sharp deflections of S1 in porphyroblasts are truncation planes and can be taken as evidence for polyphase deformation (Bell & Johnson, 1989; Johnson, 1990a, b)

Some porphyroblasts contain more complex inclusion patterns than a single straight or curved S1 pattern. Such porphyroblasts may contain truncation planes, where one pattern of S1 is truncated by another pattern (Fig. 1; Thompson et al., 1977; Karabinos, 1984). Truncation planes apparently form by a relative change in the orientation of the porphyroblast with respect to the surrounding foliation, possibly with local partial solution of the porphyroblast, followed by new porphyroblast growth. As a result, S1 in the newly added segment will have a different orientation than that in the core of the crystal (Rosenfeld, 1968; Karabinos, 1984). Bell & Johnson (1989) and Johnson (1990a, b) claim to observe truncation planes in spiral garnets, and use the presence of these planes as evidence that spiral garnets form by a sequence of separate deformation phases. In this interpretation they deduce up to eight deformation phases during all of which the garnets continued growing. However, few real truncation planes are visible in their examples. S1 is only locally discontinuous and in most places only deflected. Such structures are better described as deflection planes rather than truncation planes (Fig. 6). Deflection planes can form during a single phase of progressive deformation if porphyroblast growth is not radially continuous (Fig. 6).

Mica caps can form by dissolution of quartz and feldspar wherever the surface of a porphyroblast lies oblique to the instantaneous shortening direction of the deformation (Fig. 6a, b). After the mica cap is sufficiently developed, it may be overgrown by the porphyroblast and a deflection plane of S1, bearing some similarity to a truncation plane is formed (Fig. 6c). Figure 7 shows an example of a garnet which may have formed in this way.

Statement (8)—spiral garnets do not form by rotation during a single phase of deformation, but are an effect of polyphase deformation and growth (Bell & Johnson, 1989, 1990; Johnson, 1990a; Hayward, 1990)

Garnets with spiral inclusion patterns have traditionally been interpreted as objects which grew during rotation with respect to the kinematic frame of bulk deformation (Flett, 1912; Mügge, 1930; Rosenfeld, 1970; Schoneveld, 1979). The new interpretation by Bell & Johnson (1989) has been inspired by the occurrence of deflection planes interpreted as truncation planes, and millipede-type internal structures in some spiral garnets (Bell & Johnson, 1989; Hayward, 1990); each set of alleged truncation planes is explained as the effect of a separate phase of deformation, and a large number of deformation phases is therefore proposed for rocks with this type of porphyroblast. Millipede structures, however, can form around objects that rotate with respect to the kinematic frame of progressive deformation (statement 3), and deflection
planes can form by syntectonic overgrowth of mica caps (statement 6). We think that inclusion patterns in garnets as shown in Bell & Johnson (1989) and Hayward (1990) can also be explained as syntectonic growth of rotating garnets, for the following reasons.

Schoneveld (1979) has shown that generally two spirals are present in such garnets; one defined by quartz, interpreted as relics of the strain shadow absorbed by the garnet, and the other by opaques, interpreted as a relic of overgrown S, in mica caps. Beautiful, continuous spirals of this type are common in nature (Figs 12–14; Schoneveld, 1977, his figs 3, 4, 5, 6, 8, 9; Powell & Vernon, 1979, their figs 4–6). It is difficult to imagine how a pattern of subsequent phases of deformation and growth (Bell & Johnson, 1989, their fig 20) could form such regular spiral shapes. Schoneveld (1979) proposed that spiral patterns develop when garnets rotate at constant angular velocity and grow continuously and in a radially symmetric way. However, if during a single deformation event growth is localized and periodic rather than radially symmetric and continuous (Fig. 6), or if the angular velocity of the garnet is variable due to variable bulk strain rate, inclusion patterns similar to those in Bell & Johnson (1989) and Hayward (1990) could result. The large number of deformation phases postulated by these authors can therefore be explained as an equal number of growth phases during a single deformation event. The presence of continuous quartz spirals in many of the figures in Bell & Johnson (1989, their figs 1, 4, 6g, 8c, d) supports this idea. The quartz spirals can be explained by a model of porphyroblast rotation and syntectonic growth (Schoneveld, 1979; Schulz, 1990), but seem incompatible with a model of polyphase deformation and growth as shown in Bell & Johnson (1989, their fig. 20); it is difficult to understand why the new pressure shadows never overlap each other and stop exactly where the one from the preceding phase ended. The millipede patterns without quartz spirals presented by Bell & Johnson (1989, their figs 12–14) can be explained as sections parallel to the garnet rotation axis (Schoneveld, 1979). Notice in the figures of Bell & Johnson (1989) that wherever clear quartz spirals are present, millipedes are absent or asymmetrical while symmetric millipedes only exist in the absence of quartz spirals. The arguments in Bell & Johnson (1989) and Hayward (1990) should be based on serial sectioning to show the three-dimensional structure of S, rather than on single two-dimensional sections. This will show, for example, whether the 'millipede' structures in Bell & Johnson (1989) are real millipedes, or a sectioning effect (see statement 2). To date, three-dimensional patterns of S, in garnets have only been published as stereographic images by Schoneveld (1979, his figs 14 & 19). These patterns do not contain deflection or truncation planes.

A final consideration refers to the period of porphyroblast growth. In the Bell & Johnson (1989) model, porphyroblasts grow more or less continuously during up to eight successive deformation phases that are associated with an equal number of inversions of the kinematic framework of an entire mountain belt. The model shows considerable uplift followed by collapse related to each two phases, that would change the metamorphic conditions at any given point considerably. It seems unlikely that garnet growth could continue through such an evolution.

**FABRICS INDICATIVE OF ROTATION**

From the content of this paper it will be obvious that porphyroblast microstructures are difficult to interpret in terms of kinematic analysis. Nevertheless, we can propose a few structures which may be used as evidence for rotation of porphyroblasts with respect to each other and therefore of rotation of at least some porphyroblasts in the kinematic frame of bulk progressive deformation. One possible argument in favour of relative rotation of porphyroblasts with respect to the kinematic frame of bulk deformation in the rock is a dependence of object orientation on object shape (Fig. 15). Zwart & Calon (1977) described elongate chloritoid crystals in a schist with only one foliation, from the Urseren zone, Switzerland, that show opposite orientations of slightly
s-shaped inclusion patterns for crystals with opposite vergence of the long crystal axis and S, (Fig. 15a). According to the authors, the only possible explanation is rotation of the crystals during coaxial flattening oblique to the pre-existing foliation. Crystals which have their long axis perpendicular to the foliation as a rule do not show signs of relative rotation, as would be expected (Zwart & Calon, 1977, their fig. 5). Their conclusion is corroborated by the presence of asymmetric pressure shadows around the crystals which have developed on the lee side of the rotating porphyroblast. Schoneveld (1979) described and explained a similar relationship for amphibole crystals from Norway. In Bosost, Spanish Pyrenees, elongate andalusite porphyroblasts in mica schist have their long axes in the plane of the foliation (Zwart, 1962). The angle between S, and S, in oblong andalusite porphyroblasts depends on the orientation of andalusite in the foliation plane; crystals which have their long axes parallel to a biotite lineation in the foliation plane have parallel S, and S, (Zwart, 1962); crystals with long axes normal to the lineation have S./S, angles up to 110° (Fig. 15b). All intermediate angles are encountered in the same rock. Vissers (1989) described a similar relationship between aspect ratio of garnet porphyroblasts and the S./S, angle for samples from the Betic Cordillera, Spain (Vissers, 1989, his fig. 6). Such a relationship would be expected for rigid objects rotating with respect to kinematic axes, but not for stationary objects. Recently, Vissers & Mancktelow (1992) and Busa & Gray (1992) have presented new data which support rotational behaviour of porphyroblasts. In all these cases there is no clear preferred orientation of S, in the rock, and rotation of at least some of the crystals with respect to the foliation and the kinematic frame of the deformation seems the most likely explanation.

CONCLUSIONS

(1) Porphyroblasts in which the inclusion patterns are relatively constant in orientation over a large volume of rock despite later deformation do exist in nature. They can be explained as porphyroblasts which have grown over a planar foliation in a rock (Fyson, 1975, 1980), which is subsequently affected by development of a crenulation cleavage that anastomoses around the porphyroblasts. In such a situation, the porphyroblasts may shift and slightly rotate with respect to each other, without destruction of the preferred orientation of the inclusion patterns. This preferred orientation, however, is not necessarily an inherited unchanged orientation with respect to geographical coordinates.

(2) Rotation of porphyroblasts with respect to the kinematic frame of bulk deformation in a volume of rock can only be proven in cases where a clear relationship exists between aspect ratio and orientation of elongate porphyroblasts, and the relative rotation angle between S, and S, and S, and S. All other cases of porphyroblasts with straight S, oblique to S, are presently inconclusive.

(3) Inclusion patterns in spiral garnets, even if they contain deflection planes or millipede structures, cannot be used as sound evidence for multiple phases of horizontal shortening and extension; the inclusion patterns can be explained by continuous or periodic garnet growth during rotation of garnets in a single deformation phase. A new model for orogenesis as proposed by Bell & Johnson (1989) is therefore unfounded.

(4) In well-studied mountain belts like the Alps and the Pyrenees, no independent evidence exists for repeated changes in shortening and extensional events as envisaged by Bell & Johnson (1989). Because of the uncertainties involved in the interpretation of porphyroblast microstructures, it seems hazardous to use these patterns as exclusive evidence for new concepts of orogenesis.

FINAL STATEMENT

As matters stand, we do not claim that we understand the complete behaviour of porphyroblasts in anisotropic media, and we recognize that Bell and co-workers have made a major contribution in a field which has been sadly neglected for at least a decade by most other research groups. With the present state of affairs, however, it is unwise to use porphyroblasts for determination of shear sense without cross-checking with structures whose development is better understood. The use of porphyroblasts to determine the orientation of earlier foliations seems unfounded. Samples must be carefully investigated and individually interpreted as to the kinematics responsible for their development. More detailed experimental work must be done, such as the investigation of ‘natural experiments’, experiments with analogue materials in general non-coaxial flow fields, and finite element analysis. Evidence for rotation or non-rotation of porphyroblasts could be obtained where porphyroblasts can be found in association with fibrous veins which track the incremental extension direction; no such situations have come to our knowledge, but if they exist they would be extremely useful to decide whether porphyroblasts or foliations have rotated with respect to the kinematic frame. Only further work can tell us what geometric patterns in porphyroblasts are important and reliable, and which are not.

ACKNOWLEDGEMENTS

We thank the research group Casus Belli for useful discussion. R.A.J.T. acknowledges the Brazilian national council for research (CNPq), process no. 202267/90-3, for financing his post-doctoral stay at Utrecht University. Reviews by V. L. Hansen and P. Karabinos and suggestions by J. P. Platt, N. Mancktelow and B. Ildefonse are gratefully acknowledged.

REFERENCES


Received 10 July 1991; revision accepted 10 September 1991.