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Inferring the timing of porphyroblast growth in the absence of continuity between inclusion trails and matrix foliations: can it be reliably done?

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Abstract—The timing of porphyroblast inclusion trails can be confidently interpreted relative to surrounding external foliations only where there is continuity between the two. Where this continuity is broken, timing is ambiguous. Where single or multiple growths of two or more different porphyroblastic minerals have occurred during a relatively complex deformation history, the risk of misinterpreting the relative timing of porphyroblast growth is high, and can lead to wrong inferences about pressure–temperature–time–deformation (P–T–t–d) paths. Misinterpreting porphyroblast timing can also have considerable consequences for determining rates of fabric evolution relative to changes in metamorphic conditions. The effects of porphyroblast rotation vs non-rotation (relative to an externally fixed reference frame) on inferred P–T–t–d paths are poorly understood. However, the 'd' part of the path can differ considerably, depending on whether or not porphyroblasts are inferred to have rotated. The effect on the P–T–t part of the path depends on what effect inferences about porphyroblast rotation have on the inferred sequence of porphyroblast growth.

INTRODUCTION

Microstructural analysis aimed at determining the timing of porphyroblasts with inclusion trails (S_i) relative to one another and matrix foliations (S_e) has been revitalized over the past decade (e.g. Bell & Rubenach 1983, Bell & Brothers 1985, Bell *et al.* 1986, Jamieson & Vernon 1987, Vernon 1988, Reinhardt & Rubenach 1989, Johnson 1990, Lang & Dunn 1990, Vernon *et al.* 1993, Johnson & Vernon 1995). This resurgence in the use of porphyroblast microstructures has resulted in inferred deformation and metamorphic histories for some well-known metamorphic belts that are more complex than previous interpretations (e.g. Bell & Brothers 1985, Jamieson & Vernon 1987, Reinhardt & Rubenach 1989, Johnson 1990, Huang 1993, Jones 1994, Johnson & Vernon 1995). It has also resulted in an increased level of discussion regarding relationships between deformation and porphyroblast nucleation and growth (e.g. Bell *et al.* 1986, Bell & Hayward 1991, Johnson 1993, Vernon *et al.* 1993, Williams 1994), and rates of structural fabric evolution relative to changes in metamorphic conditions (e.g. Bell & Rubenach 1983, Reinhardt & Rubenach 1989, Williams 1994). We are optimistic about the use of inclusion trails to infer the timing of porphyroblast growth, and believe that this activity has made, and will continue to make, valuable contributions to structural and metamorphic geology. However, some difficulties have recently come to light from our detailed studies in the Cooma Complex, Australia, and so it seems appropriate to discuss the conditions under which the timing of porphyroblast growth relative to other porphyroblasts and surrounding foliations can confidently be determined, and some potential consequences of incorrect determinations of such timing.

SOME PROBLEMS AND LIMITATIONS WITH DETERMINING THE TIMING OF PORPHYROBLAST GROWTH

Figure 1 shows two situations commonly encountered in deformed metamorphic rocks. In current interpretations that follow generally the work of Bell & Rubenach (1983) and Bell *et al.* (1986), the porphyroblasts in Fig. 1 would be interpreted as having grown during the development of S_2 and the S_i would be labelled S_1. This is a reasonable interpretation for Fig. 1(a), because of the continuity between S_i and S_2. However, S_i and S_2 are not continuous in Fig. 1(b), so that the exact timing of porphyroblast growth relative to S_2 is ambiguous. Thus, the labelling in Fig. 1(b) must be tentative, because the most that can confidently be said is that S_i is older than S_2. However, many recent papers contain examples in which S_i is labelled (or interpreted in figure captions) as one generation older than the matrix foliation, in the absence of continuity between S_i and S_e (e.g. Bell & Rubenach 1983, fig. 8; Bell *et al.* 1986, fig. 31; Vernon 1988, fig. 7; Gibson 1989, fig. 3(d); Reinhardt & Rubenach 1989, fig. 18; Lang & Dunn 1990, fig. 7; Hayward 1992, fig. 12; Johnson 1992, fig. 2(c); Huang 1993, fig. 8; Jones 1994, fig. 7; Williams 1994, fig. 5). Although such

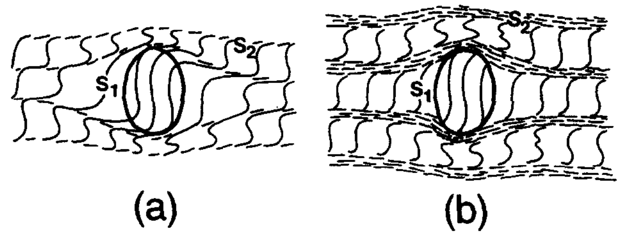

Fig. 1. (a) Porphyroblast with sigmoidal S_i and continuity between S_i and S_2. (b) Porphyroblast with sigmoidal S_i and no continuity between S_i and S_2.

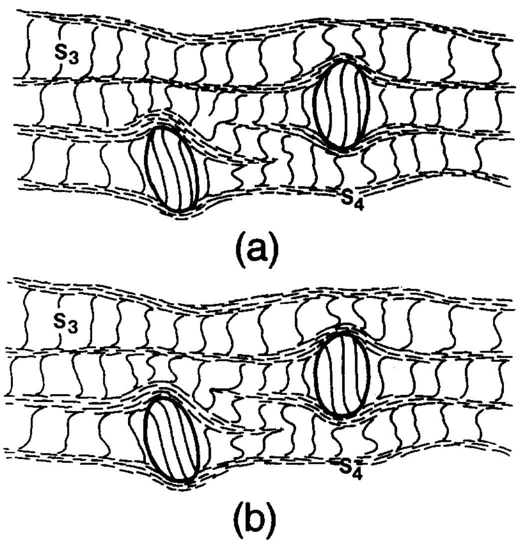

Fig. 2. Two cordierite porphyroblasts with sigmoidal S_i and no continuity between S_i and S_4. (a) The asymmetry of S_i in the porphyroblasts is the same as the asymmetry of matrix crenulations. Thus, it is possible, but difficult to demonstrate, that the S_i are S_3 and that the porphyroblasts grew during the development of S_4. (b) The asymmetry of S_i in the porphyroblasts is opposite to the asymmetry of matrix crenulations, indicating that the porphyroblasts did not grow during the development of S_4 and that the S_i may predate S_3 (see conflicting histories in Fig. 4).

an interpretation seems reasonable in the absence of evidence for additional foliation-forming events, evidence that convincingly supports or refutes the interpretation is generally difficult to find.

An area where this interpretation has been tested and found to be wrong is the Cooma Complex, Australia (Johnson *et al.* 1994, Johnson & Vernon 1995). In the cordierite–andalusite schists of the complex, S_4 is a well developed crenulation cleavage that commonly wraps cordierite porphyroblasts (Fig. 2). In Fig. 2(a), cordierite porphyroblasts contain S_i oblique to S_4, S_i curves at the margins of the porphyroblasts, and there is no continuity between S_i and S_4. The commonly accepted practice is to interpret such porphyroblasts as having grown during the development of S_4, and therefore S_i would be labelled S_3. However, microstructures like those shown in Fig. 2(b) are also found. They differ from those in Fig. 2(a) in that the asymmetry of S_i in the porphyroblasts is opposite to the asymmetry of crenulations in the surrounding matrix. This observation indicates that S_i in Fig. 2(b) predates S_4 and probably S_3.

There are numerous possible interpretations of the relative timing between the porphyroblasts in Figs. 2(a) & (b). For example, they may have grown simultaneously on different limbs of a fold that pre-dated development of both S_3 and S_4. Alternatively, they may have grown at different times, with either one pre- or post-dating the other. Considering isotopic data or other aspects of the metamorphic and deformational history may help narrow the range of possibilities, but unequivocal determination of relative timing based on the microstructures alone is difficult to impossible.

Microstructures like those in Fig. 2(b) show that S_i in porphyroblasts cannot be confidently labelled without

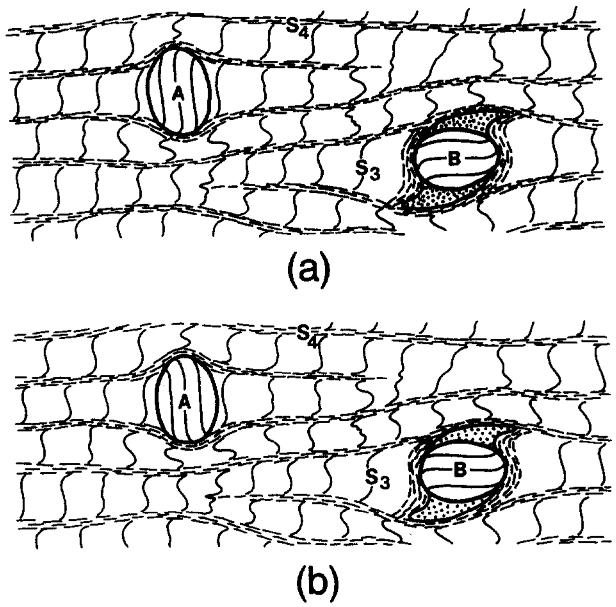

Fig. 3. Example of circumstances where relative timing between two porphyroblasts is ambiguous. The porphyroblasts could be any porphyroblastic mineral — in Cooma they would typically be cordierite, andalusite or both. The stippled area around porphyroblast B is a D_3 strain shadow. (a) In this situation the asymmetry of S_i in A is the same as the asymmetry of matrix crenulations. Thus, even though the relative timing between A and B is ambiguous, it is tempting to interpret the S_i in A as S_3, which would lead to A postdating B. (b) In this situation the asymmetry of S_i in A is opposite to the asymmetry of matrix crenulations. Thus, the S_i in A could possibly predate S_3, and the relative timing between A and B is more obviously ambiguous.

continuity between S_i and S_e, and have led us to take a more cautious approach with microstructures like those in Figs. 1(b) and 2(a). Correct interpretation of porphyroblast growth timing is important because a misinterpretation can possibly lead to an incorrect interpretation of the deformational and metamorphic history, as discussed further below.

P–T–t–d PATHS AND MISINTERPRETATION OF TIMING OF PORPHYROBLAST GROWTH

Microstructural determination of pressure–temperature–time–deformation (*P–T–t–d*) paths relies on correctly determining the timing of growth of specific metamorphic minerals relative to one another. However, in some circumstances, porphyroblast timing can readily be misinterpreted, which can lead to incorrect *P–T–t–d* paths. For example, the microstructural relationships in Fig. 3 are similar to those we have encountered in the cordierite–andalusite schists at Cooma (Johnson & Vernon 1995), and provide a practical example of the problems discussed in the previous section. In Figs. 3(a) & (b), porphyroblasts A and B have slightly curved S_i, there is no continuity between S_i and S_e, and porphyroblast B has a D_3 strain shadow folded into S_4. For Fig. 3(a), the temptation is to interpret the S_i in porphyroblast A as S_3, and porphyroblast B as pre-dating porphyroblast A. However, in Fig. 3(b) the asymmetry of S_i in porphyroblast A is opposite to the asymmetry of the matrix crenulations, indicating that the S_i in porphyroblast A probably pre-dates S_3. This realization makes the relative timing between porphyroblasts A and B a difficult problem, because A may be older than B. The relative timing between the two different porphyroblasts labelled A in Figs. 3(a) & (b) is also unclear, as discussed in the previous section.

Depending on the porphyroblastic minerals involved, the potential consequence for the inferred *P–T–t–d* path of misinterpreting the relative timing of the two porphyroblasts in Figs. 3(a) and (b) can be mild to extreme. For example, if the two porphyroblasts are the same mineral, a misinterpretation of their relative timing may have mild consequences (e.g. Johnson & Vernon 1995). However, if the two porphyroblasts are different minerals, reversing their relative timing could change the slope of an inferred prograde or retrograde *P–T–t* path, which could, at worst, lead to a change in the overall inferred path (i.e. clockwise vs anticlockwise).

TRACKING PROGRESSIVE FOLIATION DEVELOPMENT RELATIVE TO CHANGING METAMORPHIC CONDITIONS

One of the promising recent uses of porphyroblast microstructures involves evaluating rates of structural fabric evolution relative to changes in metamorphic conditions (notable examples are Bell & Rubenach 1983, Reinhardt & Rubenach 1989, and Williams 1994). The principal activity in such studies is to compare S_i patterns in various porphyroblasts, both from individual and different metamorphic zones. The overall aim of such work is to better understand the links between deformation and metamorphism, and therefore provide a better understanding of the tectonic history of mountain belts.

Correctly interpreting the timing of porphyroblasts relative to the deformation history is particularly critical in these studies, because the validity of conclusions regarding relative rates of deformation and metamorphism rely entirely on correct identification of foliations trapped as inclusion trails in the porphyroblasts. As stated previously, this is possible with confidence only in situations where there is continuity between S_i and S_e; yet many of the examples shown in the three papers cited above lack this continuity. Even if an area could be found with perfect continuity between S_i and S_e in different types of porphyroblasts, such studies have the added problem that comparisons of inclusion patterns are made across different metamorphic zones, requiring that the S_e used to time S_i be correlated over varying distances. The problems of correlation (e.g. Williams 1985) may be minimized by comparing inclusion patterns in different porphyroblasts from single samples in individual metamorphic zones (Johnson & Vernon 1995). However, to obtain the most complete picture possible, correlation between variably spaced samples is generally necessary, and a very reliable marker S_e is required to maximize the likelihood of correct correlation from one location to another. This is related to the general issue of diachroneity and heterogeneity of deformation over large areas in orogenic belts, and whether or not the relative labelling of deformation events and foliations is meaningful at such scales.

PORPHYROBLAST ROTATION AND *P–T–t–d* PATHS

The problem of whether or not porphyroblasts rotate significantly, relative to an externally fixed reference frame, during non-coaxial, ductile deformation has received much recent attention (e.g. Bell *et al.* 1992, Passchier *et al.* 1992, Visser & Mancktelow 1992, Johnson 1993, Vernon *et al.* 1993). A solution of this problem is obviously important for understanding the deformation and metamorphic histories of tectonites (e.g. Ramsay 1962, Bell 1985, Johnson 1990, 1993). However, almost no attention has been focused on the effects of considering rotational vs non-rotational histories on *P–T–t–d* paths. Johnson & Vernon (1995) evaluated the Cooma rocks on the basis of one non-rotational and two rotational histories, and found that although the '*d*' in the inferred *P–T–t–d* path varied with changes in the number of required foliations, the *P–T–t* part did not, because each of the three histories involved the same inferred sequence of porphyroblast growth.

Analysis of porphyroblast microstructures that are inferred to involve combinations of rotation of some porphyroblasts and no rotation of others leads to numerous possible deformation and metamorphic histories that are difficult, and perhaps even impossible to confirm. The practice in much of the literature on the subject is to assume that either all the porphyroblasts or none of them in a single thin section rotated during a particular deformation. Although this practice seems reasonable in the absence of evidence to the contrary, it is a simplifying step that may or may not be correct. Given the poor state of understanding, microstructural studies aimed at determining *P–T–t–d* paths may be most useful if they evaluate both rotational and non-rotational deformation and porphyroblast-growth histories. For example, several rotational and non-rotational histories can explain the microstructures in Fig. 2(b), and an example of a conflicting pair of interpretations is shown in Fig. 4. These histories can be compared with field-based structural histories and theoretical *P–T* studies, which may or may not help to select the most likely interpretation.

CONCLUDING REMARKS

We have presented microstructural relationships from the Cooma Complex that raise critical questions about the validity of inferred relative porphyroblast growth timing where there is no continuity between S_i and S_e. Because of the general lack of regions with ideal microstructural relationships, geologists wishing to make

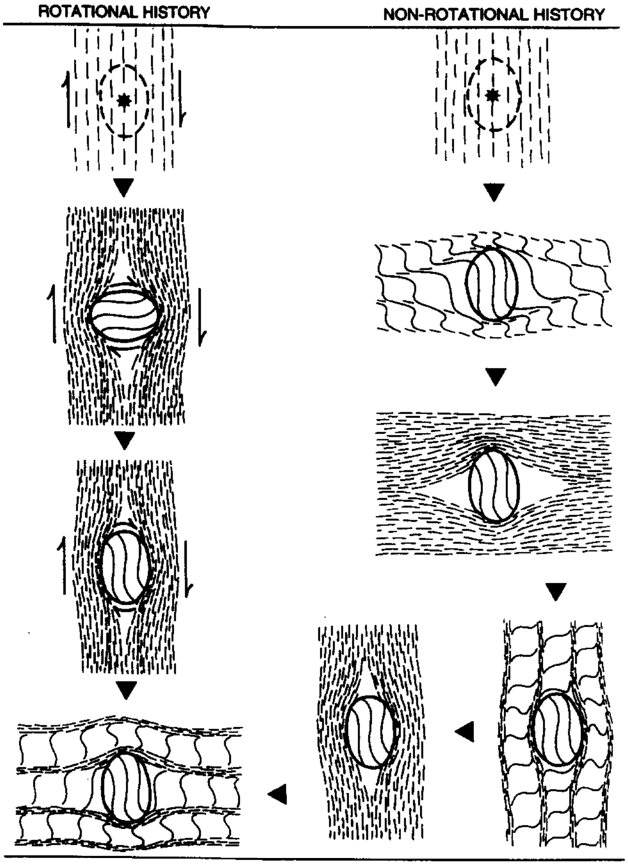

Fig. 4. A conflicting pair of interpretations for the history of porphyroblast growth and foliation development leading to the microstructural relationships in Figs. 1(b) and 2(b). On the left, a porphyroblast nucleates and begins to grow (nucleation position shown by star, final size shown by dashed outline) over a steeply-dipping foliation during 90° of clockwise porphyroblast rotation relative to an externally fixed reference frame. The porphyroblast then undergoes another 90° of rotation without growth, after which a gently-dipping crenulation cleavage overprints the steeply-dipping foliation. On the right a porphyroblast nucleates and begins to grow (nucleation position shown by star, final size shown by dashed outline) over a steeply-dipping foliation during the development of a gently-dipping crenulation cleavage. This crenulation cleavage continues to develop into an intense foliation, which is then overprinted by a steeply-dipping crenulation cleavage. This crenulation cleavage intensifies and is finally overprinted by a gently-dipping crenulation cleavage. Thus, the rotational interpretation involves only two foliations, whereas the non-rotational interpretation involves four.

detailed use of porphyroblast microstructures probably will have to contend with this problem. The difficulties encountered at Cooma may be the exception or the rule in areas of multiple porphyroblast growth and foliation development; we do not yet know. We would like to see more studies that test the validity of current interpretations of relative timing of growth, particularly where there is no continuity between S_i and S_e.

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