Porphyroblast inclusion trail geometries in the Grand Canyon: evidence for non-rotation and rotation?

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Abstract

Porphyroblasts in Paleoproterozoic supracrustal rocks of the Grand Canyon grew during a progressive deformation that involved shortening and heterogeneous development of NE-striking subvertical foliation (S_2) that crenulates and transposes an earlier foliation (S_1). Inclusion trails in syn-S_2 porphyroblast cores show a remarkably consistent NW strike across the regional transect, suggesting a lack of appreciable porphyroblast rotation relative to the trace of the NE-striking S_2 foliation. These apparently non-rotated porphyroblast cores thus preserve a regional NW-striking S_1 orientation. Porphyroblast rims and younger porphyroblasts locally overgrow NE-striking S_2 indicating that porphyroblast growth (and continued non-rotation) spanned S_2. Apparent non-rotation of most porphyroblasts across the transect is interpreted to reflect a dominance of coaxial shortening. In contrast, single thin sections show domains of these 'non-rotated' garnets with sigmoidal inclusion trails adjacent to domains where the characteristic sigmoids are rotated by about 45°. This documents local rotation of garnets relative to S_2 during a heterogeneous late or post-S_2 'reactivation' of the foliation. Thus these types of studies should continue to look for both rotational and non-rotational behaviors at all scales and continue to specify the frame of reference. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Modern tectonic and petrologic studies of metamorphic terranes within orogenic belts investigate the particular 'path' a rock took through P–T, time, and deformation 'space'. Because later tectonothermal events tend to eliminate or obscure evidence for earlier events, we search for remnants of the early parts of the path in complexly deformed regions. One type of window into the early history of a rock's deformation path is offered by low strain domains (i.e. areas little affected by later tectonothermal events due to strain partitioning and/or lower metamorphic grade). A second possible 'window' is offered by inclusion trails within porphyroblasts (e.g. Bell et al., 1986; Reinhardt

and Rubenach, 1989; Williams, 1994; Johnson and Vernon, 1995b; Aerden, 1998). However, for the latter, the interpretation of porphyroblast–matrix textures and the mechanical behavior of porphyroblasts during deformation are highly controversial (e.g. Johnson, 1993; Vernon et al., 1993; Johnson and Vernon, 1995a, b).

Two general models have evolved for explaining porphyroblast behavior during deformation. 'Non-rotation models' postulate that porphyroblasts are generally decoupled from a deforming matrix (e.g. Johnson, 1990) and do not rotate relative to an external reference frame (e.g. Ramsay, 1962; Rosenfeld, 1968; Fyson, 1975 and 1980; Bell, 1981, 1985, 1986; Bell and Rubenach, 1983; Bell et al., 1986, 1992a,b; Bell and Johnson, 1989; Steinhardt, 1989; Jung et al., 1997; Dinklage, 1998). 'Rotation models' postulate that porphyroblasts are generally relatively rigid objects that can rotate relative to the infinitesimal stretching direction (Passchier and Simpson, 1986), with degree of rotation depending on competency contrast, aspect ratio,

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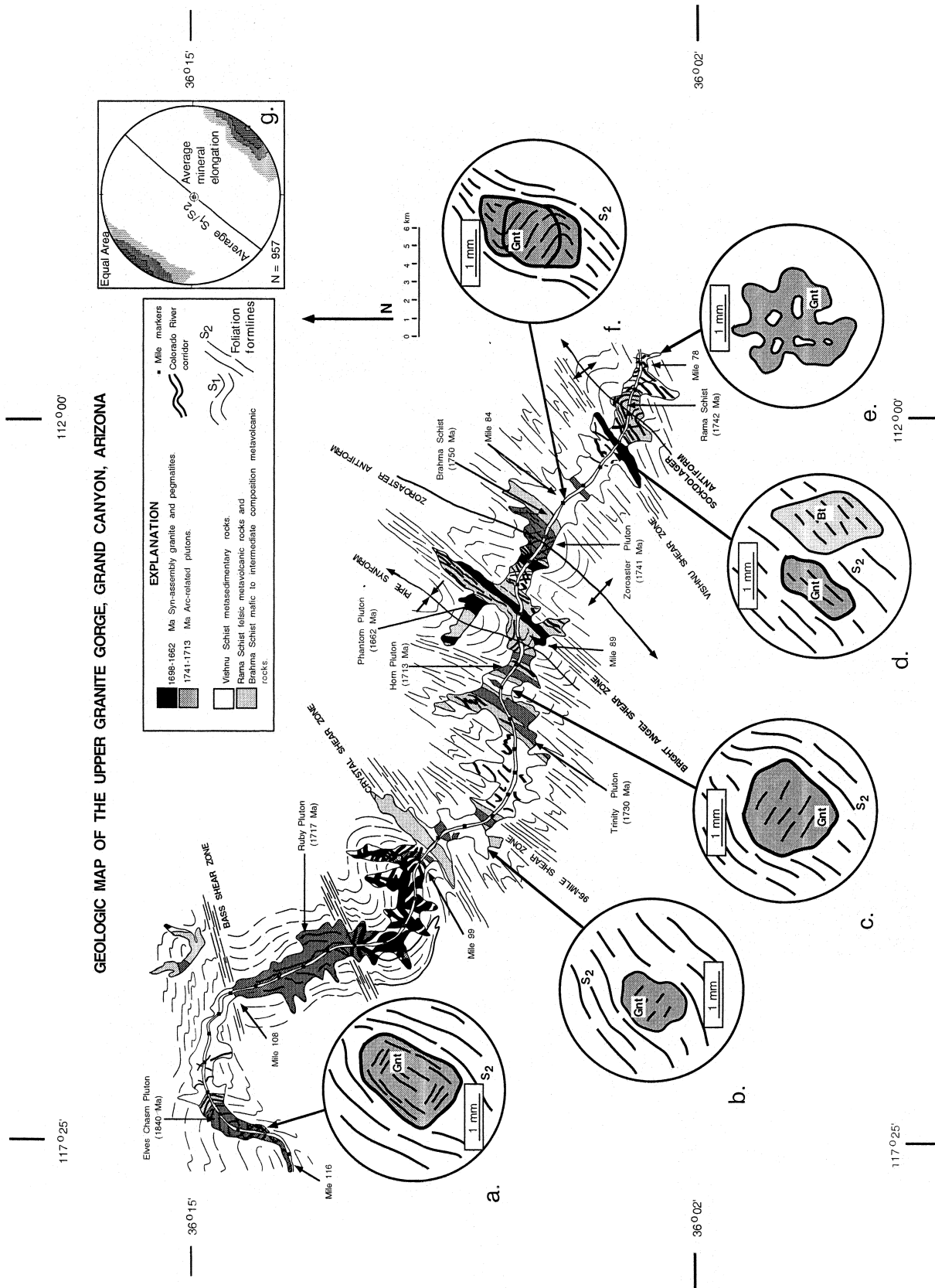
Fig. 1. Simplified geologic map of the Upper Granite Gorge (modified from Ilg et al., 1996) showing map view schematic representative porphyroblast inclusion trail and matrix fabric relationships from across the transect. (a) Typical complex inclusion trail pattern in garnets from the Elves Chasm area (miles 113–115). (b) Upper greenschist- to lower amphibolite-grade garnets preserve NW-striking inclusion trails in NE-striking schist (miles 96–98). (c) Rare inclusion trails in upper amphibolite-grade rocks show NW-striking orientations (mile 91). (d) Lower amphibolite-grade garnets and biotites preserve NE-striking inclusion trails near Vishnu shear zone (mile 81). (e) Upper amphibolite-grade garnets typically do not preserve readily interpretable inclusion trails (miles 77–81). (f) Medium amphibolite-grade garnets preserve cores with NW-striking inclusion trails and rims that show the transition to NE-striking S_2 (miles 83–85). (g) Equal area lower hemisphere plot of poles to S_0, S_1, and S_2 and the mean mineral stretching direction (⊕).

and degree of non-coaxial deformation (e.g. Rosenfeld, 1970; Ghosh, 1975; Ghosh and Ramberg, 1976; Schoneveld, 1977; Williams and Schoneveld, 1981; Lister and Williams, 1983; Passchier and Simpson, 1986; Passchier, 1987; Hanmer and Passchier, 1991; Ildefonse et al., 1992; Passchier et al., 1992; Visser and Mancktelow, 1992; Miyake, 1993; Kraus and Williams, 1998). Some workers have attempted to evaluate both rotation and non-rotation models (e.g. Johnson, 1990a, b; Hayward, 1992; Johnson, 1993; Vernon et al., 1993; Passchier and Speck, 1994; Johnson and Vernon, 1995a,b; Aerden, 1995) and it seems likely that some porphyroblasts might rotate while others do not. Perhaps determining the relative amount of rotation might be a better way to frame the question (Lister and Williams, 1983; Johnson, 1990a, b). However, there is still no consensus on general models for the extent of porphyroblast rotation during deformation.

One method to test for rotation of porphyroblasts is an evaluation of the regional consistency (or lack thereof) of included fabrics in porphyroblasts across an orogen (e.g. Fyson, 1975; Bell, 1985; Bell et al., 1986; Johnson, 1990a, b, 1992; Hayward, 1992). There are assumptions implicit to this approach that are rarely stated. First, the regional 'tectonic grain' of the orogen is assumed to be an external reference frame presumably because it often parallels a local craton margin, the principal directions of finite strain, orientations of regional folds, and/or the major shear zones, and hence provides a regional understanding of porphyroblast behavior during collisions, shortening, and shearing. Second, it is assumed (and hopefully shown by textural arguments) that the porphyroblasts under consideration are of approximately the same age and grew during development of the main 'tectonic grain'. Then, as porphyroblasts commonly overgrow and preserve an early subplanar fabric as inclusion trails, 'rotation models' predict a variable final distribution of inclusion trail orientations. The latter holds because of the heterogeneity of strain, and because of the physics of rigid particle behavior in flowing matrix, where models suggest that rigid objects will behave differently depending on their aspect ratio (e.g. Ghosh and Ramberg, 1976) and the nature of the general shear (e.g. Simpson and De Paor, 1993). In contrast, if the strike of inclusion trail orientations is consistent over a large region of folds, shear zones, and heterogeneous fabric, this seems to necessitate that porphyroblasts in general did not rotate relative to each other or to the orogenic reference frame (Johnson, 1990a, b, 1992; Hayward, 1992; Aerden, 1995; Johnson and Vernon, 1995a, b; c.f. Williams, 1998).

We apply this test to part of the Grand Canyon transect, where Proterozoic rocks are continuously exposed in a cross-strike transect for about 60 km. Our approach is to evaluate porphyroblast inclusion trail geometries relative to a heterogeneously developed, but regionally dominant NE-striking subvertical foliation (S_2). This foliation trend seems to dominate much of the Proterozoic orogen of Arizona (Karlstrom and Bowring, 1991) and is subparallel to major shear zones and province boundaries (Karlstrom and Bowring, 1988) as well as the Archean–Proterozoic suture zone in Wyoming and hence, might be a valid external reference frame. The Grand Canyon transect crosses variable lithologies, meso- and macro-scale folds, and several S_2-parallel shear zones and it contains numerous zones where deformation partitioning has preserved macroscopic 'windows' of early (S_1) geometries. It is thus a good transect to try to relate microstructures to deformation history.

The goals of this paper are: (i) to document a remarkably consistent NW strike of inclusion trails suggesting that in general porphyroblasts did not undergo appreciable rotation relative to the NE-striking S_2 fabric; thus, these inclusion trail-bearing porphyroblasts may preserve information about the early fabric geometry of the orogen; and (ii) to document adjacent cm-scale domains of rotation and non-rotation. This is interpreted to indicate that late- or post-S_2 porphyroblast rotations may have taken place by new movements on S_2 during progressive general shear.

2. Regional tectonic setting

The Colorado River in the Grand Canyon has cut through the Paleozoic strata of the Colorado Plateau, into the Paleoproterozoic basement of the Yavapai Province. The Yavapai Province is characterized by 1.75–1.74 Ga island arc metavolcanic rocks and arc basin metasedimentary rocks intruded by two suites of plutons: 1.74–1.71 Ga arc-related intermediate composition plutons and 1.70–1.66 Ga collision-related granitic plutons, dikes, and sills (Karlstrom and Bowring, 1993). This package of rocks was penetratively deformed by one or more pre-1.70 Ga events that produced a ubiquitous penetrative fabric (S_1) characterized by bedding-parallel foliation and isoclinal rootless folds. The 1.70–1.68 Ga Yavapai orogeny overprinted these earlier fabrics producing a strong, subvertical, northeast-striking foliation throughout much of the Paleoproterozoic basement in the southwestern North America (Karlstrom and Bowring, 1988, 1991; Ilg et al., 1996).

The structural geology of the Upper Granite Gorge transect is dominated by NE- and NW-striking foliation domains (Fig. 1; Ilg, 1992, 1996; Ilg et al., 1996; Ilg and Karlstrom, 1996). NW-striking domains contain S_1 foliation, often in the hinge regions of large F_2
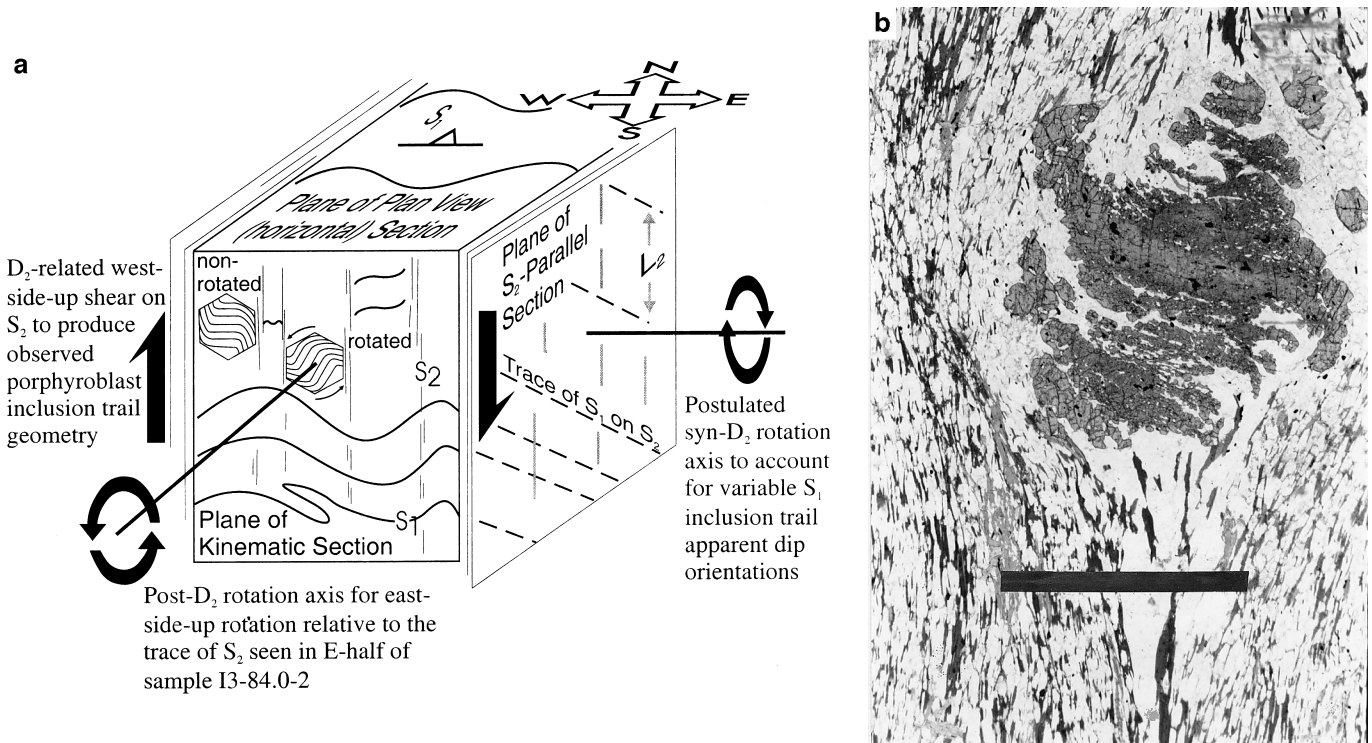
Fig. 2. (a) Schematic block diagram showing three different typical thin section orientations (horizontal, S_2-parallel, and S_2-normal/L_2-parallel), simplified S_2 and S_1 geometries, and possible syn- and post-D_2 rotation axes (see text for discussion). (b) S_2-normal/L_2-parallel plane light photomicrograph showing typical garnet core and rim geometries in medium amphibolite grade rocks (view is cross-sectional to the NE). When rim asymmetry is developed in garnet porphyroblasts in the Upper Gorge, the asymmetry usually shows a component of west-side-up as in this example. Scale bar is approximately 3 mm.

folds; NE-striking domains contain a composite sub-vertical S_1/S_2 foliation. The nature of S_2 is lithology dependent: in metavolcanic rocks and orthogneisses, it is generally a composite S_1/S_2 fabric where S_1 has been intensified on the subvertical limbs of F_2 folds. In metasedimentary rocks it is a crenulation cleavage. Crenulation cleavage development, and related transposition of S_0/S_1, are variable such that weakly to moderately overprinted S_1 domains can be found at all scales, from microlithons to map-scale domains (Fig. 1). A third generation of structures is present, but these are relatively minor kinks and weakly developed E–W- to NW-striking differentiated S_3 cleavages that do not markedly control the structural geometry (Ilg et al., 1996).

The Grand Canyon transect is divided into tectonic blocks by a series of NE-striking subvertical shear zones with intensely developed S_2 (Ilg et al., 1996; Fig. 1). Stretching lineations within these zones are subvertical, as they are throughout the transect (Ilg et al., 1996). Perhaps because fabrics are annealed, asymmetrical structures and indications of shear sense are not well developed in these zones. However, where shear sense is observed (e.g. Bass shear zone), shear is west-side-up (see also Fig. 2), with a dextral component (Ilg

et al., 1996). Because these zones appear to be more intense S_2 foliation zones, we interpret them to represent zones of general shear (shortening plus west-side-up shear) during D_2, with a predominance of NW–SE shortening. The predominance of shortening strain is suggested by observations such as the paucity of asymmetrical fabrics, an apparent shallow enveloping surface for F_2 folds, and the similarity of metamorphic pressures across the transect (Ilg et al., 1996).

Metamorphic grade varies from 650°C to 500°C across the Upper Granite Gorge, at relatively constant 6 kbar pressures (Babcock, 1990; Ilg et al., 1996). The transect contains metamorphic domains across which temperatures either remain constant or vary smoothly. Metamorphic grade typically changes abruptly across shear zones. Higher temperature regions are spatially associated with zones containing voluminous and intricate dike networks of ca 1.70–1.68 Ga granite and pegmatite. Thus, Ilg et al. (1996) suggested that advective heating from syn-D_2 plutons and dike networks caused the temperature gradients (at nearly constant pressure). Peak metamorphism, S_2 fabric development, and granitic plutonism were broadly synchronous during a progressive NW–SE directed contractional tectonothermal event that took place from 1.70 to 1.69 Ga

(Hawkins et al., 1996; Ilg et al., 1996). Thus, porphyroblasts from across the transect are considered to have grown during D_2, as is supported by porphyroblast–matrix microstructures summarized in Fig. 1 and shown in Fig. 2.

3. Methods for analysis of porphyroblast–matrix textures

In cutting thin sections, many workers use one of the reference frames, defined by: (1) finite strain axes (Ramsay and Huber, 1987), (2) infinitesimal strain axes (Lister and Williams, 1983), or (3) shear zone boundaries (Simpson and De Paor, 1993). For these reference frames, thin sections cut normal to foliation and parallel to the extension lineation should show rotation of porphyroblasts relative to the trace of the developing foliation assuming the rotation axis is subparallel to S_2 and sub-perpendicular to L_2 (Fig. 2). However, for non-rotation models where the matrix foliation can be reoriented relative to non-rotating porphyroblasts and Q-domains, some workers have used an externally fixed reference frame for porphyroblast analysis (e.g. Ramsay, 1962; Fyson, 1975, 1980; Johnson, 1990a, b). Bell and Johnson (1989) suggested that vertical and horizontal sections were the best for testing porphyroblast kinematics and the progressive deformation and metamorphic histories of mountain belts. This study is able to use both approaches simultaneously because the Grand Canyon transect is dominated by a subvertical foliation (S_2) and associated subvertical extension lineation. Many of our thin sections were cut in NW–SE vertical planes; these serve both as 'kinematic sections' (i.e. normal to S_2 foliation and parallel to the L_2 mineral stretching direction) and NW–SE cross-sectional views of the orogen (Fig. 2). For each sample we also cut horizontal thin sections to relate map patterns to porphyroblast inclusion trail geometries (Fig. 2).

We examined 360 L_2-parallel/S_2-normal thin sections that were selected from a suite of approximately 600 hand samples. Of the 360 samples for which 'kinematic' thin sections were cut, 64 contained numerous porphyroblasts; 64 horizontal sections were made from these samples. In addition, vertical sections normal to the S_1 internal inclusion trails (parallel to S_2 in this case; see Fig. 2) were made for three samples to more fully evaluate the dip of included S_1. Inclusion trails from > 500 porphyroblasts were mapped on large (up to one meter square) digitally captured, geographically oriented thin section images produced using NIH Image software.

4. Nature of porphyroblasts

Three types of porphyroblasts were used in our study—garnet, staurolite, and biotite. However, the majority of the inclusion trails occur in garnet porphyroblasts and unless otherwise noted, inclusion trails will refer to those in garnet. The included minerals are generally quartz, biotite, and Fe–Ti oxides and aligned Fe–Ti oxides and the long axis of elliptical quartz inclusions generally define inclusion trails. Garnet shows a variety of morphologies and porphyroblast–matrix relationships (Fig. 1 a–f).

4.1. High-temperature domains

High-temperature ($\geq 650°C$) metamorphic domains include the mile 78–81 area, the mile 85–96 area, and the mile 98–120 area (Ilg et al., 1996). (Note that geographic locations along the Colorado River in the Grand Canyon are given in miles downstream from Lee's Ferry, Arizona, and all sample numbers contain the river mile where the sample was collected.) Quartz and Fe–Ti oxide inclusions in garnet from high-temperature domains are generally weakly elongate but do not tend to form readily identifiable inclusion trails (Fig. 1e). This may reflect the fact that increased diffusion at higher temperature might allow inclusions to achieve lower energy (spherical) shapes. Nevertheless, a few high-temperature samples (e.g. B-91-2) show aligned elongate Fe–Ti oxide and quartz inclusion trails. These were evaluated and they show results similar to the better-preserved inclusion trails from the medium-temperature domains. Thus, although this study emphasizes data from the medium grade domains, existing data suggest that the same conclusions may apply to the high-grade domains.

4.2. Medium-temperature domains and timing of porphyroblast growth

Medium-temperature (500–600°C) domains in the Upper Granite Gorge of the Grand Canyon include the mile 81–84 area, the mile 96–98 area, and the mile 108–111 area (Fig. 1; Ilg et al., 1996). The metasedimentary Vishnu Schist of the medium-temperature domains includes metamorphosed semi-pelitic rocks. Quartz and Fe–Ti oxide inclusions are typically elongate and define easily identifiable inclusion trails. Inclusions also occur in garnets from amphibolites but these do not typically contain readily interpretable trails.

NE-striking, subvertically dipping S_2 is generally strongly developed within metasedimentary rocks and inclusion trails from garnets have four main geometries (Fig. 1). A majority of garnets have trails that are subplanar and nearly normal to the subvertical matrix
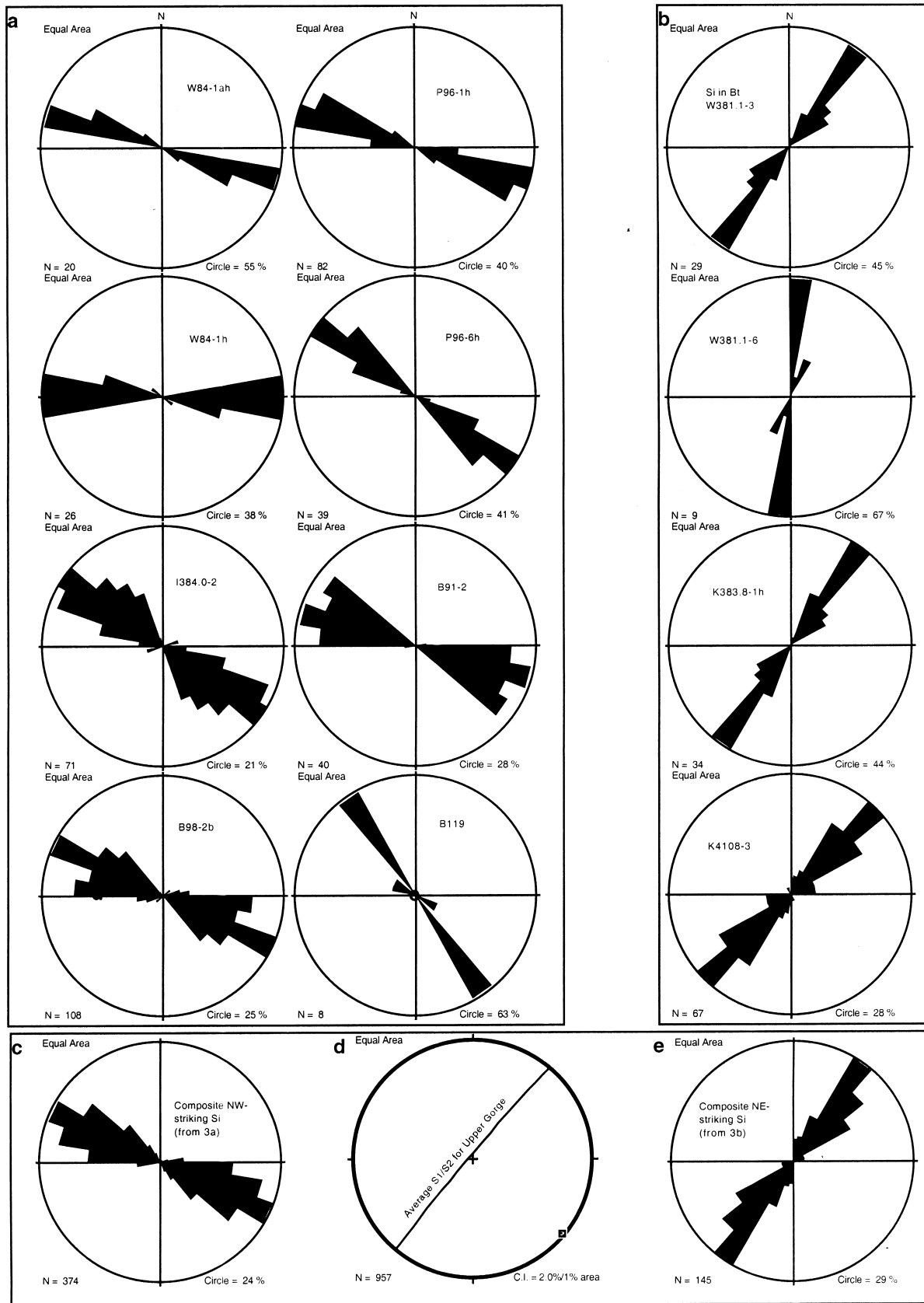
Fig. 3. Rose diagram plots of the strike of included fabrics from 12 amphibolite-grade samples showing distinct NW- (a) and NE-striking (b) orientations. (c–e) Composite rose plots for NW- and NE-striking domains and an equal area lower hemisphere projection contour diagram showing average S_1/S_2 composite foliation. Note that the composite plot of NE-striking included fabrics shows a maximum nearly identical to the plot of poles to foliation. This suggests that porphyroblasts preserving NE-striking inclusion trails overgrew S_2.
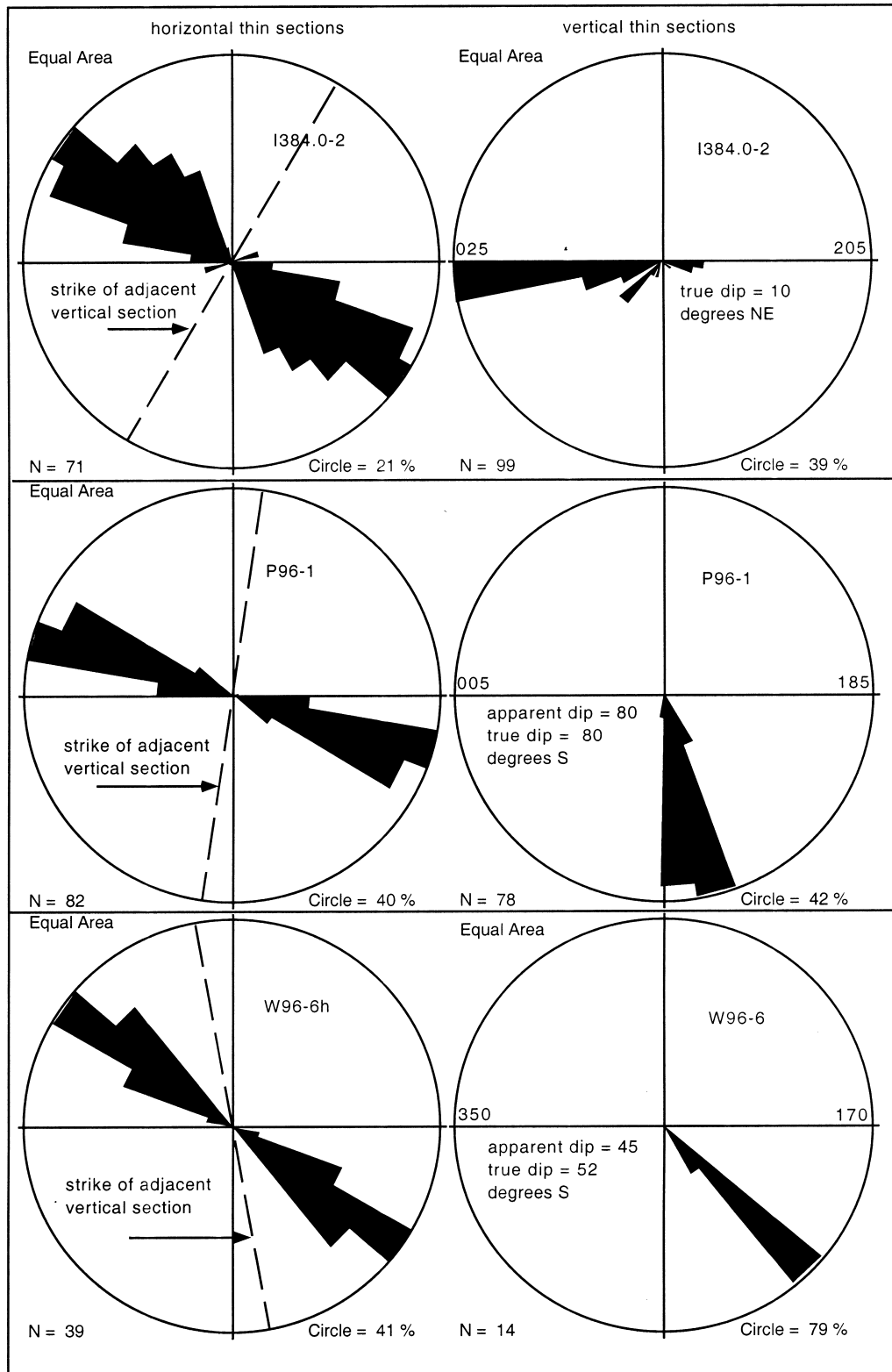
Fig. 4. Complete included fabric orientations for three samples from the Upper Gorge. These samples show consistent NW strikes (left column) but variable dips (right column). The dashed lines in the rose diagrams in the left column show the strike of the adjacent complimentary vertical section. Variable dips of included fabrics are attributed to either garnets overgrowing and consistently striking but variably dipping S_1, or passive rotation of fabric elements about the pole to S_2 (see Fig. 2; also, see text for discussion).

fabric in both horizontal and vertical thin sections (Figs. 1b and c and 2). These are interpreted to be garnets that overgrew S_1 in the early stages of F_2 because inclusion trails are gently folded. Some grains show well-developed sigmoidal inclusion trails where trails in the core of the garnet are subperpendicular to S_2, but trails bend into parallelism with S_2 in garnet rims (Fig. 1f). These grains are interpreted to have grown synchronously with progressive development of S_2. Some grains have inclusion trails that are parallel to S_2 (Fig. 1d) and show matrix micas bent around their margins indicating further D_2 shortening across S_2 after garnet growth. These are interpreted to have grown late during D_2. Garnets in the western part of the transect (Fig. 1a) show more complex trails and possibly an earlier generation of included fabric that pre-dated the early-, syn- and late-S_2 garnet growth described above. These garnets were scarce and not studied in detail here. Thus, we interpret the various garnet inclusion trail geometries to record different times of garnet growth during the ca 15 million years of progressive shortening deformation and metamorphism that created S_2.

5. Regional consistency of inclusion fabric strike

This section shows that, in spite of the well-developed NE-striking subvertical foliation in Paleoproterozoic rocks in the Grand Canyon, inclusion trails in garnets collected throughout most of the transect consistently strike either NW or NE. Different orientations are interpreted to depend on age of garnet growth relative to S_2 fabric development (early vs. late, respectively). Even though this and the next section discuss possible local rotations, the overall regional consistency of strike of included fabrics is remarkable considering the heterogeneity of S_2 fabric development, the presence of large folds, and the inferred presence of shear zones.

From a suite of 64 porphyroblast-bearing samples, 12 contained numerous garnets with abundant inclusion trails and these were evaluated in detail to determine the strike of included fabrics (Fig. 3). The other 52 samples contained porphyroblasts with only poorly defined inclusion trails and, although these were in qualitative agreement with the 12 studied, these data were not used. Of the 12 samples that contained abundant inclusion trails, three were also evaluated (in sections normal to included fabrics and parallel to S_2) for the dip of included fabrics. The samples were collected from the mile 81–84 area, the mile 91 area, the mile 96–98 area, the mile 108 area, and the mile 115 area (Fig. 1). Because inclusion trails were generally sub-planar within individual porphyroblasts, one central inclusion trail trace per porphyroblast was measured with respect to north for horizontal sections and with respect to horizontal for vertical sections. The measurements were then plotted on rose diagrams that represent a map view for horizontal sections (Fig. 3) and map plus cross-sectional view for sections for which we have 3-D inclusion data (Fig. 4). Rose diagrams show that inclusion trails were generally subparallel to each other in adjacent porphyroblasts of the same thin section. In most of the samples S_1 trails are either NW-striking (Fig. 3a) or NE-striking (Fig. 3b), with very few intermediate orientations.

The NE-striking S_2 inclusion trails (Fig. 3b) come from two areas: the medium temperature mile 81–83 area and Shinumo Creek area. In these areas, garnets (and biotites in sample W3-81.1-3) are interpreted to have overgrown well-developed S_2 and to be late compared to garnets with NW-striking S_1 inclusion trails. Note that garnets and biotites with NE-striking inclusion trails still display very consistent inclusion trail orientations suggesting that they did not, in general, rotate relative to the trace of developing S_2 foliation (Fig. 3b).

The NW-striking S_1 inclusion data come from many areas throughout the transect. The regionally consistent NW strikes of included fabrics in a transect characterized by strong but heterogeneous NE-striking S_2 (Fig. 1) suggests that the porphyroblasts grew post-S_1 and earliest syn-S_2 and that they did not rotate relative to the developing S_2 fabric. Some samples contained porphyroblasts that we interpret to have rotated (see below), but apparently, development of strong NE-striking S_2 by crenulation of NW-striking S_1 took place without regionally significant rotation of early-S_2 garnets.

However, in spite of the consistent NW strike of inclusion trails in many samples, the dip of S_1 inclusion trails in porphyroblasts measured in three sections varies from subhorizontal to subvertical (Fig. 4). This appears consistent with data from mesoscopic and macroscopic domains of preserved S_1 foliation (Fig. 1) which indicate that S_1 dips variably northeast and southwest within the hinge zones of variably plunging F_2 folds (Fig. 1). To explain the consistent NW strike of inclusions and S_1 domains, but variable dip, we see two possibilities (Albin and Karlstrom, 1991). First, it may be that porphyroblasts overgrew large NW-trending F_1 antiforms and synforms with variably oriented S_1 then did not rotate during D_2. However, the variation in plunge of F_2 folds, and variation in dip of inclusion trails, over short distances (Fig. 4), plus the lack of appropriate macro- and mesoscopic fold interference patterns makes this possibility less attractive. A second possibility is that porphyroblasts overgrew a subhorizontal S_1 and that both porphyroblasts and associated S_1 domains in F_2 fold hinge zones rotated
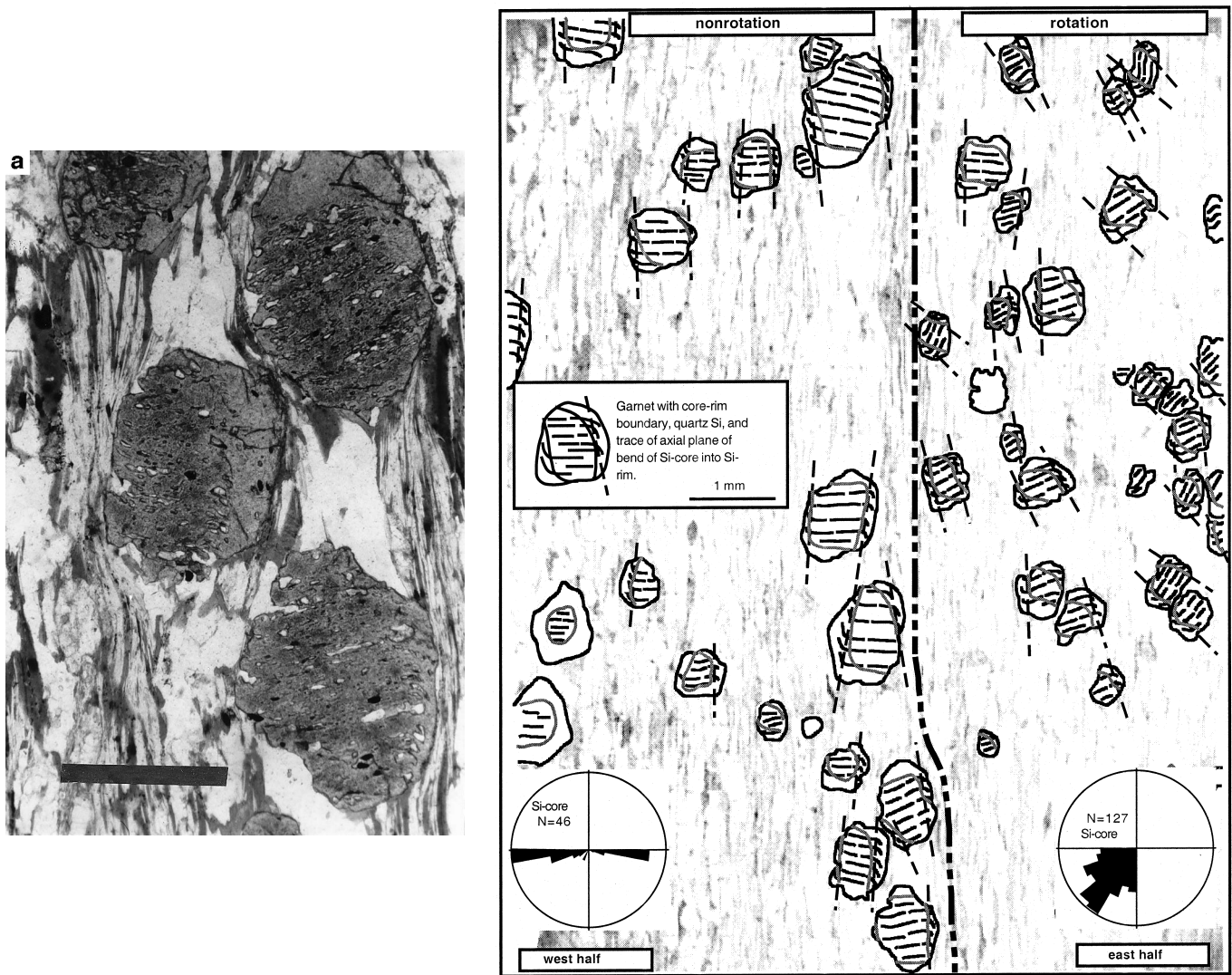
Fig. 5. (a) A plane light photomicrograph of individual garnets from sample I3-84.0-2 showing core and rim inclusion fabrics. The photomicrograph was taken of the cluster of four garnets in the lower center shown in (b). Bar scale is approximately 1 mm. (b) A cross-sectional interpretive drawing of part of an S_2-normal/L_2-parallel thin section from sample I3-84.0-2 (view is toward 030°). The figure shows the trace of included fabrics in garnet against a digitally captured background of semi-pelitic schist. Garnet core fabrics on the left side (northwest) display relatively consistent subhorizontal orientations (see rose plot) while core fabrics from garnets on the right side (southeast) have a variable but average dip of approximately 45° (see rose plot). These relationships suggest a post-D_2 east-side-up shear strain of approximately one in the right side of the thin section.

towards the subvertical extension direction about the Z-axis of the finite strain ellipsoid during passive amplification of folds due to progressive D_2 shortening (Fig. 2). In the latter case, porphyroblasts did rotate, but not due to shear on S_2 as is usually implied in rotation models.

6. Evidence for rotation and non-rotation

Although we interpret the regionally consistent NW- and NE-trending orientations of porphyroblast inclusion trails to indicate general non-rotation of porphyroblasts relative to the trace of developing S_2 foliation, there are some samples that do show rotation. Thin section I3-84.0-2 (Fig. 5), for example, contains adjacent domains that are interpreted to show non-rotation (west half) and east-side-up rotation (east half).

This sample is from semi-pelitic schist from the east limb of the Zoroaster antiform, an area where S_1 inclusion trails are subperpendicular to the NW striking matrix as discussed above (Fig. 1). Three orthogonal thin sections were cut: one normal to S_2 foliation and parallel to the subvertical mineral elongation lineation, one horizontal, and one vertical and subperpendicular to the included foliation in garnet cores (parallel to S_2 in this case). The three sections thus show: (i) a com-

bined shear sense and cross-sectional view; (ii) map view; and (iii) the true dip of included fabric. As such, this sample is ideal for assessing rotation vs. non-rotation of porphyroblasts during S_2 development and NW–SE shortening.

Garnets in this section typically have inclusion-rich cores and relatively inclusion poor, generally euhedral rim overgrowths (Fig. 5). S_1 inclusion trails within garnet cores are typically relatively straight, with the beginning of a sigmoidal bend near the edge. Inclusion trails within garnet rims are continuous with inclusion trails in the core, but typically show sharp bends towards parallelism with matrix S_2. The bends defined by inclusions in the garnet rims from the western half of the section (see below) are consistently s-shaped (west-side-up). Both the outer parts of the core and the rims apparently grew as S_2 cleavage was developing.

Garnets show the same core and rim morphologies in both the eastern and western halves of this thin section, suggesting that their growth was contemporaneous, but they are misoriented relative to each other. In the western half of the section, S_2 rim inclusions are subparallel to S_2 in the matrix and S_1 core inclusions are at a high angle to matrix foliation, similar to S_1 core inclusions from across the Grand Canyon transect (Fig. 3). In contrast, in the eastern half, S_1 core inclusions are variably west dipping and sigmoid axial planes are east dipping (Fig. 5). Because identical internal geometries define relatively uniform subhorizontal orientations on the western side and variably west-dipping orientations in the eastern side, we interpret porphyroblasts in the eastern half to have been rotated counterclockwise after garnet rim growth.

Non-rotation models would require that garnets from the eastern side overgrew a tightly crenulated and somewhat chaotic fabric. While we cannot rule this out, attempts to draw a form surface by connecting S_1 core inclusion trails met with severe incompatibilities, even when considering 50–70% shortening across this zone.

Garnets in both the eastern and western halves show asymmetrical rim development. In the western half (unrotated) of the section, resorbed or incompletely grown rims are consistently located along the upper left and lower right quadrants (Fig. 5). Rims may have preferentially overgrown mica concentrations against asymmetrical garnet cores (Fig. 5). If so, rims grew late during NW–SE shortening and west-side-up general shear. One possibility to explain the rotation domain is that preferential development of rims then created inequant or enhanced existing inequant grains that responded to continued shortening deformation by rotating sinistrally (east-side-up) in the eastern half of the section. Alternatively, garnets from the eastern side can be interpreted to record east-side-up shear

because their core inclusion trails (initially subhorizontal) have variable west dips and the axial planes to the folded rim fabrics all show east dips (initially subvertical). In either case, we see no difference in the matrix that might explain different behavior in the two domains.

A strict non-rotation end-member model cannot satisfactorily explain the observed textures. One might interpret that garnet cores in both halves of the section overgrew an existing, variably oriented S_1 fabric. Garnet rims then overgrew a second variably oriented fabric that was parallel to the present matrix fabric S_2 in the western half and variably oriented around garnets from the eastern half. Then, the present matrix fabric was developed in the entire section. However, our interpretation of regional structures is that there are two main foliations associated with amphibolite-grade metamorphic minerals (Ilg et al., 1996). The strict non-rotation interpretation requires four pre- and syntectonic foliations for which no independent mesoscopic or macroscopic evidence exists. Likewise, a strict rotation end-member model, where garnet sigmoids record progressive rotation relative to S_2 shear planes, provides an unsatisfactory explanation of observed geometries. This rotation model predicts that garnets in the western half would have had to rotate by the same amount (90°) while garnets in the eastern half would have rotated by variable amounts.

The simplest interpretation is that this section records adjacent domains of non-rotation and rotation. A postulated sequence of events for this section is that garnets overgrew an initially NW-striking subhorizontal fabric which is preserved as S_1 core inclusions in the western half of the section and in low strain (S_1) domains across the transect (see below). Garnet rims then overgrew S_2 mica domains that record a west-side-up asymmetry during the formation of the subvertical, NE-striking S_2 crenulation cleavage. Following garnet rim growth, garnets rotated by variable amounts only in certain domains, with an apparent east-side-up sense (see Fig. 2). This rotation could have been facilitated by deformation partitioning, or by some localized metamorphic effect, for example by a fluid consuming reaction involving staurolite (which is abundant in the eastern half but not in the western half of the section). By this model, an aqueous phase around the garnet porphyroblasts provides a means for decoupling between the matrix and the porphyroblasts. When the aqueous phase is consumed in a staurolite growing reaction, porphyroblasts are coupled to the matrix and rotation results (e.g. Johnson, 1990a, b).

An important point is that rotation post-dated or was late relative to the development of S_2 and the garnet growth. This is suggested by the fact that the garnet core–rim and spiral geometries are identical on

adjacent sides of the thin section with the eastern side grains rotated sinistrally by about 45°. There is no obvious difference in the matrix in the two halves of the section, and we infer that a cryptic post-garnet shear has affected the eastern side. This is a type of foliation 'reactivation' that may occur late in the retrograde path or during a later tectonic event. For the Grand Canyon, there is evidence for both. Granite emplacement and localized deformation continued in places until about 1.66 Ga (Hawkins et al., 1996) and later 1.4 Ga deformation may also have affected parts of the transect (Karlstrom et al., 1997).

The implication of adjacent domains of rotation and non-rotation in a single thin section is significant for several reasons. These results contradict the assertion of Bell (1985 and many subsequent papers by Bell and coworkers) that rigid objects in a deforming heterogeneous matrix never rotate. However, the non-rotated domain suggests that S_1 core inclusions may preserve consistent orientations (e.g. Ramsay, 1962; Fyson, 1975, 1980; Bell and Johnson, 1989; Steinhardt, 1989; Bell et al., 1992a; Aerden, 1995) across the transect and thus, support models for domains of porphyroblast non-rotation relative to the strike of developing fabrics.

7. Conclusions

The results of this study suggest either 'rotation' or 'non-rotation' porphyroblast behavior is possible during deformation, even in adjacent thin section-scale domains. More importantly, it highlights the importance of specifying the reference frame, (e.g. Kraus, 1998) timing, degree, and type of 'rotation'. However, in spite of the various possible rotations of porphyroblasts, there remains a remarkable consistency of inclusion trail orientations across the Grand Canyon transect, with NW-striking S_1 cores at high angle to NE-striking subvertical S_2 matrix, or with S_2 inclusion trails parallel to matrix. This suggests that many porphyroblasts, that grew early-, syn-, and late-D_2, did not rotate appreciably with respect to the trace of developing S_2 cleavage during ca 1.7 Ga NW–SE shortening deformation. This does not disprove rotation (especially given the puzzle of diverse dips of S_1 inclusion trails and the possibility of passive rotation of geometric elements), but it seems to preclude models for shear-related rotation of porphyroblasts relative to developing S_2 foliation for most samples. To the extent that the porphyroblasts did not rotate, they may be used to evaluate the pre-D_2 fabric geometry. In the case of Paleoproterozoic rocks in the Grand Canyon, the inclusion trail geometries suggest that S_1 was regionally NW striking. S_1 may have been variably dipping, but more likely was subhorizontal across a wide region. Thus, we infer both rotation and non-rotation behavior and point out the importance of specifying timing and reference frame when discussing porphyroblast behavior during deformation.

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