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Fabric reactivation: an example from the Hualapai Mountains, NW Arizona, USA

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Abstract

Foliation reactivation involves renewed movement on preexisting fabrics and can lead to difficulty in determining temporal and spatial relationships of fabrics to larger structures as well as correlation of fabrics to tectonic events. Porphyroblasts that contain internal fabrics allow for interpretation of the structural history of an area including the potential for foliation reactivation. In Boriana Canyon, Hualapai Mountains, NW Arizona, three vertical foliations (S_2–S_4) are preserved in the contact aureole of the 1.40 Ga Boriana granite. Foliation S_2 strikes northeast and is parallel with regional foliation that formed post- or syn-1.68 Ga. Foliation S_3 occurs throughout the canyon but is most prevalent in the contact aureole where, close to the pluton, it forms the main cleavage. Andalusite and garnet porphyroblasts overgrew S_3 crenulations. Foliation S_4 is parallel to the S_2 regional fabric and, in some outcrops, deformation associated with S_4 has decrenulated the S_3 fabric although S_3 is preserved in garnet and andalusite porphyroblasts. In these outcrops S_4 is also axial planar to F_2 folds. Recognition of fabric reactivation of this aureole allows for discrimination of foliation-forming episodes that are separated by ~250 m.y. and a better understanding of the Proterozoic geologic history for this part of NW Arizona.

1. Introduction

An important requirement to understand the development of orogenic belts and processes of crustal formation is knowledge of the timing of metamorphism and deformation (e.g. Bell and Johnson, 1989). This relationship can be determined through analysis of metamorphic porphyroblasts and tectonic foliations. In the most simple form, metamorphism is interpreted to follow deformation if porphyroblasts overgrow foliation or to predate deformation if foliation truncates metamorphic porphyroblasts. Textures such as curved inclusion trails near margins of porphyroblasts have been interpreted as indicating synkinematic porphyroblast growth, although interpretation of internal fabrics in porphyroblasts has been the subject of some debate (Bell, 1985; Vernon, 1989).

One of the requirements for successfully using foliation and porphyroblast relations is identification of the number of fabric-forming events and the timing between these events and porphyroblast growth. This may be difficult in rocks that have undergone reactivation of older fabrics (Bell, 1986), especially if the rocks lack porphyroblasts that preserve evidence of earlier fabric-forming events. A similar problem is encountered in areas where composite foliations may be produced during progressive deformation (Meneilly, 1983; Tobisch and Paterson, 1988). Lack of recognition of fabric reactivation can therefore lead to erroneous conclusions about kinematics, the number of deformational events, fabric geometry and the orogenic history of an area (Bell, 1986).

2. Background

Foliation reactivation is defined as renewed movement along preexisting foliation (Bell, 1986). New

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movement on older fabrics can occur during the same event by progressive deformation or represent a new event that removes older fabrics during renewed movement on appropriately oriented surfaces. An important aspect of foliation reactivation is that strain partitioning on a variety of scales can control the degree of reactivation where older fabrics are preserved in low strain zones, strain shadows, or porphyroblasts.

Reactivation of older foliations has been used to explain a variety of structural features including: (1) formation of bedding-parallel foliation that appears not to be associated with a folding event; (2) cleavage refraction; (3) conflicting rotation sense between porphyroblasts and other shear-sense indicators; (4) changes in lineation orientation and; (5) inconsistencies in bedding and cleavage asymmetries (Bell, 1986). Reactivation may also be important in evaluating whether, during noncoaxial deformation, porphyroblasts rotate or the surrounding matrix deforms (Bell, 1986; Bell et al., 1992; Passchier et al., 1992). Foliation reactivation has important implications for recognition of the number of fabric-forming events (e.g. Davis and Forde, 1994; Davis, 1995; Worley and Wilson, 1996). The key point to these three studies is that the number of deformational events and macroscale geometries between folds and foliations could be misinterpreted without recognition of significant foliation re-working.

3. Geologic setting

3.1. Regional geology

The Hualapai Mountains are part of the Hualapai block of northwest Arizona and form a northwest-trending uplift of Proterozoic granites, amphibolites, granitoids and sedimentary rocks (inset of Fig. 1). These rocks are within the Yavapai Province which consists of Proterozoic blocks with a basement of juvenile volcanic arc rocks deformed and assembled onto the North American craton by 1.70 Ga (Karlstrom and Bowring, 1993). The Hualapai Mountains consist of a series of volcanogenic supracrustal rocks including pillow basalts, rhyolite, and pelitic schists. Supracrustal rocks were intruded by two granites; the Hualapai plutonic complex with U–Pb zircon ages that range between 1692 and 1710 Ma and the two-mica Antler granite with a U–Pb zircon age of 1694 ± 14 Ma (Chamberlain and Bowring, 1990). These granites are roughly coincident with the age of amphibolite facies metamorphism (580–650°C, 200–300 MPa, Williams, 1991) bracketed by U–Pb ages from metamorphic zircons of 1668 ± 15 and $1687 + 13/-8$ (Chamberlain and Bowring, 1990). A second period of felsic magmatism and contact metamorphism occurred at ca. 1.40 Ga (unpublished U–Pb zircon age from S. Bowring, 1996) associated with the emplacement of the Boriana granite (Nyman et al., 1996). The area was affected by a final magmatic and thermal event at 1.1 Ga associated with emplacement of a series of mafic dikes. Evaluation of metamorphic ages from a variety of geochronometers suggests slow, isobaric cooling for this block (Chamberlain and Bowring, 1990).

4. Field relations

4.1. Local geology of Boriana Canyon

Samples analyzed for this report were collected from the Boriana Canyon area in the Hualapai Mountains (Fig. 1). Phyllites and schists within this canyon preserve a record of three fabric-forming events labelled F_2, F_3, F_4. Fabrics associated with F_1 are poorly preserved in Boriana Canyon area occurring as isolated fold hinges interfolial to the S_2 fabric. In Boriana Canyon, metamorphic effects of the older Proterozoic event are not well preserved except near the Antler granite where growth of andalusite, staurolite and garnet indicate amphibolite grade conditions (Williams, 1991). Adjacent to the 1.40 Ga Boriana granite there is a well developed contact aureole characterized by an increase in size of andalusite porphyroblasts towards the pluton contact (Fig. 1). Inner sections of the aureole are also marked by the development of sillimanite–K-feldspar assemblages with some segregation of feldspar–quartz layers suggestive of partial melting.

4.2. S_2 regional fabric

In Boriana Canyon the regional fabric (S_2) is vertical and strikes to the northeast (Fig. 2a). The age of this fabric is bracketed to be syn- or post-1.68 Ga by the observation that both the two-mica Antler granite and Hualapai granite complex are strongly foliated with fabrics parallel to S_2. The age of S_2 is also constrained to be ca. 1.68 Ga by textural observations that indicate garnet and andalusite porphyroblasts outside of the contact aureole of the 1.40 Ga Boriana granite are synkinematic with respect to S_2 (Nyman et al., 1996). Shear-sense indicators in deformed Antler granite in Boriana Canyon indicate northwest-side-up, sinistral movement. In granites and felsic volcanic rocks, the S_2 foliation is defined by aligned plagioclase feldspar porphyroclasts. In amphibolites, S_2 is defined by alignment of hornblende grains and alternating feldspar- and hornblende-rich layers. In pelitic and volcanogenic metasedimentary rocks, S_2 ranges from a

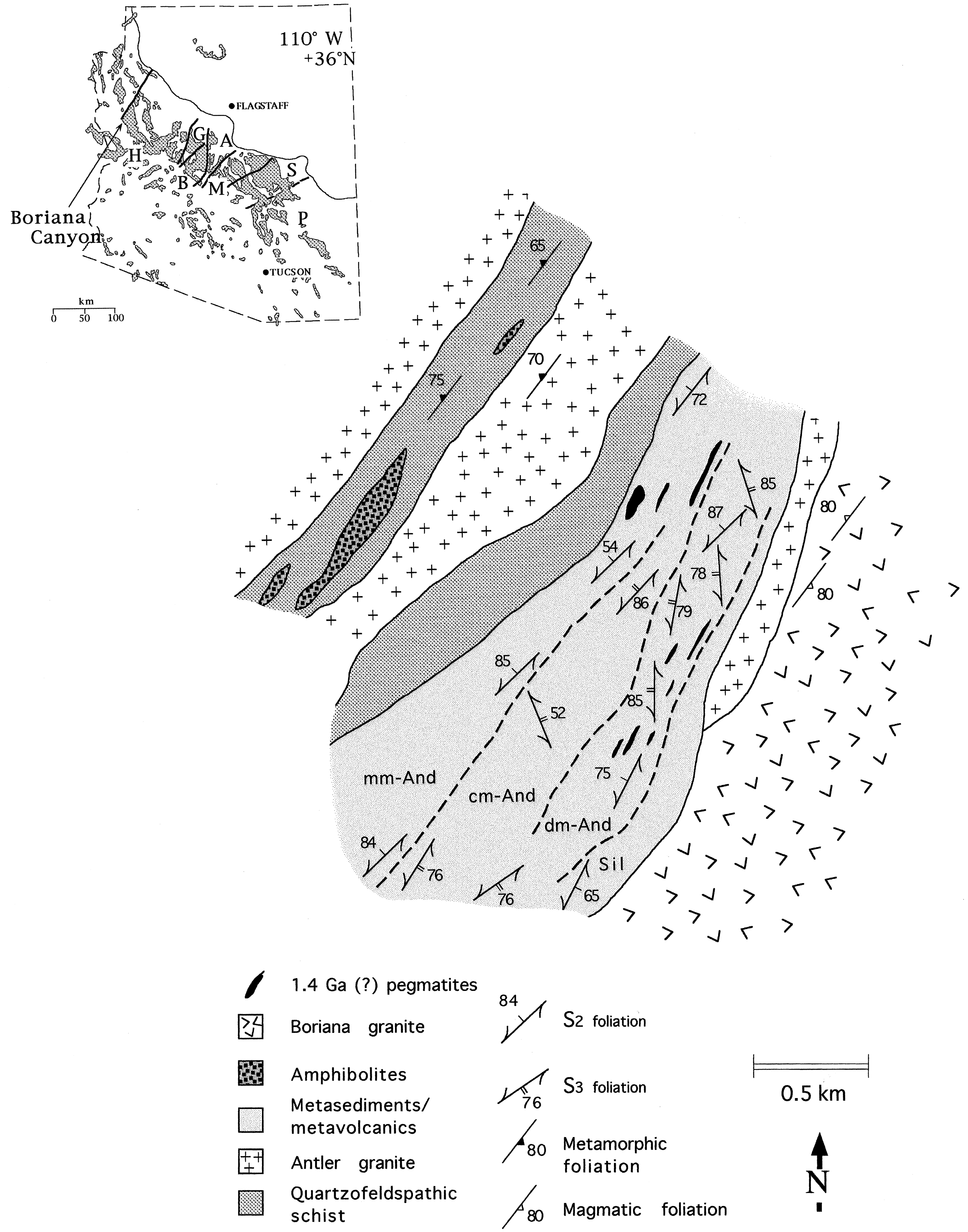

Fig. 1. Geologic map of Boriana Canyon in the vicinity of the 1.40 Ga Boriana granite. Adapted from Conway et al. (1989). Inset shows regional setting of Hualapai block (H). Stippled areas are exposures of Proterozoic rocks. Abbreviations are for the different tectonostratigraphic blocks outlined by Karlstrom and Bowring (1993): G—Green Gulch; B—Big Bug; A—Ash Creek; M—Mazatzal; S—Sunflower; P—Pinal.

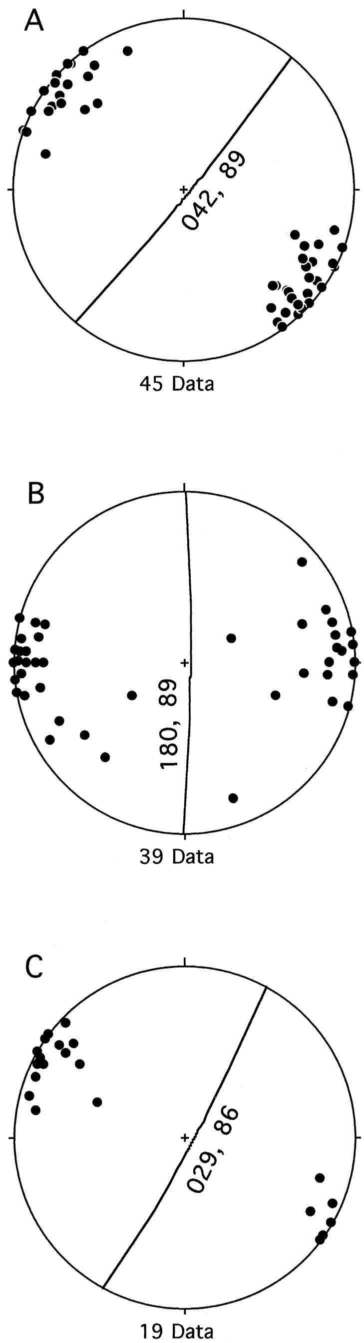

Fig. 2. Equal area nets of structures in Boriana Canyon. (a) Equal area projection of poles to S_2 regional foliation. (b) Equal area projection of poles to S_3 crenulation cleavage. (c) Equal area projection of poles to S_4 composite foliation. Note parallelism between S_2 regional foliation and S_4 foliation indicating reactivation.

phyllitic to schistose foliation that is axial planar to isoclinally folded compositional layering. Thin sections show that S_2 is defined by alternating mica- (M-) and quartz- (Q-) rich domains. In M domains, the S_2 fabric is defined by alignment of biotite and muscovite grains. L_2 lineations and F_2 fold axes are steeply plunging and subparallel.

4.3. S_3 crenulation cleavage

In the Boriana Canyon area the regional S_2 fabric is overprinted by S_3 crenulation cleavage. In general S_3 crenulation cleavage is best developed in rocks within the contact aureole of the 1.40 Ga Boriana granite. Away from the contact aureole, S_3 appears as a widely spaced crenulation cleavage. Within the contact aureole, the S_3 crenulation cleavage shows a transition from a weak crenulation associated with folding of S_2 away from the pluton to forming the dominant fabric element close to the pluton with S_2 preserved as fold hinges between closely spaced S_3 crenulations (Fig. 3). S_3 strikes to the north with steep dips (Fig. 2b). F_3 crenulation hinges and S_2/S_3 intersection lineations plunge steeply with variable trends. The absolute age of S_3 fabric is not known; however, based on the spatial association with the Boriana granite, S_3 formation appears to be associated with either regional or local, pluton-related tectonism during granite emplacement and heating at ca. 1.40 Ga.

4.4. S_4 composite foliation

The S_4 composite fabric is a foliation that is subparallel to the regional S_2 foliation (Fig. 2c) but postdates the S_3 crenulation cleavage. The S_4 composite foliation is recognizable only where S_3 crenulation cleavage is preserved, either in the rock matrix or porphyroblasts. S_4 composite foliations were only observed in the contact aureole of the Boriana granite, especially within 100–200 m of the contact, and associated with pelitic metasedimentary rocks that contain large andalusite porphyroblasts (Figs. 1 and 3). Additionally, S_4 development appears to be concentrated in zones of abundant pegmatite and aplite veins and dikes suggesting that heat supplied by fluid and magma advection may have been important to facilitating fabric reactivation. Local magma and fluid flux may have also supplied the heat necessary for growth of large andalusite porphyroblasts.

In several exposures, the development of the S_4 composite foliation shows a systematic distribution (Fig. 3). Garnet–andalusite–sillimanite schists closest to the pluton contact contain S_3 as the main fabric (Fig. 3, zone V). Within this zone, there are discrete zones of the S_4 composite foliation where S_3 is preserved in the matrix and within large andalusite porphyroblasts. Fig. 3(d) shows a 2-cm-thick zone of S_4 composite foliation that deforms S_3 crenulations and is parallel to the regional S_2 foliation. S_3 is overgrown by dm-size andalusite porphyroblasts. Fig. 3(d) also shows changes in a folded quartz vein with respect to the S_4 composite foliation. Outside of the zone of S_4 composite foliation, the quartz vein is crenulated with an axial surface parallel to the local S_3 crenulation

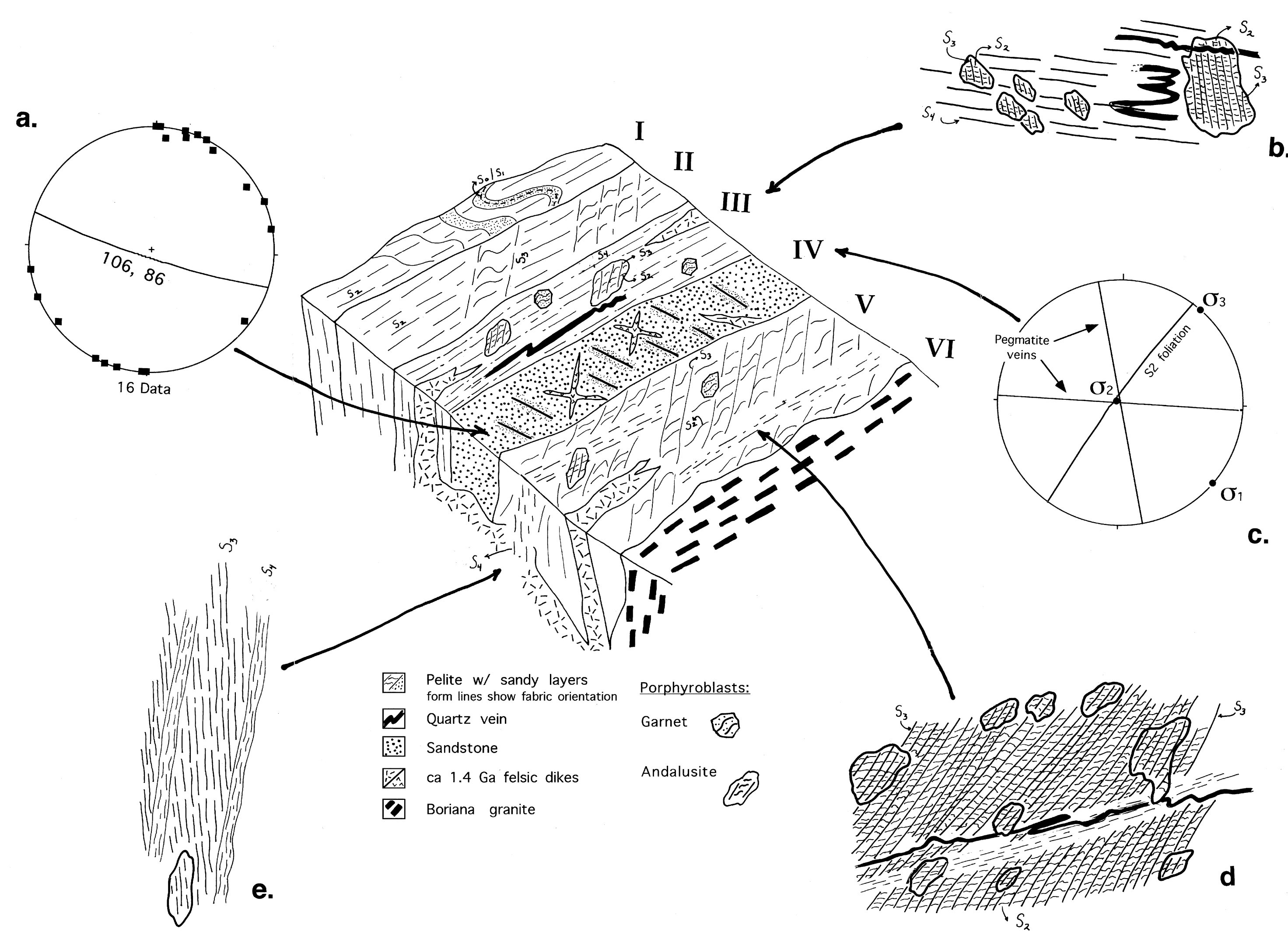

Fig. 3. Diagrams of fabric relations in contact aureole of the Boriana granite. Block diagram is schematic representation of fabric elements and observed distribution of fabrics and rock types in contact aureole; not drawn to scale. Zones I–VI are as follows: **I**. S_2 is the dominant foliation and is axial planar to F_2 folds shown. **II**. Zone of incipient S_3 crenulation development. **III**. Zone of S_4 composite foliation development. **IV**. Quartz-rich, sandy horizon cut by conjugate pegmatite veins ('v' adornment) and weathered fractures (lines surrounded by light stipple). **V**. Zone of partial S_2 reactivation and S_2/S_4 composite foliation development. **VI**. Boriana granite. Rectangles represent aligned K-feldspar phenocryst. Individual sketches. (a) Equal area projection of poles to fractures contained within quartz-rich lithologies. (b) Outcrop sketch of foliation and porphyroblast relations in zone III. Note preservation of S_2 and S_3 in andalusite porphyroblasts and S_3 folds in narrow quartz layer. S_4 composite foliation is axial planar to isoclinal folds which are probably F_2 folds that have been tightened during S_4 formation. (c) Equal area projection of conjugate set of pegmatite veins found in zone IV. (d) Outcrop sketch of zone V where S_3 and S_2 are preserved in the matrix and andalusite porphyroblasts with a narrow zone of S_4 composite foliation. Note that quartz vein is de-crenulated in the vicinity of the S_4 composite foliation. (e) Vertical section showing relation between S_3 and S_4 fabrics. Asymmetry of S_3 suggests east-side-up shear.

cleavage. The quartz vein also contains an isoclinal fold with an axial surface parallel to the local S_2 foliation. However, within the zone of S_4 composite foliation, the quartz vein is relatively straight suggesting that during development of the S_4 composite foliation, earlier folds were decrenulated. Further from the pluton, S_3 is only preserved in andalusite porphyroblasts and the main fabric is the S_4 composite foliation. This is shown in detail in Fig. 3(b) where S_3 crenulations are present in andalusite porphyroblasts, but absent from the matrix. Also in these areas, S_4 composite foliations are axial planar to folds in S_1 compositional layers. In all cases, exposures in which the S_4 composite foliation is the dominant fabric are found adjacent to 20–50 cm thick quartzose layers that are strongly fractured (Fig. 3). These vertical fractures strike east–west and are surrounded by 1–3 cm thick bleached zones (Fig. 3a). Quartz veins and rare cm-size pegmatitic veins are also found cutting the quartzose layers.

The kinematics associated with the S_4 composite foliation are poorly constrained. In general, S_4 surfaces do not contain an extension lineation. Where lineations are observed, it is difficult to determine if they are related to development of S_2, S_4, or a combination of the two fabric-forming events. In sections perpendicular to the strike of S_4 (X–Z section of the strain ellipsoid), S_3 and the reactivated fabric are nearly coplanar with a slight obliquity suggesting west-side-up movement (Fig. 3e). In sections parallel to strike (Y–Z sections) S_3 is dextrally offset by S_4. In either of these scenarios the shortening direction (Z-axis) is horizontal. A subhorizontal shortening direction is also supported by conjugate sets of pegmatitic veins observed in the contact aureole (Fig. 3c).

5. Microscopic observations

Microscopic examination of porphyroblasts and matrix relations also document the different foliation generations within the contact aureole. As previously noted, the regional S_2 foliation is homogeneous and defined by alternating Q and M domains. Alignment of biotite laths defines the foliation. In thin section, the S_3 crenulation cleavage is observed to be a spaced cleavage defined by planar bands of muscovite + biotite that separate zones of F_3 crenulation hinges. Both garnet and andalusite crystals overgrow S_3 crenulations (Fig. 4a and b). The dm-size, elongate andulasite porphyroblasts are poikioblastic forming skeletal crystals that statically replaced muscovite-rich portions of the S_3 crenulation cleavage (Fig. 4a). The S_4 composite foliation is defined by alternating Q and M domains with M domains containing aligned biotite and muscovite laths (Fig. 4a). The S_3 crenulation cleavage is cut by the S_4 composite foliation and exhibits slight rotation (Fig. 4a).

Garnet porphyroblast and matrix relations also provide a record of the foliation history of this area. Fig. 4(b) shows three garnet porphyroblasts within a relatively homogeneous matrix defined by aligned biotite $\pm$ muscovite laths. The garnet porphyroblast in the upper right corner is surrounded by a poikioblastic andalusite crystal. The garnet porphyroblasts preserve a crenulated fabric that is not observed in the matrix. Axial planes of the crenulations are steep and strike NNW, similar to S_3 orientations measured throughout the contact aureole. The axial traces of the internal crenulations are relatively constant across the thin section indicating that the garnet porphyroblasts probably have not undergone much rotation during development of the external fabric (Bell and Johnson, 1989). In detail, one of these garnet porphyroblasts (Fig. 4c) shows that the crenulated internal fabric has a complex geometric relationship with the external fabric including: (1) continuous with the external fabric (marked 1); (2) at high angles to the external fabric (marked 2) and; (3) surrounded by the external fabric (marked 3).

These porphyroblast/matrix relations are interpreted to indicate that andalusite and garnet growth in the contact aureole occurred following formation of the S_3 crenulation cleavage. In some samples, S_3 crenulation cleavage is preserved in both the matrix and dm-size andalusite porphyroblasts (Fig. 4a). However, in zones of intense S_4 composite foliation development, S_3 crenulations are preserved only in porphyroblasts and the matrix fabric consists of a homogeneous foliation (Fig. 4b). The complex porphyroblast/matrix relations observed for some porphyroblasts is interpreted to indicate pretectonic growth relative to S_4 with a small amount of rotation to produce the high angle between the external and internal fabrics (Fig. 4c, spot 2).

6. Discussion

Recognition of reactivation of earlier fabrics is vital to interpreting the deformation chronology of an area. In Boriana Canyon, S_2 and S_4 are subparallel and have a similar appearance consisting of spaced cleavages defined by Q and M domains. Distinguishing between S_2 and S_4 is possible only where S_3 is preserved in the rock matrix and/or garnet and andalusite porphyroblasts. For instance, if S_3 crenulations were not preserved in andalusite porphyroblasts as shown in Fig. 3(b), the main fabric in this exposure would likely be interpreted as S_2, since it is axial planar to folded compositional layers and parallel to the regional S_2 fabric. Based on the similar orientation between the two foliations but differences in relative timing with respect to S_3, the S_4 foliation is interpreted to have formed by reactivation of the regional S_2 foliation. Identification of reactivation suggests that, at least in

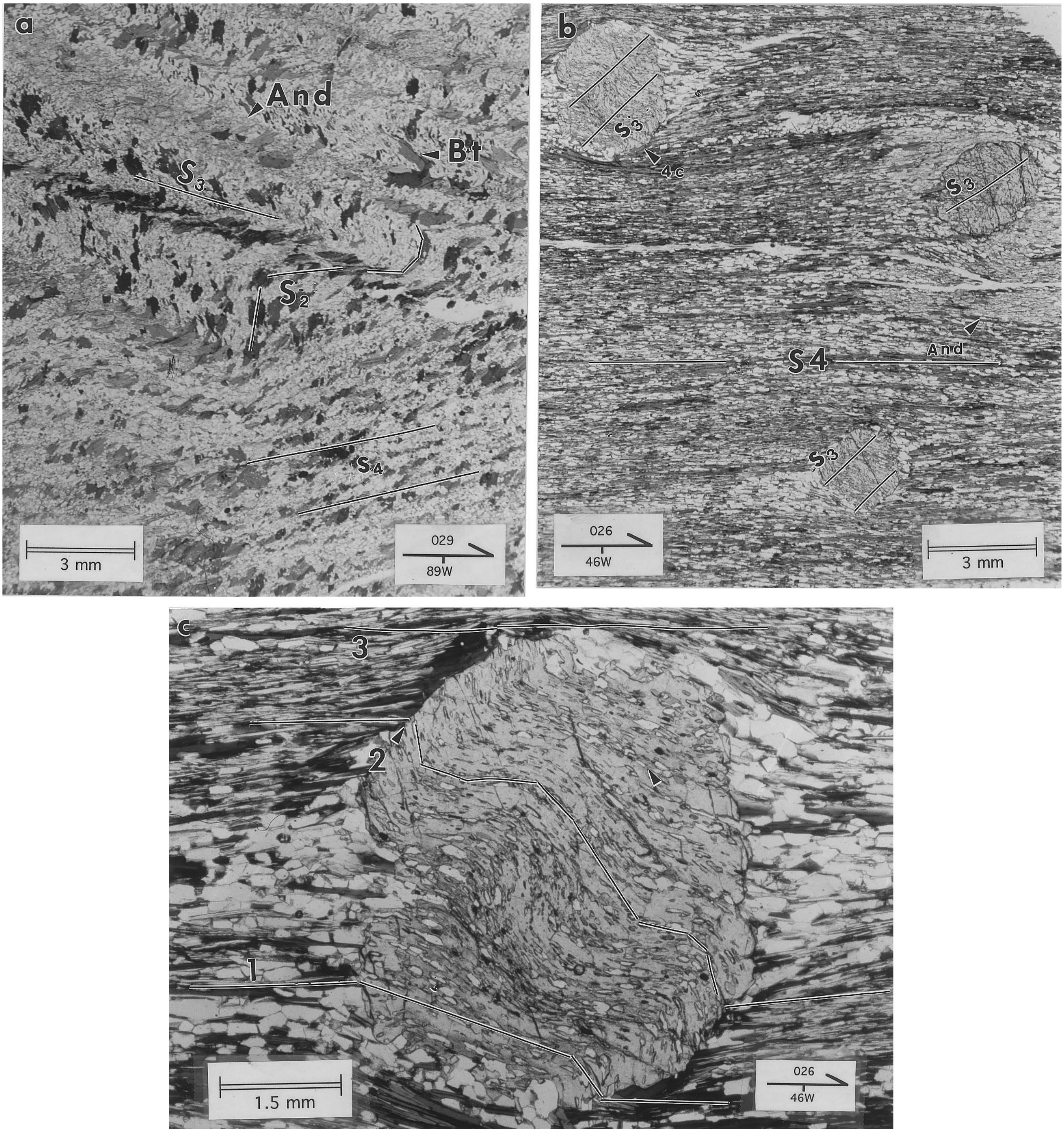

Fig. 4. Photomicrographs of thin sections showing relation between fabrics and porphyroblast growth. (a) Zone of S_4 composite foliation. Note static replacement of S_3 crenulations by skeletal andalusite. (b) Andalusite–garnet schist. Inclusion trails in garnet preserve crenulated S_2 foliation. Note that traces of S_3 axial planes are relatively constant in orientation across the thin section suggesting limited rotation of porphyroblasts. (c) Close-up of garnet in upper left corner of Fig. 3(b) showing different relationships between exterior and interior fabrics. See text for discussion.

the contact aureole of the Boriana granite, the S_2 fabric is some combination of regional and reactivated foliation.

Recognition of reactivation in the contact aureole of the Boriana granite provides an important avenue to understanding Mesoproterozoic tectonism in this area. In the Hualapai Mountains, deformation associated with the S_2 regional foliation occurred during tectonic events between 1692 and 1710 Ma, typically referred to as the Yavapai Orogeny (Karlstrom and Bowring, 1993). The kinematics of this tectonic event is generally west-side-up with a sinstral component. The age of S_3

is not well documented although the observation that S_3 is concentrated in the contact aureole of the Boriana granite suggests it may be related to deformation associated with this magmatic event and therefore may be much younger (≤300 m.y.) than S_2. However, S_3 clearly predates growth of the dm-size andalusite porphyroblasts within the contact aureole as indicated by the static replacement of S_3 crenulations by andalusite (Figs. 3 and 4). The preferred interpretation is that overgrowth of S_3 by andalusite is due to the thermal effects of 1.40 Ga magmatism outlasting deformation related to S_3 formation. Cross-cutting relations clearly indicate that reactivation of S_2 to form the S_4 foliation occurred after andalusite growth and therefore must be related to tectonism associated either with 1.40 Ga magmatism or some younger event. Based on textural observations between S_3 and S_4 (Fig. 4a), the orientation of fractures with alteration haloes (Fig. 3a) and the orientation of conjugate sets of pegmatite veins (Fig. 3c), the kinematics associated with S_4 formation involved a component of subhorizontal SE–NW shortening with a possible dextral strike-slip component. Although the absolute age of the fractures is not known, the presence of alteration haloes around the fractures and the observation that these types of fractures are found only within the contact aureole of the Boriana granite suggests a relation to ca. 1.40 Ga tectonism. A SE–NW subhorizontal shortening direction associated with the ca. 1.40 Ga Boriana granite is consistent with shortening directions from other 1.40 Ga plutons in Arizona (Nyman and Karlstrom, 1997), New Mexico (Kirby et al., 1995), Nevada (Duebendorfer and Christensen, 1995) and Colorado (Graubard, 1991; Gonzales et al., 1996).

An important regional implication of this study is that it may be difficult to distinguish between Paleoproterozoic and Mesoproterozoic tectonic events in SW United States, especially outside of 1.40 Ga aureoles (Ralser et al., 1997). Both events have similar metamorphic grades (Williams, 1991; Williams and Karlstrom, 1996) kinematics. As illustrated by this study, fabrics associated with each event maybe subparallel and have similar characteristics. Deformation associated with Mesoproterozoic tectonism may be more widely distributed and reactivation of older fabrics may have been insufficiently recognized in Proterozoic rocks of SW United States.

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