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Quadruple-pronged enclaves: their significance for the interpretation of multiple magmatic fabrics in plutons.

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Abstract: In the Tuolumne, Green Lakes, and Soldier Lake plutons central Sierra Nevada, we find domains with two well developed, magmatic foliations and a single steeply plunging magmatic lineation, all defined by similar igneous mineral populations. Mineral fabric overprinting relationships are rare, but overprinting relationships between aligned enclaves and mineral foliations at least locally indicate that one foliation in each pluton is slightly younger with both foliations locally axial planar to magmatically folded dikes. Rare "quadruple-pronged" enclaves have, in lineation perpendicular sections, opposite pairs of pronges parallel, respectively, to each of the magmatic foliations. The overprinting relationships and quadruple-pronged enclaves indicate that the two foliations record a temporal evolution in a magma chamber of syn-emplacement strain during chamber construction to post-emplacement, but melt-present, tectonic strain of relatively static chambers.

The presence of two magmatic fabrics in plutons is problematic for AMS studies, which in these cases will only give a poorly constrained average of the two fabrics. Furthermore the existence of a single magmatic lineation, even in regions of two magmatic foliations indicate that "composite" magmatic fabrics can form in plutons, that is a single fabric formed under two different strain increments. Finally the enclave relationships in these plutons provide further evidence that enclaves undergo complex magmatic histories involving early magmatic strain, subsequent rigid rotations, and potentially late increments of strain some of which may not be preserved by minerals in the surrounding matrix.

INTRODUCTION

Analyses of magmatic fabrics, that is foliations and lineations formed during crystal alignment in the presence of a melt, is a powerful tool for evaluating ancient strain fields in arcs since these fabrics are easy to date (i.e., U/Pb age of crystallization), typically form in rocks without a complex array of older structures (e.g., the multiple structures in many metamorphic rocks), and form in relatively weak rocks (crystal-melt mushes), thus making them sensitive indicators of regional strain. However, an understanding of the causes responsible for the formation of magmatic fabrics remain controversial. Paterson *et al.* (1998) summarized previous studies, which have variously attributed the driving forces of magmatic fabric formation to strain caused by flow during either magma ascent, final emplacement or internal magma chamber processes, or to tectonic strains imposed on relatively static magma chambers. Because of this uncertainty it is important to improve our understanding of which type(s) of processes formed magmatic fabrics and thus whether they preserve information about magmatic processes, regional tectonism, or both.

An exciting additional complexity to this issue is the recent recognition that more than one magmatic foliation may be preserved in plutons. Examples of two magmatic foliations/lineations in plutons have been reported by Bouchez *et al.* (1981) in the GuÃrande pluton, France, by Blumenfeld and Bouchez (1988) in sheared migmatites, by Bilodeau and Nelson (1993) in the Sage Hen Flat pluton, California, and by Schulmann *et al.* (1997) in the deep borehole EPS-1 near Soultz-sous-ForÃªt, France. Previous explanations for multiple magmatic fabrics include differential rotation of minerals with different axial ratios during noncoaxial strain (Blumenfeld and Bouchez, 1988), formation of metastable orthogonal linear fabrics under a combination of pure and simple shear (Willis, 1977), and formation of orthogonal foliations where minerals with different axial ratios are aligned parallel to unequal elongation components during coaxial flow (Jezek *et al.*, 1994; Schulman *et al.*, 1997). All of the above explanations assume that the two fabrics formed at the same time and by the same cause. We suggest that given the above controversy about the driving forces responsible for fabric formation, another possibility should be considered: whether or not different magmatic fabrics record different processes, or strain increments at different times and thus record information about the temporal evolution of a magma chamber.

In our ongoing studies of plutons in the central Sierra Nevada, we have recognized two or more magmatic foliations in several plutons including the Tuolumne Batholith (TB), and the Green and Soldier Lake plutons immediately east of the TB (Figure 1). In general two magmatic foliations are well defined and often occur at high angles to one another. In each of these plutons microgranitoid enclaves are common and show a range of relationships to the two magmatic foliations sometimes being statistically parallel to one or the other and less commonly being folded. We also find a very unusual type of microgranitoid enclave that, although roughly elliptical in shape, in detail has four pronges or protrusions formed at ~70Â° to 90Â° to each other with each opposite pair of pronges being parallel to one of the magmatic foliations in the surrounding matrix. We suggest that the nature of these enclaves and their relationship to the two magmatic foliations provide important constraints on the timing and type(s) of information recorded by the different foliations.

Below we describe particularly clear examples of two magmatic foliations in three different plutons, often with a single, shared mineral lineation. We will examine the relationships between these foliations and both the elliptical and the "quadruple-pronged" enclaves, as well as late magmatically folded, aplite dikes, and discuss the implications for the interpretation of the magmatic foliations. Our observations suggest that magmatic foliations can record a temporal evolution of each magma chamber during which older magmatic foliations may be frozen in during strain coeval with magma flow and crystallization in chambers and slightly younger foliations, which crosscut internal contacts and are locked in during regional tectonic strain of relatively static chambers (e.g., TB example). In addition, a comparison between adjacent plutons indicates that the slightly older margin parallel foliation may or may not be preserved in some plutons and that the two preserved magmatic foliations instead record a polyphased tectonic evolution (e.g., Green and Soldier Lake plutons). This confirms that magma chambers have the ability to record at least part of a continuous history, from strain caused by internal flow to strain caused by evolving regional deformation. We also conclude that the presence of a single mineral lineation even in domains where two foliations exist indicates that some preserved magmatic fabrics may be composite, that is having formed during more than one event as has already been established in metamorphic rocks (Tobisch and Paterson, 1988, Luneburg and Lebit, 1998).

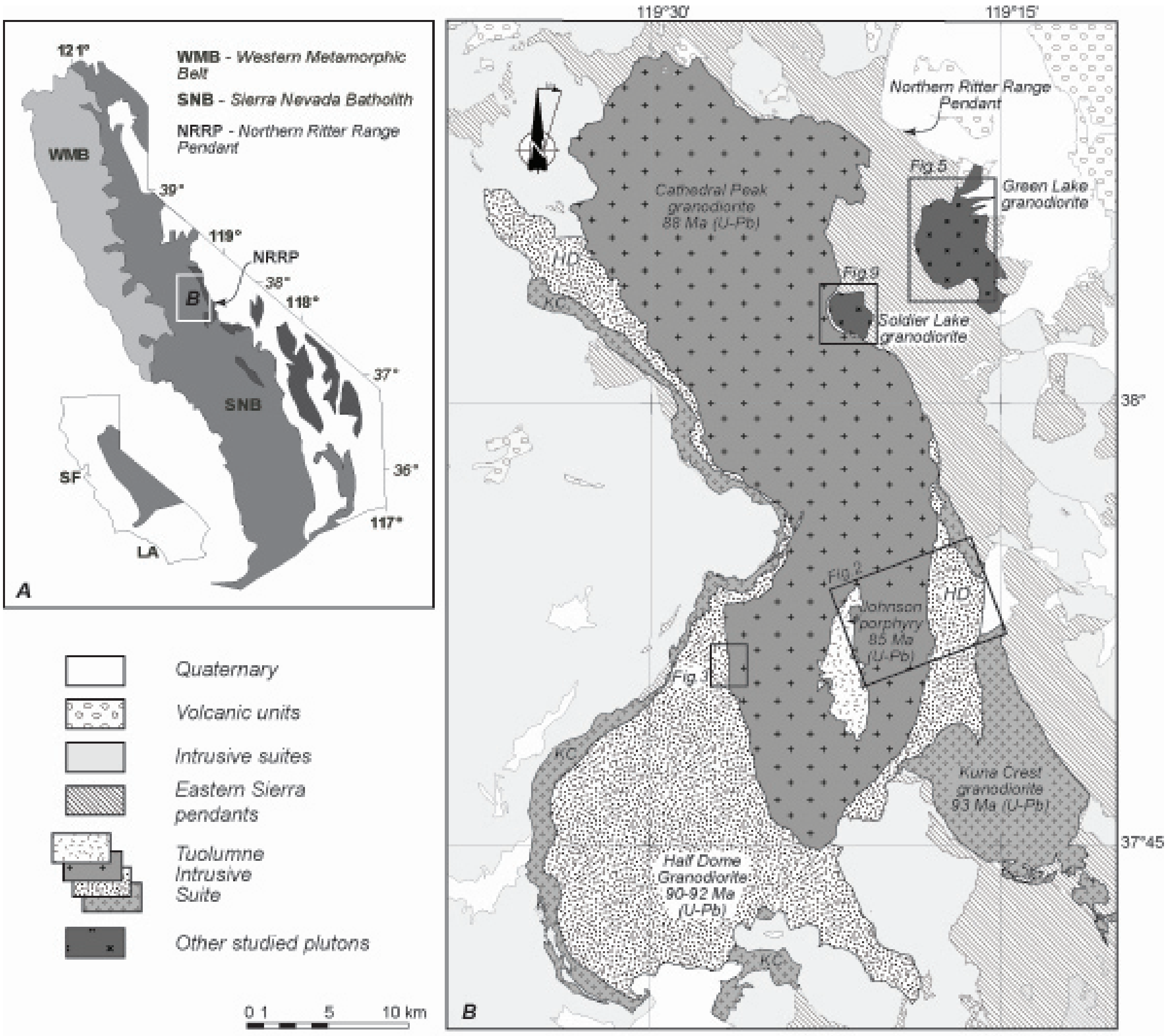

Figure 1. Map of central Sierra Nevada, California showing three plutons (Tuolumne Batholith in center of map and Soldier and Green Lakes plutons to the NE) discussed in text. Inset shows location in California.

Examples from three Sierran plutons

The three plutons discussed below all occur in the central Sierra Nevada Batholith, California (Figure 1). The Tuolumne Batholith (TB) forms a large (>1500 kmÂ°~), ~92-83 Ma body underlying much of Yosemite National Park (Bateman, 1992). A series of smaller, older, and sometimes poorly dated plutons are exposed immediately east of the TB. We have examined two of these, the Soldier Lake and Green Lake plutons.

Tuolumne Batholith

The Tuolumne batholith consists of four recognized phases (Bateman, 1992): (1) an outer dioritic to tonalitic phase called the Kuna Crest (includes the Glen Aulin and Glacier Point tonalites and Kuna Crest granodiorite), (2) the Half Dome granodiorite, which consists of an outer equigranular (Khde) and inner porphyritic facies (Khdp); (3) the kspar megacrystic Cathedral Peak granodiorite, and (4) the Johnson porphyry granite. Bateman and Chappell (1979) argued that this normally zoned intrusive suite formed from a single parent melt by in situ crystal fractionation. However, a subsequent geochemical study of enclaves (Reid *et al*., 1983) and a REE study by Kistler and others (1986) showed that at least two separately evolved pulses were required, in part derived from mixing of basaltic and granitic magmas, and that the inner siliceous phases could have no more than 15% mantle component. Recent geochronologic work (Kistler and Fleck, 1994; Fleck *et al*., 1996; Coleman and Glazner, 1997; Coleman *et al*. 2002) indicates that different pulses in this suite have moderately different ages (up to 1-3 Ma apart) and that the suite was constructed and crystallized over a 7-11 Ma period, supporting Kistler and others' conclusion. Because of these latter studies, this body is by definition not an intrusive suite and we therefore use the name Tuolumne Batholith (TB).

In the TB (Figure 1) we have locally mapped multiple magmatic foliations defined by aligned magmatic biotite, hornblende, and plagioclase, only two of which are widespread (Figure 2, 3). Below we focus on these two foliations. A slightly older ~N-S to NNW-SSE foliation (S1) is typically subparallel to internal contacts, whereas the younger foliation (S2) is ~ WNW-ESE and cuts across all internal contacts (Figure 2, 3)(see also Bateman 1992). Locally, S2 is parallel to the axial planes of gentle to open folds of late aplitic to pegmatitic dikes (Figure 4), the tightest of which are associated with up to 26% shortening (Paterson and Zak, unpublished data). These two foliations

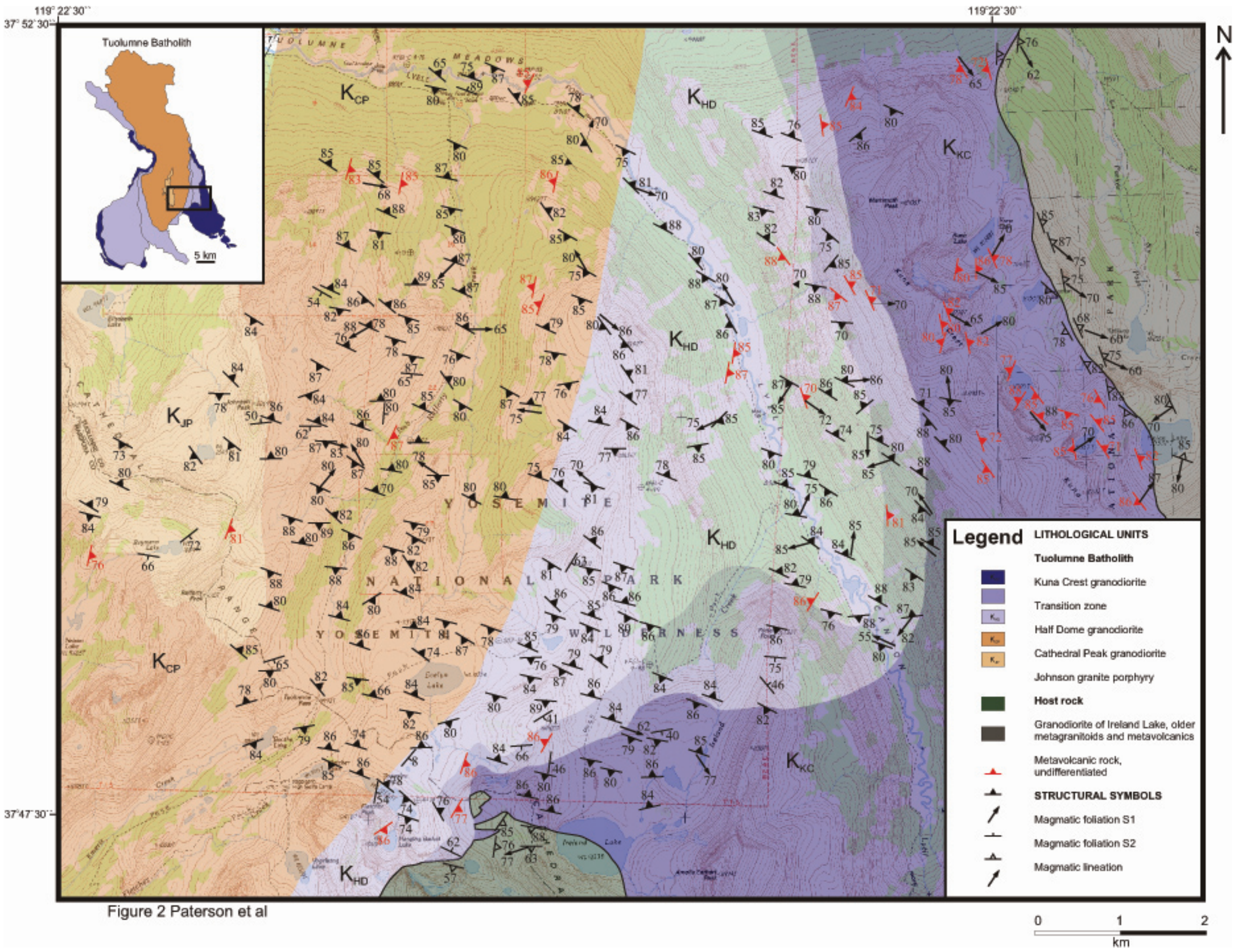

Figure 2. Map of corridor across eastern half of Tuolumne Batholith (location shown on Figure 1) showing location and patterns of two magmatic foliations in TB. A steep magmatic lineation occurs throughout this mapped region. Note that one foliation is roughly NS and margin parallel and a second bends from a more NS orientation in the outher Kuna Crest to WNW-ESE orientations in inner units and cuts across all internal contacts. Mapping completed by J. Zak and S. Paterson.

are both associated with slightly flattening to strongly constrictional fabric ellipsoid shapes with steeply plunging long axes defined in the field by a magmatic lineation (stereonets in Fig, 2, 3; photo in Figure 4). The magmatic lineation (L1) is defined by the alignment of igneous minerals and sometimes elongate enclaves. In areas where constrictional fabrics are developed, a steep L1 can be seen in all vertical sections establishing that L1 is not simply an intersection lineation.

Enclaves are widespread in the Kuna Crest and Half Dome phases, and their long axes may be parallel to either foliation, though more commonly they are parallel to S1. In some locations, enclave shapes mimic the constrictional mineral fabrics, but in other locations they do not. Figure 4b shows enclaves with oblate shapes aligned parallel to S1, but at high angles to the overprinting and ~ WNW- ESE S2. Minerals in the enclaves are parallel to the host magmatic foliation, S1 not to the long axes of the enclaves. Rarely enclaves are boudinaged parallel to the vertical lineation, indicating vertical stretch, but enclave boudinage also occurs in foliation planes in directions at high angles to the lineation (thus either the finite strain is in the flattening field or rigid rotation of enclaves has occurred).

We also have found rare "quadruple-pronged" enclaves in the Half Dome and Kuna Crest phases of the TB always in subhorizontal, lineation perpendicular surfaces. The first to be discovered (by L. Teruya) is located in the equigranular Half Dome granodiorite about 300 m from the contact between the equigranular and porphyritic facies of the Half Dome phases near Tenaya Lake (Figure 3, 4d). While most enclaves in this area are oriented in generally NS or EW directions parallel to magmatic foliations in the matrix, this enclave stands out as having opposite corners parallel to both. Regionally, when vertical sections through the enclaves are available, enclave long axes, including "quadruple-pronged" enclaves, typically plunge greater than 70o. We thus assume that the long axis of this enclave is also oriented vertically parallel to the steep L1 in the surrounding matrix, therefore implying that the intermediate enclave axis, striking 004 , is parallel to the older, margin parallel S1 (here parallel to the inner porphyritic and outer Half Dome contact) and that the short enclave axis, striking 267 , is parallel to the younger, crosscutting S2 (Fig 3, 4d). Other examples, typically with more pronounced bulges protruding from the otherwise elliptical shape, have been located along the eastern margin of the Half Dome and Kuna Crest (Figure 4e, 4f). In most

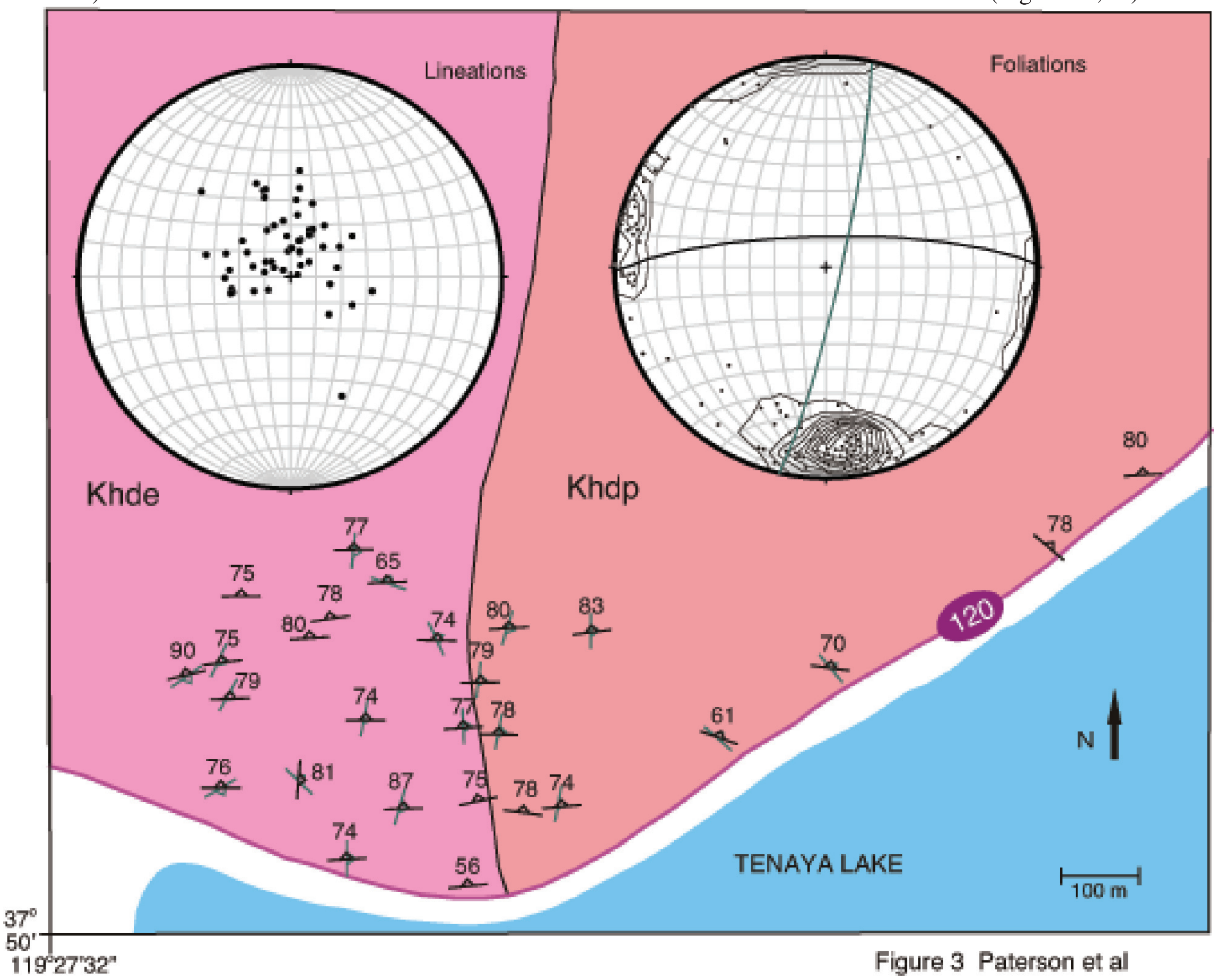

Figure 3. Map of outer equigranular (Khde) and inner porphyritic (Khdp) Half Dome granodiorite showing contact (location shown on Figure 1) and relationship to two magmatic fabrics. Equal area stereonets show steep orientation of magmatic lineation and maxima of two magmatic foliations in this region. Note that the EW magmatic foliation is not deflected across this contact. Mapping completed by L. Teruya.

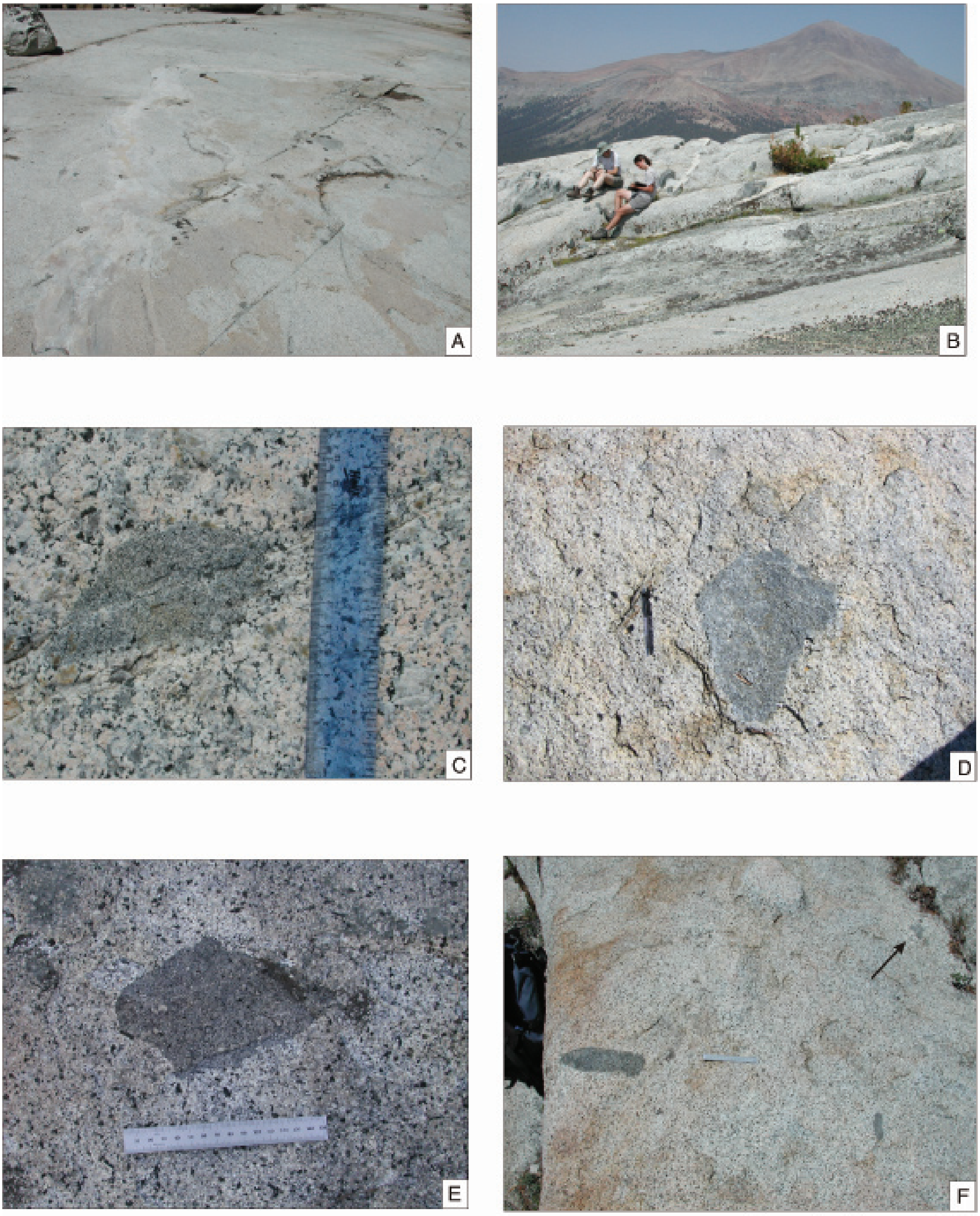

Figure 4: Paterson et al

Figure 4 Photos from the Tuolumne Batholith as follows: (a) magmatic fold with secondary parasitic folds of an aplitic dike. 20 cm hammer for scale is parallel to an axial planar, WNW-striking magmatic foliation. Note aligned enclaves parallel to this foliation in core of fold. Unfolding this fold indicates about 28% shortening perpendicular to the foliation. (b) Slightly constrictional and steeply plunging enclaves parallel to the magmatic lineation in the Half Dome granodiorite. Metavolcanic host rocks (brown colored in background) along the eastern margin of the batholith. (c) Single, elliptical enclave overprinted by WNW-striking magmatic fabric parallel to 15 cm ruler. Note that minerals in enclave also parallel to the magmatic foliation and that long axis of enclave at high angle to foliation. (d) Quadruple-pronged enclave from area shown in Figure 3. 10 cm pencil parallel ~NS magmatic fabric. (e) Quadruple-pronged enclave from area shown in Figure 2 in Half Dome granodiorite. 15 cm ruler parallel ~WNW-striking magmatic fabric. (f) Two populations (~WNW and ~NS) of aligned enclaves in Half Dome granodiorite. Arrow points to small quadruple-pronged enclave. 15 cm ruler for scale.

cases the relationships to L1 and S1 and S2 in the matrix are the same, the only rare exception being that the short and intermediate enclave axes sometimes flip orientation in L1 perpendicular sections.

Green Lake Pluton (GLP)

The GLP is a small (~ 5 by 6 km) elliptical body emplaced within the Saddlebag Lake pendant exposed along the eastern margin of the Tuolumne Batholith (Figure 1). The pendant consists of Paleozoic basement unconformably covered by Mesozoic volcanic units related to formation of the Sierra Nevada batholith (e.g. Schweickert and Lahren, 1999; Greene, 1995) (Figure 5). This pluton is a relatively homogeneous equigranular granodiorite which intrudes a more mafic facies (granodioritic to tonalitic composition) along its western margin (near a wall-roof transition). The latter represents an early pulse of the Green Lake intrusion since a magmatic foliation is continuous across their mutual contact (Figure 5). The Green Lake pluton has been recently dated by R. Mundil who obtained a U/Pb on zircon of 168 Ma and S. Nomade who obtained younger Ar^{40}/Ar^{39} cooling ages on hornblende and biotite (S. Nomade and R. Mundil, pers. comm. 2003). The details of these ages will be reported elsewhere.

The GLP is also characterized by domains with two, sub-orthogonal magmatic foliations (Figure 5). Foliations are defined by biotite and/or hornblende, to a lesser degree plagioclase, and by microgranitoid enclaves. The main NW-striking foliation (S1) is parallel to the regional cleavage in volcanic host rock around the pluton, while the other foliation (S2) occurs at a high angle and appears to be axial planar to open, map scale, folds affecting S1. Both magmatic foliations are associated with a single, subvertical lineation, L1 (Figure 5).

Microgranitoid enclaves are common in the GLP and because of the presence of excellent exposures of a variety of enclave types, we have completed a more detailed study of them in this pluton. Their compositions consist of a mixed population of diorite to granodiorite. The more mafic enclaves are fine- to medium-grained with acicular hornblendes while the granodioritic enclaves are characterized by equigranular, medium-grained textures. Enclave long axes range between a few centimeters to several decimeters. Regardless of their composition and/or

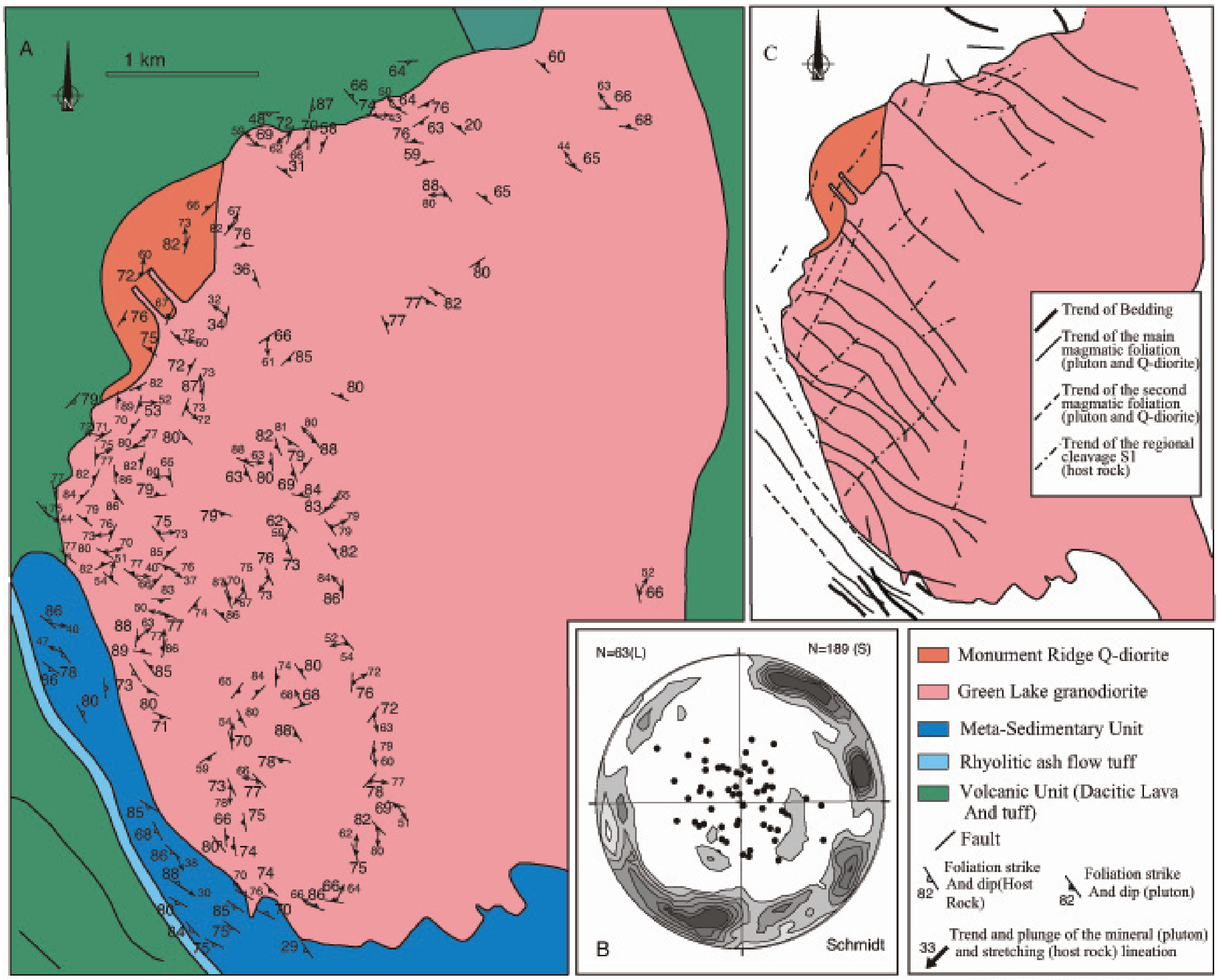

Figure 5: Paterson et al

microstructures three main populations of enclaves can be distinguished based on their shapes and relationships to magmatic foliations (Figures 6, 7), although all typically have their long axes parallel to L1 (X axis of the finite fabric ellipsoid).

* Type I enclaves are characterized by elliptical shapes with their intermediate axis (Y) parallel to the NW-striking magmatic foliation, S1 (Fig 7b). In most cases, enclave axes are statistically parallel to both S1 and L1. However oblique or apparently unstrained enclaves are common (Figure 6b).

* Type II enclaves are typically smaller enclaves and rather rare and have intermediate axes parallel to the second NE-striking foliation, S2. Associated with type II enclaves, we also find Type I enclaves (parallel to S1) subsequently folded with S2 axial planar, suggesting a temporal relationship between S1 and S2 (Figure 7c).

* Type III enclaves are quadruple-pronged enclaves and are quite well represented in the GLP (Figure 7d). When long axes are visible they plunge steeply parallel to L1 in the magma host. In L1 perpendicular sections, their characteristics define two sub-types. The most common variety have roughly elliptical shapes, but with well defined pronges or bulges, indicating that the small portions of the enclave near the intermediate and short axis terminations were extended relative to the rest of the enclave (Figure 7d). Less commonly they have angular, rhombohedral shapes, which may or may not require stretch of the enclave. The pronges or rhombohedral corners define two suborthogonal axes parallel to S1 and S2, indicating that a single enclave may potentially record increments of at least two different strain fields (Figure 7d). Indeed these enclaves raise the issue of the chronology of foliation formation, that is whether S1 and S2 form simultaneously or successively. As suggested above the Type I, folded Type I and Type II enclaves indicate that the pluton acquires foliations successively whereas the quadruple- pronged enclaves suggests simultaneous formation since only a single lineation occurs and no overprinting of one foliation by the other is observed. We return to this issue in the discussion section.

Soldier Lake pluton (SLP)

The SLP lies between the Green Lake pluton and the Cathedral Peak facies of the TB, separated from the latter by a narrow pendant of metamorphosed volcanic and volcaniclastic rocks (Figure 1, 9). The pluton is compositionally and microstructurally comparable to the Green Lake pluton although smaller (~ 3 by 3 km) and slighly more mafic in some regions. Along its western and southwestern margins the SLP is intruded by, and thus older than a leucocratic dike swarm emanating from the 86 Ma Cathedral Peak facies. Dating of the SLP is presently in progress with initial U/Pb zircon analyses suggesting a slightly discordant but approximately 95 Ma age (R. Mundil, pers. comm., 2003).

Magmatic foliations and lineation are well developed in this pluton. Magmatic lineation, L1, is consistently steeply plunging throughout the pluton (Figure 8). The best developed magmatic foliation, S1 strikes NW-SE at approximately 320Â° and only locally shows deflection or change in intensity as the pluton margin is approached (Figure 9). Typically, this foliation is continuous with a metamorphic foliation in the host rocks. Elsewhere the two foliations are not continuous: we suspect that the host rock foliation has been deflected during emplacement of the adjacent Cathedral Peak phase of the TB.

In local domains a second ENE-WSW striking (70- 80Â°) magmatic foliation, S2 occurs (Figure 9). Again we see no field or optical differences between the mineral populations that define either magmatic foliation and no obvious overprinting relationships between the two foliations. We have seen no structures in the host rock parallel to this second foliation.

All three types of enclaves observed in the GLP also occur in the Soldier Lake pluton. The most common are type I parallel to S1 and with their long axes parallel to L1. But in the domains where a second magmatic foliation occurs, we typically see both type I and type II enclaves statistically parallel to the two foliations (Figure 10). In L1 perpendicular sections in these same regions, rare Type III enclaves occur with pronges or rhombohedral corners parallel to S1 and S2 respectively (Figure 10).

Late aplitic to pegmatitic dikes also occur in the SLP. Most are not significantly deformed. But where gentle to open folding of these dikes occur, the axial planes are subparallel to S1 (Figure 10).

DISCUSSION

The above three plutons, all located in a small region of the central Sierra Nevada, display several similar structural characteristics. Each has a single, steeply plunging magmatic L1 and domainally at least two (the TB has additional fabrics in local domains) steeply dipping magmatic foliations best seen in L1 perpendicular sections. Both foliations are defined by alignment of igneous hornblende and biotite, and to a lesser degree plagioclase and only rarely kspar (enclave alignment is discussed below). We see no microstructural differences in the characteristics of the minerals parallel to either foliation although no chemical analysis have been as yet completed. Initial quantitative fabric analyses in thin sections and by AMS analyses (e.g., Teruya *et al.*, 2000) confirm the existence of L1 and the two foliations. S1 and S2 are only rarely seen to overprint one another at the meter scale. More typically only one occurs in a domain or both appear simultaneously as orthogonal foliations sharing a single composite lineation. In the latter case minerals are statistically aligned parallel to one foliation or the other, but no overprinting is observed. (Figure 7d, 10)

It is important to note that the single, steeply plunging mineral lineation (parallel to X axis of finite strain recorded by minerals, where X>Y>Z) is typically associated with each foliation and when both foliations are present, is parallel to the intersection of the two (Figure 11). Thus S1 and S2 are parallel to the X-Y and X-Z planes of finite strain recorded by mineral fabrics and their formation would only require a minor change in the relative amount of extension/shortening parallel to Y (intermediate) and Z (short) axes of strain. Given that the overall degree

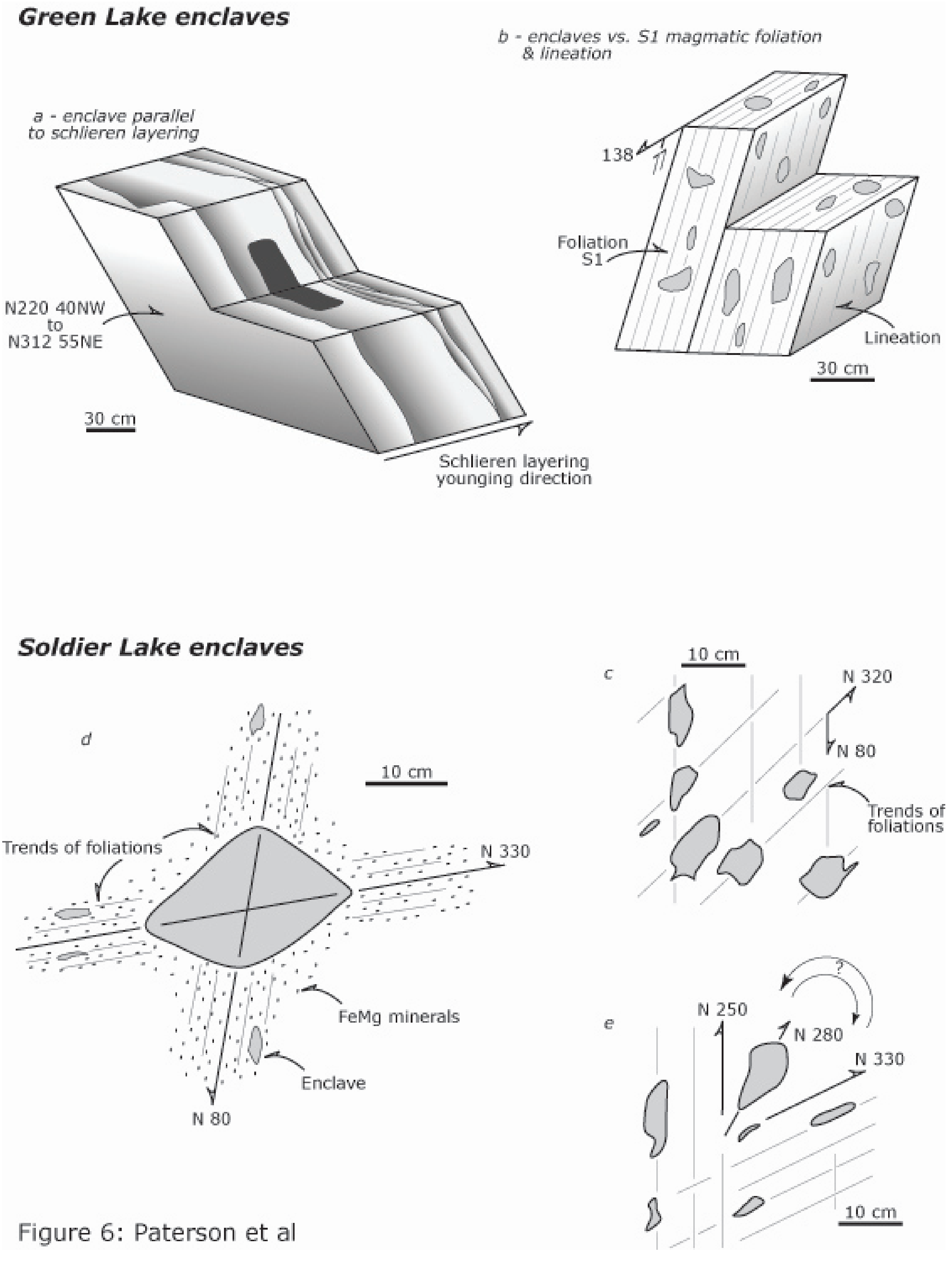

Figure 6. Summary diagram for enclaves and structures in Green Lakes (GLP) and Solider Lake (SLP) plutons. (a) block diagram describing an enclave parallel to the schlieren layering (GLP); (b) block diagram showing relationships between enclaves, the main foliation and mineral lineation (S1) in the GLP; (c) both S1 and S2-parallel enclaves on a single outcrop (SLP); (d) diagram depicting a quadruple-pronged enclave which axes are parallel to the magmatic fabric defined by biotite and amphibole minerals (SLP); (e) besides S1 and S2-parallel enclaves, a third intermediate type appears defining an intermediate direction.

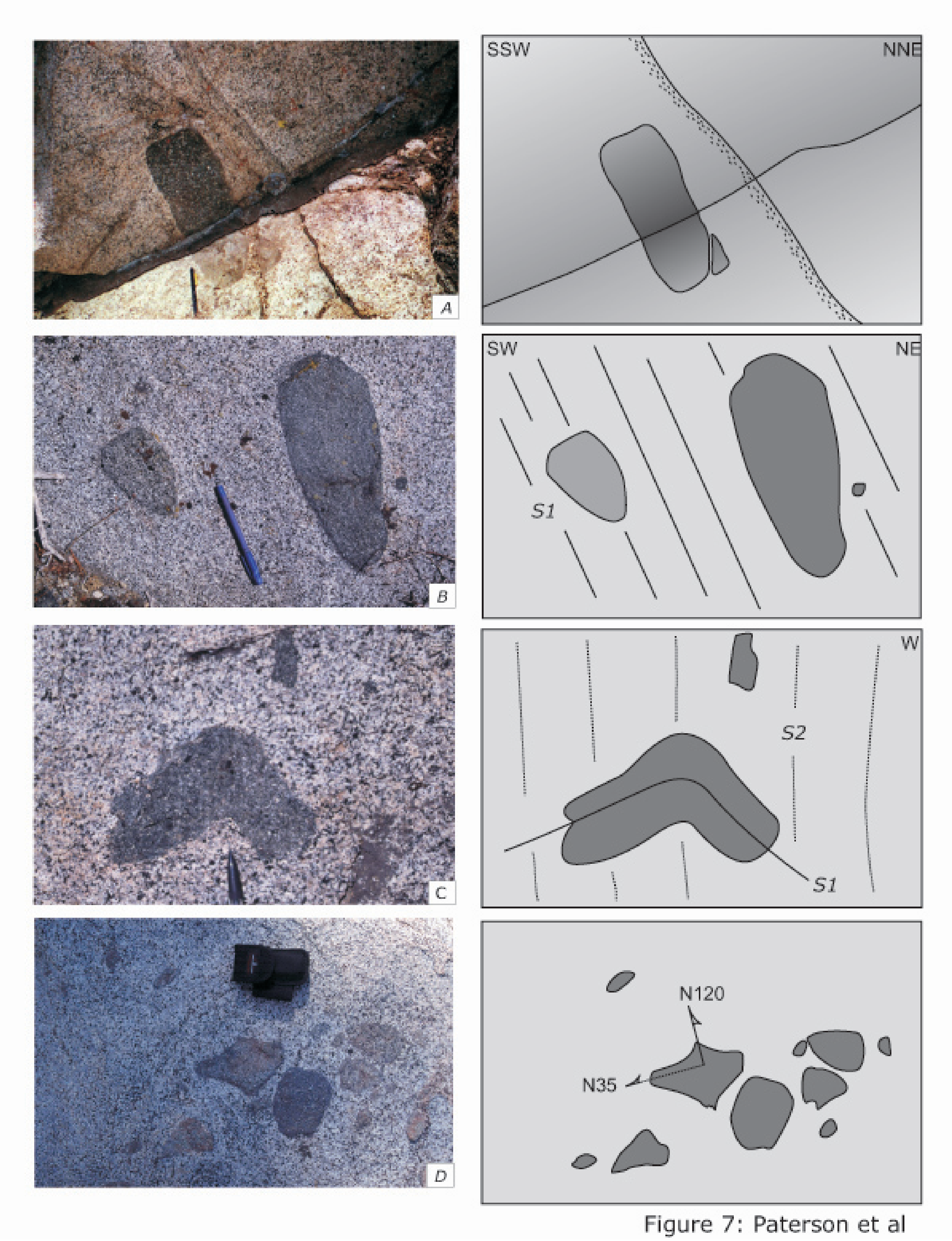

Figure 7. Photos and drawings of single and quadruple-pronged enclaves in Green Lakes pluton. Main features characterizing the relationships between fabrics and enclaves in the GLP. (a) dioritic square-shaped enclave parallel to schlieren layering; (b) two enclaves (granodioritic and microdioritic) parallel to the main foliation S1; (c) folded enclave and its axial plane magmatic foliation underline by microdioritic S2-parallel enclaves; (d) quadruple-pronged enclave - its axes correspond to the main directions defined by S1 and S2. Note that this enclave is rimmed by a chilled margin.

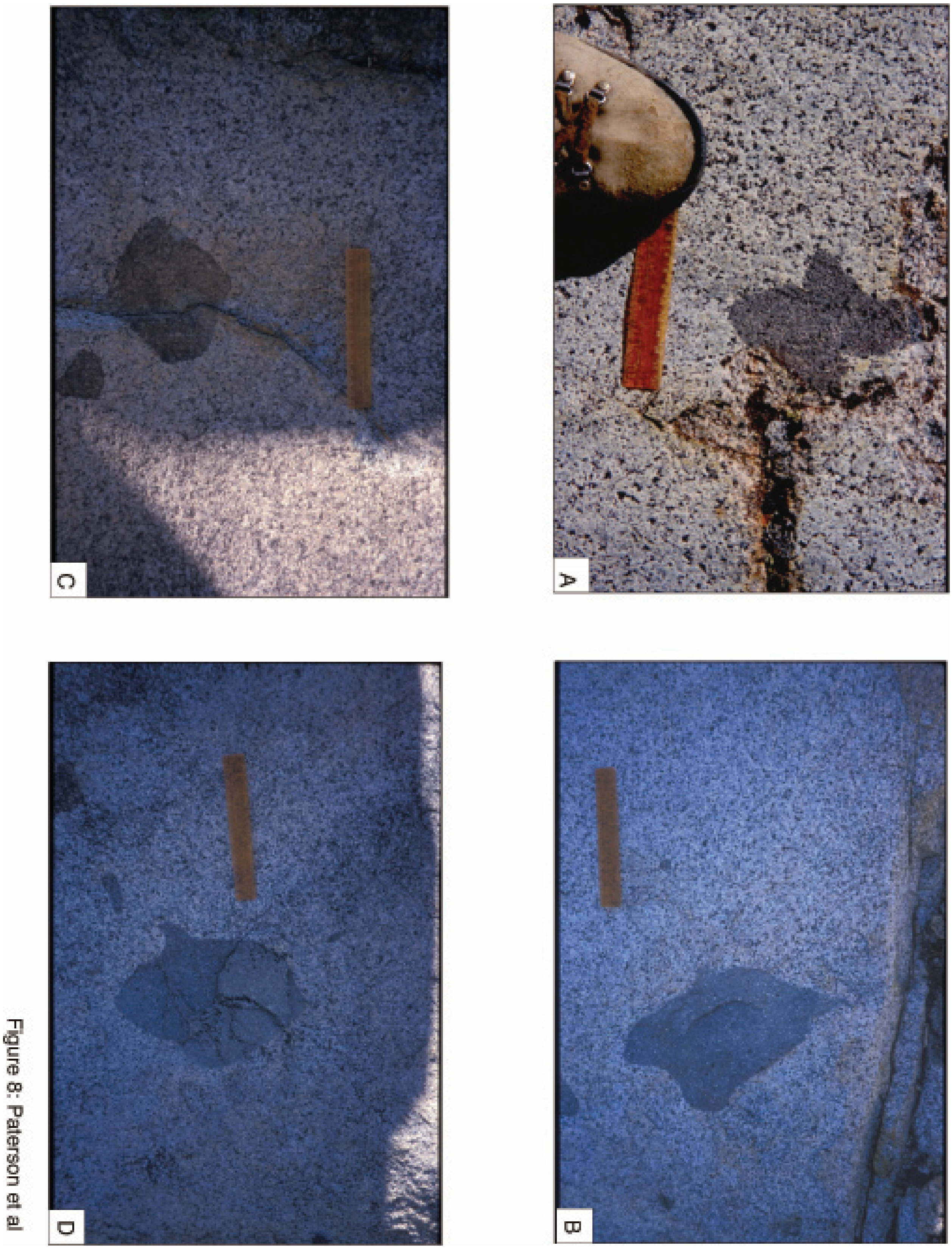

Figure 8. Photos of quadruple-pronged (a, b, d) or rhombohedral (c) enclaves in the Green Lakes pluton. 15 cm ruler for scale in all photos. Each set of opposite "pronges" are parallel to one of the two magmatic fabrics outlined in

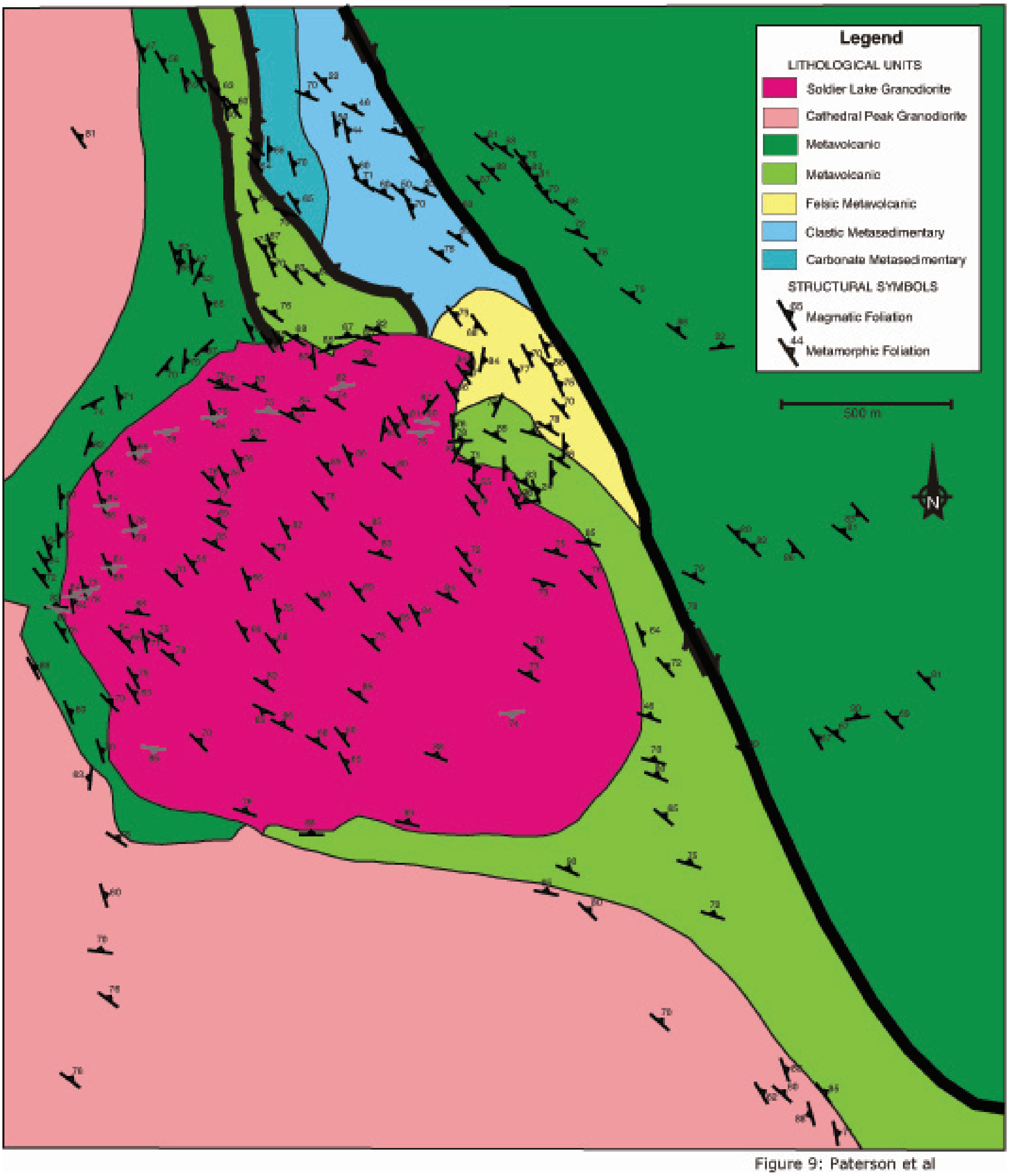

Figure 9. Map of the Soldier Lake pluton (see Figure 1 for location) showing two magmatic foliations in pluton and single subsolidus foliation in metamorphic host rocks. Cathedral Peak phase of the Tuolumne batholith forms westerm margin of map. Steeply plunging magmatic lineation occurs throughout this region except in some shear zones. Note that NW-striking foliation passed through pluton into host rock with little to no deflection at the boundary with SLP. Mapping completed by S. Paterson, J. Onezime, and colleagues.

of mineral alignment parallel to S1 and S2 is never particularly high, large changes in the magnitude of strain along Y or Z are not required to form the two foliations. The above observations also suggest that L1 records strain that occurred during formation of both foliations, and thus is a composite structure reflecting finite strain. Examples of such composite structures have been documented in metamorphic rocks by Tobisch and Paterson (1988) and Luneburg and Lebit (1998).

Enclaves also show similar characteristics in each pluton. Where vertical exposures exist, we have determined that enclave long axes are statistically parallel to L1 (Figure 4b, 10, 11). In L1 perpendicular sections most are elliptical in shape and statistically parallel to S1 or S2, although cases where long and intermediate axes of enclaves not parallel to either foliation occur (Figure 10). 3D enclave shapes, however, are quite variable at all scales from oblate to constrictional and do not necessarily reflect strain recorded

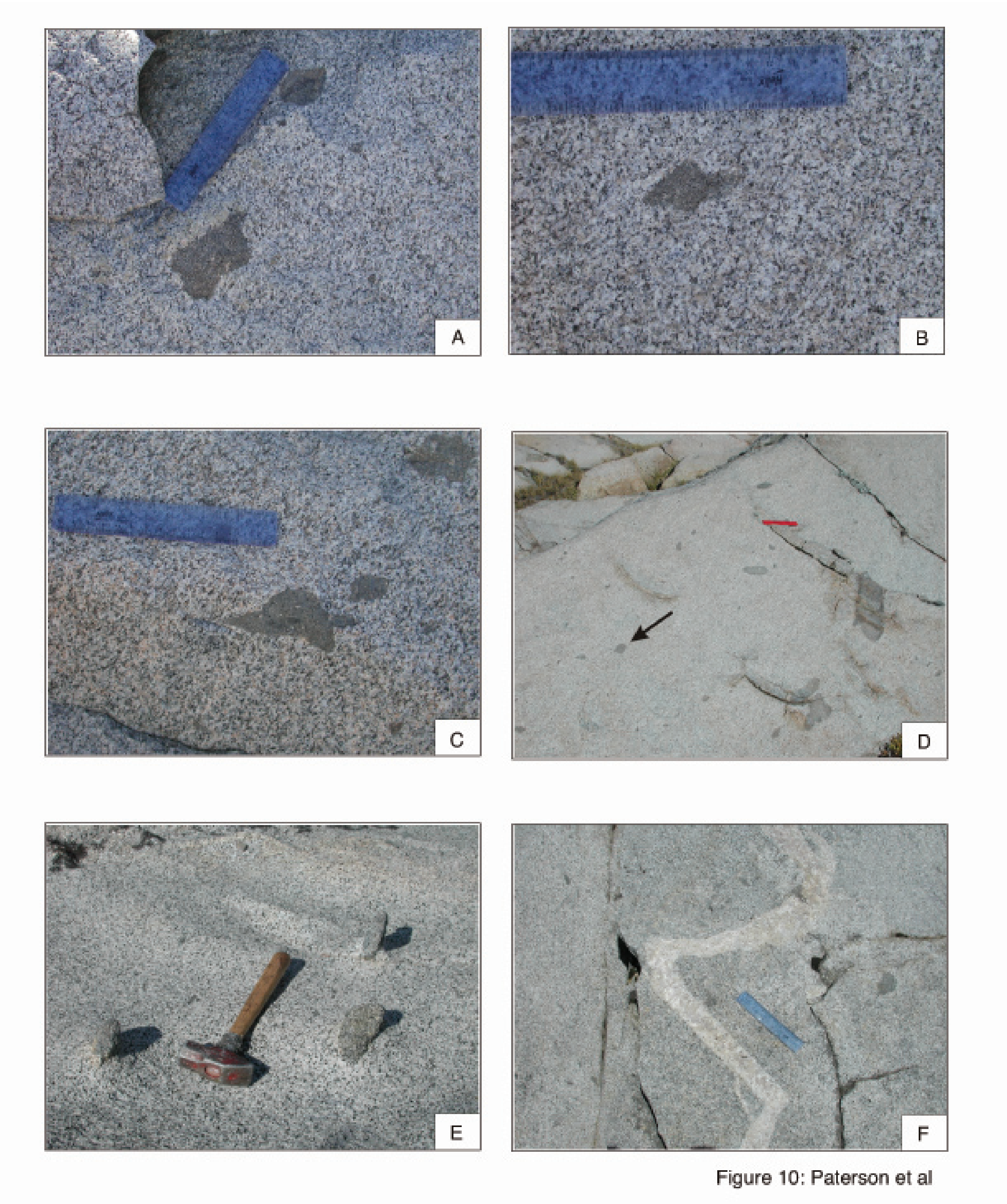

Figure 10. Photos of features in the Soldier Lake pluton. 15 cm ruler or 20 cm hammer for scale. (a) rhombohedral and quadruple-pronged enclaves with long axes parallel to NW striking magmatic fabric in surrounding matrix. (b) quadruple-pronged enclave with short axis parallel to NW-striking magmatic fabric. (c) quadruple-pronged enclave with opposite pronges parallel to magmatic fabrics in matrix; (d) two populations of enclaves parallel to two magmatic fabrics in matrix (see Fig. 9). Arrow points to rhombohedral enclave. (e) elliptical enclaves with steeply plunging long axes parallel to steeply plunging magmatic mineral lineation common throughout this pluton. (f) folded aplitic to pegmatitic dike with an axial planar, NW-striking magmatic foliation parallel to ruler.

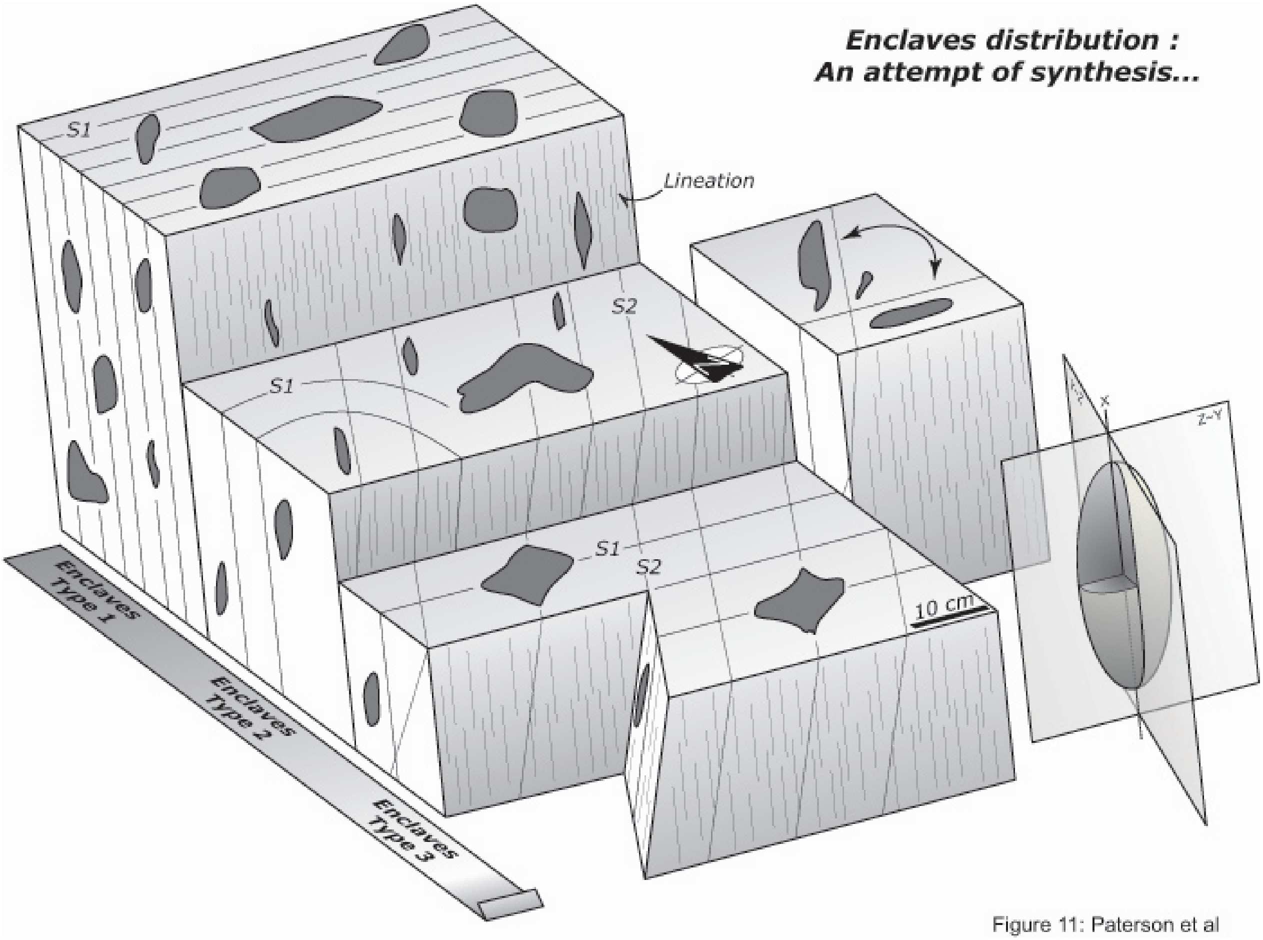

Figure 11. Synthetic block diagram summarizing enclaves distribution vs. magmatic foliations and a possible explanation for the formation of quadruple-pronged enclaves, recording strain related to the formation of both S1 and S2 foliations. The strain ellipsoid proposed wherein Y and Z are comparable is in favour of both foliations development.

by minerals in the surrounding matrix nor to adjacent enclaves (Paterson *et al*., 1998; Paterson *et al*., in press). Furthermore enclave ratios are significantly larger than both AMS and mineral fabric ellipsoid ratios (Paterson *et al*., 1998; Teruya 2000) indicating that they are not a good record of the strain experienced by the host mineral fabrics.

In domains where S1 and S2 exist, elliptical enclaves may be parallel to each, although the size of enclaves parallel to the second foliation tends to be smaller (Figure 10). Rare quadruple-pronged enclaves occur in L1 perpendicular sections in which opposite pronges are parallel to S1 and S2 (Figures 4, 7, 9, 10). Although mineral fabrics typically don't show overprinting relationships, a comparison of enclave and mineral fabrics provides us with two examples of overprinting: (1) cases where a foliation defined by aligned, Type I enclaves is overprinted by a foliation defined by magmatic minerals in the surrounding host and sometimes within the enclave (Figure 4), and (2) cases where Type I enclaves are folded and have a new axial planar foliation defined by minerals and smaller Type II enclaves in the surrounding host (Figures 7c, 10). These two observations indicate that one foliation is at least locally slightly younger than the other in each pluton. And finally in all three plutons late aplitic to pegmatitic dikes show a range of relationships from unfolded to mildly folded, but in the latter case typically have their axial planes parallel to one of the foliations.

Elsewhere (Paterson *et al*., in press) we have examined the behavior of enclaves during magmatic strain and concluded that they spent much of their magmatic lifespan as rigid objects, or at best as objects that strain much more slowly than the matrix (see also Scaillet *et al*., 2000). Thus our interpretation of enclave behavior in these plutons is the following: (1) enclaves shapes (a function of initial enclave formation and internal strain) were mostly developed at high temperatures prior to preservation of the mineral fabrics in the surrounding matrix; (2) the enclaves subsequently rigidly rotated such that the long axes became parallel to S1 (Figure 4, 7, 10); and (3) the larger enclaves became rheologically "locked in" during formation of S2 (Figure 7, 10). We suggest that this "locking in" of enclaves occurred because it was rheologically difficult for the large enclaves to rotate and displace a large volume of increasingly viscous (due to increasing cystal percent and effective viscosity of melt as temperature decreased) crystal-rich host. In contrast, individual magmatic minerals and small enclaves, presumably bound by melt films and small melt pockets, could continue to rotate parallel to a new foliation and do so with relatively little strain (Ildefonse, 1997). (4) During the formation of S2, the smaller enclaves and crystals could still rotate parallel to the new foliation by a process of melt-aided grain boundary sliding (Park and Means, 1996).

Our interpretation of the rare quadruple-pronged enclaves is as follows. Their roughly elliptical shapes were obtained during initial enclave formation and by strain in the magmas at high temperatures (Williams and Tobisch, 1994; Scaillet *et al*., 2000). Their preserved orientations then occurred during decreasing temperatures largely by rigid rotation parallel to S1 and L1 where they typically became rheologically trapped, or at best could only strain at much slower rates relative to the surrounding crystal mush. Any subsequent extension of enclaves would largely occur parallel to L1 at slow strain rates. However, in L1 perpendicular sections small amounts of extension parallel to S1 and S2 might occur depending on whether the strain associated with S1 or S2 was oblate (extension occurs) or plane to prolate (no extension) during fabric formation. Local bulging during this extension would have been most rapid in directions parallel to the X and Y principal axes (recall that the X axis remains steep in these plutons but that the Y axis may flip between S1 and S2) and may have been enhanced because of the viscosity constrast between the enclaves and surrounding magmas (e.g, Smith 2000) and/or by late melts migrating into the enclave (Paterson *et al*., in press).

In the introduction we noted that previous explanations for the formation of two magmatic fabrics include

(1) differential rotation of minerals with different shapes or axial ratios during noncoaxial strain (Blumenfeld and Bouchez, 1988),

(2) formation of metastable orthogonal lineations under a combination of pure and simple shear (Willis, 1977), and

(3) formation of orthogonal lineations where minerals with different axial ratios are aligned parallel to unequal elongation components during coaxial flow (Jezek *et al*., 1994; Schulman *et al*., 1997). Our observation that identical mineral species and mineral shapes define both foliations rules out hypotheses #1 and #3. Hypotheses #2 may play a role but cannot be the dominant cause since our two fabrics are foliations rather than lineations and are commonly not perfectly orthogonal. Furthermore our observations of overprinting relationships between the two foliations is not consistent with any of the above hypotheses and instead suggests that they record different strain increments and thus record information about the temporal evolution of each magma chamber.

Each pluton, at least one of the magmatic foliations (S1 in the GL and SL plutons and potentially both in the TB) is relatively continuous with subsolidus foliations in the surrounding host rocks (Figures 2, 5, 8). Thus these are examples of the coupled magma-host rock systems discussed by Paterson *et al*. (1998). This coupling provides further evidence that at least these coupled foliations reflect regional strain superposed on relatively static magma chambers. The significance of the second foliation, S2, in each pluton remains uncertain. S2 is very domainal in the Soldier and Green Lake plutons, but is usually the dominant foliation in the TB. And the orientations of S2 in all three plutons are highly unusual in the Sierra Nevada and are not continuous with any pervasive host rock structures (we have identified a few outcrops along the eastern margin of the TB in which late crenulations display E-W axial planes). The significance of S2 orientations, which vary between plutons remains uncertain and is one goal of our continuing research. Given that S2 typically postdates S1 foliations, which overprint internal boundaries and are associated with regional strain, we think it highly unlikely that S2 is related to chamber construction. However, the formation of S2 may be related to small increments of strain caused by the final crystallization of chambers (possibly related to an interplay between the Î”V of crystallization and/or anisotropic elastic recovery), or to small increments of regional strain, such as those thought to domainally form conjugate kinks in the Sierra Nevada (Tobisch and Fiske, 1976; Paterson, 1989).

The presence of two magmatic fabrics (and locally others in TB) in plutons is particularly problematic for anisotropy of magnetic susceptibility (AMS) studies in plutons, notably in cases where the two fabrics are not recognized prior to the AMS sampling. This is because AMS studies determine a single fabric ellipsoid, which is forced by the procedure to have orthorhombic symmetry. In the above plutons this AMS-based fabric ellipsoid will reflect some poorly constrained average of the two or more fabrics, none of which need have orthorhombic symmetry. However, if the fabrics are first recognized and mapped, then careful sampling and AMS studies of the gradients from domains dominated by one fabric to domains dominated by the other may prove particularly valuable in understanding late increments of strain associated with each fabric. We thus emphasize the need for careful mapping of magmatic foliation and lineation patterns in conjuction with any detailed AMS studies. And given that the magmatic mineral fabrics may or may not show overprinting relationships, it is extremely important not only to look for abrupt changes in orientation of the different fabrics, but to look for overprinting relationships between mineral fabrics and structures defined by enclaves, axial planes of magmatically folded dikes, and of magmatic layering.

CONCLUSIONS

* In the central Sierra Nevada, two well developed, magmatic foliations and a single steeply plunging magmatic lineation defined by identical igneous minerals as well as aligned enclaves occur in the Tuolumne, Green Lake, and Soldier Lake plutons.

* Overprinting relationships indicate that at least locally one foliation in each pluton is slightly younger than the other with the younger foliation typically associated with smaller enclaves: both foliations are locally parallel to the axial planes of folded dikes.

* Rare quadruple-pronged enclaves occur in regions where both foliations are developed and are best developed in lineation perpendicular sections.

* The overprinting relationships and quadruple- pronged enclaves indicate that these foliations record a temporal evolution of strain increments in a magma chamber. The strain increments may reflect a change from strain caused by flow during chamber construction

to tectonic strain of relatively static chambers (TB), strain caused by two tectonic events, or tectonic strains superimposed by strain reflecting late crystallization and elastic recovery of chambers.

* The presence of two magmatic fabrics in these plutons provides a cautionary note in regard to the casual application of AMS studies in plutons and indicates the need for careful field studies coupled to any quantitative fabric studies.

* The existence of a single magmatic lineation, even in regions of two magmatic foliations indicate that “composite” fabrics can form in plutons, that is a single structure formed by superposition of two different strain increments. This blurs the distinction between interpreting fabrics as those strictly related to internal flow processes from others strictly related to regional tectonism imposed on static chambers.

* The enclave relationships described from these plutons provide further evidence that enclaves record complex magmatic histories involving early strain, subsequent rigid rotations, and potentially late increments of strain some of which may not be preserved by minerals in the surrounding matrix. We therefore continue to urge caution in using enclaves as a measure of magmatic strains in plutons (see also Paterson *et al*., in press).

* The characterization of the suborthogonal fabrics needs further investigation in order to fully constrain their significance, including an examination of: (i) chemical signatures of minerals preferentially oriented parallel to each foliation; (ii) microstructures of each mineral population; (iii) careful AMS studies of gradients between domains dominated by each fabric; (iv) host rock structures to see if rare, suborthogonal structures occur regionally as well.

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REFERENCES

Bateman, P. C. 1992. Plutonism in the Central Part of the Sierra Nevada Batholith, California. US Geological Survey Professional Paper 1483, 1-186.

Bateman, P. C., and Chappell, B.W., 1979. Crystallization, fractionation, and solidification of the Tuolumne intrusive series, Yosemite National Park, California. Geological Society of America Bulletin 90, p. 465-482.

Bilodeau, B.J. and Nelson, C.A., 1993. Geology of the Sage Hen Flat pluton, White Mountains, California. Geol. Soc. Am. Map and Chart Series MCH-077, scale 1:24,000.

Blumenfeld, P. and Bouchez, J.-L. 1988. Shear Criteria in granite and migmatite deformed in the magmatic and solid states. Journal of Structural Geology 10, 361-372.

Bouchez, J.L., Guillet, P., and Chevalier, F., 1981. Structures d’ Ã©coulement liÃ©es a la mise en place du granite de GuÃ©rande (Loire-Atlantique, France). Bull. Soc. geol. France XXIII (4), 387-399.

Coleman, D.S. and Glazner, A.F., 1997, The Sierra Crest magmatic event; rapid formation of juvenile crust during the Late Cretaceous in California. International Geology Review, 39, no.9, 768-78.

Coleman, D.S., Glazner, A.F., and Gray, W., 2002, U-Pb geochronologic evidence for incremental filling of the Tuolumne Intrusive Suite magma chamber. Geological Society of America Abstracts with Programs, 34, no. 6, 269.

Fleck, R.J., Kistler, R.W., and Wooden, J.L., 1996, Geological complexities related to multiple emplacement history of the Tuolumne intrusive suite, Yosemite National Park, California: Geological Society of America Abstracts with Programs, 28, 65-66.

Greene,D.C.,1995, The stratigraphy, structure, and regional tectonic significance of the northern Ritter Range pendant, eastern Sierra Nevada, California. Ph.D. thesis, Reno, University of Nevada, 270p.

Ildefonse, B., Arbaret, L., and Diot, H., 1997. Rigid particles in simple shear flow: is their preferred orientation periodic or steady-state? In J.L. Bouchez, D.H.W. Hutton, and W.E. Stephens (editors) Granite: From Segregation of Melt to Emplacement Fabrics, Kluwer Academic Publishers, The Netherlands, p. 177-185.

Jezek, J., Melka, R., Schulmann, K., and Venera, Z., 1994. The behavior of rigid triaxial ellipsoid particles in viscous flows. Modeling of fabric evolution in a multiparticle system. Tectonophysics, 229, 165-180.

Kistler, R.W., and Fleck, R. J., 1994, Field guide for a transect of the central Sierra Nevada, California: Geochronology and isotope geology: United States Geological Society Open-File Report 94-267.

Kistler, R.W., Chappell, B.W., Peck, D.L., and Bateman, P.C., 1986. Isotopic variation in the Tuolumne Intrusive Suite, central Sierra Nevada, California. Contrib. Mineral. Petrol. 94, 205-220.

Luneburg, C. M., and Lebit, H. D. 1998, The development of a single cleavage in an area of repeated folding: Journal of Structural Geology, 20, no. 11, 1531-1548.

Park, Y., and Means, W. D. 1996, Direct observation of deformation processes in crystal mushes: Journal of Structural Geology, 18, no. 6, 847-858.

Paterson, S. R., 1989, A reinterpretation of conjugate folds in the central Sierra Nevada,

California. Geol. Soc. Am. Bull. 101, 248-259.

Paterson, S. R., Yoshinobu, A. S., Yuan, E. S., Miller, R. B., Fowler, T. K., Jr. & Schmidt, K. L. 1998. Interpreting magmatic fabric patterns in plutons. Lithos 44(1-2), 53-82.

Paterson, S.R., Pignotta, G.S. & Vernon, R. H. submit. Evaluating the quantitative significance of microgranitoid enclave shapes and orientations, Journal of Structural Geology, in press.

Reid, J., J.B., Evans, O. C. & Fates, D. G. 1983. Magma mixing in granitic rocks of the central Sierra Nevada, California. Earth and Planetary Science Letters 66, 243-261.

Scaillet, B., Whittington, A., Martel, C., Pichavant, M. & Holtz, F. 2000. Phase equilibrium constraints on the viscosity of silicic magmas 2: Implications for mafic-silicic mixing processes. In: The Origin of Granites and Related Rocks (edited by Barbarin, B., Stephens, W. E., Bouchez, J. L., Clarke, D. B., Cuney, M. & Martin, H.). Transactions of the Royal Society of Edinburgh: Earth Sciences 91, Bristol, 61-72.

Schulmann, K., Jezek, J. & Venera, Z. 1997. Perpendicular linear fabrics in granite: Markers of combined simple shear and pure shear flows? In: Granite: From segregation of melt to emplacement fabrics (edited by Bouchez, J. L., Hutton, D. H. W. & Stephens, W. E.). Kluwer Acedemic Publishers, Dordrecht, 159-176.

Schweickert, R. & Lahren, M. 1999. Triassic caldera at Tioga Pass,Yosemite National Park, California: structural relationships and significance. Geological Society of America Bulletin 111 (11), 1714-1722.

Smith, J. V. 2000. Structures on interfaces of mingled magmas, Stewart Island, New Zealand. Journal of Structural Geology 22, 123-133.

Teruya, L. A., and Miller, R. B., Significance of multiple magmatic fabrics at two internal contacts within the Tuolumne Intrusive Suite, Sierra Nevada batholith, California, Geological Society of America Bulletin Abstracts with programs, 32, 7, A-231, 2000.

Tobisch and Fiske, Significance of conjugate folds and crenulations in the central Sierra Nevada, California, Geological Society of America Bulletin, 87, 1411-1420, 1976.

Tobisch, O. T. and Paterson, S. R., 1988, Analysis and interpretation of composite foliations in areas of progressive deformation. Journal of Structural Geology, 10, 745-745.

Williams, Q. & Tobisch, O. T. 1994 Microgranitic enclave shapes and magmatic strain histories: Constraints from drop deformation theory. Journal of Geophysical Research 99, 24,359-24,368.

Willis, D.G., 1977. A kinematic model of preferred orientation. Geological Society of America Bulletin 88, 883-894.