ABSTRACT

For the first time, four distinct magmatic fabrics are documented in a composite plutonic body, the Tuolumne batholith, central Sierra Nevada, California, USA. One type of fabric was formed by strain caused by highly localized magma flow (type 1), whereas the other three chamber-wide fabrics recorded strain increments during boundary processes along batholith margins (type 2) superimposed by increments of heterogeneous regional tectonic strain (types 3 and 4). Our present work indicates that, in contrast to studies that consider magmatic fabrics to be simple structures formed by a single process, magmatic lineations and foliations in plutons may reflect accumulated finite strain and form as composite structures recording multiple strain increments in relatively static, actively deforming and rheologically complex crystal mushes at lower melt percentages. We demonstrate that multiple magmatic fabrics in a single batholith may record remarkably different processes and thus preserve a temporal record of strain in the batholith from strain during internal chamber processes to post-emplacement regional tectonic strain. However, it may be commonly very problematic to infer the exact nature of flow or even fabric-forming process from the preserved rock record. Our study also exemplifies how examination of magmatic fabric patterns in plutons, complemented with geochronology, may provide crucial constraints on the interplay among successive magma emplacement, fabric preservation, temporal evolution of strain fields in a crystallizing magma chamber, and the development of crystal-mush zones.

Keywords: batholith, magmatic fabric, magma chamber, magmatic arc, pluton, Sierra Nevada.

INTRODUCTION

Since the pioneering work of Cloos (1925), patterns of magmatic fabrics in plutons (i.e., foliations and lineations formed in the presence of melt; Paterson et al., 1989, 1998; Vernon, 2000) have been widely used to interpret a variety of geologic processes in Earth’s crust. In general, fabrics in plutons may record finite strain resulting from a variety of magmatic processes (e.g., magma flow, convection, magma ascent and emplacement), increments of regional tectonic strain, or a superposition of diverse processes in the most complex cases (Paterson et al., 1998, 2003; Žák et al., 2005). In combination with precise radiometric dating, fabrics in plutons may be also used to track the changing strain and inferred stress fields in arcs and orogens through time, as well as to examine the links between magmatism and regional tectonic processes in orogenic belts.

Modern studies commonly address the formation of magmatic fabrics at three different scales: (1) at the pluton scale, by the mapping of foliation and lineation patterns in order to evaluate chamber-wide processes and the degree of coupling between pluton and host-rock structures, (2) at the outcrop scale, by determining fabric characteristics and their temporal and geometrical relationship to other structures; and (3) at the grain scale, using microstructural observations in order to constrain likely fabric-forming mechanisms and magma rheology. The formation and significance of magmatic fabrics in plutons remain, however, matters of lively debate and vigorous scientific discussion resulting in contrasting interpretations of magmatic fabrics, of fabric-forming processes, and of the relationships of fabrics to strain and magma flow (see Paterson et al., 1998, for review).

In regard to the interpretation of chamber-wide fabric patterns, some studies have downplayed the importance of foliations overprinting internal intrusive boundaries and have attributed fabric formation to magma flow, ascent, or emplacement. In this paper, we define emplacement as the construction of the full dimensions of a pluton or batholith (i.e., all host rock has been displaced), which, however, does not necessarily imply the completion of internal processes operating within the remaining magma chamber prior to its full crystallization. Thus, if a pluton is “emplaced,” it is no longer significantly changing its dimensions, but may still have a magma chamber (region of interconnected melt) within it. In contrast to the still popular kinematic interpretation that magmatic foliations and lineations represent flow planes and flow lines in a magma body, respectively, Paterson et al. (1998), Paterson and Miller (1998), and Paterson and Vernon (1995) have published several examples of both nested and sheeted plutonic complexes where magmatic foliations overprint internal contacts between juxtaposed magma pulses. They have used this observation to suggest that fabrics reflect post-emplacement strain before final crystallization of a magma chamber and have no direct relationship to flow during ascent or emplacement.

An additional complexity is the recent recognition that more than one magmatic fabric may form and be preserved in a pluton. To date, several studies have documented two magmatic
In this paper, we document for the first time the preservation of four different magmatic fabrics in a composite plutonic body, specifically the Tuolumne batholith, central Sierra Nevada (California, USA). We present detailed structural observations of magmatic fabrics at different scales (individual exposures, kilometerscale domains, batholith-wide patterns) in order to document the formation of three batholith-wide magmatic fabrics and one group of local magmatic fabrics preserved in this batholith. We conclude that one group of localized magmatic fabrics was formed during strain caused by local magmatic flow, whereas the three batholith-wide fabrics record internal chamber processes and subsequent increments of regional tectonic strain, the latter imposed on an already constructed, increasingly static magma chamber. We then use our detailed field observations to discuss fabric formation and implications for the interpretation of magmatic fabrics, magma chamber construction models, and time scales of magmatic processes in the upper crust.

GEOLGY OF THE TUOLUMNE BATHOLITH

Overview

The Tuolumne batholith is an ~1000 km² Late Cretaceous composite batholith, exposed in the central Sierra Nevada, California, USA (Fig. 1; see Bateman and Chappell, 1979; Bateman, 1992; and Žák and Paterson, 2005, for detailed description of regional geology). The batholith was emplaced into Early Cretaceous granitoids and Protoreozoic–early Paleozoic metasedimentary screens to the south and west, and low-grade metasedimentary and metavolcanic rocks of early Paleozoic to Cretaceous age and Triassic to Cretaceous plutons to the east and north. Contacts with host rocks are steeply dipping, and sections are both discordant and concordant to the host-rock structures (e.g., lithological boundaries, foliations). The depth of batholith emplacement has been estimated at 7–9 km (Ague and Brimhall, 1988; Webber et al., 2001).

Figure 1. Simplified geologic map of the Tuolumne batholith and its host rocks, located in the central Sierra Nevada, California, United States (index map). The geologic map shows the four main nested intrusive units of the batholith with U-Pb radiometric ages according to Coleman et al. (2004). Bold boxes indicate locations of three corridors mapped at 1:24,000 scale in this study. ECG—El Capitan Granite, GLP—Green Lakes pluton, KKP—Kuna Crest Granodiorite, KHN—(outer) equigranular Half Dome Granodiorite, KHP—(inner) porphyry Half Dome Granodiorite, KCP—Cathedral Peak Granodiorite, KJP—Johnson Granite Porphyry, SLF—Soldier Lake pluton, SNB—Sierra Nevada Batholith, TB—Tuolumne batholith, WMB—western metamorphic belt.
The Tuolumne batholith consists of the following four main intrusive units, which are arranged (nested) concentrically and become more felsic progressively inward (Fig. 1; Bateman, 1992; Bateman and Chappell, 1979): (1) the outermost Kuna Crest unit (Kuc), to the east (and its equivalents along the western and southern margins), which is essentially a fine- to medium-grained, equigranular tonalite, quartz diorite, to biotite-hornblende granodiorite, typically with abundant envelope swarms; (2) the Half Dome Granodiorite (Khd), which consists of an outer equigranular and inner porphyritic variety, which is generally much coarser grained than Kuc, and is characterized by the presence of large (up to ~2 cm in length) prismatic euhedral hornblendes and conspicuous sphene (in contrast to the porphyric variety, which contains large [up to ~3 cm in length] K-feldspar phenocrysts; (3) the K-feldspar megacrystic Cathedral Peak (Kcp) Granodiorite, which forms the most voluminous part of the Tuolumne batholith and typically consists of biotite granodiorite that contains abundant large (3–10 cm in size) K-feldspar phenocrysts set in a medium-grained matrix; and (4) the central (innermost) unit, the Johnson Granite Phorphyry (Kjg), which is a fine-grained, equigranular granite that locally contains sparse K-feldspar phenocrysts.

Recent geochronological data (Coleman et al., 2004; Matzel et al., 2005) estimate the U-Pb ages of the main intrusive units of the batholith as follows: 93.1 ± 0.1 (the tonalite of Glen Aulin), 93.5 ± 0.7 Ma (the Kuna Crest Granodiorite), 92.8 ± 0.1 Ma (eastern body of the outer Half Dome Granodiorite), 91.7 ± 0.2 (western body of the outer Half Dome Granodiorite), 88.8 ± 0.8 Ma (inner Half Dome Granodiorite), 88.1 ± 0.2 Ma (Cathedral Peak Granodiorite; Coleman et al., 2004), 86 Ma (Cathedral Peak Granodiorite; Matzel et al., 2005), and 85.4 ± 0.1 (the Johnson Granite Phorphyry).

Previous Fabric Studies

The first map showing foliation patterns in the Tuolumne batholith was completed by Cloos (1936) across the central part of the batholith. Cloos’ map shows three main units (the Half Dome and Kuna Crest units are combined) with no foliation in the Johnson Granite Phorphyry, a steep margin-parallel foliation bending into WNW foliation in the Cathedral Peak Granodiorite, and an older foliation in the outer unit that is truncated along the Cathedral Peak contact. Later maps by Brodersen (1962) and Chesterman (1975) indicate ~NW-SE–trending steep magmatic foliations in the northern part of the Cathedral Peak Granodiorite, whereas Bateman and Chappell (1979) described a strong, margin-parallel ~N-S foliation in the outer units (Kuna Crest Granodiorite and its equivalents) and explained the formation of this foliation and flattening of microgranitoid enclaves as a result of emplacement of younger magma surges. These authors also noted that foliations weaken inward and strike diagonally across the Half Dome and Cathedral Peak Granodiorite. Bateman (1979) showed the presence of two regional magmatic foliations (~N-S to NNW-SSE and ~WNW-ESE foliation) on the 1:24,000 scale U.S. Geological Survey (USGS) geologic map of the Tuolumne batholith without any interpretation of the significance of these fabrics. Paterson and Vernon (1995) compiled published foliation data from the Tuolumne batholith into an overall foliation map showing that the ~WNW-ESE magmatic foliation cuts across most internal contacts, while some contacts have local domains of margin-parallel, ~N-S to NNW-SSE foliations.

Teruya and Miller (2000) used field and anisotropy of magnetic susceptibility (AMS) studies to characterize both a margin-parallel and an ~E-W crosscutting magmatic fabric near the Half Dome and Cathedral Peak contacts near Tenaya Lake. They interpreted the latter fabric to reflect regional strain superimposed on emplacement-related fabric formed during final solidification of the magma chamber. Paterson et al. (2003) also pointed out that the ~N-S to NNW-SSE foliation is slightly older than the ~WNW-ESE foliation and interpreted these two regional magmatic foliations as a result of the temporal evolution of strain imposed on an already-emplaced magma chamber.

Recently, Glazner et al. (2004) noted that the Half Dome Granodiorite contains a magmatic fabric that is continuous in the field in spite of their geochronologic evidence that rocks containing the fabric crystallized at significantly different times. They concluded that such a fabric is time-transgressive and implies notably uniform strain associated with emplacement increments added at significantly different times.

MAGMATIC FABRICS IN THE TUOLUMNE BATHOLITH

Next we provide a description of magmatic fabrics in the Tuolumne batholith that range from small-scale fabrics related to localized magma flow to regional-scale fabric patterns. We will pay particular attention to the fabric characteristics and the temporal and geometrical relationships among fabrics, other magmatic and host rock structures, and pluton/host-rock contacts observed at the scale of individual exposures in the batholith. Based on field observations and fabric characteristics at different scales, we have defined four different magmatic fabrics (referred to as type 1–4 throughout this paper) in the Tuolumne batholith. Type 1 fabric is related to structures that formed during localized magma flow, whereas the other three steep fabrics occur across the entire batholith. Type 2 fabric is always contact-parallel, regardless of contact orientation. Type 3 strikes ~NNW-SSE, and type 4 strikes NW-SE to E-W. Summary characteristics and interpretations of each type of fabric are addressed in detail in the Discussion section.

Magmatic Fabrics Formed During Localized Magma Flow

A variety of magmatic fabrics related to localized magmatic flow is preserved in the Tuolumne batholith. These fabrics are here referred to as type 1. Localized flow resulted in the following structures (Fig. 2): (1) simple planar to gently curved mafic schlieren; (2) schlieren troughs or channels, where mafic schlierens occur at margins of channel-like structures (Fig. 2B); (3) schlieren tubes (i.e., entirely enclosed schlieren layers forming tube-like bodies typically with steep axes) and ladder dikes (i.e., migrating magma tubes in which margin-parallel schlieren truncate one another; Reid et al., 1993; Weinberg et al., 2001; Žák and Paterson, 2005; Fig. 2A); (4) small-scale plumes that consist of mafic-rich to K-feldspar megacryst-rich rocks, some of which are bounded by mafic accumulations (Paterson et al., 2005); and (5) local sheetlets or dikes. The schlierens in these structures always grade from finer-grained mafic margins to coarser-grained felsic interiors. Although these structures occur in all intrusive units in the Tuolumne batholith, they are most common in the Half Dome and Cathedral Peak Granodiorites. The significance of these structures for this study is that the geometry, size (decameters to tens of meters scale), and local occurrence indicate that they were formed by local magmatic processes (e.g., flow in channels or rise as diapirs).

The magmatic fabrics in these structures are defined by the planar and/or linear alignment of igneous crystals (hornblende, biotite, feldspar phenocrysts). In the schlieren layers, troughs, tubes, and migrating tubes, a planar alignment of these crystals forms a foliation parallel or slightly oblique to the schlieren planes. The foliation is thus also roughly parallel to the boundaries of these structures (Fig. 2C). In rare cases, where the mafic margins of schlieren are exposed, we typically see the following pattern of mineral lineations (Fig. 2D): (1) lineations have steep plunges in schlieren layers; (2) in troughs, the lineations, defined only by large euhedral hornblendes, are parallel to axes.
of the troughs, possibly indicating the magma flow direction in these structures; (3) surprisingly, in the steeply plunging tubes, the large hornblendes define both subhorizontal and the steeply plunging lineations one might expect. In regions away from schlieren, minerals in these structures typically become realigned parallel to one of the regional fabrics discussed in the following sections.

In the subvertical plumes, we typically see a variety of fabric patterns. Margin-parallel foliation commonly occurs on the sides and tops of the plume, particularly where mafic margins occur. In plume tails, the foliation and, less commonly, the lineation are subparallel to the margins. Within plumes, foliations are common, many of which are parallel to one of the regional foliations discussed in the following sections. However, we locally find a subhorizontal foliation as if late settling and compaction of crystals occurred in the plume.

In sheets or dikes, four types of fabric patterns occur: (1) margin-parallel foliations and variable lineations; (2) foliation and lineation patterns are at variable angles to the dike or sheet margins, but are parallel to regional foliations (described herein as type 3–4); (3) “comb layering” that forms mineral alignment perpendicular to the walls of the sheets and/or dikes (rare); and (4) in extremely rare cases, a concave foliation pattern that changes from margin-parallel (near walls) to margin-perpendicular (in centers) orientations.

Chamber-Wide Fabric Patterns

We mapped the chamber-wide fabric patterns at 1:24,000 scale, in two 8–10-km-wide, approximately E-W to SW-NE corridors across the Tuolumne batholith, and we examined all intrusive units, their internal contacts, and host-rock aureoles (corridors 1 and 2; Figs. 1, 3, and 4). We also mapped fabrics at the same scale in one extrusion or lobe extending southeast from the main batholith that consisted entirely of the...
Kuna Crest Granodiorite (corridor 3; Figs. 1 and 5). Next, we describe the chamber-wide fabric patterns in each of these areas to emphasize the general patterns of chamber-wide fabrics and their relationship to host-rock structures.

**Corridor 1**

This ~E-W corridor, ~9 km wide and 11 km long, extends across the shortest dimension of the batholith (Figs. 1 and 3) and includes all of the main intrusive units except for the Johnson Granite Porphyry. The largest and central part of the corridor consists of the Cathedral Peak Granodiorite; however, on both sides of the Cathedral Peak Granodiorite complex, contact relationships exist with the Half Dome and Kuna Crest units.

To the west, the host El Capitan Granite forms an arcuate, easterly bulging contact with the tonalite of Glen Aulin (equivalent to the Kuna Crest Granodiorite). The contact is sharp and locally highly irregular with many complexities such as irregular steps or stopped blocks within the tonalite. Here, the two outer units of the Tuolumne batholith form narrow (ten to hundreds of meters) zones that are roughly parallel to the contact with the El Capitan Granite, and are truncated by the Cathedral Peak Granodiorite along a sharp, locally stepped arcuate contact. In places, the Cathedral Peak Granodiorite cuts outward into the outermost tonalite of Glen Aulin (Fig. 3).

At the eastern end of this transect, the contact with host-rock metavolcanics is steeply dipping and generally strikes ~N-S or ~NNW-SSE. The Kuna Crest and the Half Dome Granodiorite form zones roughly parallel to the host-rock contact but are truncated in the Sawmill Canyon area. To the north of the Sawmill Canyon area, the Cathedral Peak intrudes the host-rock metavolcanics, and the outer intrusive units (Kuna Crest and Half Dome Granodiorites) are missing.

Magmatic fabrics in corridor 1 are generally steeply dipping and associated with a steeply plunging magmatic lineation. The ~E-W to ~NW-SE magmatic foliation (type 4) is dominant throughout the Cathedral Peak Granodiorite, although in a few places, the ~N-S to NNW-SSE foliation (type 3) associated with a steeply plunging lineation is also observed, particularly along the eastern margin of the batholith, where the granodiorite intrudes host-rock metavolcanics. The simple foliation pattern of the main part of the corridor becomes more complex along both margins of the batholith. Along its western margin, the ~E-W to ~NW-SE magmatic foliation commonly overprints irregular contacts between the intrusive units (i.e., tonalite of Glen Aulin and Half Dome Granodiorite), but another magmatic foliation (type 2) is parallel to contact irregularities and to the general orientation of the contacts, which strike NE-SW in the southern section of the El Capitan Granite bulge. In sections where the contacts strike ~E-W (the northern margin of the bulge of the El Capitan Granite), foliation strikes ~N-S (type 3) and is at a high angle to the contacts.

Complex relationships also exist between different intrusive units along the eastern margin of the Tuolumne batholith in the Sawmill Canyon area (see Figure 6 in Žák and Paterson, 2005, for map and details of rock units). Here the Kuna Crest Granodiorite intrudes volcanic and volcaniclastic host rocks in the southern portion of the area. It is abruptly truncated in the Sawmill Canyon area along an ~E-W contact by younger intrusive units and is not seen again farther north along the eastern or northern margins of the Tuolumne batholith. The outer equigranular Half Dome Granodiorite, which intrudes the Kuna Crest unit, is also truncated in the Sawmill Canyon area along the same ~E-W contact as the Kuna Crest, but appears again farther north. Both of the above units are truncated by a series of mingled and strongly sheeted units that consist of rocks derived from magmas similar to the Half Dome and Cathedral Peak Granodiorites. Finally, the Cathedral Peak Granodiorite intrudes the western margin of the Half Dome in the southern part of this area, but farther north, it increasingly steps to the east and cuts out all other units. The Cathedral Peak Granodiorite also truncates the mingled zones, partially fills the gap between the northern and southern segments of the Half Dome, contributes to the mingled zones, and forms late dikes that intrude across all other units or extend into the volcanic and volcaniclastic host rocks.

We mapped all four magmatic fabrics in this area. The foliation and lineation preserved in the most mafic portions of schlieren in numerous schlieren layers, troughs, tubes, and sheets (type 1) is locally overprinted by a steeply dipping (~70°–89°) ~N-S to NNW-SSE foliation (type 2 or 3) that is subparallel both to the generally ~N-S–striking contact of the Kuna Crest Granodiorite with the metatavolcanic host rock and to the foliation in the metavolcanic host rock. This magmatic foliation is associated with a steeply plunging magmatic lineation, which is most intensely developed in the outer Kuna Crest Granodiorite; however, it is also locally preserved in the mingled zones, the Half Dome Granodiorite, and the Cathedral Peak Granodiorite farther away from the eastern contact. In regions where the batholith–host-rock contact curves or takes abrupt steps, we also see a foliation that is parallel to the host-rock contact (type 2), regardless of the contact geometry and discordant to host-rock structures. A younger, well-developed, ~WNW-SEE foliation (type 4) bears a steeply plunging magmatic lineation cuts across all the structures and intrusive contacts described here and can be found in the batholith at even short distances from its eastern margin.

**Corridor 2**

This ~10-km-wide and 13-km-long E-W corridor extends across the eastern half of the widest part of the Tuolumne batholith (Figs. 1 and 4) and exposes the following units from east to west: Jurassic metavolcanics and metasediments in the eastern aureole, Kuna Crest Granodiorite, equigranular Half Dome Granodiorite, porphyric Half Dome Granodiorite, Cathedral Peak Granodiorite, and the eastern half of the Johnson Granite Porphyry. The host-rock margin strikes ~NNW-SSE where it consists of Jurassic metavolcanics, or forms highly irregular steps to the south where it consists of older, strongly deformed plutons intruding the metavolcanics. In this part of the batholith, the contact between the Kuna Crest and Half Dome Granodiorites is gradational over several hundred meters and generally strikes NNW-SSE except for where it becomes irregular in the southern part of the area. The contacts between Half Dome and Cathedral Peak Granodiorites
Four magmatic fabrics in the Tuolumne batholith

El Capitan granite (102 Ma)

Domain of margin-parallel (Type 2) fabric

NW-SE to N-S magmatic foliations (Type 3, poles, N = 81)

NW-SE to E-W magmatic foliations (Type 4, poles, N = 316)

Tuolumne batholith

Corridor 1

Marginal-parallel magmatic foliations (Type 2, poles, N = 81)

Magmatic lineations (All, N = 81)

Lithologic units
- Kuna Crest Granodiorite
- Mingled units
- Half Dome Granodiorite
- Cathedral Peak Granodiorite
- Eastern Sierra Pendants

Structural symbols
- Magmatic foliation (Type 2)
- Magmatic foliation (Type 3)
- Magmatic foliation (Type 4)
- Magmatic lineation

Fig. 6 in Zák and Paterson (2005)
Figure 4. Geologic map of corridor 2 (south of Tuolumne Meadows). Multiple magmatic fabrics are preserved in the area. Type 2 or 3 foliations are oriented ~N-S or NNW-SSE and thus are subparallel to internal contacts between intrusive units or the batholith margin. The dominant fabric is ~NW-SE foliation (type 4), which overprints all internal contacts. Magmatic lineations, associated with each foliation, are steeply plunging throughout the area. Stereonets (equal-area, lower-hemisphere projections) show orientations of different magmatic foliations and the magmatic lineation. KKC—Kuna Crest Granodiorite, KGA—tonalite of Glen Aulin, KHD—Half Dome Granodiorite, KCP—Cathedral Peak Granodiorite.

Figure 5. Geologic map of corridor 3 (across the southern lobe of the Kuna Crest Granodiorite). Steeply dipping magmatic foliations are parallel to the outer margins of the lobe, forming an arcuate pattern (type 2, margin-parallel fabric). The type 3 and 4 fabrics are preserved mainly in the younger Kuna Crest Granodiorite units (northernmost, central unit and units III and IV). Magmatic lineations are steeply plunging, regardless of the strike of the foliation.
and Cathedral Peak Granodiorite and Johnson Granite Porphyry are sharp and strike NE-SW and N-S, respectively.

The dominant fabric along the eastern margin of the batholith is the ~N-S to ~NW-SE foliation (type 2 or 3) associated with a steeply plunging (~70°–90°) magmatic lineation trending SE or E. This foliation is parallel to the ~NW-SE–striking outer margin of the batholith but also to regional host-rock structures. Farther to the west, it is only locally preserved in the Cathedral Peak Granodiorite and in the Johnson Granite Porphyry. At the eastern contact with the host rock, magmatic fabrics in the Kuna Crest Granodiorite are overprinted by a narrow (~5–10-m-wide) zone of margin-parallel, ~NW-SE subsolidus foliation concordant to the foliation in the host-rock metavolcanics. Here, the stretching lineation plunges ~60°–85° to the SE.

In the remainder of this corridor, the dominant fabric is an ~E-W to WNW-ESE (type 4) steeply dipping foliation (~70°–90° dip) and a steeply plunging (~70°–90°) magmatic lineation. This foliation cuts across all intrusive contacts and irregularities along margins and is also weakly developed in the Johnson Granite Porphyry (Titus et al., 2005). Interestingly, we locally find the ~E-W to WNW-ESE foliation in the Kuna Crest Granodiorite, even within meters of the margin with host rock and locally even at high angles to dike margins of Kuna Crest Granodiorite that intrude the host rock adjacent to the main batholith. The ~E-W to WNW-ESE foliation decreases in intensity inward and is weakest in the central part of the Tuolumne batholith in regions adjacent to or within the Johnson Granite Porphyry (e.g., Johnson Peak area).

The fabric pattern becomes more complex on the northwestern slope of Mammoth Peak (see Figure 2 in Žák and Paterson, 2005; for map and details), where a 0.5-km-wide and several-kilometer-long, ~N-W–striking sheeted unit is developed along the gradational contact between the Kuna Crest and Half Dome Granodioriters (Žák and Paterson, 2005). Multiple magmatic foliations are developed in this area. Foliations locally preserved parallel to schlieren layers, schlieren troughs, and margins of sheets (type 1) are overprinted by a dominant ~N-S to NNW-SSE steeply dipping foliation (type 2 or 3), which is associated with a steeply plunging magmatic lineation and is roughly parallel to both sheet margins and to the contact between the Kuna Crest and Half Dome Granodioriters. However, the dominant fabric in this area is represented by an ~WNW-ESE steeply dipping foliation (type 4) and steeply plunging lineation (~70°–90° plunge). In this domain, the ~WNW-ESE magmatic foliation overprints the sheeted zone without significant changes in orientation, and thus postdates emplacement of the sheets. The latter magmatic foliation is parallel to axial planes of magmatically folded sheets.

**Corridor 3: Kuna Crest Lobe**

Corridor 3 extends across the southeastern lobe of the Tuolumne batholith toward the NW of Waugh Lake (Figs. 1 and 5). The lobe is made up of the Kuna Crest Granodiorite, which shows a range of textural and some compositional variations (Memeti et al., 2005; Memeti et al., 2006) defining zones I–V (Fig. 5). All contacts between the zones within the lobe are gradational within tens of meters except for the southern sharp contact of unit III, which extrudes from the center toward the lobe tip to form unit IV. In all Kuna Crest Granodiorite units, mafic schlieren layers, sheets, tubes, and troughs are preserved only locally.

The contact of the Kuna Crest Granodiorite with the host-rock metavolcanics strikes ~NW-SE along both sides of the lobe and becomes highly irregular and stepped at the lobe tip in the southeastern part of the mapped area (Fig. 5). The metavolcanic host rock is dominated by a steep ~NW-SE foliation and steeply plunging lineation, although foliation strikes locally vary, particularly at the eastern side of the lobe and the lobe tip (Fig. 5).

A prominent subsolidus foliation and lineation is developed in an up to 500-m-wide zone at the northeastern lobe margin and locally also along another sections of the lobe margin (Memeti et al., 2006). The subsolidus fabrics are oriented like the magmatic foliations and lineations, which are both steeply dipping and plunging (~75°–90°) throughout corridor 3 (Fig. 5). Only a locally occurring type 1 foliation and lineation is preserved in the most mafic portions of schlieren layers, troughs, tubes, and sheets. The dominant foliation pattern in the lobe is parallel to its margins (type 2). In the northwesternmost central unit and the southeastern part of the corridor (mainly in units III and IV), foliation trajectories strike ~NW-SE and thus are generally parallel to the host-rock structures but do not mimic the orientation of the contact to the adjacent unit (type 3). An ~ESE-NNW foliation (type 4) can be observed in rare, small domains throughout the lobe, and its strike is at a high angle to both the overall foliation strike and the contact with the host rocks. In summary, the Kuna Crest Granodiorite lobe provides an intriguing example of how the magmatic fabric pattern changes from margin-parallel foliation (type 2) at the batholith–host-rock contacts to become increasingly replaced by the ~NW-SE–striking (type 3) and locally by ~E-W–striking (type 4) foliations toward the lobe center and tip (Fig. 5).

**CHARACTERISTICS OF THE MAGMATIC FABRICS AS SEEN IN INDIVIDUAL EXPOSURES**

Typically, all magmatic foliations in the Tuolumne batholith are defined by the alignment of hornblende and biotite, less so by plagioclase, and in the porphyritic units (inner Half Dome and Cathedral Peak Granodiorites), by a generally weaker and more variable alignment of K-feldspars phenocrysts (Fig. 6). In the Johnson Granite Porphyry, where the foliation is generally weak, the main foliation-forming minerals are K-feldspars phenocrysts, although in places, small aggregates of biotite grains or biotite in schlieren may also define the foliation. The magmatic lineation is defined by the alignment of igneous minerals (the same that define the foliation) and elongate microgranular enclaves (Fig. 6A). It typically plunges steeply to vertically (~70°–90° plunge) in all intrusive units throughout the majority of the Tuolumne batholith (stereonets in Figs. 3, 4, and 5). The lineation typically occurs in each of the regional foliations and is parallel to the intersection lineation where two foliations are present at the same location. In some areas, constrictional fabrics (L or L ≫ S) are developed, in which case, the magmatic lineation can be seen in all vertical sections, thus establishing that it is not simply an intersection lineation.

**Relative Timing of the Magmatic Fabrics**

Although relative temporal relationships between the magmatic fabrics of different orientations (Figs. 7 and 8) in the Tuolumne batholith cannot be established at many exposures, we have been able to establish the following relationships at a number of stations. The type 1 fabrics in mafic schlieren or sheets are almost always overprinted by both the ~N-S to NNW-SSE or ~E-W to ~NW-SE chamber-wide foliation (Fig. 8A). The general pattern is that type 1 fabrics are best preserved in the mafic layers, whereas the overprinting fabrics are best developed in the more felsic portions of these structures (Fig. 8A). However, in some places, even crystals in the mafic schlieren are realigned, in which case the fabrics that formed during localized magma flow are entirely obliterated.

We have most convincingly established the relative timing of the ~N-S to ~NNW-SSE fabric (type 3) and the ~E-W to NW-SE foliations (type 4) along the eastern margin of the batholith. In many cases, elongated microgranitoid enclaves are parallel to the ~N-S to ~NNW-SSE foliation (type 3) and are overprinted by a younger, ~E-W to NW-SE mineral magmatic foliation (type 4) in the surrounding host (Fig. 8B) and, locally,
also within the enclaves. In lineation-perpendicular faces, we also recognized cases where the narrow tips of these enclaves parallel to the ~N-S to ~NNW-SSE foliation (type 3) are reoriented parallel to the ~E-W to NW-SE foliation (type 4; Figs. 8C and 8D) or have opposite prongs parallel to type 3 and Type 4 foliation (quadruple-pronged enclaves; Paterson et al., 2003; Figs. 7A and 8D). The ~E-W to NW-SE foliation (type 4) also discordantly overprints both sharp or gradational margins of ~N-S-oriented magmatic sheets (Mammoth Peak area) and sharp, straight margins of late aplitic dikes and stoped blocks (Potter Point and Sawmill areas, Figs. 7C and 7D). These observations indicate that the ~E-W to NW-SE foliation (type 4) is at least locally younger than the ~N-S to ~NNW-SSE foliation (type 3). These timing relationships clearly establish that type 1 fabrics are the oldest and type 4 the youngest. The best constraints we have about timing relationships for the type 2 magmatic fabric are in the Kuna Crest Granodiorite lobe (corridor 3; Fig. 5). There, crosscutting relationships establish that the marginal units are the oldest, and they become increasingly young toward the center and the tip of the lobe. Type 2 fabrics mainly occur in the older units, and the younger units are dominated by type 3 fabrics. We thus suggest that magmatic fabric type 2 in this lobe formed most likely before fabric type 3. However, in most cases, relationships are equivocal, which suggests that these two fabrics may overlap in age.

**Relationship of Magmatic Fabrics to Stoped Blocks**

We have recognized several zones of abundant stoped blocks in the Tuolumne batholith (Zák and Paterson, 2005) that provide additional constraints on fabric formation. A particularly informative example occurs 1 km east of Potter Point in Lyell
Canyon (location shown in Fig. 3) within the wide gradational contact between the Kuna Crest and equigranular Half Dome Granodiorites (Žák and Paterson, 2005). This area is characterized by a modal decrease in mafic minerals, modal increase in euhedral hornblendes, and a decreasing amount of sphene in an inward direction from Kuna Crest to Half Dome Granodiorites (the dominant transitional rock type here is referred to as the “transitional” Kuna Crest Granodiorite).

In this domain, some wider zones show evidence of breakup of the host “transitional” Kuna Crest Granodiorite into separate angular to subangular stoped blocks that occur within the enclave-rich, equigranular Half Dome Granodiorite (Fig. 7D). The stoped blocks are up to 3–5 m in size and typically have sharp margins. The “transitional” Kuna Crest Granodiorite was also intruded here by two superimposed sets of ~1–2-m-thick composite mafic-felsic sheets: older, more mafic sheets strike ~NW-SE, and younger, more felsic sheets strike ~NE-SW. The sheets typically have very sharp and straight boundaries.

A late magmatic fabric overprints all of these structures. The fabric is defined by a steeply dipping ~E-W to WNW-ESE magmatic foliation (type 4) and a steeply plunging magmatic lineation. The foliation is parallel to axial planes of magmatically folded aplitic dikes and
discordantly overprints sharp and straight margins of dikes and irregular, but sharp margins of stoped blocks of Kuna Crest Granodiorite with no change in its orientation (Figs. 7C and 7D). We see similar relationships elsewhere along both external and internal margins.

Relationships among Magmatic Fabrics, Batholith–Host-Rock Contacts, and Host-Rock Structures

We further examined the host rock along both the western and eastern margins of the Tuolumne batholith and made some preliminary observations from the northern and southern margins as well.

To the west, where the host rock is made up of the older 102 Ma El Capitan Granite, the contact of the Tuolumne batholith with the leucocratic El Capitan Granite is highly irregular. The magmatic foliation in the El Capitan Granite, defined by weak alignment of biotite, is sharply truncated by the contact with the Tuolumne batholith, regardless of which unit of the batholith occurs along the contact. Foliation patterns are typically discordant across this contact.

To the east, where the Tuolumne batholith intrudes low-grade early Paleozoic to Jurassic metasedimentary and metavolcanic rocks of the Saddlebag Lake and Northern Ritter Range Pendants along an ~NNW-SSE contact, the fabric patterns and relationships of magmatic fabrics to host-rock structures are more complex (e.g., Sawmill Canyon area) and vary along strike. Broadly speaking, the host-rock foliation is oriented subparallel to the batholith margin and is typically developed as a steeply NE-dipping (75°–80°) metamorphic foliation associated with a steeply SE-plunging stretching lineation and highly variable kinematics. The foliation is also parallel to compositional banding in metavolcanic rocks. The orientation of the
host-rock foliation is subparallel to the NNW-SSE magmatic fabric (type 3), and, at least locally, where the host-rock contact takes steps, it is at high angles to the margin-parallel magmatic foliation. In several host-rock domains along the eastern margin and in pendants along the western margin of the batholith, the ~NNW-SSE foliation is locally overprinted by later crenulations, fracture cleavage, box folds, kink bands, or conjugate reverse faults that are compatible with ~N-S shortening (Economos et al., 2005). The axial planes of these folds and associated fabrics are subparallel to ~NW-SE to E-W magmatic foliation (type 4) in nearby units of the Tuolumne batholith.

The largest mapped section along the eastern edge of the batholith consists of Kuna Crest Granodiorite juxtaposed against metavolcanic host rock, in which the character of structures adjacent to this contact varies strongly along strike. In sections where the contact was modified by magmatic stoping and therefore is highly irregular and very sharp at the submeter scale, structures in the Kuna Crest Granodiorite are largely magmatic and have evidence for subsolidus deformation only in local domains. Commonly, margin-parallel magmatic foliation (type 2), layering, or mafic schlieren are preserved along the contact. In places where the contact is straight and the Kuna Crest Granodiorite is compositionally more homogeneous, magmatic structures in the granodiorite may be overprinted by a narrow, contact-parallel zone (meters to decameters wide) of subsolidus deformation. However, we observed numerous examples where the ~N-S magmatic foliation is preserved at the contact with no evidence for subsolidus deformation. In many cases, the ~E-W magmatic foliation (type 4) is also preserved at the ~N-S–striking contacts with no evidence for subsolidus deformation or a continuation of fabrics into the host rock at the submeter scale.

**DISCUSSION**

**Interpretation of Four Magmatic Fabrics in the Tuolumne Batholith**

We propose that four distinct magmatic fabrics (types 1–4) that have different orientation, relative timing, and relationship to structures in the host rock and to internal contacts between the intrusive units, are preserved in the Tuolumne batholith (see Table 1 for summary of distinguishing fabric characteristics). They are interpreted as follows:

1. Type 1 fabrics, where not overprinted by one of the chamber-wide magmatic fabrics (such as in Fig. 8A), are represented by foliation and lineation in structures related to localized

<table>
<thead>
<tr>
<th>FOLIATION TYPE AS USED IN THIS PAPER</th>
<th>ORIENTATION OF ASSOCIATED MAGMATIC LINEATION</th>
<th>RELATIONSHIP TO HOST-ROCK STRUCTURES</th>
<th>GEOMETRICAL RELATIONSHIP TO HOST-ROCK CONTACTS</th>
<th>LOKELY CAUSE OF MAGMATIC FABRIC</th>
<th>STRAIN CAUSED BY MAGMATIC STOPING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Variable over meter scale</td>
<td>Parallel to regional foliation</td>
<td>Unrelated</td>
<td>Parallel to N-S or E-W margins</td>
<td>At high angle regional foliation</td>
</tr>
<tr>
<td>Type 2</td>
<td>Margin-parallel to nearby margins</td>
<td>Parallel to regional foliation</td>
<td>Parallel to N-S contacts</td>
<td>Parallel to N-S or E-W margins</td>
<td>At high angle regional foliation</td>
</tr>
<tr>
<td>Type 3</td>
<td>Steeply plunging (75°–90°)</td>
<td>Parallel to N-S or E-W margins</td>
<td>Parallel to N-S contacts</td>
<td>Parallel to N-S or E-W margins</td>
<td>At high angle regional foliation</td>
</tr>
<tr>
<td>Type 4</td>
<td>Steeply plunging (75°–90°)</td>
<td>Parallel to N-S or E-W margins</td>
<td>Parallel to N-S contacts</td>
<td>Parallel to N-S or E-W margins</td>
<td>At high angle regional foliation</td>
</tr>
</tbody>
</table>

Note: K<sub>C</sub>—Kuna Crest Granodiorite, K<sub>H</sub>—Half Dome Granodiorite, K<sub>C</sub,—Cathedral Peak Granodiorite, K<sub>J</sub>—Johnson Granite Porphyry.
magma flow (described above). Thus, we interpret the mineral alignment in the type 1 fabrics as largely having formed by strain resulting from highly localized flow along the margins of these structures, although they also may reflect other processes that operate in crystal-rich mushes (e.g., Weinberg, 2001; Table 1). The relative timing of these fabrics indicates that they formed in crystal-rich magmas (deeply dipping walls do not collapse or show mixing, and both accessory and felsic minerals physically accumulated during flow) during and after emplacement, but well before final crystallization of the chamber (matrix magmas in some cases intrude and break apart these local structures). These fabric patterns are clearly decoupled from host-rock structures and regional deformation. Type 1 fabrics are best preserved in mafic layers (Figs. 2C and 8A). It is commonly the case that a few centimeters away from mafic layers, the magmatic minerals become realigned parallel to one of the chamber-wide fabrics (Fig. 8A). We thus suggest that type 1 fabrics formed during local perturbation of magma flow, but as soon as the local perturbation slowed, crystals in felsic regions (with lower solidus temperatures) immediately reoriented in response to the chamber-wide strain field. If true, this implies that the magma chamber was already under either ~N-S or ~E-W contraction during formation of these structures, and that this regional strain field was temporarily overridden during localized magma flow.

2. Type 2 fabrics are represented by a foliation and steeply plunging lineation that are always parallel to nearby batholith-host-rock or internal contacts, regardless of the contact orientation (e.g., in the Kuna Crest lobe and the Glen Aulin area; Figs. 5, 6B, and 7; Table 1). The interpretation of the formation of this fabric is a bit problematic since several processes can cause margin-parallel mineral alignment (Paterson et al., 1998), including (1) expansion of a magma chamber; (2) convection within the magma chamber; (3) emplacement of inner magma batches or magma surges; (4) internal flow along margins or chamber walls; and/or (5) refraction of stress in a crystalizing magma chamber. We can directly rule out the first two explanations since we see neither evidence for expansion within the batholith nor in the host rock, and preserved widespread internal boundary zones in the Tuolumne batholith also argue against large-scale magma convection recorded by mineral fabrics. Therefore, the latter three internal processes, or a combination of those, are plausible explanations for the formation of the type 2 fabric. It is intriguing to view type 2 fabrics as a batholithic-scale version of type 1 fabrics, which are a result of local strain caused by flow of magma along rigid boundaries during ascent or emplacement.

3. Type 3 fabrics are represented by a typically ~NNW-SSE-striking foliation and a steeply plunging lineation (Table 1). Although the type 3 foliation is best developed in Kuna Crest and Half Dome Granodiorites, it is also observed in the inner parts of the Cathedral Peak Grano- diorite; however, it is less common to absent in the innermost Johnson Granite Porphyry. This type 3 magmatic foliation is parallel to the regional cleavage and has a similar orientation to the magmatic foliations in the nearby Soldier Lake and Green Lakes plutons and in other plutons elsewhere in the central Sierra Nevada (e.g., Paterson et al., 2003). These fabrics overprint all internal contacts. Therefore, this fabric appears to be coupled with regional processes (~NE-SW shortening), does not seem to be related to any of the chamber boundary processes, and probably represents increments of regional tectonic strain imposed on the already emplaced, but still crystallizing magma chamber.

4. Type 4 fabric is an ~E-W to NW-SE magmatic foliation associated with a steeply plunging lineation and is the most widespread because it is preserved in all intrusive units of the batholith (Figs. 3 and 4; Table 1). This foliation overprints internal contacts between intrusive units, locally overprints all other foliations, enclaves, sharp margins of stoned blocks, and magmatic sheets, and locally is associated with late host-rock structures. Hence, we believe it is highly unlikely that type 4 fabrics are related to chamber construction or other internally driven processes.

This fabric classification is based in part on chamber-wide patterns and overprinting relationships. In single exposures, the fabric is typically characterized by only one or at most two of the three chamber-wide foliations described here (types 2–4) and is almost always associated with the single, well-developed, steeply plunging mineral lineation (Figs. 3, 4, 5, and 6A). Thus, ambiguity in foliation designation can occur at a single exposure, particularly near margins, because the margin-parallel foliation can be subparallel to either the N-S (type 3) or E-W (type 4) chamber-wide foliations, depending on the orientation of the margin. The single, steeply plunging lineation, visible at most outcrops, is parallel to the steeply plunging axes of most schlieren tubes and is associated with all of the three chamber-wide magmatic fabrics (types 2–4). Therefore, it may record strain that occurred during formation of all four of the fabrics. If so, this single, steeply plunging magmatic lineation represents anywhere from one to several increments of vertical stretch, each caused by a different process, such as (1) local magma ascent (type 1 fabric); (2) vertical extension of older magma during formation of the type 2 fabric; (3) vertical extension during regional ~E-W contraction (type 3 fabric); and (4) vertical extension during ~N-S contraction or transpression (type 4 fabric).

Based on these observations, we propose that the chamber-wide magmatic fabrics in the Tuolumne batholith record the temporal evolution of a heterogeneous finite strain field (several superposed strain increments) imposed on the batholith during its magmatic history. The finite strain field is characterized by steep (subvertical) orientation of the maximum finite stretch represented by the steeply plunging magmatic lineation associated with the types 2–4 foliations (and parallel to long [x] axis of the finite strain ellipsoid). The axis of maximum finite shortening (c axis of the finite strain ellipsoid) and the intermediate axis (y) were subhorizontal (perpendicular to steep magmatic foliations of types 2–4) and variously rotated in response to strain increments through time (cf. Nokleberg and Kistler, 1980).

Our explanation for this is that individual magmatic minerals, presumably bound by melt films and small melt pockets, rotated parallel to the x-y and x-z planes of the finite strain ellipsoid to form a new foliation recorded by mineral fabrics (e.g., type 3 and type 4), and could do so with a relatively minor change in the relative amount of extension/shortening parallel to the y (intermediate) and z (short) axes of finite strain by a process of melt-aided grain-boundary sliding (Park and Means, 1996). Given that the overall degree of mineral alignment parallel to each foliation is not particularly high, large changes in the magnitude of strain along y or z are not required to form the two superposed foliations. In our view, the Tuolumne batholith represents a heterogeneously deformed body in which the amount of strain parallel to the y and z axes of the finite strain ellipsoid associated with the type 3 or 4 magmatic fabrics is close, and thus the importance and structural record of each direction (type 3 or type 4 fabric) may vary from one domain to another. These two fabrics may be, at least in some places, broadly contemporaneous, whereas in other places, they show clear overprinting relationships.

Summary of Fabric-Forming Processes in the Tuolumne Batholith

We propose the following hypotheses to explain magmatic fabric development in the Tuolumne batholith.

Type 1 fabrics formed diachronously throughout the batholith whenever magma locally flowed in variably shaped channels through what must
have been crystal-rich mushes. This local flow along more rigid boundaries resulted in velocity gradients that rotated crystals subparallel to channel margins. As the magma in the channels crystallized and/or channel flow deceased, other processes could begin to reorient any crystals still growing or not locked in.

We envision a similar process, but at a much larger scale, for the formation of the type 2 fabrics. Large-scale flow along internal margins (caused by emplacement of younger pulses or magma surges) resulted in flow gradients and strain that aligned crystals parallel to margins. Once this flow slowed or ceased, then other processes could begin to realign grains in these crystal mushes. We think it is likely that this chamber-wide flow at least partially overlapped with the local channel flow, since the two fabrics frequently have ambiguous timing relationships.

At the same time as these two local and chamber-wide flows were occurring, we suggest that the chamber was under a weak regional stress field, which resulted in slow strain of the chamber. Strain caused by local or chamber-wide flow would swamp this regional strain. But as flow slowed down or ceased, then regional strain would begin to realign crystals still bounded by melt in less mafic or younger magmas, or align growing crystals. This regional strain field was first dominated by ~ENE-WSW shortening and vertical extension and then dominated by ~NNE-SSW shortening and vertical extension. The switch in the orientation of the strain field may have occurred around the time that the Cathedral Peak Granodiorite was emplaced (88–86 Ma), since type 3 fabrics are more common in the older units and absent in the Johnson Granite Porphyry, and type 4 fabrics are best developed in the younger units.

The ~ENE-WSW shortening that resulted in the type 3 fabrics apparently began well before emplacement of the Tuolumne batholith, since we see identical fabric orientations in older plutons, and it probably contributed to regional strain in the host rocks. One possible explanation for the shortening that resulted in type 4 fabrics would be the regional transpressional strain associated with the large-scale dextral transpressional zones in the Sierra Nevada magmatic arc (Blanquart and Tikoff, 1997; Tikoff and Greene, 1997; Tikoff and Teysier, 1992; Greene and Schweickert, 1995; Tikoff et al., 2005; Titus et al., 2005). However, the type 4 fabrics are also compatible with coaxial ~N-S to ~NE-SW contraction recorded by some of the structures in nearby host rocks and ponds thought to form conjugate kinks in the Sierra Nevada (Tobisch and Fiske, 1976; Paterson, 1989; Economos et al., 2005). Similar ~NW-SE to ~WNW-ESE host-rock foliations (schistosities) and axial planes of dominantly developed folds were also reported by Nokleberg and Kistler (1980) from the Eastern Sierra pendants, and they were interpreted as a result of Cretaceous deformation superposed on earlier syn- to post-Neovadan ~NNW-SSE structures. Based on our study, we cannot yet rule out either of these two possibilities for type 4 fabric formation.

Another hypothesis that might be taken into account is that a single heterogeneous strain field existed during formation of both type 3 and type 4 fabrics, but it had variable magnitudes of strain parallel to the y and z axes of finite strain ellipsoid as suggested by Paterson et al. (2003). However, this hypothesis does not easily explain the regional and temporal pattern and transitions from one fabric into another, particularly as observed in the lobes extending out from the main batholith.

Chronology of Fabric Acquisition in the Tuolumne Batholith

The formation of the four magmatic fabrics in the Tuolumne batholith provides an intriguing example of the interplay between emplacement of successive batches of magma, magmatic fabric development, and the temporal evolution of strain fields in a crystallizing magma chamber. As noted earlier, the ages of pulses in the Tuolumne batholith are now well known and range from 93 Ma for the outermost units (Kuna Crest Granodiorite) to 85 Ma for the central Johnson Porphyry Granite. These U/Pb zircon ages decrease inward in the outer units, but are fairly tightly clustered in the Cathedral Peak unit (Coleman et al., 2004; Matzel et al., 2005).

Because of the low zirconium saturation temperatures in the Tuolumne batholith (J. Miller, 2006, personal commun.), the U/Pb zircon ages record an age which represents a time near the magma solidus, thus not necessarily a time when the magma was emplaced. Initial hornblende ⁴⁰Ar/³⁹Ar cooling ages indicate rapid cooling to below the solidus in this chamber, and the cooling times young inward (J. Matzel and P. Renne, 2006, personal commun.). These results indicate that fabric acquisition in the Tuolumne batholith was likely time transgressive, with outer units “freezing in” fabrics before inner units did.

The specific timing of fabric preservation at any single locality in a chamber likely occurs when the magma attains high crystallinity (perhaps more than ~70%–80%) in front of solidification fronts migrating through the chamber. However, we argue that in large batholiths the formation of the type 2 fabrics is best explained by melt in less mafic or younger magmas, or crystallization fronts migrating through the chamber. We think it is likely that this process began to reorient any crystals still growing or not locked in.

The specifc timing of fabric preservation at any single locality in a chamber likely occurs when the magma attains high crystallinity (perhaps more than ~70%–80%) in front of solidification fronts migrating through the chamber. However, we argue that in large batholiths the formation of the type 2 fabrics is best explained by melt in less mafic or younger magmas, or crystallization fronts migrating through the chamber. We think it is likely that this process began to reorient any crystals still growing or not locked in.
during solidification. (2) These fabrics are time transgressive and are the result of a uniform strain field that remained constant over the ~8 m.y. duration that it took to construct the Tuolumne batholith (Glazner et al., 2004). (3) The intrusion of the Cathedral Peak Granite could have remelted the earlier units enough (through the contact heating along with fluids derived from crystallization of the younger magma pulses) so that all units could have acquired the later chamber-wide fabrics together. In such scenario, the type 1 and 2 foliations could have been acquired in a time transgressive fashion in response to diachronous emplacement of each unit. In contrast, the type 3 and 4 fabrics could have been acquired late after emplacement of the Cathedral Peak Granite, which could have induced remelting in the outer units that were emplaced as much as 5 m.y. earlier.

However, all of these hypotheses have trouble accommodating all the observations for type 3 and 4 fabrics. Recall that at outcrop scale, when we find evidence of relative timing, type 4 fabrics always postdate type 3 fabrics. This observation would imply that the regional strain field changed from the time of type 3 fabric formation to type 4, which then would have to have occurred at least several times if these fabrics were time transgressive. Furthermore, observations from both within the main batholith and the lobes that extend away from the main chamber, which crystallized more rapidly, indicate that the relationships among all four fabrics are more complicated. There seems to be an evolution of type 2 fabric switching to type 3 and locally to type 4 in the 93–92 Ma Kuna Crest unit (see Kuna Crest lobe, Fig. 5), whereas the latter two fabrics outlast the Half Dome Granodiorites (92–88 Ma), and only type 4 fabric was still forming by the time the Johnson Granite Porphyry (ca. 85 Ma) crystallized. In slight contradiction to this general pattern, we see type 4 fabrics locally preserved in the outer Tuolumne batholith units.

If the remelting of the older units of the batholith by the Cathedral Peak Granite took place (alternative #3), field evidence for such (e.g., reinursion and melt remobilization and relocation textures, gradational [diffuse] transitions, exchange of melts and their mixing and mingling due to the reheating and melt remobilization) should be preserved, particularly along the Cathedral Peak–inner Half Dome Granodiorite contact, and evidence should decrease away from the contact. However, such field evidence for large-scale remelting of the older units by the intrusion of the Cathedral Peak Granodiorite has not been observed. Instead, the contact is sharp and discordantly cuts across structures in the older units (Żak and Paterson, 2005).

Given these complications, we do not believe that any simple model of fabric evolution in the Tuolumne batholith is likely to be correct.

Implications for Previous Interpretations of Fabrics in the Tuolumne Batholith

None of the previous fabric studies in the Tuolumne batholith recognized all four fabric types; thus it is somewhat problematic to compare results. However, our results contrast with those of Cloos (1936) because we recognize a foliation in the Johnson Porphyry granite, observe two foliations that overprint internal contacts, do not find magmatic foliations truncated along the Cathedral Peak contact, and interpret fabrics to represent late strain in the chamber caused by flow (type 1, 2) or regional strain (type 3, 4) rather than fabrics representing flow planes and directions. Bateman and Chappell (1979), and Bateman (1992) suggested that the strong margin-parallel foliation in the outer units (type 2 and locally type 3) formed as a result of emplacement of younger magma surges, and we agree that this is one possible cause of the type 2 fabrics. We also agree with these authors’ conclusions that a foliation (type 4) strikes diagonally across the Half Dome and Cathedral Peak Granodiorite and weakens in intensity inward and that two foliations are present in some outcrops. We further agree with Teruya and Miller (2000) that a margin-parallel (type 2) and an –E-W overprinting magmatic fabric (type 4) occur near the Half Dome and Cathedral Peak contacts near Tenaya Lake and that the latter fabric reflects regional strain superimposed on the former fabric, which was formed during internal processes.

Recently, Glazner et al. (2002, 2003, 2004) and Coleman et al. (2004, 2005) proposed that the outer units of the batholith were constructed through amalgamation of numerous discrete injections and evolved into a more texturally homogeneous body with time. They concluded that the Tuolumne batholith “began its life as a large dike swarm” (Glazner et al., 2002, p. 269) and that the Half Dome pluton accumulated as separate pulses that solidified between injections (Glazner et al., 2003). If true, this model has significant implications for the interpretation of magmatic fabrics in the Tuolumne batholith. Glazner et al. (2004) noted that magmatic fabric in the batholith “appears continuous in the field” and inferred that these fabrics are time transgressive and imply notably uniform strain associated with emplacement increments added at significantly different times (Glazner et al., 2004).

In contrast, our four fabrics would imply that the discrete injections (if they existed) stayed above the solidus long enough to allow (1) local flow of magma in channels through the dikes to form type 1 fabrics; (2) some process by which fabrics parallel to the batholith margin or major internal contacts (type 2) overprinted dike contacts and were consistently more intensely developed nearer than farther away from these main margins; and (3) all discrete pulses to be overprinted by two regional fabrics (type 3 and 4) that maintained approximately similar or gently varying orientations throughout the batholith. We see little to no evidence that the continuous, regional fabric patterns, overprinting relationships, and any of our four fabrics (types 1–4) preserve any record of incremental assembly of the Tuolumne batholith by many discrete pulses or dikes as presented by Coleman et al. (2004, 2005) and Glazner et al. (2002, 2003, 2004).

Implications for Fabric Studies in Plutons

It follows from this discussion that in contrast to the still popular view that magmatic fabrics are simple structures formed by a single process, magmatic foliations and lineations (1) always reflect finite strain and are subparallel to the x-y plane and x axis of the finite strain ellipsoid, respectively, (2) can be easily reset by small increments of younger strain, (3) may form as polyphase, composite structures recording multiple strain increments caused by remark-ably different processes, and (4) may form in relatively static (not flowing large distances) but still actively deforming (straining), crystal-rich mushes at low melt percentages (perhaps as low as 10%–20%) after construction of magma chambers. In the Tuolumne batholith, we suggest that the preserved batholith-wide fabrics record uncertain and ambiguous (type 2) or no (type 3 and 4) information about magma flow during ascent of magma or initial chamber construction, and that the only “emplacement” information recorded is about the regional strain field. Consequently, it may be rather problematic to infer the nature and kinematics of magma flow during pluton filling or even the fabric-forming causes from the preserved rock record.

In the Tuolumne batholith, examples of the challenges in determining the causes of fabric formation include (1) understanding the type 1 fabric, for which we cannot establish the exact nature of magma flow and/or the contribution of other processes, such as filter pressing, in forming this fabric; (2) recognizing type 2 and 3 fabrics along ~NNW-SSE contacts (e.g., eastern margin of the Tuolumne batholith; Fig. 4) and type 2 and 4 fabrics along ~WNW-SEE contacts (e.g., northern margin of the eastern bulging contact of the El Capitan Granite with the Tuolumne batholith; Fig. 3), which may result from either processes along margins or regional
It is thus important to look for cases where multiple magmatic fabrics exist or where different superimposed processes result in a single (composite) fabric. In the Tuolumne batholith, we were able to recognize the different fabrics and their relative timing by doing the following: (1) looking for different statistical maxima of mineral or enclave orientations at a single outcrop; (2) comparing enclave long-axis orientations to mineral fabrics in the enclaves to mineral fabrics in the matrix (Paterson et al., 2004); (3) looking for quadruple pronged enclaves and enclaves with bent tips (Paterson et al., 2003); (4) looking for overprinting relationships between fabrics and of fabrics relative to internal contacts, to xenoliths in the batholith, and to folded dikes; (5) examining batholith-wide patterns of different fabrics; and (6) determining if fabrics were coupled or decoupled from host-rock structures (Paterson et al., 1998).

We also note that composite fabrics and multiple fabrics, particularly those with the same orientation, are problematic to interpret using solely quantitative methods such as image analysis, electron backscatter diffraction (EBSD), and anisotropy of magnetic susceptibility (AMS). Given that magmatic fabrics may be complex structures recording increments of regional tectonic strain superimposed on relatively static already constructed magma chambers and may form in rheologically complex crystal-rich mushes at lower melt percentages, our study also calls in question the applicability of numerical and analogue modeling to explain and quantify fabric formation and strain in plutons. On the other hand, if the multiple fabrics are first recognized and carefully mapped, then quantitative studies of the gradients from domains dominated by one fabric to domains dominated by another may prove particularly valuable in understanding late increments of strain associated with each fabric. Correct interpretation of fabrics in a pluton thus requires observations at different scales and examination of field relationship of fabrics to other magmatic structures, particularly internal contacts between intrusive units.

Are multiple magmatic fabrics common in other plutons or is the Tuolumne batholith rather unique? Once we began looking for multiple magmatic fabrics, it is our experience that plutons commonly preserve a dominant fabric and in some cases also locally preserved a second fabric. The Tuolumne batholith case may be somewhat unique in that it is a long-lived system (8 m.y.), it is formed from multiple pulses, and none of the fabrics is particularly strong. Thus, it is possible that other plutons formed over much shorter durations and/or that older, weaker fabrics in these plutons were overprinted in cases where the preserved fabric is relatively strong. We also note that there may have been a change in the orientation of the regional strain field during construction of the Tuolumne batholith resulting in one additional fabric, and that chamber flow locally swamped the regional strain field and resulted in another fabric. Neither one of these latter two processes necessarily occurs in other plutons.

CONCLUSIONS

In the first example to date, four magmatic fabrics are described from a single batholith, which shows evidence that multiple magmatic fabrics can be preserved in a single magmatic body. In the Tuolumne batholith, one type of fabric formed by strain caused by highly localized magma flow (type 1), whereas the other three chamber-wide fabrics recorded strain increments during boundary processes along batholith margins (type 2) superimposed by increments of heterogeneous regional tectonic strain (type 3 and 4). There appears to be an evolution of type 2 fabric switching to type 3 and locally to type 4 in the 93–92 Ma Kuna Crest unit, whereas the latter two fabrics outlast the Half Dome Granodiorites (92–88 Ma), and only type 4 fabric was still forming by the time the Johnson Granite Porphyry (ca. 85 Ma) crystallized. Given these complications, we do not believe that any simple model of fabric evolution is likely to be correct.

In contrast to studies considering magmatic fabrics as simple structures formed by a single process, we emphasize that magmatic lineations and foliations in plutons reflect finite strain and may form as polyphase composite structures recording multiple strain increments. We have shown that multiple magmatic fabrics in a single batholith may record remarkably different processes and thus preserve a temporal record of heterogeneous strain in the batholith from strain during internal chamber processes to postemplacement regional tectonic strain. However, it may be commonly very problematic to infer the exact nature of flow or even fabric-forming process from the preserved rock record.

Our study exemplifies how examination of magmatic fabric patterns in plutons, when complemented with geochronology, may provide crucial constraints on the interplay among successive magma emplacement, fabric preservation, temporal evolution of strain fields in a crystallizing magma chamber, and the development of crystal-mush zones.

ACKNOWLEDGMENTS

We thank Associate Editor John Fletcher, Sven Morgan, and three other anonymous reviewers for their constructive reviews and valuable comments, which significantly improved the original manuscript. Robert Miller is acknowledged for discussions about the Tuolumne batholith. Vojtěch Janoušek is thanked for discussions on U/Pb zircon ages. We also thank the Yosemite National Park Rangers and particularly Ranger Michelle Woods for their constant support and interest in our research. This work was supported by a National Science Foundation grant EAR-0073943 (to Paterson) and by Czech Academy of Sciences grant no. KJB 3111403 (to Žák).

REFERENCES CITED


Chesterman, C.W., 1975, Geology of the Matterhorn Peak Quadrangle, Mono and Tuolumne Counties, California: California Division of Mines, Map Sheet 22.

Christian, E.H., 2005, Contrasting processes in silicic magma chambers: Evidence from very large magma

Christiansen, E.H., 2005, Contrasting processes in silicic magma chambers: Evidence from very large magma

Žák et al.
Four magmatic fabrics in the Tuolumne batholith


