Spring 2013

Structure, Construction, and Emplacement of the Yosemite Valley Intrusive Suite and the Yosemite Creek Granodiorite in the Central Sierra Nevada Batholith

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DOI: <https://doi.org/10.31979/etd.wtyy-e7z3>
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STRUCTURE, CONSTRUCTION, AND EMPLACEMENT OF THE YOSEMITE VALLEY
INTRUSIVE SUITE AND THE YOSEMITE CREEK GRANODIORITE IN THE CENTRAL SIERRA
NEVADA BATHOLITH

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

by

Brendon L. Johnson

May 2013

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The Designated Thesis Committee Approves the Thesis Titled
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May 2013

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ABSTRACT

STRUCTURE, CONSTRUCTION, AND EMPLACEMENT OF THE YOSEMITE VALLEY INTRUSIVE SUITE AND THE YOSEMITE CREEK GRANODIORITE IN THE CENTRAL SIERRA NEVADA BATHOLITH

By Brendon Johnson

The 103-98 Ma El Capitan and Taft granites and the ~97 Ma Yosemite Creek Granodiorite intrude plutonic and metasedimentary rocks in the central Sierra Nevada batholith. The El Capitan Granite and Yosemite Creek Granodiorite are divided in this study into several texturally and compositionally distinct units, whereas the Taft Granite is relatively homogeneous. Injection of a few large increments of magma or many increments intruded close in time probably formed small (2 km^3) to large ($\geq 20 \text{ km}^3$ for Taft Granite) chambers in the Yosemite Valley Suite and parts of the Yosemite Creek Granodiorite. Units of the Yosemite Creek Granodiorite that intruded as steep, narrow sheets probably solidified shortly after intrusion. Emplacement of Yosemite Creek magmas was facilitated by wedging aside of host rock, stoping, and possibly ductile flow. The plutons have steep, dominantly NE-striking magmatic foliations, some of which are discordant to contacts and record regional strain that contrasts with the regional strain field interpreted from plate kinematics. The major Mt. Hoffman shear zone comprises thousands of narrow (meter-scale) NE-striking, reverse-slip ductile shear zones that deformed the eastern part of the El Capitan Granite prior to intrusion of the Taft Granite. Other sizable solid-state shear zones of this age in the region strike NW, and thus the regional strain field was likely heterogeneous from 103-98 Ma.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the help of several people. My wife Jamie Clay Johnson was essential, assisting me in the field for three weeks, providing invaluable editing advice, and letting me know when my ideas were just too 'creative'. Ryan McKee, Zach Michels, and Joe Petsche were also great field assistants, and I thank them sincerely for their time. Thanks to the National Park Service for allowing me to conduct research in Yosemite National Park without difficulty and the San Jose State University Geology department for supporting me. My committee members Jonathan Miller and Ellen Metzger were very helpful in guiding me onto the right track research-wise. Finally, I would like to extend my utmost thanks to my advisor Robert Miller, who mentored me in performing this research and helped me hone my writing skills.

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INTRODUCTION

Granitoid plutons record information useful for elucidating the magmatic and tectonic evolution of magmatic arcs. Despite many recent advances, the construction and emplacement of granitoid plutons remain controversial topics. Much research suggests that plutons, such as those in the Sierra Nevada batholith, are constructed incrementally (e.g., Pitcher and Berger, 1972; Wiebe and Collins, 1998; Brown and McClelland, 2000; Miller and Paterson, 2001; Glazner et al., 2004; Matzel et al., 2006; Zak et al. 2007; Annen, 2009) on timescales of thousands (e.g., Michel et al., 2008) to millions of years (e.g., Coleman et al., 2004); however, the number and size of increments that make up a pluton, the amount of time elapsed between each increment, and the presence and size of a magma chamber at any one time during construction are contentious. In this study, a magma chamber is defined as an area in the crust with mobile, eruptible magma (e.g., Bachmann and Bergantz, 2004; Glazner et al., 2004; Bachmann and Bergantz, 2008; Miller et al., 2011). Many (e.g., Clemens and Mawer, 1992; Paterson and Vernon, 1995; Clarke and Clarke, 1998; Wiebe and Collins, 1998; Barbey et al., 2008; Paterson et al., 2011) offer that plutons are assembled by increments intruded close enough in time to create a steady-state magma chamber. In this scenario, the flow of magma can generate features such as schlieren (e.g., Komar, 1972; Barriere, 1981) and other magmatic structures (e.g., Clarke and Clarke, 1998; Weinberg et al., 2001; Paterson et al., 2009), and chemical diversity may be produced by

magma mixing and crystal fractionation at the site of construction, and/or by magma mixing and compositional variation in magmas supplied from the source region.

Dynamic processes may homogenize magma within the chamber and obscure internal contacts (e.g., Bergantz, 2000). In many cases, it may be difficult to differentiate between processes constructing magma chambers because of the multiple processes operating at the level of emplacement.

In an alternative model, plutons are constructed by small batches of magma that are separated sufficiently long enough in time that an active magma chamber rarely forms (e.g., Coleman et al., 2004; Glazner et al., 2004). According to Coleman et al. (2004) and Johnson and Glazner (2010), thermal annealing may obscure internal contacts, and chemical heterogeneities in plutons are acquired at the source of magmatism and not at the final location of construction (Reid et al., 1993). In plutons constructed in this fashion, it is hypothesized that features such as schlieren form by variations in chemical diffusion rates and/or periodic supersaturation and nucleation of different mineral phases (Boudreau, 1995; Boudreau et al., 1997; Bartley et al., 2009).

Many of the processes involved in accommodating magma may do so without necessarily changing crustal volume (e.g., Paterson and Vernon, 1995). These material transfer processes include ductile flow, stoping, assimilation, floor subsidence, magmatic wedging, and extension. Some processes, such as roof uplift, are capable of changing the volume of the crust. In most cases, pluton emplacement requires multiple processes operating at different rates, times, and scales (e.g., Paterson et al., 1996;

McNulty et al., 2000; Zak and Paterson, 2005; Yoshinobu et al., 2009; Saint Blanquat et al., 2011).

Addressing the magmatic and tectonic evolution of magmatic arcs with respect to the models and processes discussed above is facilitated by a well-exposed plutonic system. The Cretaceous Yosemite Creek Granodiorite and the plutons that comprise the Yosemite Valley Intrusive Suite of the central Sierra Nevada batholith provide an excellent natural laboratory to study the construction of plutons and the material transfer processes accompanying emplacement. Access, exposure, and topographic relief are excellent, allowing for detailed mapping and interpretation of contact relationships and internal structures.

Geologic Setting

The Mesozoic Sierra Nevada batholith is an almost continuous expanse of arc plutonic rocks that lies west of the North American craton, and extends NW-SE for ~640 km (Bateman, 1992). Many contributions in pluton research have focused on the central Sierra Nevada batholith in part due to excellent exposure and ease of access. In particular, the 94-86 Ma Tuolumne Intrusive Suite (Fig. 1) has received much study (e.g., Calkins, 1930; Bateman and Chappell, 1979; Kistler et al., 1986; Coleman et al., 2004; Zak et al., 2007; Paterson, 2009; Memeti et al., 2010b). Compared to the

Figure 1. The central Sierra Nevada batholith. Filled box shows location of the study area. Yosemite Valley Intrusive Suite – YVIS. Modified from Huber et al. (1989).

Tuolumne suite, little research has focused on the adjacent older plutonic and metasedimentary rocks to the west. This study focuses on these older rocks.

Metasedimentary rocks occur as isolated bodies within the Yosemite Valley Intrusive Suite and crop out along the contact between this suite and the Tuolumne Intrusive Suite (Fig. 1). In the study area, metasedimentary rocks include quartzite, calc-silicate hornfels, biotite schist, and marble. These rocks are compositionally similar to the relatively large May Lake pendant, which borders the SE corner of the study area (Plate 1), and probably correlate to rocks in the Snow Lake pendant ~15 km to the north (Fig. 1) because the May Lake and Snow Lake pendants are similar (Lahren and Schweikert, 1989). Protoliths of the Snow Lake pendant are thought to correlate with Cambrian rocks from the Mojave Desert region, or southern Sierra Nevada, and to have been translated northwards by 200-400 km of dextral displacement between 148 Ma and 102 Ma on the Mojave-Snow Lake fault (Lahren and Schweikert, 1989; Grasse et al., 2001; Thompson et al., 2007; Memeti et al., 2010a).

The 103-100 Ma (Stern et al., 1981; Ratajeski et al., 2001; Taylor, 2004) Yosemite Valley Intrusive Suite is comprised of the El Capitan and Taft granites. In the study area, I subdivided the El Capitan Granite into the granodiorites of Mt. Hoffman and Double Rock, and equigranular and medium-grained El Capitan Granite. The Yosemite Valley Intrusive Suite intruded during a period of high-flux magmatism (Coleman and Glazner, 1997; Ducea, 2001) into the 121-105 Ma Fine Gold Intrusive Suite and metasedimentary rocks, including the pendants discussed above (Bateman, 1992; Lackey et al., 2012).

Currently cropping out over $\sim 500 \text{ km}^2$, the Yosemite Valley Intrusive Suite was probably significantly larger, possibly on the order of 1000 km^2 or more, before removal by younger intrusions to the east, north, and south (Fig. 1). Previous research on the suite has focused on the Yosemite Valley area (Ratajeski, 1999; Ratajeski et al., 2001, 2005) and farther south (Karpowicz, 2004; McFarlan, 2007). Little research on the construction, emplacement, and structure of the suite has taken place to north of the Yosemite Valley area, with the exception of information reported on geologic maps by Kistler (1973) and Bateman et al. (1983) and reconnaissance in theses by Taylor (2004) and Petsche (2008).

The Yosemite Valley Intrusive Suite and metasedimentary rocks were intruded by the 98-97 Ma Yosemite Creek Granodiorite (Burgess et al., 2009). In this study, the granodiorite was subdivided into five units that range from equigranular hornblende diorite to porphyritic biotite granodiorite. Aside from geologic maps by Kistler (1973) and Bateman et al. (1983) and a brief description by Bateman (1992), little geologic work has been completed on the Yosemite Creek Granodiorite until recently. Petsche (2008) and Fulmer and Kruijer (2009), working SW of the study area, provide limited reconnaissance on the southern portion of the Yosemite Creek Granodiorite.

The map-scale, NW-striking, 98-87 Ma Quartz Mountain (Tong, 1994; Tobisch et al., 1995), 95-90 Ma Bench Canyon (McNulty, 1995; Titus et al., 2005), and ~ 88 Ma Cascade Lake (Tikoff et al., 2005) shear zones deform parts of the east-central Sierra Nevada batholith (Fig. 1), but shear zones have not been previously mapped in the study

area. Near the map area, localized zones of ductile shear occur in the El Capitan Granite and neighboring 93 Ma Kuna Crest Granodiorite of the Tuolumne Intrusive Suite (Kistler, 1973).

Methods

This thesis concentrates on investigating the structure of the Yosemite Valley Intrusive Suite, Yosemite Creek Granodiorite, and adjacent metasedimentary rocks to supplement ongoing efforts to understand the construction and emplacement of plutons, particularly those in the Sierra Nevada batholith. Mapping at a 1:24,000 scale over a 55 km² area was performed to resolve the geological relationships in more detail than done by previous work (1:62,500 scale) (Kistler, 1973; Bateman et al., 1983). Foliations and lineations were measured and their patterns were used to determine if these structures formed dominantly by regional strain or internal magmatic processes. Magmatic features such as schlieren, enclaves, and internal contacts were studied to understand the dynamics of the magmatic systems. Contacts were examined in detail to help evaluate material transfer processes during emplacement. Thin sections of each unit were analyzed for approximate mode, texture, and microstructures. Analysis of ductile shear zones allowed elucidation of kinematics and temperatures of solid-state deformation.

ROCK UNITS

Metasedimentary Rocks

Metasedimentary rocks occur in four small isolated bodies in the eastern part of the study area where they are enclosed by the El Capitan Granite and Yosemite Creek Granodiorite (Plate 1). These bodies have steep sides, are elongate with long axes trending N-NNE, and are comprised of quartzite, biotite schist, and calc-silicate rock. Two bodies of marble occur in the SE part of the map area.

The largest metasedimentary body is a pendant located in the NE part of the study area, herein named the Tuolumne Peak pendant (Plate 1). The pendant is $\sim 1 \text{ km}^2$ in area and is surrounded by equigranular El Capitan Granite, except on the north where the pendant is intruded by the granodiorite of Mt. Hoffman. A steeply dipping, N-NNE striking foliation defined by biotite is developed in all rocks in the pendant. Interlayered massive quartzite and biotite schist dominate; quartzite is locally interlayered with calc-silicate rock. Layers of quartzite range from 1-30 m in thickness and in places can be traced for >200 m. Diffuse, discontinuous biotite layers in the quartzite are 1-10 mm thick. More continuous biotite schist forms layers that are 1 cm->10 m in thickness and extend for <1-30 m. Calc-silicate rock forms discontinuous layers that are 1 cm-10 m thick; rare boudins of calc-silicate rock are surrounded by quartzite (Fig. 2). A few tight, steeply plunging outcrop-scale folds deform the biotite schist.

Figure 2. Boudins of calc-silicate rock in quartzite. Outcrop face is sub-vertical, hammer is 28 cm long. Dark minerals are clinopyroxene. Some boudin ends are tapered.

The elongate, $\sim 0.25 \text{ km}^2$ body in the southern part of the map area (Plate 1), separates the coarse- and medium-grained units of the Yosemite Creek Granodiorite, herein named the Yosemite Creek pendant. It is composed of interlayered quartzite ($\sim 60\%$) and biotite schist ($\sim 40\%$) (Fig. 3). Quartzite and schist layers have thicknesses similar to those in the Tuolumne Peak pendant. Foliation in the metasedimentary rocks strikes N to NNE, dips steeply, and is parallel to most contacts with the Yosemite Creek

Figure 3. Biotite schist boudin in quartzite matrix. Outcrop is sub-horizontal, field book is 19 cm in length.

Granodiorite and to foliation in the Tuolumne Peak pendant. Abundant xenoliths of biotite schist and quartzite are enclosed by the coarse-grained Yosemite Creek Granodiorite within 50 m of the pendant. The majority of these xenoliths have aspect ratios of $\sim 3:1$. Most xenoliths are irregularly shaped, range in size from <1 cm in diameter to 2 m by 3 m in map view, and have similarly oriented foliations. Sheets of porphyritic Yosemite Creek Granodiorite that are 1-20-m wide intrude the pendant interior and enclose xenoliths that are <1 m² in map view.

Two elongate bodies of marble with massive outcrop character crop out in the eastern part of the study area. Equigranular El Capitan Granite intrudes a ~ 0.25 km²

body and the Mt. Hoffman granodiorite intrudes a smaller body to the north (Plate 1). Marble is comprised of equant, euhedral crystals that are 1 mm-1 cm in length. A 1.5-m-wide zone of garnet-epidote skarn formed along the southwest contact of the southern body.

Quartzite and biotite schist in the study area probably correlate to the quartzite and impure quartzite members, respectively, of the May Lake pendant (Taylor, 2004). Quartzite is composed of 90-95% quartz grains with irregularly shaped grain boundaries and abundant subgrains. Anhedral K-feldspar, biotite, and plagioclase are included in the quartz and comprise 5-10% of the quartzite. Biotite schist commonly has compositional layering that is parallel to foliation, and is defined by alternating fine-grained quartzo-feldspathic layers that are ~6 mm thick and medium- to fine-grained biotite- and muscovite-rich layers that are ~6 mm to >1 m thick (Fig. 4). Quartzo-feldspathic layers host polygonal mosaics of quartz, plagioclase, and K-feldspar, whereas biotite-rich layers host recrystallized biotite and few polygonal mosaics. The schist consists of 15-25% quartz, 15-25% plagioclase, and up to 5% K-feldspar as round grains that are 0.1-0.3 mm in diameter. Biotite and muscovite are 0.2-1 mm long and make up 30-40% and 5-10%, respectively, of the schist. In one sample, anhedral andalusite porphyroblasts up to 1 cm in diameter compose as much as 25% of the schist and have abundant inclusions of quartz (Fig. 4). Equant opaque oxides comprise 3-5% of the schist.

Andalusite

Figure 4. Photomicrographs of compositional layers in biotite schist. Photomicrographs taken under cross-polars. (A.) Quartzo-feldspathic layer. (B.) Biotite- and muscovite-rich layer. Box in (B.) shows andalusite with quartz inclusions.

Calc-silicate rocks are foliated and strongly recrystallized; most grains are ≤ 1 mm in diameter. Widespread layering is defined by layers of very fine-grained quartz and feldspar that are up to 5 mm in thickness alternating with coarser-grained diopside-rich layers that are up to 2 mm in thickness (Fig. 5). Modes of the sample examined in thin section are 50-55% diopside, 20-25% plagioclase, 15-20% quartz, 5% epidote, 2% chlorite, and <1% zircon. Weakly developed porphyroclastic texture is marked by diopside crystals up to 2.5 mm in diameter and set in a matrix of quartz and plagioclase.

Figure 5. Compositional and grain-size layers in calc-silicate rock. Coarser-grained layers contain more clinopyroxene. Photomicrograph is under cross-polars.

Yosemite Valley Intrusive Suite

The El Capitan and Taft granites comprise the Yosemite Valley Intrusive Suite (Bateman, 1992). This suite intrudes the metasedimentary rocks described above and older plutonic rocks to the west (Fig. 1) (Huber et al, 1989).

El Capitan Granite

The 103-102 Ma (Stern et al., 1981; Ratajeski et al., 2001; Taylor, 2004) El Capitan Granite makes up ~80% of the Yosemite Valley Intrusive Suite and the majority of outcrop in the study area. Huber et al. (1989) assigned many 103-102 Ma plutons (e.g., granodiorites of Double Rock, Mt. Hoffman, Harriet Lake, etc.) located throughout Yosemite National Park to the El Capitan Granite. In this study, the El Capitan Granite has been subdivided into the granodiorites of Mt. Hoffman and Double Rock following Kistler (1973) and the newly named equigranular El Capitan Granite and medium-grained El Capitan Granite (Plate 1). Throughout this thesis, the granodiorites of Mt. Hoffman and Double Rock will be referred to as the Mt. Hoffman and Double Rock granodiorites for simplicity.

In the study area, the El Capitan Granite ranges from K-feldspar phyric porphyritic granodiorite to medium-grained granite and has a color index of ~10, contrasting with a value of ~7 estimated by Bateman (1992) for the entire El Capitan

Granite (diagnostic criteria for major units in the study area shown in Table 1).

Hornblende constitutes a low percentage of the mode, in contrast to the El Capitan Granite near Yosemite Valley (e.g., Ratajeski et al., 2001), which is nearly devoid of hornblende. Schlieren and enclaves occur locally.

Most units comprising the El Capitan Granite are not radiometrically dated. The Mt. Hoffman granodiorite yielded a U-Pb zircon date of 102.7 ± 0.3 Ma (Taylor, 2004). Taylor (2004) inferred that the equigranular granite described here is ~ 103 Ma, because it is similar to the ~ 103 Ma El Capitan Granite in Yosemite Valley studied by Ratajeski et al. (2001). Relative age relations of some units can be reasonably interpreted. The equigranular El Capitan Granite contains xenoliths of the Mt. Hoffman granodiorite, and medium-grained El Capitan Granite intrudes the Mt. Hoffman granodiorite and equigranular El Capitan Granite. Double Rock granodiorite is not in contact with other El Capitan units in the study area, and its age relative to these other rocks is uncertain.

Magmatic foliation in all units of the El Capitan Granite is dominantly NE-striking, steeply dipping, and defined by biotite, hornblende, and plagioclase. Locally, in the Mt. Hoffman granodiorite, coarse-grained euhedral K-feldspar crystals are aligned parallel to the NE-striking foliation. Magmatic lineation trends variably, plunges steeply, and is best defined by biotite and hornblende. Foliation and lineation intensities are generally consistent throughout the El Capitan Granite, except in the Mt. Hoffman shear zone (see description of Mt. Hoffman Granodiorite below) and within 3 m of some metasedimentary contacts. Local solid-state foliation and lineation are defined by

Table 1. Diagnostic criteria for differentiating units and sub units in the study area. Units arranged in order of relative age.

Suite	Unit	Sub unit	Distinguishing characteristics
Yosemite Valley Intrusive Suite			
	<i>El Capitan Granite</i>		
		Mt. Hoffman granodiorite	Porphyritic, with elongate K-spar phenocrysts. Hornblende occurs locally. Schlieren, other magmatic structures and ductile shear zones are most common in this unit.
		Equigranular	Similar mineralogy to the Mt. Hoffman granodiorite, but lacks phenocrysts. Xenoliths of Mt. Hoffman granodiorite occur locally. Deformed locally, but to a lesser extent than the Mt. Hoffman granodiorite.
		Double Rock Granodiorite	Higher color index than the other Yosemite Valley Intrusive Suite rocks. Commonly has hornblende.
		Medium-grained	Intrudes as small masses into other units of the El Capitan Granite.
	<i>Taft Granite</i>		Low color index, commonly <5. Magmatic structures such as schlieren and enclaves and solid-state deformation are very rare.
	<i>Yosemite Creek Granodiorite</i>		
		Coarse-grained	Coarser grained than other Yosemite Creek Granodiorite rocks. Enclaves are highly oblate or elongate.
		Medium-grained	Medium-grained texture, commonly mingled with the mafic unit. Intrudes the coarse-grained unit and mingled with the mafic unit.
		Mafic	Much higher color index than the other units. Mingled with the medium-grained unit.
		Porphyritic	Commonly has a porphyritic texture. Schlieren occur locally along contacts. Dioritic enclaves common. Sphene composes >1% of the mode. Intrudes the coarse, medium-grained, and mafic units.
		Tonalitic	Higher mode (>50%) of plagioclase than other sub-units. Few enclaves, many xenoliths. Intrudes the medium-grained unit.

biotite and quartz.

Mt. Hoffman Granodiorite. The 102.7 ± 0.3 Ma Mt. Hoffman granodiorite (Taylor, 2004) is a coarse-grained, porphyritic granite to granodiorite exposed in the eastern part of the study area. The granodiorite is ~3 km wide and extends for >5 km in the map area. It has a color index ranging from 5-20.

The Mt. Hoffman granodiorite is distinguished by subhedral to euhedral K-feldspar phenocrysts reaching up to 4 cm in length that comprise 20-40% of the granodiorite. The phenocrysts enclose biotite, hornblende, and plagioclase. Anhedral quartz is 1-6 mm in diameter and 10-40% in modal abundance; it locally encloses hornblende. Tabular, subhedral plagioclase is 1-6 mm long and makes up 10-15% of the granodiorite; 1-5% is part of myrmekitic intergrowths. Normal zoning is common, and oscillatory zoning occurs locally. Up to 15% of the rock is composed of subhedral hornblende that is 1-4 mm in length. Subhedral biotite is 0.25-1.5 mm long and comprises up to 15% of the rock. Secondary sphene after biotite and hornblende averages ~1% of the granodiorite, and locally reaches 8%. Allantite, zircon, apatite, and secondary epidote are present in trace amounts.

In one locale, Mt. Hoffman granodiorite next to the Tuolumne Peak pendant was probably metasomatized. This interpretation is made on the basis of abundant garnet (10-15%), sphene (8%), and diopside (20-25%).

Masses of fine-grained diorite up to 0.3 by 1 km are enclosed by the granodiorite

~2 km WNW of Mt. Hoffman (Plate 1, Fig. 6). A 2-m-wide zone between the two rock types is marked by abundant enclaves and by K-feldspar and plagioclase phenocrysts in the diorite. These phenocrysts are absent in the interior of the diorite and were probably derived from the granodiorite and incorporated during magma mingling, implying that the two magmas were coeval. In the Yosemite Valley area, granitic and dioritic rocks are also mingled in the El Capitan Granite (Ratajeski et al., 2001, 2005).

Hundreds of schlieren are developed within 1 km of the eastern boundary of the Mt. Hoffman granodiorite. Schlieren dip steeply, are <2 m thick, extend for 1-70 m, and are rhythmic (Fig. 7). Most schlieren are planar to crescent shaped and have sharp contacts between each successive schliere. Cross-cutting relationships and mineral grading (Fig. 7) indicate that schlieren young to the SE. Fabrics defined by minerals in the schlieren are NE-striking, consistent with the dominant magmatic foliation in the study area. Enclaves are absent in the schlieren-rich domain, but abruptly appear 1 km west of the contact with the Tuolumne Intrusive Suite.

A variety of magmatic features occurs on the crest of the ridge between Mt. Hoffman and Tuolumne Peak. Hundreds of alternating mafic and felsic layers, which are 1-3-cm thick and extend for 10-30 cm (Fig. 8), are in contact with schlieren (Fig. 9). The mafic and felsic layers are differentiated from schlieren by a lower aspect ratio and higher concentration of fine-grained mafic minerals. These layers occur in a folded tabular body that is 3 m by 20 m in map view. The mafic and felsic layers trend roughly

Figure 6. Mingling between Mt. Hoffman granodiorite and diorite. Pencil for scale.

Figure 7. Schlieren in Mt. Hoffman granodiorite. Pencil is 14 cm long and points SE (towards bottom of figure). Cross-cutting relationships suggest schlieren young to the SE.

Figure 8. Alternating felsic and mafic layers in Mt. Hoffman granodiorite. These layers resemble the ridge and pillar structures of Zak et al. (2005, 2009). Arrow points SE; pencil next to arrow is 14 cm long.

perpendicular to the long axis of the tabular body and resemble the ridge and pillar structures of Zak and Paterson (2005) and Zak et al. (2009). Fold wavelengths vary from 0.5-4 m and axial planes are oriented $212/80^{\circ}$ NW, sub-parallel to the strike of the dominant regional magmatic foliation.

Figure 9. Ridge and pillar structures in contact with schlieren. This is the same locality as Fig. 8. Marker for scale is 14 cm long and points SE.

Steeply plunging, oval-shaped tubes (Fig. 10) and wavy, sub-circular (on sub-horizontal faces) chaotic schlieren (Fig. 11) occur near the folded ridge and pillar structures. Mafic minerals comprising the margins of these tubes lack a preferred orientation. In chaotic schlieren, grains are concordant to the NE-striking foliation in places, and parallel to schlieren boundaries in others. Some chaotic schlieren are truncated by one another (Fig. 11).

Aplite and pegmatite dikes with sharp, straight boundaries intrude the Mt. Hoffman granodiorite. Dikes range from 3 cm-1 m in width and extend for 1->150 m. Some aplite dikes are cored by pegmatite or vice versa. Dikes commonly strike N-S and dip variably (see Structure of the Study Area, p. 48).

Thousands of NE-striking, steeply dipping, reverse-slip ductile shear zones deform the Mt. Hoffman granodiorite in a 1-2-km-wide zone extending for >5 km, referred to as the Mt. Hoffman shear zone (Fig. 12). Most rocks in the shear zone have a porphyroclastic texture defined by K-feldspar and quartz porphyroclasts up to 2 cm in diameter set in a matrix of recrystallized biotite, hornblende, quartz, and plagioclase (Fig. 13). Quartz forms rare ribbons up to 6 mm long and, in places, an oblique fabric. Pockets of polygonal mosaics of K-feldspar, plagioclase, and quartz are common.

Figure 10. Oval-shaped tube in Mt Hoffman granodiorite. Pencil points NE, parallel to the foliation inside and outside of the tube.

Figure 11. Chaotic schlieren in Mt. Hoffman granodiorite. Parts of these schlieren resemble deformed tubes. Marker (center of photo) points NE (right), parallel to foliation.

Figure 12. Mt. Hoffman shear zone and eastern portion of the study area. Wavy foliation symbols indicate outcrop-scale ductile shear zones dipping $>60^\circ$. Cross-hatched area represents area deformed by abundant shear zones.

Figure 13. Mt. Hoffman granodiorite in the Mt. Hoffman shear zone. Note porphyroclastic texture and zoning in plagioclase. Recrystallized groundmass is composed of K-feldspar, biotite, hornblende, quartz, and plagioclase. Photomicrograph is under cross-polars.

Double Rock Granodiorite. The Double Rock granodiorite (Kistler, 1973) occurs in the western part of the study area (Plate 1). Larger masses of the granodiorite have dimensions ranging from 1 by 1 km to 3 by 15 km and crop out several km northwest of the map area (Kistler, 1973). The equigranular, enclave-bearing granodiorite has a color index ranging from 10-25, and is higher on average than that of other units of the El Capitan Granite.

Subhedral, tabular plagioclase is 1-4 mm long, and comprises 45-50% of the Double Rock granodiorite; myrmekitic texture is common. Normal zoning in plagioclase is common and better developed than in other members of El Capitan Granite. Interstitial quartz has a modal abundance of 20-25%. Grains are typically 2-4 mm in diameter, and rarely reach 1 cm. Anhedral K-feldspar is 1-4 mm long and makes up 10-15% of the granodiorite. Biotite, hornblende, sphene, and allanite form aggregates distributed throughout the rock. Grains of chloritized biotite are 0.5-1.5 mm in length and make up 5-15% of the mode. Tabular, subhedral hornblende is typically 2-3 mm long and has a modal abundance of 5-10%. Trace minerals include secondary sphene after hornblende, allanite, and zircon.

Equigranular El Capitan Granite. The equigranular El Capitan Granite contains xenoliths of Mt. Hoffman granodiorite, and intrudes the Tuolumne Peak pendant and one of the marble bodies (Plate 1). This enclave-bearing granite has a color index

ranging from 5-15 and forms large, irregularly shaped masses that are >1 km in length.

The Mt. Hoffman shear zone deforms roughly half of the equigranular granite (Fig. 12).

Anhedral quartz is 2-6 mm in diameter, comprising 20-35% of the equigranular granite. Subgrains in quartz are common and many are elongate. K-feldspar composes 20-40% of the rock and is 0.4-1 cm in length; inclusions of biotite, plagioclase, and quartz are common. Tabular plagioclase is 1-5 mm long, makes up 15-40% of the granite, and is commonly in contact with myrmekite. Plagioclase has poorly developed normal zoning and rare oscillatory zoning. Biotite forms 1-2-mm-long grains that make up 5-15% of the mode. Up to 5% of the granite is composed of subhedral hornblende that is 0.5-2 mm in length. Trace minerals include allanite and zircon, and secondary epidote and sphene.

Within the Mt. Hoffman shear zone, the rock is locally porphyroclastic.

Porphyroclasts of quartz and K-feldspar are set in a recrystallized matrix of quartz, plagioclase, and biotite. Quartz, K-feldspar, and plagioclase grains that are 0.01-0.08 mm in diameter commonly form equant mosaics with polygonal grain boundaries (Fig. 14).

Medium-grained El Capitan Granite. Medium-grained El Capitan Granite is equigranular to porphyritic and has a color index of ~5. The granite intrudes the Mt. Hoffman granodiorite and equigranular El Capitan Granite, and truncates outcrop-scale ductile shear zones in the Mt. Hoffman shear zone. It forms discordant bifurcating

bodies that are approximately 3 by 15 m in map view (Plate 1). The granodiorite North of Tuolumne Peak is texturally similar, has less K-feldspar, and an unknown age relation.

Figure 14. Mosaic texture in equigranular El Capitan Granite. Recrystallized mosaics are composed of K-feldspar, plagioclase, biotite, and quartz. Photomicrograph is under cross-polars.

Taft Granite

The poorly dated, 102-98 Ma (Stern et al., 1981; Ratajeski et al., 2001) Taft Granite is a homogeneous, coarse-grained leucogranite with a color index of 2-7. The El Capitan Granite and the Yosemite Creek Granodiorite bracket the age of the Taft Granite based on the intrusive relationships of the units. Following Huber et al. (1989), the

Alaskite of the Ten Lakes of Kistler (1973) and the Ten Lakes Leucogranite of Bateman et al. (1983) are included in the Taft Granite. The granite appears in the field area as bodies that are mostly ~1 km across (Plate 1) and as xenoliths in the Yosemite Creek Granodiorite.

Taft Granite in the study area is only rarely mingled with mafic magmas, in contrast to the bodies of granite to the south near Yosemite Valley (Ratajeski et al., 2001; Coleman et al., 2005; McFarlan, 2007). Schlieren, enclaves, and mafic dikes are found locally in the northern part of the study area. Internal contacts and aplite and pegmatite dikes were not observed.

Magmatic foliation and lineation are weak and difficult to discern due to the dearth of mafic minerals. Foliation dominantly strikes NE and dips steeply ($>60^\circ$); steep NW-striking foliation characterizes the western portion of the field area (see Structure of the Study Area, p. 43). Magmatic lineation plunges steeply and generally trends SW. Steeply dipping, NE-striking, solid-state foliation defined by elongate quartz grains and aggregates occurs in the northern part of the map area.

K-feldspar comprises up to 50% of the mode as anhedral to subhedral orthoclase (20-45%) grains that are 2-5 mm in length. Microcline forms interstitial grains that are 1-2 mm in diameter and compose 5-15% of the mode. Simple twins, perthitic texture, and inclusions of biotite and plagioclase are common in both types of K-feldspar. Interstitial quartz composes 30-40% of the granite; grains are 1-6 mm in diameter and include biotite, plagioclase, and K-feldspar. Rectangular “chessboard” subgrains are

common (Fig. 15), indicating deformation at high temperatures (Kruhl, 1996).

Plagioclase makes up 5-20% of the granite, forming tabular and rounded grains that are 1-3 mm in length. A few grains have subtle normal or oscillatory zoning. Pockets of equant feldspar and quartz are ~0.5 mm in diameter. Subhedral biotite is 0.5-1 mm in length, and composes 3-10% of the granite. Biotite is commonly included in the cores of plagioclase, which are typically saussuritized. Alteration to chlorite, white mica, or sphene is common. Subhedral garnet comprises up to 1% of the granite and is 1-3 mm in diameter. The lack of evidence for recrystallization in the granite, and the absence of abundant inclusions in the garnet suggest that the garnet is magmatic. Trace amounts of primary sphene and allanite occur near biotite.

Figure 15. "Chessboard" subgrains in quartz in Taft Granite. Photomicrograph is under cross-polars.

Granodiorite North of Tuolumne Peak

Bateman et al. (1983) mapped a porphyritic granodiorite that they referred to as the granodiorite North of Tuolumne Peak. This unit sharply intrudes the El Capitan and Taft granites, and resembles medium-grained El Capitan Granite. The granodiorite encloses xenoliths of the Mt. Hoffman granodiorite within 30 m of some contacts. Schlieren, including one ladder dike, are common near these contacts, but enclaves are absent.

Plagioclase composes 30-40% of the granodiorite, typically forming tabular, normally zoned crystals that are 1-5 mm in length. Some cores are nearly completely saussuritized. Myrmekitic intergrowths are common. Interstitial quartz makes up 25-35% of the granodiorite, forming irregularly shaped grains that are 0.5-2 mm in diameter. Bimodal subhedral to anhedral K-feldspar comprises 20-25% of the granodiorite, forming 3-5-mm-long grains of orthoclase, and ~1-mm-long interstitial microcline. Biotite is ≤ 0.75 mm in length and makes up ~10% of the granodiorite, enclosing allanite. Accessory minerals include allanite, oxides, and apatite.

Yosemite Creek Granodiorite

The ~97 Ma (Burgess, 2009) Yosemite Creek Granodiorite is herein subdivided into five units on the basis of composition and texture (Table 1). Each unit of the

Yosemite Creek Granodiorite is generally homogenous. In map view, these units form equant masses that are ~1 by >2 km, and as tabular masses intruded as concordant sheets that are 10-40 m to >2 long and 0.5-1-m-wide discordant sheets that extend for 3-10 m. The majority of the Yosemite Creek Granodiorite intrudes the Taft Granite (Plate 1).

Magmatic foliation and lineation are steep, and are principally defined by biotite, hornblende, and plagioclase. Foliation is more intense than lineation in >95% of outcrops; lineation is stronger locally near the Ten Lakes and Yosemite Creek.

Coarse-grained unit of the Yosemite Creek Granodiorite

Coarse-grained Yosemite Creek Granodiorite is an equigranular granodiorite to tonalite that intrudes the Yosemite Creek pendant and Taft Granite in the southwestern part of the study area (Plate 1). The coarse-grained unit is sharply intruded by the medium-grained, mafic, and porphyritic members, indicating that the coarse-grained rocks are some of the oldest in the Yosemite Creek Granodiorite. Enclaves are distributed throughout the granodiorite, composing ~5% of the coarse-grained rocks. Aspect ratios of enclaves are commonly ~3:1 and locally up to ~7:1. Near the Yosemite Creek pendant, oblate dioritic enclaves locally comprise up to 40% of the rock (Fig. 16).

Figure 16. Oblate enclaves in coarse-grained Yosemite Creek Granodiorite. Pencil for scale in center of photograph.

Equant to tabular plagioclase makes up 40-60% of the coarse-grained unit. Grains are typically 1-5 mm in length and rarely as long as 1 cm; most plagioclase has well-developed oscillatory zoning. Quartz constitutes 30-40% of the granodiorite, forming equant or interstitial crystals that are 1-6 mm in diameter. Minor subgrains generally form “chessboard” patterns, indicating deformation at high temperatures (Kruhl, 1996). K-feldspar comprises 5-20% of the granodiorite, forming 1-2-cm-long subhedral crystals, and 1-7-mm-long interstitial grains. Inclusions of biotite and plagioclase are common; sphene and hornblende are found in lesser quantities. Hornblende and biotite commonly form aggregates with accessory minerals and oxides. Subhedral biotite is 1-2 mm in diameter and makes up 10-15% of the granodiorite. Alteration of biotite to sphene and chlorite is common. Hornblende grains up to 1 cm in length enclose biotite and apatite and make up ~1% of the mode. Sphene comprises 2% of the mode as magmatic crystals that are 0.5-1 mm in length and display rare polysynthetic twins. Zircon, apatite, and zoned allanite occur in trace amounts.

Medium-grained unit of the Yosemite Creek Granodiorite

The medium-grained unit of the Yosemite Creek Granodiorite is the most abundant phase, and ranges from granodiorite to tonalite. This unit appears either as >2 by ~1 km masses or as 10-50-m-wide sheets that extend for >2 km. Color index ranges from 10 to 25 and is higher in the northern part of the field area. The medium-

grained unit encloses enclaves next to the mafic Yosemite Creek Granodiorite near contacts, implying that the two units are probably co-magmatic (Fig. 17).

Figure 17. Mingling in Yosemite Creek Granodiorite. Mingling is between the mafic and medium-grained units. Pipe is 15 cm long.

Dioritic enclaves are concentrated within 1-2 m of contacts, are uncommon away from contacts, and are extremely rare in the northern part of the study area. Additionally, several sheets of granodiorite that are ~1 m wide and >50 m long intrude the Taft Granite in the northern part of the study area. These sheets have wavy and straight contacts, and enclose small xenoliths (~5 by 15 cm) of the granite (Fig. 18).

Figure 18. Sheets of medium-grained Yosemite Creek Granodiorite. Note irregularly shaped and straight contacts with the Taft Granite, and xenoliths of the granite in the granodiorite.

Subhedral to euhedral plagioclase constitutes 35-60% of the medium-grained granodiorite and ranges from 1-4 mm in length. Many of the small crystals have well-developed oscillatory or normal zoning. Plagioclase is commonly inclusion free, but rare grains have abundant biotite and hornblende inclusions. Interstitial K-feldspar is 0.5-1 mm in diameter and generally comprises <10% of the granodiorite, but reaches up to 20% locally. Equant quartz represents 15-35% of the mode. It ranges from 0.1-3 mm in diameter, and is commonly 1-2 mm. Minor amounts (<15%) of quartz display “chessboard” subgrains and contain inclusions of plagioclase and K-feldspar. Subhedral biotite that is 0.2-2.5 mm across makes up 10-25% of the granodiorite and is commonly altered to sphene and chlorite. Hornblende composes <5% of the granodiorite and is <1 mm in length. Primary and secondary sphene crystals are 0.5-1.5 mm across and comprise up to 1% of the granodiorite. Other accessory minerals include allanite, apatite, and zircon.

Mafic unit of the Yosemite Creek Granodiorite

Mafic Yosemite Creek Granodiorite consists of fine- to coarse-grained tonalite, quartz diorite, and diorite that intrude the medium-grained Yosemite Creek Granodiorite and Taft Granite as tabular bodies. In the northern part of the field area, the mafic rocks intrude as concordant, ~10-30-m-wide sheets that extend for >100 m and as masses that are ~0.5 by 1 km.

Plagioclase comprises 35-45% of the unit and has normal zoning that has fewer zones than in the coarse-grained and porphyritic units. Plagioclase is tabular and 0.2-3 mm in length. It is commonly saussuritized. Subhedral to equant hornblende is generally 1-2 mm long, and ranges from 0.5-6 mm in length. Hornblende composes 35-45% of the unit and encloses plagioclase. Chloritized biotite is 0.75-2 mm long and makes up 5-10% of the rock. Anhedral quartz comprises <5% of the unit and is <1 mm in diameter. Sphene is likely an alteration product of biotite, forming trace amounts of anhedral grains near biotite. Prismatic crystals of apatite ranging up to 0.75 mm long constitute up to 2% of the unit.

Porphyritic unit of the Yosemite Creek Granodiorite

Porphyritic Yosemite Creek Granodiorite intrudes the coarse-grained granodiorite as an irregularly shaped body (Plate 1) and the Yosemite Creek pendant as sheets that range from ~2 by 20 m up to >100 m by >1 km. Near the Yosemite Creek pendant, the granodiorite encloses roughly equant xenoliths of quartzite and biotite schist that are 15-20 cm in diameter. The porphyritic granodiorite is similar to the transitional Yosemite Creek Granodiorite of Petsche (2008) and the marginal Yosemite Creek Granodiorite of Fulmer and Kruijer (2009).

Rare schlieren are developed near contacts between the porphyritic and coarse-grained units. Schlieren dip steeply, strike sub-parallel to the contacts, and bend around

irregularities in the contacts. Cross-cutting relationships indicate that schlieren generally young to the south, away from the older coarse-grained granodiorite.

Dioritic enclaves are common in the porphyritic granodiorite. Most enclaves are fine-grained, elongate, and have bimodal aspect ratios of $\sim 1.5:1$ and $\sim 5:1$. Enclaves with higher aspect ratios are elongate parallel to foliation and are distributed throughout the porphyritic granodiorite. These enclaves are 1-4 cm in width and 10-50 cm in length. Enclaves with the lower aspect ratios are 10-30 cm in width and 15-50 cm in length and are localized in circular concentrations that are 2-5 m in diameter. These concentrations may define steeply plunging tubes (Fig. 19).

Enclave swarms are also associated with schlieren in one place along the contact between coarse-grained and porphyritic Yosemite Creek Granodiorite (Fig. 20). Plagioclase phenocrysts similar in size and shape to those in the porphyritic granodiorite occur in many enclaves.

Euhedral to subhedral tabular plagioclase is 1-6 mm in length, most commonly ~ 2 mm in length, and comprises 35-45% of the granodiorite. Many crystals exhibit well-developed oscillatory zoning and have saussuritized cores that enclose biotite and hornblende. Interstitial quartz is 1-2 mm in length and makes up 20-30% of the granodiorite. "Chessboard" subgrains and inclusions of plagioclase are common in the quartz. Biotite makes up 10-20% of the granodiorite, forming 1-4-mm-long grains. Hornblende is 2-4 mm in length and alters to, and contains inclusions of, biotite. Most

Figure 19. Schlieren and enclaves in porphyritic Yosemite Creek Granodiorite. Enclaves have lower aspect ratios than those in Fig. 20 and occur in circular concentrations.

of the granodiorite contains <1% hornblende, but hornblende reaches up to 10% in modal abundance in a small area that was mapped as Sentinel Granodiorite by Kistler (1973). The restricted extent and apparent gradational contacts between the hornblende-rich and adjacent porphyritic rocks suggest that the two are related. Sphene composes ~2% of the granodiorite in the form of primary 1-mm-long crystals and as an alteration product of biotite.

Figure 20. Mingled contact in the Yosemite Creek Granodiorite. The contact separates coarse-grained and porphyritic Yosemite Creek Granodiorite and strikes NW. Enclaves, schlieren, and magmatic faults (red lines) occur near the contact. Pencil points SSW.

Tonalitic unit of the Yosemite Creek Granodiorite

Medium-grained, locally porphyritic tonalite occurs in a 1 km² area near Grant Lakes (Plate 1). In map view, the tonalitic unit covers the smallest area and is sub-circular.

Subhedral plagioclase comprises 50-60% of the tonalite and forms 1-5-mm-long tabular grains. Well-developed oscillatory and normally zoned crystals are common. Resorption textures and saussuritized cores occur locally. Interstitial quartz is 0.5-2 mm in diameter and makes up 15-20% of the tonalite. Biotite forms aggregates of subhedral 0.5-1.5-mm-long grains that comprises up to 20-25% of the mode. Aligned biotite and plagioclase define foliation. Allanite and secondary sphene are present in trace amounts.

“Myriad zone” of the Yosemite Creek Granodiorite

Approximately 15% of the Yosemite Creek Granodiorite exposed in the study area occurs as abundant bodies of medium-grained and mafic Yosemite Creek Granodiorite that intimately intrude the Taft Granite and Mt. Hoffman granodiorite. This area is called the “myriad zone” after Kistler (1973) (Plate 1). Individual intrusions of Yosemite Creek Granodiorite in this zone are roughly tabular in shape, and range from discontinuous bodies that are 1 by 3 m in area, up to masses with dimensions of

15-30 m by >100 m. Eastward across the “myriad zone”, the proportion of Mt. Hoffman granodiorite increases relative to the Taft Granite. Contacts in the “myriad zone” are sharp and planar regardless of length.

STRUCTURE OF THE STUDY AREA

Magmatic foliation and lineation, other magmatic structures, and solid-state features occur in many rocks of the study area. Planar structures typically strike NE, oblique to the NW-striking structures in other parts of the Yosemite Valley Intrusive Suite, Yosemite Creek Granodiorite, Sentinel Granodiorite, and Tuolumne Intrusive Suite (Bateman, 1992; Zak and Paterson, 2005; Petsche, 2008).

Magmatic Foliation

Steeply dipping magmatic foliation, primarily defined by biotite and hornblende, occurs in all plutonic rocks of the study area (Plate 1). The dominant foliation in the study area is typically NE-striking, although there is considerable scatter in orientation (Fig. 21) (Bateman, 1992). Foliation intensity is moderately strong in the El Capitan Granite and Yosemite Creek Granodiorite, and is weaker in the Taft Granite. Within 1-3 m of metasedimentary bodies, magmatic foliation commonly intensifies and is deflected parallel to contacts, but does not show this pattern near contacts between plutons.

Figure 21. Poles to magmatic foliations. Poles projected onto a lower-hemisphere stereograph. Contour interval is 2 sigma using the method of Kamb (1959).

This fabric commonly transgresses contacts (Fig. 22), overprints most schlieren in the Mt. Hoffman granodiorite, and is generally parallel to the long axes of elongate enclaves.

Figure 22. NE-striking foliation transgressing a contact. The contact strikes SE and separates equigranular El Capitan Granite from Mt. Hoffman granodiorite. Pipe is 13 cm long and is aligned parallel to foliation.

A discontinuous, steeply dipping, NW-striking foliation with variable intensity also appears in domains scattered throughout the field area, and is most common in the SE part of the area (Plate 1). This fabric is dominant in the porphyritic Yosemite Creek

Granodiorite (Plate 1), where no NE-striking fabrics are observed and the long axes of elongate enclaves also trend NW. Schlieren bend around irregularities along the contact between the porphyritic rocks and the coarse-grained unit. Platy and elongate minerals defining these schlieren are oriented parallel to schlieren boundaries, and thus are not apparently overprinted by regional strain. In all other intrusive units, NW-striking foliation is generally subordinate to the NE-striking foliation.

In $<1 \text{ km}^2$ regions of the tonalitic unit of the Yosemite Creek Granodiorite, and in the southern part of the Mt. Hoffman granodiorite, foliation lacks a systematic strike (Plate 1). Foliation dips steeply and strikes NE, NW, and WNW in different outcrops.

Magmatic Lineation

Magmatic lineations are weak and principally defined by biotite and hornblende. They plunge steeply ($>50^\circ$) with a maxima of $\sim 80^\circ$ (Fig. 23) and trend variably, but locally have similar trends (Plate 1). Shallowly ($<45^\circ$) plunging lineations comprise $\sim 30\%$ of the measured fabrics; many occur in the coarse-grained and northern part of the mafic and medium-grained units of the Yosemite Creek Granodiorite.

Lineations intensify along with foliation within 1-3 m of the Tuolumne Peak pendant. Lineation in the equigranular El Capitan Granite unit is much more intense than foliation in a 1-m-wide zone next to the pendant, where plagioclase defines the lineation and has aspect ratios of $>10:1$.

Figure 23. Lower-hemisphere stereographic projections of magmatic lineations. Contour interval is 2 sigma using the method of Kamb (1959).

Dikes

Aplite and pegmatite dikes intrude most plutonic units with sharp, planar contacts; dikes with irregularly-shaped contacts occur locally. Dikes range from 10-100 cm in width and can be traced for 1->100 m. Many of these dikes are composite, and are cored by 1-4-cm-thick aplite or pegmatite. Dikes locally taper, step over, and continue. Dike overlaps reach >1 m and separations are <1 m. Aplite and pegmatite dikes truncate enclaves and other internal structures. Dikes have a consistent strike in some domains (Fig. 24). In the NW quadrant of the map area, they strike NW to WNW, whereas in the SE quadrant they strike ~N-S. Most (66%) of the dikes dip <45°. Where dikes are cross-cutting, shallowly dipping dikes commonly, but not invariably, cut steeper dikes.

Minor mafic dikes intrude various units throughout the field area. In one locality, a porphyritic mafic dike sharply intrudes the porphyritic Yosemite Creek Granodiorite and utilizes a pre-existing aplite dike (Fig. 25).

Figure 24. Map of aplite and pegmatite dikes in the study area.

Figure 25. Mafic dike intruding porphyritic Yosemite Creek Granodiorite. The mafic dike intrudes along a pre-existing aplite dike. The sharp color change in the granodiorite is due to weathering. Camera case is 10 cm long.

Ductile Shear Zones

Ductile shear zones are abundant in the eastern part of the study area, but are rare elsewhere. A 2-km-wide corridor of concentrated ductile shear extends for greater than 6 km, deforming the Mt. Hoffman granodiorite and equigranular El Capitan Granite (Fig. 12). This previously unrecognized high-strain zone is called the Mt. Hoffman shear zone. The 2-km-wide corridor is largely protomylonitic, with >1000 individual mylonitic to ultramylonitic ductile shear zones. Individual shear zones are NE-striking, SE- dipping, 1 cm-30 m wide, extend for 1-100 m along strike, and have nearly down-dip lineation (Fig. 26). Most shear zones record SE-side up reverse-slip, documented by S-C fabrics and σ -type porphyroclasts of K-feldspar on vertical rock faces normal to foliation and parallel to lineation. Porphyroclasts on horizontal faces show conflicting kinematics. These observations are compatible with a significant component of simple shear. S- and C- surfaces are primarily defined by biotite; hornblende rarely forms S surfaces. Rare C' surfaces are defined by biotite. The Mt. Hoffman shear zone also deforms the equigranular El Capitan Granite, but shear in this granite is characterized by diffuse ductile shear zones that deflect foliation less than zones in the Mt. Hoffman granodiorite (Fig. 27).

Figure 26. Ductile shear zone in Mt. Hoffman granodiorite. Rock surface is subhorizontal.

Ductile shear zones in the El Capitan Granite are estimated to have formed at $>450^{\circ}\text{C}$ given the recrystallization of quartz, K-feldspar, plagioclase, and biotite (Fig. 14). Quartz contains abundant subgrains and is widely recrystallized. Subgrains and recrystallized grains are similar in size and dimension, implying that recrystallization occurred by subgrain rotation. Away from individual ductile shear zones, rectangular, “chessboard” subgrains are common in quartz (Fig. 15), indicating high temperatures during deformation (Kruhl, 1996). The lack of subgrains and the presence of irregularly shaped grain boundaries in K-feldspar and plagioclase imply recrystallization by grain-

Figure 27. Diffuse ductile shear zone in equigranular El Capitan Granite. Curvature indicates top-to-the-SE reverse slip.

boundary migration. Polycrystalline mosaics of quartz and feldspars are best developed in the equigranular El Capitan Granite (Fig. 14), indicating greater recrystallization than in other units of the El Capitan Granite, perhaps because of deformation at higher temperature, and/or lower strain rates.

The timing of deformation in the Mt. Hoffman shear zone is indicated by: 1) deformed equigranular El Capitan Granite xenoliths enclosed by undeformed Taft

Granite; 2) truncation of individual shear zones by the medium-grained El Capitan Granite; and 3) the presence of deformed aplite dikes in the Mt. Hoffman granodiorite. These relationships suggest that the shear zone initiated after intrusion of the Mt. Hoffman granodiorite, equigranular El Capitan Granite, and deformed aplitic dikes, and before intrusion of the medium-grained El Capitan and Taft granites and undeformed aplitic dikes.

Ductile shear zones are rare (<20 observed) in the Yosemite Creek Granodiorite and Taft Granite and are scattered throughout the study area. These shear zones average 3 cm in thickness, strike NE, dip steeply to the NW and SE, and record reverse-shear. They have characteristics similar to those in the Mt. Hoffman shear zone, but are younger than the latter zone, which predates the Taft Granite. Microstructures are estimated to have formed at >450° C given the recrystallization of quartz and feldspar. Polygonal polycrystalline mosaics are less common in the two samples examined in thin section than in those from rocks in the Mt. Hoffman shear zone.

Magmatic shear zones and faults are rare (<5 observed) in the study area, and were only recognized in the Yosemite Creek Granodiorite. Most are located near the contact separating the porphyritic and coarse-grained granodiorites (Fig. 20).

Solid-State Deformation Outside of Ductile Shear Zones in Plutonic Rock

Most plutonic units show weak solid-state deformation outside of ductile shear zones. Deformation is typically manifested as subgrains and/or undulose extinction in quartz, deformation twins in plagioclase, kinked biotite grains, and bent plagioclase and biotite. Less common are the recrystallization of quartz and the development of core and mantle structures in K-feldspar and plagioclase.

Rare discontinuous, solid-state foliations are restricted to the northern parts of the Taft Granite proximal to the large intrusion of medium-grained Yosemite Creek Granodiorite. They are NE-striking, steeply dipping ($>60^\circ$), and defined by quartz. Solid-state lineations were difficult to measure; they plunge steeply, are nearly down-dip, and trend variably.

Structure of Metasedimentary Rocks

Metasedimentary rocks record a well-developed, steeply dipping ($>60^\circ$), N-NE-striking foliation, except for marble, which is massive and has no observable fabric. Foliation is folded into parallel, tight folds, which have wavelengths of <1 m and variable amplitudes. Hinge lines plunge 44° to 78° and trend variably ($n=9$). Axial planes of most folds are slightly bent, implying weak refolding (Fig. 28).

Figure 28. Refolded folds in biotite schist. Axial trace is dashed in red, pencil points south.

Boudins of biotite schist and calc-silicate rock enclosed in quartzite are common in the Yosemite Creek pendant and locally abundant in the southern part of the Tuolumne Peak pendant. Individual calc-silicate boudins are rectangular or have tapered ends; each segment ranges from 1 cm-3 m in length (Fig. 2). Biotite schist boudins vary in size, are oval shaped, and have dimensions of 6-25 cm by 0.25-3 m (Fig. 3).

The steeply-dipping foliation observed in the metasedimentary rock may have developed from regional thrusting (Tobsich et al., 2000). Thrusting probably occurred between 164-105 Ma based upon the geochronology of volcanic units that are inferred to have originally overlain the metasedimentary rocks (Tobisch et al., 2000).

Contact Relations

Contacts between units are sharp and irregular in map view. Some subunits display limited mingling along contacts, but gradational contacts are not observed between major units. Most contacts in the study area trend NE-SW.

Metasedimentary and Plutonic Rocks

Metasedimentary rocks are in contact with the Mt. Hoffman granodiorite, equigranular El Capitan Granite, and porphyritic and coarse-grained units of the Yosemite Creek Granodiorite. Intrusion of these plutonic rocks did not induce significant strain and/or deflect structures in the metasedimentary host rock. Thus, structural aureoles are narrow or absent.

Contacts of the Mt. Hoffman granodiorite and equigranular El Capitan Granite with the Tuolumne Peak pendant are sharp, curved in map view, and steeply dipping. Magmas of the two units do not penetrate the pendant. In one locale, anomalous

mineral assemblages in the Mt. Hoffman granodiorite occur within a few meters of the pendant (see Rock Units, p. 17).

Coarse-grained and porphyritic units of the Yosemite Creek Granodiorite have sharp, arcuate intrusive contacts with the Yosemite Creek pendant. Abundant (>50) xenoliths of quartzite and biotite schist occur within a 40-m-wide zone next to the pendant. Xenoliths have dimensions of 2 by 2 cm to 2 by 3 m in map view and increase in abundance closer to the pendant (see Rock Units, p. 10).

Contacts Between Plutonic Rocks

The vast majority of contacts between plutonic units are sharp and steep (>60°). Contacts mostly trend NE, and extend for several km; these contacts are planar at the outcrop scale, but are somewhat wavy at the map scale (Plate 1). Plutonic host rocks show minimal deflection or strain near contacts, except for the discontinuous solid-state foliation in the northern part of the Taft Granite.

Stepped and/or embayed contacts occur locally at the outcrop scale. The granodiorite North of Tuolumne Peak intrudes the Mt. Hoffman granodiorite as anastomosing sheets, creating sharp, stepped contacts, and encloses xenoliths of the Mt. Hoffman granodiorite that are ~25 by 20 cm near the southern contact between the two units. Taft Granite and coarse-grained Yosemite Creek Granodiorite share irregularly shaped, wavy contacts that are deeply embayed in places (Fig. 29).

Figure 29. Irregularly shaped, embayed contact. The contact separates coarse-grained Yosemite Creek Granodiorite (above) from Taft Granite (below). Note mafic accumulations in the granodiorite next to the contact. Field book for scale.

The porphyritic and coarse-grained units of Yosemite Creek Granodiorite have an irregularly shaped contact, and magmatic faults, schlieren and enclave swarms are developed in places near their contact (Fig. 20). In addition, this contact separates NE-striking foliation in the coarse-grained granodiorite from NW-striking fabrics in the porphyritic granodiorite (Fig. 30). Near Grant Lakes, irregularly shaped contacts separate the xenolith-rich medium-grained and tonalitic Yosemite Creek units from the older Taft Granite (Fig. 31). Rarely, sheets of the northern part of the medium-grained

unit of the Yosemite Creek Granodiorite intrude the Taft Granite with sharp, irregularly shaped contacts, surrounding granite xenoliths with dimensions of ~5 by 25 cm (Fig. 18).

Rare diffuse, gradational contacts can generally only be traced for 10-50 m, and are marked by the mingling of mafic and felsic magmas. Mingling between the mafic and the more felsic medium-grained Yosemite Creek Granodiorite generally occurs within 2 m of contacts near the Ten Lakes. Similarly, Mt. Hoffman granodiorite and coeval dioritic intrusions produce enclaves within a 2-m-wide zone (Fig. 6).

Figure 30. Contact in the Yosemite Creek Granodiorite. The contact separates porphyritic Yosemite Creek Granodiorite (on right) with NW-striking foliation (parallel to elongate enclaves) from coarse-grained granodiorite with NE-striking foliation. Pencil points SSE, parallel to the contact.

Figure 31. Xenoliths of Taft Granite. Xenoliths are enclosed by the tonalitic unit of the Yosemite Creek Granodiorite. Note aligned, swirled concentration of xenoliths below person.

DISCUSSION

Construction of the Yosemite Valley Intrusive Suite and Yosemite Creek Granodiorite

The size, and even presence, of a magma chamber, and the number, size, and tempo of increments that may assemble a chamber are contentious. Frozen magma chambers are commonly interpreted to be plutons (e.g., Miller and Miller, 2002; Bachmann and Bergantz, 2004) based on common chemical features that link exposed ignimbrites to plutons interpreted to represent source magma chambers (Glazner et al., 2008). However, the spatial extent of a pluton does not necessarily represent the total

volume of a magma chamber at any given time because magma chambers may be dynamic and/or transient features (Glazner et al., 2004; Annen, 2009). Thus 'magma chamber' and 'pluton' are not completely interchangeable terms. Consequently, several models have been proposed for the construction of magma chambers. The applicability of some of these models to plutons in the study area is discussed below.

Yosemite Valley Intrusive Suite

The El Capitan Granite was constructed by at least four petrographically distinct magmas, which are separated by steep contacts. A homogeneous domain of Mt. Hoffman granodiorite is $\sim 2 \text{ km}^2$; assuming a minimum thickness of 1 km, this is compatible with the formation of a magma chamber that is $\geq 2 \text{ km}^3$. Using the same assumption of thickness, magmas of the 20 km^2 Taft Granite may have assembled a $\geq 20 \text{ km}^3$ chamber based on the homogeneity of the granite. The abrupt change from enclave-bearing rocks west of the ridge that connects Mt. Hoffman and Tuolumne Peak, to schlieren-rich rocks (and minimal enclaves) east of the ridge, suggests two magma chambers with different internal processes or one evolving chamber with different responses to injection of mafic magma. The enclave-bearing portion of the Mt. Hoffman granodiorite may represent a more dynamic chamber that was capable of distributing dioritic material throughout the unit.

Gravity-driven processes such as the destabilization of crystal piles in a chamber (e.g., Irvine et al., 1998; Solgadi and Sawyer, 2008), rather than crystallization phenomena (e.g., Boudreau, 1995; Boudreau et al., 1997; Bartley et al., 2009) are interpreted to generate the schlieren because large (>1 cm) undeformed K-feldspar crystals are aligned, and the chaotic and oval-shaped schlieren indicate a magma chamber capable of flow (e.g., Paterson, 2009). Mineral grading was probably produced by a combination of grain dispersive pressure and shear flow of magmas (e.g., Komar, 1972; Barriere, 1976, 1981; Irvine et al., 1998; Solgadi and Sawyer, 2008; Paterson, 2009) allowing larger, felsic crystals to migrate away from the denser mafic portions. Segregation by filter-pressing of melt may have also occurred (e.g., Weinberg et al., 2001; Solgadi and Sawyer, 2008). Alternatively, each schliere in the Mt. Hoffman granodiorite may represent the boundary of a magmatic increment that was capable of flow and physical interaction with the host magma. In this case, the cross-cutting pattern of schlieren suggests construction from NW to SE, towards the margin of the granodiorite by >50 increments of magma. Schlieren did not likely result from late localized dilatational 'crack seal' in a relatively rigid system (e.g., Paterson et al., 2008) because the schlieren occur over a 1.5-km-wide area. Chaotic and oval-shaped schlieren may represent tubes of magma, where the oval-shaped tubes remained stationary and the chaotic schlieren migrated (e.g., Paterson, 2009).

The Double Rock granodiorite and the equigranular El Capitan Granite lack internal contacts and schlieren and are homogenous except for enclaves located

sparsely throughout the units. These features are consistent with a dynamic magma chamber that was large enough to distribute mafic material.

Discordant sheets of the medium-grained granite cut the Mt. Hoffman granodiorite and the equigranular granite with steep, sharp contacts. This indicates that at least some El Capitan Granite magmas intruded into rheologically strong material and solidified rapidly.

The Taft Granite is petrographically homogeneous and lacks internal contacts, schlieren and enclaves. Thus, the field evidence is compatible with the formation of a sizeable magma chamber.

Yosemite Creek Granodiorite

Five units, ranging from granodiorite to diorite, were intruded as thin sheets and larger bodies to comprise the Yosemite Creek Granodiorite. The different intrusive styles of the Yosemite Creek Granodiorite are consistent over >800 m of elevation, and thus, are not related to exposure level. In addition, the majority of the granodiorite intrudes the homogeneous Taft Granite, suggesting that host rock heterogeneity does not explain the intrusive styles.

Mafic and medium-grained Yosemite Creek Granodiorite are the largest units of the granodiorite and form large bodies in the north, and narrow sheets with high aspect ratios in the “myriad zone” and elsewhere. They are mingled where in contact, with

gradational contacts in a few 1-50-m-wide zones in the northern part of the map area. The mingling relationships suggest that the medium-grained granodiorite and mafic rocks were hot and interacted with one another while both contained melt. Given the number of localities displaying mingling, and the large quantity of sheets of the medium-grained unit, it is likely that the mafic and medium-grained (more felsic) units were constructed of many (>50) increments of magma. Based on the high aspect ratios, the narrow bodies of the medium-grained unit did not form magma chambers at the present level of exposure. These narrow bodies may be connected to larger intrusions above or below. The larger bodies in the NE were assembled by numerous small increments or by a few large increments, possibly forming a magma chamber. Enclaves concentrated along the perimeter of the unit suggest that the magma chamber was not turbulent and/or that mingling occurred late in construction and was focused along the pluton perimeter. The overall petrographic homogeneity of the medium-grained and mafic units suggests that both units were constructed by variable quantities of magmatic sheets from common sources.

The coarse-grained unit is petrographically homogeneous and lacks internal contacts. Enclaves distributed throughout the granodiorite suggest that the magma chamber was capable of mechanically distributing coeval magmas.

The porphyritic unit of the Yosemite Creek Granodiorite is a large body in the southern part of the field area. Enclaves with high aspect ratios are dispersed throughout the unit, and schlieren are concentrated within 10 m of the contact with the

coarse-grained unit where they bend around the contact. Mafic minerals that compose schlieren generally are aligned parallel to schlieren boundaries and are interpreted to have formed by internal magmatic processes (e.g., Barriere, 1981). These relationships also suggest that a magma chamber was assembled that produced schlieren along contacts and dispersed enclaves.

In the tonalitic unit, thousands of Taft Granite xenoliths of varying size imply a high rheological and/or thermal contrast between the intrusion and host (e.g., Clarke et al., 1998). Thermal fracturing of cooled granite by the tonalitic magmas probably progressively disaggregated the host into xenoliths of varying size. Disaggregation most likely occurred quickly because the viscosities of magmas rapidly increase during stopping and disaggregation (Glazner, 2007). An energetic chamber is inferred to have formed with magma of low enough viscosity to produce the observed features. Xenoliths concentrated within 2 m of some contacts are deflected parallel to the contacts and probably record flow along the walls of the chamber (Fig. 31).

As previously suggested, most units of the Yosemite Creek Granodiorite are interpreted to represent one or more magma chambers that were sufficiently large to facilitate internal processes capable of homogenizing some units, disaggregating xenoliths, and dispersing enclaves. It is unlikely that the Yosemite Creek Granodiorite as a whole represents a single evolving magma chamber, as the sharp contacts between units indicate major rheological contrasts. Direct evidence of the number of increments is lacking. The numerous sheets and bodies with mingled mafic and medium-grained

granodiorite may represent many increments of magma or one contact exposed at multiple sites.

Emplacement of the Yosemite Valley Intrusive Suite and Yosemite Creek Granodiorite

The emplacement of plutons may be facilitated by a variety of mechanisms, including ductile flow, stoping, assimilation, floor subsidence, magmatic wedging, and extension. In most cases, pluton emplacement requires multiple mechanisms operating at different rates, times, and scales (e.g., Paterson and Vernon, 1995; McNulty et al., 2000; Zak and Paterson, 2005; Yoshinobu et al., 2009; Saint Blanquat et al., 2011).

The plutons in the study area were emplaced into host rocks at depths of 4-11 km (Ague and Brimhall, 1988). Host rocks to the El Capitan Granite are not preserved except for the metasedimentary rocks located in the eastern part of the study area (Plate 1). In the map area, plutons typically intrude other plutons, i.e. the Taft Granite solely intrudes the El Capitan Granite, and the Yosemite Creek Granodiorite mostly intrudes the Yosemite Valley Intrusive Suite.

Ductile Flow

Some plutons in the central Sierra Nevada batholith were emplaced, at least in part, by the vertical flow of host rock in structural aureoles (e.g., Saleeby, 1990;

Paterson and Vernon, 1995; Paterson et al., 1996; Zak and Paterson, 2005). In the study area, however, structural aureoles are weakly developed or absent in the metasedimentary and plutonic host rocks. Structural aureoles may be removed by stoping (e.g., Paterson et al., 1996), but xenoliths in the map area, appear to be strained to roughly the same extent as nearby host rock. The discontinuous solid-state foliation in the northern Taft Granite may represent a narrow structural aureole resulting from intrusion of the northern medium-grained unit of the Yosemite Creek Granodiorite. The weakness of this fabric and the narrowness of the zone of solid-state deformation imply that a volumetrically significant portion of the host was unlikely to have been transported through the aureole.

Stoping

Stoping may be a significant material transfer process for some plutons (e.g., Hutton, 1982; McNulty et al., 1996; Paterson et al., 1996; Clarke et al., 1998). In many cases, however, a supporting xenolith record is lacking at the exposure level and the role of stoping remains controversial (e.g., Glazner and Bartley, 2006; Clarke and Erdmann, 2008; Paterson et al., 2008).

Xenoliths are rare in the Yosemite Valley Intrusive Suite, and thus stoping was probably not an important material transfer process, unless xenoliths sank and/or were displaced downward by convection in a magma chamber. In contrast, all units of the

Yosemite Creek Granodiorite, with the exception of the mafic unit, contain xenoliths.

Xenoliths are distributed throughout these units, but are concentrated within 100 m of contacts. They are most common in the tonalitic and medium-grained units near Grant Lakes, where there are >1000 xenoliths of Taft Granite that range from blocks with dimensions exceeding 10 by 15 m down to disaggregated xenocrysts that are ~1 mm in diameter. Orientations of magmatic foliations in most xenoliths are discordant to their nearest neighbors, indicating that they were rotated and thus presumably stoped. The quantity of stoped blocks suggests stoping was an important (>10%) material transfer process for the tonalitic unit, and was at least locally important for the medium-grained unit.

Porphyritic and coarse-grained granodiorite enclose fewer than 100 metasedimentary xenoliths that are distributed within 30 m of the Yosemite Creek pendant. Most of these xenoliths have similar foliation orientations and may represent: 1) blocks translated from intrusion of the granodiorite; 2) screens of interconnected masses with intrusions anastomosing around them; and/or 3) stoped blocks that were reoriented with the long axis of the block rotated to the least principal direction of strain. The small percentage (<10%) of xenoliths that are rotated relative to one another were probably stoped. Overall, the volume of xenoliths exposed in the coarse-grained and porphyritic units is small relative to the size of the units; thus, stoping was probably only a limited material transfer process.

Assimilation

Lack of chemical data precludes a complete evaluation of assimilation. Regardless, anomalous mineral assemblages suggestive of assimilation and/or metasomatism were only observed within 10 m of one contact, which was between Mt. Hoffman granodiorite and the Tuolumne Peak pendant (see Rock Units, p. 17). Near Grant Lakes, magmas represented by the tonalitic and medium-grained units of Yosemite Creek Granodiorite were able to disaggregate Taft Granite into individual crystals during emplacement. This thorough disaggregation suggests that these Yosemite Creek magmas assimilated at least a small portion of Taft Granite.

Roof Uplift, Floor Subsidence

Uplift of the roof may be a major process during emplacement of shallow-level plutons such as those in parts of the central Sierra Nevada batholith (e.g., Morgan et al., 1998; Saint-Blanquat et al., 2001). Roof uplift occurs by piston-like motion accompanied by marginal faults and/or the bending and draping of roof rocks (e.g., Pollard and Johnson, 1973; Corry, 1988).

The applicability of roof uplift in the study area is tenuous because the Yosemite Valley and Yosemite Creek plutons were emplaced at depths (>5 km) greater than those

compatible with roof uplift (Ague and Brimhall, 1988; Cruden and McCaffrey, 2001).

Direct evidence for roof uplift, such as marginal faulting, was not observed. Most of the roof has been removed, however, and thus it is difficult to evaluate whether bending and draping of the roof rocks occurred.

Floor subsidence has been widely proposed as a material transfer process. Structures commonly attributed to floor subsidence include shearing along pluton walls, and/or the downward sagging of host rock (e.g., Bridgewater et al., 1974; Corry, 1988; Cruden, 1998). Ductile deformation of the host rocks is minimal, or absent in the study area, and downward sagging of host rocks is not observed. Pluton floors are not exposed, however; thus evidence supporting floor subsidence for plutons in the study area is lacking. Lack of convincing evidence for the emplacement mechanisms discussed above suggest that floor subsidence may have facilitated emplacement by process of elimination.

Magmatic Wedging

Wedging aside of metamorphic host rock has been proposed as a significant material transfer process during the emplacement of some plutons (e.g., Brown, 1994; Collins and Sawyer, 1996; Weinberg, 1999; Miller and Paterson, 2001; Mahan et al., 2003). Wedging is typically inferred to occur by intrusion along pre-existing anisotropies such as foliation in the host rocks.

In the study area, there is no evidence of magma wedging during emplacement of the Yosemite Valley Intrusive Suite, whereas this process probably occurred at least to a limited extent during intrusion of the Yosemite Creek Granodiorite. The Yosemite Valley rocks do not penetrate the Tuolumne Peak pendant, and xenoliths are exceedingly rare. In contrast, numerous sheets of the coarse-grained and medium-grained units of Yosemite Creek Granodiorite intrude the Yosemite Creek pendant and enclose many unrotated xenoliths within 30 m of the pendant. These sheets are interpreted to have laterally translated the metasedimentary rocks.

Yosemite Creek sheets also commonly intrude plutonic host rocks, and, with the exception of the porphyritic unit, are concordant to the NE-striking foliation of the Yosemite Valley Intrusive Suite. These observations are compatible with exploitation of foliation by sheets and associated wedging. These sheets may have coalesced to form the larger bodies of Yosemite Creek Granodiorite (such as those in the NE), and facilitated the vertical transport of host rock (e.g., Weinberg, 1999; Miller and Paterson, 2001).

Dilation Associated with Regional Strike-Slip Faulting

Extensional structures related to regional strike-slip faults can localize the emplacement of plutons (e.g., Hutton, 1982, 1988; Tikoff and Teyssier, 1992). Regional strike-slip faults have been documented in the central Sierra Nevada batholith on the

east side of the Tuolumne Intrusive Suite (e.g., Sierran Crest fault system; Tikoff and Teyssier, 1992). The closest regional fault to the study area is the Quartz Mountain shear zone which is >20 km to the south (Fig. 1). This shear zone initiated at ~98 Ma and records reverse-slip, not strike-slip (Tong, 1994; Tobisch et al., 1995). Moreover, only reverse-shear zones have been recognized in the study area; thus fault-related dilation is unlikely to have operated.

Summary of Emplacement

The field evidence for definitively distinguishing between different material transfer processes in the study area is inconclusive, in part because there is little preserved meta-supracrustal host rock, and pluton roofs and floors are not exposed. Much of the field evidence, such as the scarcity of xenoliths and lack of a well-developed aureole, can be used to argue against, rather than for, a specific process.

Emplacement of the Yosemite Valley Intrusive Suite is particularly enigmatic. The lack of xenoliths in the suite suggests that stoping was not important for these rocks. Stopping was involved to varying degrees, however, in the emplacement of the Yosemite Creek Granodiorite. All units of the granodiorite, except the porphyritic unit, likely exploited pre-existing foliation and wedged the host aside, facilitating emplacement of the long thin sheets and conceivably the larger masses. The lack of evidence for regional dilation during emplacement implies that wedging was

accompanied by vertical transport. Magmatic wedging of sheets accompanied by vertical transport is rarely documented in the central Sierra Nevada batholith. There is little convincing evidence of extensive material transfer by ductile flow. The best candidate is the solid-state foliation in the Taft Granite adjacent to parts of the northern medium-grained Yosemite Creek Granodiorite. Assimilation provided little, if any space for the plutons. No evidence of floor subsidence, or piston-like roof uplift was documented. The presence of contractional shear zones and lack of strike-slip and normal shear zones argue strongly against emplacement by dilation in fault zones.

Development of Foliation

Magmatic foliations form in response to variable components of internal magmatic processes and regional stresses (e.g., Paterson et al., 1998). Several plutons in the central Sierra Nevada batholith are interpreted to have magmatic foliations that record weak regional strain (e.g., Zak and Paterson, 2005; McFarlan, 2007; Petsche, 2008). In the study area, NE-striking magmatic foliation is interpreted to record regional strain on the basis of the following field observations: 1) magmatic foliation transgresses contacts (Fig. 22); 2) minerals defining schlieren in the Mt. Hoffman granodiorite are overprinted by the NE-striking fabric; 3) strikes of magmatic foliation and reverse ductile shear zones (solid state) in the Mt. Hoffman shear zone are

coincident; and 4) NE-striking magmatic foliation is consistent in orientation and intensity throughout the study area except near ductile shear zones.

NW-striking foliation occurs as a weak, discontinuous fabric in some Yosemite Valley Intrusive Suite rocks, and a dominant fabric in the porphyritic unit of the Yosemite Creek Granodiorite. NW-striking foliation is consistent with magmatic foliations in rocks that are <98 Ma elsewhere in the central Sierra Nevada batholith and have been interpreted to have developed from NE-SW shortening compatible with plate convergence at that time (Tobisch et al., 1995; Zak and Paterson, 2005; Petsche, 2008). If both the NE- and NW-striking foliations are regional fabrics, then the strain field shifted during the time interval between the construction of the medium-grained, mafic, and tonalitic units of the Yosemite Creek Granodiorite and the porphyritic unit.

Significance of NE-striking Structures

The NE strike of structures inferred to record regional strain in the study area conflicts with orientations of regional structures in coeval rocks in the central Sierra Nevada, and the expected NE-SW shortening from plate kinematics, as discussed above. The NE strikes imply that either the regional strain field was markedly heterogeneous or that structures in the study area were originally NW-striking and subsequently deflected into the current orientation.

Rigid body rotation of structures and contacts in the study area by forceful emplacement of the Tuolumne Intrusive Suite is one explanation for the NE strikes, as the contact of the intrusive suite trends NE adjacent to the study area (Fig. 1). There are several problems, however, with this hypothesis. Contacts and foliations do not strike NE in the porphyritic unit of the Yosemite Creek Granodiorite, which seemingly requires the porphyritic rocks to act independently from the rest of the granodiorite. Additionally, NE-trending structures and contacts extend for >10 km NW of the Tuolumne Intrusive Suite (Fig. 1), indicating that the suite would have to juxtapose a rock area of >1000 km² with the porphyritic rocks.

Speculative scenarios for creating the NE-striking foliation and other NE-striking structures, such as the Mt. Hoffman shear zone, include: 1) refraction of regional strain normal to the pluton contacts; and/or 2) strain from internal processes in a large magmatic system. In the latter scenario, all plutons north of the Sentinel Granodiorite acted as one system that built inwards. The study area represents a small portion of this larger system where only NE-striking fabrics are observed. Intrusion of younger nested plutons focused strain into the Mt. Hoffman shear zone (Fig. 32). Plutons that intrude the El Capitan Granite, such as the Sentinel Granodiorite, are interpreted to intrude along WNW-striking foliation in the host, facilitating the development of WNW-striking fabrics in the granodiorite. This scenario needs to be tested by detailed mapping of any additional contacts and high-precision geochronology to determine the emplacement and construction history of the proposed larger magmatic system.

Figure 32. Concentric foliation model. The yellow outlined area represents the extent of the proposed original intrusion of El Capitan Granite. Black lines define the strike of magmatic foliations. This intrusion had internal processes capable of producing the observed concentric foliations. Nested plutons intruded to center of the yellow outlined area, producing enough strain to create the Mt. Hoffman shear zone.

CONCLUSIONS

1. In the Yosemite Valley Intrusive Suite, the El Capitan Granite is composed of at least four units, whereas the Taft Granite is homogeneous. Contacts between the units dip steeply, compatible with construction by vertical increments of magma. The cross-cutting relationships between different schlieren suggest that at least part of the Mt. Hoffman granodiorite was built from NW to SE.
2. Five units comprise the Yosemite Creek Granodiorite. Contacts between units are sharp with the exception of the mingled contact between the medium-grained and mafic rocks. All contacts are steep, supporting construction by vertical increments of magma.
3. Direct evidence for emplacement of the Yosemite Creek Granodiorite is limited, but magmatic wedging was probably a significant material transfer process. Stoping was locally important for the medium-grained and tonalitic units. Parts of the medium-grained unit in the NE part of the field area may have been accommodated by ductile flow of Taft Granite in a narrow, discontinuous aureole.
4. Magma chambers formed during construction of most intrusions in the study area as exemplified by schlieren, widely distributed enclaves, and the internal homogeneity of most of the bodies. The number, size, and tempo of increments that constructed the chambers are difficult to constrain, but many (>50) increments intruded close in time constructed parts of the medium-grained and mafic units of the Yosemite

- Creek Granodiorite. Large increments, or small increments intruded over a short time interval likely constructed the other plutons in the study area, forming magma chambers that were 2-20 km³.
5. Two magmatic foliations dominate in different parts of the study area. A regional NE-striking magmatic foliation overprinted schlieren and contacts in rocks that are >97 Ma. A NW-striking fabric is the dominant fabric in the porphyritic unit of the Yosemite Creek and is a discontinuous fabric in the El Capitan Granite.
 6. The NE-striking Mt. Hoffman shear zone is comprised of >100, 5 cm-2 m-thick, steeply dipping, reverse-slip ductile shear zones that deformed the Mt. Hoffman granodiorite at >450°C. The shear zone is has a different orientation than other regional shear zones in the central Sierra Nevada batholith.
 7. NE-striking structures in the study area do not fit the conventional understanding of the regional strain field from 103-98 Ma. These NE-striking structures are enigmatic, and were generated from a component of NE-SW shortening.

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