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Structure, Construction, and Emplacement of the Late Cretaceous Sonora Pass Intrusive Suite: Central Sierra Nevada Batholith, California

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STRUCTURE, CONSTRUCTION, AND EMPLACEMENT
OF THE LATE CRETACEOUS SONORA PASS INTRUSIVE SUITE:
CENTRAL SIERRA NEVADA BATHOLITH, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Monika B. Leopold

December 2016

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The Designated Thesis Committee Approves the Thesis Titled

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OF THE LATE CRETACEOUS SONORA PASS INTRUSIVE SUITE:
CENTRAL SIERRA NEVADA BATHOLITH, CALIFORNIA

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December 2016

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ABSTRACT

STRUCTURE, CONSTRUCTION, AND EMPLACEMENT
OF THE LATE CRETACEOUS SONORA PASS INTRUSIVE SUITE:
CENTRAL SIERRA NEVADA BATHOLITH, CALIFORNIA

By: Monika B. Leopold

The >1000 km², ~95-88 Ma Sonora Pass intrusive suite is the oldest and most northern of the four voluminous, normally-zoned Late Cretaceous suites of the Sierra Nevada batholith. It consists of the older, marginal, equigranular Kinney Lakes hornblende-biotite granodiorite and the inner, porphyritic to megacrystic Topaz Lake biotite granodiorite. The suite intruded the ~109 Ma Bummers Flat biotite granodiorite, Jurassic diorites, and Pre-Cambrian to Cambrian metasedimentary rocks of the Snow Lake pendant. The Topaz Lake granodiorite records evidence of the development of a sizable magma chamber. The Bummers Flat and Kinney Lakes granodiorites were likely constructed by many increments, were capable of flow and disaggregation of host and co-magmatic mafic rocks, are marked by widespread schlieren, and may have not formed a single magma chamber. Accommodation of magmas was facilitated by multiple material transfer processes; stoping was the best documented process, followed by minor ductile flow and magmatic wedging of the Kinney Lakes granodiorite. There is no direct evidence for transfer processes during emplacement of the Topaz Lake granodiorite. Magmatic foliation within the study area records regional tectonic strain and complex internal magmatic processes. Solid-state structures including steep ductile shear zones, foliations, and lineations occur within the Bummers Flat granodiorite. One of these structures, the Toe Jam Lake shear zone, may extend for 10s of km, likely formed during ENE-WSW shortening, and probably predated the Sonora Pass intrusive suite.

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INTRODUCTION

Granitoid plutons provide natural laboratories to study the generation, ascent and emplacement of magmas into the continental crust. These plutons are excellent recorders of the magmatic and tectonic evolution of magmatic arcs, but despite overwhelming amounts of research, the origin of compositional diversity, construction, and emplacement of plutons is still widely debated.

Many plutons, such as those from the Sierra Nevada batholith, are compositionally zoned, as defined by the broad transition from outer mafic phases that grade inward to more felsic phases (e.g., Bateman and Chappell, 1979; Bateman, 1992). Early authors on the petrology of the Sierra Nevada batholith, such as Bateman and Chappell (1979), attributed compositional zoning to in-situ fractional crystallization of a single large magma body. Kistler et al. (1986) argued that compositional zoning rather reflects mixing between separate mantle and crustal derived melts. Decades later, despite large amounts of data from field, geochemical, isotope, and thermal studies, the compositional zonation and differentiation of plutons remains an enigma and many hypotheses remain (e.g., Coleman et al., 2004; Bartley et al., 2008; Burgess et al., 2008; Gray et al., 2008; Memeti et al., 2010a; Paterson et al., 2011).

It is now widely accepted that igneous complexes are formed incrementally by the addition of a few to numerous pulses of magma (e.g., Pitcher and Berger, 1972; Hutton, 1982; McNulty et al., 1996; Wiebe and Collins, 1998; Bergantz, 2000; Miller and Paterson, 2001; Coleman et al., 2004; Paterson et al., 2008; Economos et al., 2010; Memeti et al., 2010a; Paterson et al., 2011) over timescales of thousands (Michel et al., 2008; Eddy et al., 2016) to millions of years (e.g., Coleman et al., 2004; Matzel et al., 2006; Miller et al., 2007; Shea et al., 2016). However, the number and size of individual increments, the duration of magmatic pulses, and the size and duration of resulting magma chambers remains contentious.

Interaction between increments can explain the compositional diversity, but homogenous appearance found in many plutons, which largely reflects source heterogeneity, magma mixing/mingling, and/or crystal fractionation at deep levels or the emplacement level (e.g., Economos et al., 2010; Memeti et al., 2010a). Dynamic processes interacting between increments can homogenize magmas, obscuring contacts or completely erasing them (Bergantz, 2000). These processes may also create structures such as schlieren, tubes, mechanical accumulations of crystals, pipes, and other magmatic structures found in many plutons (Barriere, 1981; Weinberg et al., 2001; Žák et al., 2007; Paterson, 2009).

Alternatively, Coleman et al. (2004), Glazner et al. (2004), Michel et al. (2008), and others propose that plutons are constructed by small, episodic magma increments at rates several orders of magnitude smaller than required to maintain a steady-state magma chamber, inferring that a pluton may be completely solid when a younger increment is injected. These authors suggest that internal contacts may be obscured by thermal annealing, and chemical evolution of a suite is dominated by processes during magma generation in the lower crust, not at the emplacement level. In this model, magmatic features such as K-feldspar megacrysts, schlieren, and ladder dikes form by chemical diffusion, thermal cycling, and/or “textural coarsening” (Bartley et al., 2009; Johnson and Glazner, 2010; Glazner and Johnson, 2013).

Similar to construction processes, the emplacement of large plutons also presents major problems. Emplacement is defined as the processes that occur after magma has ascended during the growth, assembly, and crystallization of the pluton (McNulty et al., 2000). Material transfer processes that aid emplacement include, but are not limited to, ductile flow, stoping, assimilation, floor subsidence, magmatic wedging, roof uplift, and extension. One process does not necessarily dominate, and it is likely that many processes

operate at different rates during the emplacement of a large intrusive complex (e.g., Paterson et al., 1996; Žák and Paterson, 2005; Yoshinobu et al., 2009; Saint Blanquat et al., 2011).

Evaluating models and processes of pluton construction and emplacement in magmatic arcs is expedited by the study of well-exposed plutonic suites, such as the Sonora Pass intrusive suite (SPIS) of the Sierra Nevada batholith. This suite is marked by large topographic relief, allowing for detailed mapping, evaluation of contacts, fabrics, compositional heterogeneity, and other internal features.

Geologic Setting

The Sierra Nevada batholith in eastern California is comprised of Mesozoic plutonic rocks and makes up the majority of the Sierra Nevada Mountain range (Fig. 1). The batholith strikes NNW and can be traced for ~600 km, varying in width from ~80-120 km (Bateman and Wahrhaftig, 1966). It straddles the boundary between the Paleozoic North American craton and accreted Paleozoic and early Mesozoic oceanic crust to the west (e.g., Saleeby et al., 2003). These differing crustal sources are correlated with the abundance of tonalities to the west and granodiorites to the east (Bateman and Wahrhaftig, 1966). The batholith was emplaced into strongly deformed, but generally weakly-metamorphosed strata ranging in age from Proterozoic to Cretaceous (Bateman, 1992).

The Sierra Nevada batholith is composed of $\sim 0.7 \times 10^6$ km³ of largely granodiorite magmas and is interpreted to be ~30-35 km thick (Bateman and Wahrhaftig, 1966; Ducea, 2001). It was variably active between 220 Ma and 80 Ma with episodic magmatic flare-ups (Coleman and Glazner, 1997; Ducea, 2001; Saleeby et al., 2003; Cecil et al., 2012), separated by ~25-70 m.y. long magmatic lulls (e.g., DeCelles et al., 2009). Two significant flare-ups took place in the Jurassic (160-150 Ma) and particularly

Figure 1. Generalized geology of the Sierra Nevada batholith. Inset shows location of the batholith in relation to the North American Cordilleran magmatic arc. Plate 1 is the location of the study area within the Sierra Nevada batholith. Main figure modified from Lackey et al. (2012), and smaller inset modified from Anderson (1990).

in the Late Cretaceous (100-85 Ma). About 78% volume of the Sierra Nevada batholith, including the four large ($>1000 \text{ km}^2$) normally zoned intrusive complexes found along the crest of the eastern Sierra Nevada, were emplaced during the Late Cretaceous flare-up (Coleman and Glazner, 1997; Ducea, 2001). These large intrusive suites are of similar composition and are, from south to north, the Mt. Whitney, John Muir, Tuolumne, and Sonora Pass intrusive suites (Fig. 2)

The ~95-88 Ma (U/Pb zircon, Sensitive High Resolution Ion Microprobe - Reverse Geometry, or SHRIMP-RG) Sonora Pass intrusive suite (SPIS) (e.g., Bateman, 1992; Macias, 1996) consists of the marginal, ~95-92 Ma Kinney Lakes granodiorite (Huber, 1983), and the internal ~92-88(?) Ma Topaz Lake granodiorite (Guisso, 1981; Huber, 1983; Wahrhaftig, 2000) (Fig. 3 and Plate 1). The Sonora Pass suite intruded ~109 Ma host rocks of the Bummers Flat granodiorite on the west and metasedimentary rocks with Cambrian and Proterozoic protoliths of the Snow Lake block in the south (Lahren and Schweikert). Bodies of diorite, gabbro, and metasedimentary rock are also scattered within the Bummers Flat granodiorite (Fig. 3).

Methods

This thesis builds on previous 1:62,500 mapping of Huber (1983) and Wahrhaftig (2000), and concentrates on the structure, construction, and emplacement of the Sonora Pass intrusive suite and its host rocks. Five weeks of field work were completed during the summer of 2013 and included 1:24,000 geologic mapping of ~45-50 km^2 in two areas in the Emigrant Wilderness, California. The orientations of igneous features, such as foliations, lineations, dikes, and schlieren, were measured. Post-solidification structures, such as shear zones and solid-state foliations, were also measured, and ~50 oriented samples were collected throughout the study area. Thin-sections were analyzed to determine modal mineralogy, textures, microstructures, and deformation of the Sonora

Figure 2. Late Cretaceous zoned intrusive suites of the Sierra Nevada batholith. Modified from Hirt (2007) and Lackey et al. (2012). Dark gray colors within the suites denote older marginal units, and lighter gray colors are the younger, inner-most units.

Figure 3. Geologic map of the Sonora Pass intrusive suite. Map was compiled from the Dardanelles Cone, Sonora Pass, Pinecrest, and Tower Peak (1:62,500) geologic quadrangles (Guisso, 1981; Huber, 1983; Wahrhaftig, 2000). Much of the Topaz Lake granodiorite is covered by Tertiary volcanic rocks. Study areas are denoted by red rectangles.

Pass intrusive suite and its host rocks. U-Pb zircon geochronology (SHRIMP-RG) data were collected by Jonathan Miller and Callie Sendek (San José State University). Their data are included within this thesis.

UNIT DESCRIPTIONS

This chapter focuses on field descriptions and petrographic analysis of major units in the study area. Internal features such as enclaves, schlieren, mineral accumulations, and felsic dikes are described in detail. All grain sizes are reported in terms of lengths of the long axes. Units are described from oldest to youngest.

Host Rocks

Tom's Canyon Metasedimentary Pendant and Xenoliths

First mapped by Huber (1983), the Tom's Canyon metasedimentary pendant and associated xenoliths are located in the far western part of the study area within the Bummers Flat granodiorite (Plate 1). The pendant consists mostly of quartzo-feldspathic schists, calc-silicate rocks, minor quartzites, and rare garnetites (Fig. 4), which were metamorphosed to the amphibolite facies. The pendant ranges in width from a few meters to ~100 m and is ~2.5 km in length. In close proximity to the pendant are metasedimentary xenoliths that range from 10 cm to ~100 m in diameter (Fig. 5). Hydrothermal alteration occurred locally.

Samples taken from different parts of the pendant and nearby xenoliths were grouped into three categories based on composition: 1) quartzo-feldspathic rocks with strong alignment of biotite; 2) hydrothermally altered metamorphic rocks; and 3) amphibolite-facies calc-silicate rocks. Quartzo-feldspathic rocks are fine to medium grained (>0.1–2.5 mm), and consist of quartz (50-70%), plagioclase (12-25%) and biotite (14-30%). Plagioclase forms relict euhedral 2-2.5 mm phenocrysts, with twinning and normal zoning that are extensively overprinted by metamorphic textures (Fig. 6). Strong

Figure 4. Tom's Canyon metasedimentary pendant. View looking south. Leopold Lake is located on top of the ridge. Note layers parallel to strong foliation. Width of photograph is ~100 m.

Figure 5. Outcrop photographs of the Tom's Canyon metasedimentary rocks. A) Small metasedimentary xenolith within the Bummers Flat granodiorite. B) Strongly foliated quartzo-feldspathic rocks with concordant granodiorite sheets that intruded along the foliation plane. Photograph is 1 m wide. C) Amphibolite-grade calc-silicate rocks. Photograph is 2.5 m wide.

Figure 6. Photomicrographs of quartzo-feldspathic Tom's Canyon pendant rocks. Quartz, plagioclase and biotite dominate the mineralogy of the samples. A) and B) Relict growth zoning in plagioclase. C) and D) Asymmetric tails on plagioclase. Note the strong alignment of biotite in all pictures. Scale applies to all photomicrographs.

foliation is defined by biotite and minor aligned plagioclase. Hydrothermally-altered rocks range from garnetites to skarn, and are mostly fine-grained. Lower-temperature hydrothermally-altered rocks have abundant chlorite and sericite. Calc-silicates rocks are fine-grained and consist of mostly diopside (50%) and quartz (40%), with minor plagioclase (5%), and garnet (5%) (Fig. 7).

Fourteen zircons from a calc-silicate rock were dated using SHRIMP-RG and have a wide spread of ages, which are mostly discordant. Concordia ages range from 1.0 Ga - 2.7 Ga. Given the few detrital zircons dated, it is not possible to interpret a protolith age, other than it is Meso(?) - Proterozoic or younger (Fig. 8)

Snow Lake Block Miogeoclinal Metasedimentary Rocks

Located in the far southeastern portion of the eastern study area, the Snow Lake block of Lahren and Schweikert (1989) and Lahren et al. (1990) is a 7 km² pendant of Neo-Proterozoic through Middle Cambrian passive margin strata containing quartzite, micaceous quartzite, biotite schist, calc-silicate schist, and marble (Lahren and Schweikert, 1989; Lahren et al., 1990; Grasse et al., 2001; Thompson et al., 2007; Memeti et al., 2010b). The Snow Lake block is correlated with other metasedimentary pendants along the crest of the Sierra Nevada mountains that are inferred to have been translated dextrally along the proposed Early Cretaceous Mojave-Snow Lake fault (Lahren and Schweikert, 1989; Lahren et al., 1990; Grasse et al., 2001; Thompson et al., 2007; Memeti et al., 2010b) (Fig. 9). These correlative rocks are part of the Inyo and Death Valley facies of the Cordilleran miogeocline, exposed 50-200 km to the south and southeast of these Sierran metasedimentary pendants (Lahren and Schweikert, 1989; Lahren et al., 1990; Grasse et al., 2001; Thompson et al., 2007; Memeti et al., 2010).

Quartzites and muscovite schists of the Snow Lake block are intruded by the Sonora Pass intrusive suite. Abundant xenoliths of varying sizes are found in the margin

Figure 7. Photomicrograph of a calc-silicate rock from the Tom's Canyon pendant. Quartz grains have bimodal grain sizes. Note tilt walls on larger quartz grain left of center (red arrows). Garnets are small and euhedral, completely extinct grains in cross-polars.

Metasedimentary rocks
in Bummers Flat
granodiorite. Note wide
range of ages, which
are mostly discordant.
Oldest ages are ca. 2.6 -
2.7 Ga (N=14)

Bummers Flat granodiorite
Mean $^{206}\text{Pb}/^{238}\text{U}$ age =
 109.8 ± 1.2 Ma
MSWD = 1.38 (N=10),
and excludes 2 older
zircons. Age of youngest
zircon is ca. 107 Ma.

Figure 8. Concordia diagrams of host rocks and the Sonora Pass intrusive suite rocks. Dated using the SHRIMP-RG at Stanford University, and completed by Jonathan S. Miller and Callie Sendek, both of San José State University.

Kinney Lakes
granodiorite
Mean $^{206}\text{Pb}/^{238}\text{U}$ age =
 95.6 ± 1.5 Ma
MSWD = 1.15
(N=11), excludes 1
older zircon.
Age of youngest
zircon is ca. 92 Ma.

Topaz Lake
granodiorite
Mean $^{206}\text{Pb}/^{238}\text{U}$ age =
 90.1 ± 1.1 Ma
MSWD = 1.59 (N=9),
excludes 2 older
zircons. Age of
youngest zircon is ca.
88 Ma.

Figure 9. Mojave-Snow Lake fault (MSLF) zone. The Snow Lake block and Tom's Canyon pendant are located within the study area. Modified from Memeti et al (2010).

of the suite (Fig. 10). Quartzites are fine- to medium-grained ($\leq 0.1\text{-}3\text{ mm}$), and are mostly quartz ($\leq 90\%$), accessory muscovite ($\leq 10\%$) and chlorite ($\leq 1\%$) (Fig. 11). Many of the quartzites also contain garnet-rich layers ($\sim 3\text{-}5\text{ mm}$ thick), and others have a strong foliation marked by oblate lenses of muscovite and secondary chlorite. The schists are fine-grained ($\leq 0.1\text{-}0.75\text{ mm}$) and consist of muscovite ($\sim 50\%$), iron oxides ($\sim 30\%$), quartz ($\sim 15\%$), and accessory chlorite ($\sim 5\%$) and garnet ($\leq 1\%$) (Fig. 11). Iron oxides are strongly aligned in foliation.

Older Mafic Rocks

A suite of largely older mafic rocks located in the extreme southern end of the eastern study area is in contact with the Snow Lake block and the Kinney Lakes granodiorite. These mafic rocks are part of the $\sim 148\text{ Ma}$ (U-Pb zircon) Koguma intrusive suite (Lahren et al., 1990; 1994). Rock types within this suite are intermediate to ultramafic igneous rocks, including, but not limited to, quartz diorite, hornblende diorite, hornblende gabbro, hornblendite, pyroxenite, and dunite. This suite is proposed to have intruded along the Sachse thrust, which was active from post Early-Triassic and pre-latest Jurassic, and is thought to be the plutonic roots of the Independence dike swarm (Lahren et al., 1994).

The Koguma suite in the study area is mostly fine- to medium-grained ($\sim 0.25\text{-}2.5\text{ mm}$), porphyritic quartz diorite, with a color index of 65. Rocks contain mostly hornblende ($\sim 47\%$) and plagioclase ($\sim 30\%$), with minor biotite ($\sim 15\%$) and quartz ($\sim 5\%$), and accessory apatite ($\leq 2\%$) and iron oxides ($\leq 1\%$) (Fig. 12). Biotite and hornblende are set in a matrix of mostly plagioclase and quartz. There are a few $1\text{-}2.5\text{ mm}$ plagioclase phenocrysts with normal growth zoning, which are heavily sericitized and/or overprinted by deformation twinning.

Figure 10. Photographs of Snow Lake block xenoliths. Xenoliths are located in the margin of the Kinney Lakes granodiorite. A) Foliated quartzite. Xenolith boundaries (red lines) and solid-state foliation (black lines) highlighted. B) Snow Lake quartzite. Note steep dips. Hammer and 52 mm lens cap for scale.

Figure 11. Photomicrographs of Snow Lake metasedimentary xenoliths. A) Quartzite. B) Foliated micaceous quartzite. Note chessboard extinction. C) and D) Muscovite schist with abundant iron oxides. Scale applies to all photomicrographs.

Figure 12. Photomicrograph of quartz diorite host rock. Hornblende and biotite laths are set within a matrix of plagioclase and minor quartz.

Bummers Flat Granodiorite

The ~109 Ma Bummers Flat granodiorite is a medium- to coarse-grained, porphyritic biotite granodiorite with a color index of 18-35. The granodiorite contains conspicuous, ≤ 2 cm, quartz and K-feldspar phenocrysts. Enclaves, schlieren, and mafic bodies are found throughout the granodiorite. Compositional and textural variations also occur throughout the granodiorite, but mappable granodiorite subunits have not been recognized. Numerous map-scale “mafic” bodies are, however, enclosed within the granodiorite in the study area and display varying contact relationships with the granodiorite. Previous workers (Huber, 1983) have referred to these bodies as diorites and gabbros, but among these bodies are also tonalitic bodies comagmatic with the granodiorites.

The Bummers Flat granodiorite consists mostly of quartz (~40%), plagioclase (25-30%), K-feldspar (~10-20%), and biotite (10-15%) (Fig. 13). Subhedral to anhedral quartz grains range in length from 0.1-20 mm, and occur as both as part of the fine-grained (0.1-2 mm) matrix and as local phenocrysts (2-20 mm). Checkerboard subgrains, polygonal grain boundaries, and undulatory extinction are widespread. Euhedral to subhedral plagioclase laths range in length from 0.1-6 mm, and average 1-2 mm. Plagioclase locally forms phenocrysts, which commonly enclose biotite and quartz. Normal zoning is common and oscillatory zoning occurs locally. Deformation twinning is ubiquitous. Euhedral to subhedral K-feldspar ranges in length from 0.1-20 mm, and average 2-5 mm. K-feldspar locally occurs as phenocrysts, and commonly encloses biotite and plagioclase. Carlsbad and scotch-plaid twinning are ubiquitous. Seritization is common. Biotite is 0.2-1.5 mm in length, and occurs interstitially or is enclosed locally within quartz, plagioclase, and K-feldspar phenocrysts. Accessory minerals present include apatite, sphene, and iron oxides.

Figure 13. Photomicrograph of typical Bummers Flat granodiorite. Note growth zoning in plagioclase.

A 2-km-long by 1-km-wide protrusion of the Bummers Flat granodiorite penetrates the Kinney Lakes granodiorite (Plate 1), and is referred to informally as the “thumb.” It contains mafic bodies with pygmatically folded quartz veins. Solid-state foliations within the “thumb” strike mostly due north, slightly oblique ($\sim 10^\circ$) to magmatic foliations in the Bummers Flat granodiorite ($\sim 349^\circ$, steeply dipping). Foliations in the “thumb” are also discordant to those in the surrounding Kinney Lakes granodiorite. The Bummers Flat “thumb” is widely intruded by felsic dikes (Fig. 14).

Map-scale mafic bodies within the Bummers Flat granodiorite display variable contact relationships with the surrounding rock. Mafic rocks either occur as angular fragments and predate the host Bummers Flat granodiorite (Fig. 15), or display diffuse boundaries and other features suggestive of mixing and mingling with the surrounding granodiorite (Fig. 16).

Mafic rocks that have been broken into angular fragments are prominent throughout Bummers Flat granodiorite. They occur as small xenoliths to mappable bodies. These angular bodies have an equigranular, fine-grained texture, but also occur as coarse-grained rocks with abundant epidote hydrothermal alteration. The mafic rocks range from hornblende-biotite tonalite to quartz diorite and consist of plagioclase ($\sim 35\%$), hornblende ($\sim 30\%$), biotite ($\sim 15\%$), quartz ($\sim 10\%$), and secondary chlorite (10%), with a color index of ~ 55 . These rocks exhibit sharp, chilled boundaries with the enclosing granodiorite, and commonly are undeformed, whereas the surrounding rocks recording contain magmatic foliation and/or folds or boudins. They are abundantly intruded by quartz-rich veins. Foliation is absent within the angular mafic rocks, but their long axes commonly trend parallel to the regional foliation.

Mafic rocks exhibiting inferred mixing and mingling relationships with the granodiorite are common throughout the Bummers Flat unit. These mafic rocks

Figure 14. Outcrop photograph of the Bummers Flat "thumb". Photograph was taken near the eastern contact with the Kinney Lakes granodiorite, looking south. Light gray rock is Bummers Flat granodiorite with solid-state fabrics. Mafic rocks characteristic of the Bummers Flat granodiorite are seen in the left corner. Note multiple generations of felsic dikes. Person for scale.

Figure 15. Older mafic rocks in the Bummers Flat granodiorite.
A) Blocks of mafic rocks within the Bummers Flat granodiorite.
B) Folded felsic veinlets within fine-grained mafic rock. Pencil and 52 mm diameter lens cap for scale.

Figure 16. Co-magmatic mafic rocks of Bummers Flat granodiorite. A) Multiple mafic intrusions with varying color indices parallel to magmatic foliation. B) Inferred hybridization of mafic rocks and granodiorite (Kbf). Note strong banding within the hybrid zone. 52 mm in diameter lens cap for scale.

have diffuse and ‘wispy’ boundaries with the surrounding granodiorite (Fig. 16). Co-magmatic mafic rocks commonly have a pronounced foliation similar to the surrounding granodiorite. They are porphyritic, fine-to-coarse grained, hornblende-biotite granodiorites and tonalites. They have a color index of ≤ 35 , and consist of plagioclase (~25-35%), quartz (~20-45%), K-feldspar (~0-14%), hornblende (~5-15%), and biotite (~10-15%), and trace amounts of accessory apatite and iron oxides. Chlorite is common, making up close to 10% of the rocks. Overall, these mafic rocks are interpreted to be related to the Bummers Flat granodiorite on the basis of their contact relationships and similar mineralogy; however, they are distinguished from typical Bummers Flat granodiorite by their abundant hornblende and higher color index.

Schlieren within Bummers Flat granodiorite are mostly discontinuous (Fig. 17). They are common near the Tom’s Canyon pendant next to zones of packed phenocrysts, and between two compositionally or texturally different types of Bummers Flat rocks. Ring-like schlieren also occur locally.

Sonora Pass Intrusive Suite

The ~95-88 Ma Sonora Pass intrusive suite is composed of the Kinney Lakes granodiorite and the younger Topaz Lake granodiorite. Rocks of the Sonora Pass intrusive suite intruded the Snow Lake metasedimentary rocks, older diorites, and the ~109 Ma Bummers Flat granodiorite.

Kinney Lakes Granodiorite

The ~95-92 Ma (U/Pb SHRIMP-RG) (see Fig. 8) Kinney Lakes unit is an equigranular to porphyritic, medium- to coarse-grained, biotite-hornblende to hornblende-biotite granodiorite, but also includes minor monzogranite and tonalite. The color index ranges between 10-30, and is typically 20. Compositional and textural variations occur throughout the Kinney Lakes granodiorite. Enclaves, schlieren and mafic bodies are also

Figure 17. Schlieren in the Bummers Flat granodiorite. A) Planar schlieren disrupted by chaotic schlieren and then truncated by granodiorite. B) Trough-like schlieren with accumulated plagioclase phenocrysts in the center. C) Banded schlieren, truncated by younger schlieren. D) Tube or ring schlieren with sharp internal boundaries and more diffuse outer boundaries. Pencils and 52 mm diameter lens cap for scale.

found throughout the unit, but are considerably more abundant in the eastern study area. The granodiorite is intruded by the Topaz Lake granodiorite to the north and east.

The Kinney Lakes granodiorite consists mostly of quartz (20-35%), plagioclase (20-40%), K-feldspar (15-30%), biotite (8-15%), hornblende (3-15%), and sphene ($\leq 1\%$) (Fig. 18). Quartz is mostly interstitial, ranging from 0.1-3 mm, but also occurs as 3-6 mm phenocrysts. Tabular plagioclase ranges between 0.5-6 mm in length, and averages 2-3 mm. It locally forms phenocrysts, but is mostly interstitial. Normal zoning is common. Plagioclase commonly is poikilitic with euhedral inclusions of biotite. Plagioclase shows minor sericitic alteration of its cores and deformation twinning. K-feldspar crystals range in length from 1-10 mm, and average ~ 5 mm. K-feldspar is rarely interstitial, and mostly forms zoned phenocrysts, which commonly contain concentrically arranged, euhedral to anhedral inclusions of biotite, hornblende, and quartz. Carlsbad twinning, scotch-plaid twinning and perthite are ubiquitous with seritization common. Biotite ranges in length from 0.25-6 mm, forming euhedral to subhedral crystals. Biotite and hornblende commonly have undergone minor chloritization. Hornblende laths range in length from 0.25-6 mm. Crystals are typically euhedral to subhedral, and locally form phenocrysts that commonly enclose plagioclase and biotite. Sphene forms euhedral, wedge-shaped to anhedral crystals, and ranges in length from 0.1-2.5 mm. Sphene is widespread and helps distinguish the Kinney Lakes granodiorite from other plutons in the study area, due to its abundance and larger size. Zircon, apatite, and iron oxides occur in trace amounts.

Mafic schlieren are widespread within the Kinney Lakes granodiorite. They are mostly concentrated near marginal and internal contacts, and also concentrated in a 200-m-wide and 1-km-long zone in the interior of the pluton (see Plate 1). The schlieren are mostly discontinuous and sub-planar to planar. Some, however, are curved, concentric, intricately disrupted, or openly to tightly folded.

Figure 18. Typical Kinney Lakes granodiorite. A) Outcrop view. Note aligned mafic minerals. B) Photomicrograph under crossed-polars.

Schlieren are defined by thin (0.25-20 cm), alternating layers of mafic and felsic mineral accumulations. Color index ranges from 10-90. Mafic layers are defined by euhedral, 1.5-5-mm-long hornblende, 0.5-2.5-mm-long biotite, and 1-4-mm-long wedge-shaped sphene. Mafic minerals within schlieren are strongly aligned parallel to magmatic foliation, and schlieren as a whole are also parallel to magmatic foliations. Contacts between layers range from sharp to diffuse over a mm to cm scale. The majority of schlieren measured dip variably towards the north, and the few discontinuous schlieren that dip to the south trend broadly concordant to the contact with the Topaz Lake granodiorite.

Sub-units of Kinney Lakes Granodiorite

Kinney Lakes granodiorite displays variable textures and modes. Within its margin, the granodiorite is finer-grained, more equigranular, has a lower color index, is devoid of mafic rocks and schlieren, and displays margin-parallel fabrics and the best developed solid-state deformation. In the interior, the Kinney Lakes granodiorite is equigranular to porphyritic, contains widespread, continuous to discontinuous schlieren, abundant small mafic bodies, mafic enclave swarms, and dispersed enclaves. Foliations transition from weak solid-state to magmatic inwards. Near the contact with Topaz Lake granodiorite, the Kinney Lakes granodiorite is coarse-grained and porphyritic, contains minor wispy schlieren and enclaves, and has higher abundances of K-feldspar. K-feldspar mostly forms as <1 cm phenocrysts.

On the basis of color index and contact relationships, the Kinney Lakes granodiorite can be divided into three sub-types: 1) mafic granodiorite; 2) felsic granodiorite; and 3) late granite dikes. Although distinguished in this thesis, the different sub-types were not mapped separately due to the scale of mapping.

Kinney Lakes Mafic Granodiorite. The Kinney Lakes mafic granodiorite (Fig. 19) is a dark-gray, equigranular to porphyritic, fine- to coarse-grained biotite-hornblende granodiorite to hornblende-biotite tonalite with a color index of 30-50. Mafic rocks in the unit occur as outcrop to map-sized bodies. They are concentrated near the main internal contact with Topaz Lake granodiorite, or within or near schlieren. On the basis of contact relationships, mafic rocks are either younger or co-magmatic with the granodiorite.

The mafic granodiorite is composed of plagioclase (~25%), quartz (~20%), K-feldspar (~15%), biotite (10-25%), hornblende (15-20%), and sphene ($\leq 1\%$). The tonalites are dominantly composed of plagioclase (~35%), quartz (~10%), K-feldspar (5%), hornblende (~35%), and biotite (~15%) (Fig. 19C).

The larger bodies of mafic granodiorite range in length from 25 m to 300 m, and are found everywhere except the outer margin. Coarse-grained, mafic bodies are small (25-50 m in length), porphyritic, and have diffuse contacts with the surrounding granodiorite (Fig. 19A). They have only been found in the western study area, near abundant schlieren. Fine-grained mafic bodies are found in the eastern study area as outcrop-sized bodies (≤ 10 s of m) or as large as 200-m-long porphyritic bodies containing plagioclase phenocrysts set in a fine-grained groundmass of anhedral quartz, plagioclase, biotite, and hornblende.

Within the eastern study area, mafic enclaves are abundant ~ 500 m from the margin to the unit center. Enclaves are typically lenticular to elongate, 3 cm to 50 cm long, and elongate parallel to surrounding foliations. Enclave density distribution is mostly 3 to 4 enclaves per square meter. Some enclaves occur in swarms. Individual enclaves within swarms are ellipsoidal in shape and vary in size from several cm to 10s of cm.

Figure 19. Photographs and photomicrograph of mafic Kinney Lakes granodiorite and tonalite.

A) Coarse-grained biotite-hornblende granodiorite on right (C.I.=30) and typical Kinney Lakes granodiorite on left. B) Fine-grained biotite-hornblende tonalite (C.I.=50) in typical Kinney Lakes granodiorite. Note strong foliation in mafic rocks and sharp contacts. C) Mafic tonalite. Note abundant plagioclase. 52 mm in diameter lens cap for scale in A) and B).

Kinney Lakes Felsic Granodiorite. The Kinney Lakes felsic granodiorite is an equigranular to porphyritic, fine- to medium-grained rock with a color index of ~3-10. It has a bright-white appearance in outcrop (Fig. 20). This granodiorite is abundant within the margin of Kinney Lakes granodiorite in the western study area, but is absent within the eastern study area. Enclaves, schlieren, and metasedimentary xenoliths occur rarely. Contacts between the felsic granodiorite and typical Kinney Lakes granodiorite are cryptic and likely gradational over 10s of m.

The Kinney Lakes felsic granodiorite consists of plagioclase (~40%), quartz (~40%), K-feldspar (~8%), biotite (~7%), hornblende (~4%), and accessory minerals ($\leq 1\%$) such as sphene, apatite, and iron oxides (Fig. 20). Myrmekite is widespread. Euhedral to subhedral plagioclase grains range from 0.5-3 mm, average 2-3 mm, and locally form phenocrysts. Normal zoning is common within the phenocrysts. Seritization of plagioclase cores is common and deformation twinning is widespread. Anhedral to subhedral quartz grains range from 0.1-3 mm. Quartz locally forms phenocrysts, but mostly occurs within the fine-grained matrix. Quartz underwent minor recrystallization and displays undulatory to weak chessboard extinction. K-feldspar ranges in length from 0.5-2 mm. Crystals are typically subhedral to anhedral, and locally form phenocrysts that enclose anhedral quartz, and euhedral biotite and hornblende. Scotch-plaid twinning and seritization are common. Biotite grains are 0.25-3 mm long and range from euhedral to anhedral. Hornblende grains are 0.5-2 mm long, range from euhedral to anhedral, and occur locally as ragged, altered phenocrysts. Minor chloritization affects the mafic minerals.

Magmatic foliation is well-defined by the alignment of hornblende and biotite and is mostly NW-trending and steeply dipping. Solid-state fabrics were not observed within the Kinney Lakes felsic granodiorite.

Figure 20. Kinney Lakes felsic granodiorite. A) Outcrop photograph of felsic granodiorite (right) in contact with banded mafic granodiorite (left). 52 mm in diameter lens cap for scale. B) Photomicrograph under crossed-polars. Note abundance of plagioclase and quartz, and skeletal hornblende (red arrow).

Planar schlieren that occur at a few locations within the felsic granodiorite generally strike northwest and mafic layers have sharp southwestern boundaries. Trough-like schlieren imply a younging direction to the northeast.

Late Granite Dikes. Felsic dikes intrude and sharply cross-cut fabrics within the Kinney Lakes granodiorite, Bummers Flat granodiorite, and the Snow Lake block. They are fine- to coarse-grained, porphyritic biotite granite with a color index of ≤ 3 . These dikes occur sporadically in the study area, but are mostly concentrated near the margins of the Kinney Lakes granodiorite. Granite dikes consist mostly of quartz (40-45%), K-feldspar (35-45%), plagioclase (10-15%), and biotite (3-5%) (Fig. 21). Anhedral quartz grains vary from 0.1-5 mm and locally form phenocrysts, but are mostly interstitial. Checkerboard sub-grains and recrystallized grains, with polygonal grain boundaries, are widespread. K-feldspar grains typically are 1.5-7.5 mm in length, and mostly occur as poikilitic phenocrysts containing inclusions of anhedral quartz, and euhedral to subhedral muscovite. Myrmekite is common. Carlsbad twinning, scotch-plaid twinning and perthite are ubiquitous with seritization common. Anhedral to subhedral plagioclase laths typically are 0.1-5 mm in length, and locally occur as phenocrysts. Normal growth zoning is present, but strongly overprinted by deformation twinning and sericite. Biotite is 0.5-3 mm long, and mostly interstitial.

Topaz Lake Granodiorite

The ~92-88 Ma (SHRIMP-RG) Topaz Lake granodiorite is a light gray to tan (where weathered), porphyritic, medium- to coarse-grained biotite granodiorite to monzogranite with a color index of 4-20, but normally ~10 (Fig. 22). The Topaz Lake granodiorite intruded the Kinney Lakes granodiorite in a concentric pattern to the south and west within the study area. Schlieren, phenocryst accumulations, mafic enclaves,

Figure 21. Photomicrographs of late granite dikes. A) Coarse-grained dike. Note chessboard extinction of quartz and poikilitic K-feldspar. B) Fine-grained dike. Note K-feldspar abundance. Scale applies to both photomicrographs.

Figure 22. Outcrop photographs of Topaz Lake granodiorite. A) Porphyritic granodiorite. Note enclaves are associated with the contact with Kinney Lakes granodiorite. Photograph was taken near the contact. B) Megacrystic granodiorite. Note K-feldspar sizes. 52 mm diameter lens cap for scale in both photographs.

and other magmatic features are found throughout the granodiorite. Compositions and textures vary, but mappable subunits have not been recognized, and the granodiorite is more homogenous than the Kinney Lakes granodiorite.

The Topaz Lake granodiorite consists mostly of plagioclase (25-40%), quartz (20-40%), K-feldspar (10-40%), biotite (3-10%), hornblende (1-10%), and sphene ($\leq 1\%$) (Fig. 23). Euhedral to subhedral plagioclase grains range from 1.5-10 mm in length. Plagioclase locally forms euhedral phenocrysts. Normal zoning is common and oscillatory zoning occurs locally (Fig. 23). Deformation twins and seritization of cores is common within plagioclase, and myrmekite occurs locally. Subhedral to anhedral quartz ranges from 0.5-6 mm in diameter and averages 3 mm. Quartz locally forms phenocrysts, which enclose hornblende, plagioclase, and sphene. Most rocks show checkerboard subgrains, and minor grain boundary migration and recrystallization. K-feldspar ranges in length from 1.5-90 mm, predominantly forms phenocrysts, but occurs in the matrix as well. The phenocrysts commonly contain concentrically-arranged euhedral to anhedral inclusions of biotite, sphene, quartz, and plagioclase. Carlsbad twinning, scotch-plaid twinning and perthite are ubiquitous with seritization common. Biotite occurs as euhedral books, typically 0.5-6 mm in length. It forms local phenocrysts, with euhedral to anhedral inclusions of quartz, plagioclase, and apatite. Biotite also occurs interstitially. Many grains of biotite are weakly chloritized. Hornblende is less common in the Topaz Lake granodiorite than in the Kinney Lakes granodiorite, and decreases in abundance away from the contact with the outer granodiorite. It is 0.25-4 mm long, and euhedral to anhedral. Hornblende laths are skeletal, patchy, and partially chloritized. Sparse sphene ranges from 1.5-20 mm in length. Zircon, apatite, and secondary epidote are present in trace amounts.

Weak magmatic foliation is defined by aligned biotite and locally by tabular plagioclase and sphene. Solid-state foliation is absent.

Figure 23. Photomicrographs of Topaz Lake granodiorite. A) Porphyritic granodiorite. B) Megacrystic granodiorite. Note poikilitic K-feldspar left of center. Scale applies to both photomicrographs.

Schlieren are abundant in the Topaz Lake granodiorite near the contact with Kinney Lake granodiorite, but are scarce to non-existent within the megacrystic rocks (Fig. 24). Schlieren measured within the study area trend roughly E-W, and dip moderately to the south. K-feldspar phenocrysts are strongly aligned in schlieren, but show no preferred orientation outside of the schlieren. Schlieren are typically discontinuous in length (<10 m) and <1 m wide, but where continuous, swaths can be traced for over 100-m, and are greater than 3-m-wide. Within the thicker and longer schlieren swaths, K-feldspar phenocrysts are densely packed against the margins of schlieren.

Magmatic tubes, sheets, and graded K-feldspar phenocryst accumulations occur locally within the Topaz Lake granodiorite (Fig. 25). Most are isolated, but these structures are common in at least one area southeast of Granite Dome (Plate 1).

Mafic enclaves are rare within the Topaz Lake granodiorite and much less common than in the Kinney Lakes granodiorite. They typically occur with schlieren, and near the Kinney Lakes contact. These enclaves also have a lower color index than those in the Kinney Lakes granodiorite.

STRUCTURE

This chapter describes the structure of all units, and begins with the oldest rocks.

Host Rocks of the Sonora Pass Intrusive Suite

Pre-Cretaceous Rocks

Tom's Canyon Pendant. The 10-100 m-wide, >2.5-km-long metasedimentary pendant within the Bummers Flat granodiorite strikes mostly N to NW, with steep to vertical dips. Well-developed foliation has an average strike of 173° and dip of 79° to the west. Lineation averages 71°/225° (Fig. 26). The pendant contacts are parallel to

Figure 25. Magmatic structures in the Topaz Lake granodiorite. A) Tube-like structure with a K-feldspar accumulation surrounded by schlieren. B) Magmatic pipe of coarse-grained K-feldspar. Exposure is sub-vertical. Photograph is about 3 m wide.

Figure 26. Stereographic projection of lineation and poles to foliation in metasedimentary host rock and xenoliths.

magmatic foliations within the Bummers Flat granodiorite. The pendant is intruded by Bummers Flat granodioritic dikes that are boudinaged or exhibit pinch and swell structure (Fig. 5B). These granodioritic dikes may be the “quartzite lenses” of Huber (1983).

Twenty-five m by 50 m metasedimentary xenoliths are enclosed in the Bummers Flat granodiorite about 100-200 m west of the northern part of the Tom’s Canyon pendant. Foliation and lineation in the xenoliths are discordant to that in the pendant. For example, one xenolith has a difference of $\sim 45^\circ$ in foliation strike and of $\sim 25^\circ$ in lineation plunge.

Snow Lake Block. A 7 km² metasedimentary body of the Snow Lake block is located in the eastern study area. Within the main body, foliations strike N-NW and dip moderately ($50-70^\circ$) (Wahrhaftig, 2000). Xenoliths of the Snow Lake block occur within the margin of the Sonora Pass intrusive suite, and range from 10 cm to 100 m across strike and from 10 cm to 300 m along strike. They are found as far as 1 km from the main body. The long axes of xenoliths strike parallel to the margin, and dip moderately to steeply ($59-70^\circ$) to the north. Strong foliation in the xenoliths is parallel to solid-state foliation within the host Kinney Lakes granodiorite.

Xenoliths of the Snow Lake block have irregular, ‘wispy’ boundaries (Fig. 27). Directly in contact and extending for 30 cm from the xenoliths, solid-state foliations within the Kinney Lakes granodiorite deflect around the xenoliths (Figs. 10 and 27). Elongation of quartz and darker inclusions within the xenoliths is common (Fig. 28).

Older Mafic Rocks. The older, scattered bodies of diorite and quartz diorite adjacent to the Snow Lake block are weakly foliated. Foliation averages $155^\circ/82^\circ$ SW within the largest body. Hundreds of quartz diorite to diorite xenoliths, ranging in length from centimeters to meters, have angular, sharp contacts with the surrounding Kinney Lakes granodiorite (Fig. 29), and the long axes of the xenoliths have no preferred orientation. The xenoliths also lack an internal foliation.

Figure 27. Fabrics within a Snow Lake block xenolith. A) Typical outcrop. B) Inset displays internal fabrics. Note small ductile shear zones defined by deflected, asymmetric dark inclusions, and elongation of quartz lenses and the dark inclusions (black arrows). 52 mm diameter lens cap for scale.

Figure 28. Contact between Kinney Lakes granodiorite and foliated quartzite xenolith. Arrows point to elongated quartz. 52 mm diameter lens cap for scale.

Figure 29. Quartz diorite to diorite xenoliths in the marginal Kinney Lakes granodiorite. A) Typical outcrop exposure. Hammer for scale. B) Zone of concentrated xenoliths.

Bummers Flat Granodiorite

The Bummers Flat granodiorite displays both magmatic and solid-state structures, and has complex relationships with co-magmatic to older mafic bodies and late felsic dikes. This unit was studied within 3 km of the Sonora Pass intrusive suite in the western study area, and it is not known if the relationships described here characterize the entire pluton.

Magmatic Structure. Mafic Rocks. Many mafic rocks in the Bummers Flat granodiorite are intruded by felsic to granodioritic veins and dikes. Two structural relationships are recorded depending on the orientation of the injections. Some of the veins and dikes that strike N-NW are boudinaged or exhibit pinch-and-swell structures, whereas those that strike E-W are tightly folded (Fig. 30). Fold hinge lines in these bodies trend mostly northwest ($300\text{--}320^\circ$) with a few trending southwest ($200\text{--}215^\circ$), and are moderately to steeply plunging. Folds are predominantly tight to isoclinal with wavelengths of 20-50 cm (Fig. 30). Folds mostly exhibit thickening within their hinges, and many are cross-cut by straight veins parallel to magmatic foliation.

Dynamic Magmatic Zones. These zones are defined as heterogeneous areas of Bummers Flat granodiorite marked by mafic intrusive sheets, widespread evidence for co-mingling of magmas, magmatic shear zones, and diorite and metasedimentary (schist and calc-silicate) xenoliths. Many different contact and structural relationships exist within these zones, which are found near the Tom's Canyon metasedimentary pendant.

The largest of these zones is located ~100 m east of the Tom's Canyon pendant. Here, Bummers Flat granodiorite and co-magmatic mafic sheets (~0.25-1 m thick) appear to co-mingle (Fig. 31). Mafic sheets have gradational to 'wispy' contacts with granodiorite and are elongate in a N-NW direction, parallel to magmatic foliations, and

Figure 31. Dynamic magma zone within Bummers Flat granodiorite.
Note mafic rocks within the granodiorite.

most dip steeply. Within the co-mingled sheets are metasedimentary and diorite xenoliths, ranging from centimeters to a few meters long. These xenoliths also have ‘wispy’ boundaries with the surrounding rocks. About 10 m west of this zone, co-magmatic mafic sheets striking parallel to magmatic foliation are boudinaged, or exhibit pinch-and-swell structure. In one place, boudinaged mafic sheets wrap around angular diorite xenoliths. Mafic sheets at this location have sharp contacts with the surrounding granodiorite. About 5 m west of these sheets, large rheological contrasts are illustrated by the juxtaposition of more angular diorite xenoliths and strongly foliated granodiorite.

Foliation and Lineation. Magmatic foliations in the Bummers Flat granodiorite strike mostly N-NW, averaging 349° , and dip steeply to the NE or SW (Fig. 32). Foliations are defined by the alignment of biotite and plagioclase. Magmatic foliation changes locally in orientation and intensity. Complex foliation orientations are found near schlieren, mafic bodies, dynamic magma zones, shear zones, and metasedimentary xenoliths.

Late Felsic Dikes. Bummers Flat granodiorite is widely intruded by felsic dikes that range in thickness from 1 cm to 50 m, and can be traced for up to 500 m. The dikes mostly have steep dips and a wide range of strikes (Fig. 33). Dikes have sharp contacts with the granodiorite (Fig. 34C), and cut magmatic and solid-state foliations of the pluton. In some locations, however, they are offset by magmatic faults (Fig. 34A) or shear zones.

The greatest concentration of felsic dikes in the Bummers Flat granodiorite is near the eastern contact with the Kinney Lakes granodiorite (Plate 1). In this area, felsic dikes occur in swarms, and in some locations make-up nearly 50% of the outcrop (Fig. 35B). Dikes mostly strike SW or N, and dip steeply. These dikes commonly brecciate and isolate pieces of granodiorite (Fig. 35A). Many of the dikes contain internal flow banding

B) Lineations and poles to solid-state foliations.

Figure 33. Poles of felsic dikes in the study area. Note the variable orientations of dikes within each unit.

Figure 34. Outcrop photographs of felsic dikes intruding the Bummers Flat granodiorite. A) Dike cross-cutting foliation within the Toe Jam Lake shear zone. Red pencil is parallel to solid-state foliation. Note more leucocratic margins in dike. Dike likely was offset by a magmatic faults. B) Felsic dike containing mafic and granodiorite xenoliths. C) Typical outcrop of a felsic dike. 52 mm lens cap for scale.

Figure 35. Outcrop photographs of felsic dikes near the contact with Kinney Lakes granodiorite. A) An isolated xenolith of Bummers Flat granodiorite with solid-state foliation contained in a felsic dike. Note sharp corners of xenolith. B) Felsic dike zone. Darker rocks are Bummers Flat granodiorite. Photograph is ~2 m wide. C) Internal flow banding. Red pencil for scale.

(Fig. 35C), and are surrounded by thin, wispy schlieren directly outside of the dike walls. In addition, there are multiple generations of felsic dikes that cross-cut each other near the Kinney Lakes contact.

Another type of felsic dike that intrudes the Bummers Flat granodiorite has sharp contacts and contains xenoliths. The xenoliths are fine- to coarse-grained, relatively mafic rocks (C.I. >30), or coarse-grained hornblende granodiorite, similar to the Bummers Flat granodiorite. The felsic (C.I. <10) matrix contains 1-3 mm hornblende crystals strongly aligned parallel to the dike wall (Fig. 34B). These dikes cross-cut magmatic and solid-state foliations of the Bummers Flat granodiorite at roughly right angles.

Solid-State Structure. Ductile shear zones. Ductile shear zones are found throughout the Bummers Flat granodiorite, but are concentrated in the Toe Jam Lake shear zone. They range from 10s of cm to ≥ 3 km in length, and range in width from a few cm to ~300 m (Fig. 36 and Plate 1). Magmatic features, such as enclaves, mafic bodies, and magmatic foliation, are truncated and deformed by ductile shear zones. Shear zones trend mostly N-NW and dip steeply to vertical, but locally vary in orientation. Lineation plunges from 30-75°. Displacement of smaller shear zones range from 1 cm to 9 m, and the Toe Jam Lake shear zone has an unknown, but likely much greater displacement.

The Toe Jam Lake ductile shear zone deforms the Bummers Flat granodiorite ~200-500 m from the contact with Kinney Lakes granodiorite. The shear zone is ~300 m wide and 3 km long in the study area, continues for at least several kilometers along strike to the southeast (Turner and Miller, 2016), and for an unknown distance to the northwest. The Toe Jam Lake shear zone strikes NW and dips steeply to the SW. Lineation plunges steeply to the west. Well developed S-C fabrics are dominantly defined by biotite and quartz (Fig. 37). These fabrics are associated with abundant σ -type porphyroclasts of plagioclase and record west-side-up reverse slip. .

Figure 36. Outcrop photographs of ductile shear zones. A) Typical outcrop. Note curvature of foliation and mafic enclaves. B) Grain-size reduction and slight curvature of foliation in a shear zone. Pencils and 52 mm in diameter lens cap for scale.

Figure 37. Outcrop photographs of the Toe Jam Lake shear zone. A) Blue pencil denotes strong lineation in the foliation surface. B) Intense solid-state fabric cut by a felsic dike of Kinney Lakes granodiorite.

Microstructural analysis of rocks within the Toe Jam Lake shear zone and associated smaller shear zones indicates extensive solid-state deformation of quartz, plagioclase, and K-feldspar. Quartz grains in and adjacent to shear zones display a variety of microstructures (Fig. 38). These include chessboard subgrains, slight bulging recrystallization, irregularly-shaped grain boundaries due to grain boundary migration, and in some cases complete recrystallization to polygonal mosaics. Plagioclase and K-feldspar also show bulging recrystallization, and grain boundary migration, which implies deformation temperatures likely exceeded $\sim 500^{\circ}\text{C}$ (Hirth and Tullis, 1992; Kruhl, 1996). Overall, rocks within this shear zone experienced extensive recovery and recrystallization.

Foliation and Lineation. Solid-state foliations are found outside of ductile shear zones within the Bummers Flat granodiorite. They are defined by the elongation of plagioclase and K-feldspar, and particularly by biotite and quartz aggregates. Foliations predominantly strike N-NW and dip steeply (Fig. 32). Lineations plunge steeply. Solid-state foliations are mostly parallel to the contacts with the Kinney Lakes granodiorite (see Plate 1).

Sonora Pass Intrusive Suite

Kinney Lakes granodiorite

Magmatic and to a lesser extent solid-state structures provide insight into the construction and emplacement of the Kinney Lakes granodiorite. These structures include schlieren, magmatic and solid-state foliation and lineation, and felsic dikes.

Magmatic Structure. Schlieren. Within both study areas, Kinney Lakes granodiorite contains abundant schlieren. In the western study area, schlieren occur in two domains. One domain incompletely borders the Bummers Flat “thumb” (Plate 1). Swaths of schlieren, ranging from chaotic to planar, vary in thickness from 1 m to 100s

Figure 38. Photomicrograph of microstructure in the Toe Jam Lake shear zone. Note quartz porphyroblast, grain-size reduction of quartz and biotite (red arrows), grain boundary migration recrystallization of quartz (red circle), and myrmekitic texture (blue arrow).

of m, and are continuous in length from a few m to 100s of m (Fig. 39). Schlieren on the western border of the “thumb” have mostly west to south dips. Near the northern tip of the “thumb,” schlieren trending 137° truncate schlieren trending 280° . Schlieren troughs near the “thumb” consistently young towards the east or southeast, regardless of dip direction. Dispersed swaths of schlieren on the east side contain mafic enclaves and autoliths of granodiorite.

The second domain is located ~700-800 m east of the Bummers Flat “thumb”. Here, schlieren are more discontinuous and commonly folded, and are associated with abundant magmatic mafic enclaves (Fig. 40). Within this domain, there are schlieren swaths, tabular mafic enclave swarms, and felsic granodiorite sheets. The granodiorite sheets are ~30-100 m thick, and separate 1.5-5 m thick tabular mafic enclave swarms and swaths of schlieren. Schlieren swaths or tabular mafic enclave swarms are ~50-100 m in length. Felsic granodiorite sheets vary in strike from 330° to 60° , and dip steeply to the east.

Within the eastern study area, schlieren are most abundant in a swath near the contact with Topaz Lake granodiorite. This swath is 500-700 m wide and ~3 km long (Plate 1). Within this swath, individual schlieren are continuous in length from ~10 m to ~400 m (Fig. 41), with thicknesses varying from 1 m to 100s of m. Planar schlieren mostly strike E-W, and have moderate to steep dips ($58-74^{\circ}$) to the south. Schlieren troughs denote consistent younging to the south.

Magmatic Faults. Magmatic faults within Kinney Lakes granodiorite formed in the narrow septum of the granodiorite separating the “thumb” from the main body of Bummers Flat granodiorite. Faults offset felsic dikes from cms to a few m. Faults strike E-W, and have mostly vertical dips. Magmatic faults are also present ~50 m east of the Bummers Flat “thumb.” Here, faults displace folded schlieren.

Figure 39. Outcrop photographs of Kinney Lakes schlieren near the Bummers Flat “thumb.” A) Chaotic to semi-planar schlieren. Photograph is ~20 m wide. B) Moderately east-dipping, planar to semi-planar schlieren. Person for scale.

Figure 41. Outcrop photographs of Kinney Lakes schlieren in the eastern study area. A) Swath of schlieren, outlined in red, is 30 m thick, and extends for ~200 m. B) Photograph is a continuation of schlieren in (A). Photograph is looking NNW. Note planar layers. C) Another swath of schlieren extending for ~30 m along strike. Photograph is looking west. D) Continuous and planar schlieren.

Foliation and Lineation. Well-defined magmatic foliation and lineation occur throughout the Kinney Lakes granodiorite and are defined by the alignment of hornblende and biotite. Two sets of magmatic foliation occur within the granodiorite: 1) a more widespread, NW-trending, steeply dipping foliation; and 2) a less common, ENE-trending, steeply dipping foliation (Fig. 42A). Both sets of foliation have equal intensity and do not change intensity near contacts. Lineations in the granodiorite are steeply plunging.

Late Felsic Dikes. Late felsic dikes are abundant throughout the margin of the Kinney Lakes granodiorite and within the Bummers Flat “thumb,” but are less common towards the contact with Topaz Lake granodiorite. The felsic dikes generally lack a pronounced preferred orientation (Fig. 33), except in the eastern study area, where they strike ENE and dip steeply to the NNW. Here, dikes intrude along solid-state foliations and have chilled margins. In one locality, the dikes isolate xenoliths of Kinney Lakes granodiorite (Fig. 43B). A similar relationship is seen in the western study area, where dikes contain xenoliths of Bummers Flat granodiorite (Fig. 44). Multiple generations of dikes cross-cut each other and solid-state foliations in both the “thumb” and main body of the Bummers Flat granodiorite (Figs. 14 and 35).

Solid-State Structure. Foliation and Lineation. Strong solid-state foliations defined by the elongation of quartz, plagioclase, hornblende, and biotite occur in the Kinney Lakes granodiorite within the eastern study area. The most intense solid-state foliations in this area are near the metasedimentary and diorite contacts in the south. Here, foliations strike mostly ENE to NE, concordant with the host rock contact, and are steeply dipping (Plate 1 and Fig. 42). Enclaves and xenoliths within this area have also been extensively elongated parallel to the foliation. Solid-state foliation intensity gradually weakens northward and transitions to magmatic foliations ~1.5 km south of the Topaz Lake granodiorite contact. Solid-state foliations were not observed in the western area.

Figure 42. Stereographic plots of foliations and lineations within the Kinney Lakes granodiorite.

A) Lineations (red triangles) and poles to magmatic foliation (black circles). Kamb contour interval of 2σ .

B) Poles to solid-state foliation.

Figure 43. Outcrop photographs of coarse-grained felsic dikes in the Kinney Lakes granodiorite. A) Typical outcrop. B) Xenoliths of Kinney Lakes granodiorite are outlined by dotted black lines. Xenoliths have sharp contacts with the dikes and contain solid-state foliations. C) A series of dikes parallel to solid-state foliation. Dikes strike E-W and dip to the north. Person and 52 mm diameter lens cap for scale.

Figure 44. Photographs of Kinney Lakes felsic dikes intruding the Bummers Flat “thumb.” A) Fine-grained dike displaying sharp contacts with the Bummers Flat granodiorite. B) Sharp contact between a dike and Bummers Flat granodiorite. Foliation in the xenolith has rotated relative to foliation in granodiorite hosting the dike. 52 mm diameter lens cap for scale.

Microstructure. Analysis of the Kinney Lakes granodiorite possessing solid-state foliations indicate extensive deformation of quartz, plagioclase, and K-feldspar. (Fig. 45). Quartz displays a variety of microstructures, which include chessboard subgrains, tilt walls, and grain boundary migration and recrystallization. These microstructures suggest that deformation occurred at temperatures of at least 300° C (Hirth and Tullis, 1992; Kruhl, 1996). K-feldspar and plagioclase display recrystallized polygonal mosaics, extensive deformation twinning, and bulging recrystallization around grain edges. These microstructures suggest that deformation temperatures likely exceeded 500°C (Hirth and Tullis, 1992).

Topaz Lake Granodiorite

Foliation and Lineation. Magmatic foliations within the Topaz Lake granodiorite are weak. They mostly strike NW with steep (65-89°) SW or NE dips. A second, less common set of foliations strikes ENE with steep (65-89°) NNW or SSE dips (Fig. 46). Magmatic foliation in the granodiorite is defined mostly by aligned biotite books and K-feldspar phenocrysts. Lineations are very difficult to measure due to a lack of vertical exposure or weak intensity, but where measured, are generally steeply plunging.

CONTACTS

Host Rocks

Tom's Canyon Metasedimentary Pendant and Bummers Flat Granodiorite

The contact between the Tom's Canyon pendant and Bummers Flat granodiorite ranges from sharp to diffuse. It trends from 164-200°, dips steeply, and is parallel to magmatic foliations of the Bummers Flat granodiorite and to the nearby Toe Jam Lake shear zone (Plate 1). Sheets of Bummers Flat granodiorite intrude the pendant concordantly. Many of these granodiorite sheets have been boudinaged within the metasedimentary rocks (Fig. 5).

Figure 45. Photomicrographs of microstructures within the Kinney Lakes granodiorite. A) Chessboard extinction (red arrow), bulging recrystallization (red circle), and tilt walls (blue circle) are displayed by quartz grains. B) Strong bulging recrystallization of quartz (red circle). Scale applies to both photomicrographs.

Figure 46. Poles to magmatic foliation of the Topaz Lake granodiorite.
Kamb contour interval of 2σ .

Snow Lake Block, Older Mafic Rocks, and Kinney Lakes Granodiorite

The Kinney Lakes granodiorite is in contact with metasedimentary rocks and older quartz diorites in the eastern study area (Plate 1). The contact was traced for ~2.5 km, and is gradational over 100s of m. It trends between 255-275°, and likely dips moderately to steeply to the north. Solid-state foliations in the granodiorite are parallel to the contact. Xenolith abundance increases southward towards the contact.

Near the contact with the Snow Lake block, the abundant metasedimentary xenoliths in the Kinney Lakes granodiorite range in size from 10 cm to 100 m across strike and 10 cm to 300 m along strike. The long axes and internal foliations of the xenoliths are aligned parallel to the gradational contact and to the solid-state foliation within the granodiorite (see Snow Lake Block in STRUCTURE).

Angular quartz diorite xenoliths are also concentrated within the outer ~500 m of the Kinney Lakes granodiorite (Fig. 29 and Plate 1). The long axes of the xenoliths show no preferred alignment, and the xenoliths lack internal foliations.

Bummers Flat Granodiorite and Kinney Lakes Granodiorite

This contact ranges from sharp to gradational over 100s of m. Near the contact, each unit has a similar color index, and the characteristic quartz and plagioclase phenocrysts of the Bummers Flat granodiorite are absent, making it difficult to map the contact. Huber (1983) originally mapped this contact as a large, “thumb-shaped” protrusion of the Bummers Flat granodiorite in the Kinney Lakes granodiorite (Plate 1), and I concur, although I mapped the boundaries differently. On the eastern and northern sides of the “thumb,” the contact is sharp to gradational, and there are abundant schlieren in the Kinney Lakes granodiorite. Sharp contacts trend N-NW, and dip steeply to the west. On the western side of the “thumb,” schlieren are rare in the Kinney Lakes granodiorite, and numerous felsic sheets intrude the Bummers Flat granodiorite. Sheet

abundance on the west side decreases farther south, where the Kinney Lakes granodiorite gradually pinches out, and the rock returns to 50% or more of Bummers Flat granodiorite. Felsic sheets intrude up to 1 km south of the contact with the Bummers Flat granodiorite, and cross-cut solid-state foliations (Fig. 35).

Sonora Pass Intrusive Suite

Topaz Lake Granodiorite and Kinney Lakes Granodiorite

The major internal contact in the Sonora Pass intrusive suite is between the Topaz Lake and Kinney Lakes granodiorites. Its characteristics are consistent throughout the study area. The contact has variable trends, from 026°-045° in the eastern study area to ~145° in the western study area. The contact consistently dips steeply (77-80°) outwards towards Kinney Lakes granodiorite.

Next to the contact, the Topaz Lake granodiorite is defined by a 1.5-m-wide heterogeneous zone of rounded to ellipsoidal mafic enclaves, disrupted schlieren bands, and accumulations of euhedral hornblende, biotite, and sphene (Fig. 47). Enclaves range in length from a few cm to ~1 m, and have a color index of ~30. Topaz Lake granodiorite is largely homogenous inward from the narrow heterogeneous zone. Within the eastern study area foliations within the Topaz Lake rocks are slightly discordant (~25°) to the contact, whereas, in the western study area they are concordant.

Near the contact in the eastern study area, Kinney Lakes granodiorite is mostly homogenous with the exception of shallowly dipping (20°), strongly lineated schlieren within ~8 m of the contact. Schlieren trend ENE, parallel to the contact, but are discordant to foliations in the Kinney Lakes granodiorite (Fig. 48). Magmatic foliations are highly discordant (~85-90°) to the contact in the eastern study area, whereas in the western study area they are concordant.

Figure 47. Photograph of the Topaz Lake granodiorite (Ktl) and Kinney Lakes granodiorite (Kkl) contact. The contact is denoted by pencils and red dashed line. 52 mm diameter lens cap for scale. Photograph was taken in the eastern study area.

Figure 48. Outcrop photographs of schlieren in Kinney Lakes granodiorite near the Topaz Lake contact. A) Typical outcrop. B) Hornblende-defined lineation in schlieren. 52 mm in diameter lens cap for scale.

DISCUSSION

Plutons commonly record the magmatic and tectonic histories of an arc. In the following sections, I discuss mechanisms of pluton construction, material transfer processes operating during pluton emplacement, scenarios for foliation development, and the formation of other magmatic features within the plutons in the study area.

Construction of Plutons

Bummers Flat Granodiorite

The Bummers Flat granodiorite displays a wide range of compositional and textural heterogeneity throughout the study area. This heterogeneity and the lack of well-defined internal contacts implies construction via increments that intermingled but did not fully mix. The presence of schlieren supports this interpretation, as they likely formed in a crystal-rich dynamic magmatic system (e.g., Barriere, 1981; Paterson, 2009). Furthermore, the presence of a variety of Bummers Flat rocks in dynamic magma zones (see section in STRUCTURE) indicates the recycling of earlier parts of the system.

The numerous mafic rocks within the Bummers Flat unit have a wide range of rheological contrasts with the granodiorite. Coarse- to fine-grained diorite and local hornblendite have sharp contacts with the surrounding granodiorite. These mafic bodies may be temporally related to the southern diorites (e.g., Koguma Suite) in the eastern study area, which are considerably older than the Bummers Flat granodiorite. Alternatively, they may represent less-evolved magmas of the Bummers Flat system and be only slightly older than the granodiorite, but with a sufficient hiatus to explain the differences in rheology. I prefer the first explanation on the basis of the similarity in composition with the southern diorites. Precise dating is needed to test this interpretation.

Multiple intrusions of different types of granodiorite and mafic rocks typify the margin of the Bummers Flat granodiorite. In contrast to the older mafic rocks, mappable contacts were not distinguishable, the differing rock types have complex contact

relationships ranging from sharp and chilled, to co-mingled, to heterogeneously mixed, and it is difficult to establish timing relationships. In short, the Bummers Flat granodiorite records a complex construction history.

Sonora Pass Intrusive Suite

Kinney Lakes granodiorite. The Kinney Lakes granodiorite varies compositionally and texturally. It contains abundant mafic enclaves, mafic bodies, and schlieren throughout the study area.

Relatively mafic rocks ranging from mafic granodiorite to tonalite are ~25 m to 300 m in length and are scattered throughout the Kinney Lakes unit. Several coarse-grained mafic-rich granodiorite bodies, located centrally within the Kinney Lakes granodiorite in the western study area, have diffuse contacts with the surrounding granodiorite (see Fig. 19A). These relatively mafic rocks probably were, in part, coeval with the dominant granodiorite.

Mafic granodiorite bodies in the eastern study area are porphyritic (See Kinney Lakes mafic-rich granodiorite in UNIT DESCRIPTIONS) and have diffuse contacts with the host granodiorite. They differ texturally from the mafic granodiorite in the western study area. These porphyritic mafic bodies are probably related compositionally and share a similar source to coeval coarse-grained mafic bodies in the western study area, but likely record a different crystallization history.

Mafic enclaves are common in the Kinney Lakes granodiorite within both study areas, but their abundance changes abruptly near host rock contacts, where they disappear. The abundance of disaggregated mafic rocks throughout the pluton, especially in the eastern study area, suggests there was multiple inputs of mafic magma, which had variable degrees of interaction with the host granodiorite. It is unknown whether mafic magmas interacted with the granodioritic magma during ascent, at the emplacement level, or both.

Mafic schlieren are also common within both study areas, but are mostly restricted to internal contacts or to large mapped swaths (see Plate 1). Schlieren are thought to result from material sorting due to physical and chemical gradients (e.g., Pitcher, 1997; Barbey et al., 2008; Dietl et al., 2010), which can include: (1) the assimilation of host rock (Pitcher and Berger, 1972); (2) magma mingling (Frost and Mahood, 1987); (3) gravitational sedimentation of crystals (Irvine, 1987); or (4) flow segregation of crystals near boundaries, such as pluton-host rock contacts or intraplutonic contacts between individual magma pulses (Dietl et al., 2010).

Schlieren provide important information about magma dynamics and rheology (Wiebe et al., 2007). Within the western study area, schlieren surrounding the Bummers Flat “thumb” likely record flow against a rigid boundary, given the proximity to the contact, and strikes parallel to the contact. In contrast, within the eastern study area, a swath of schlieren ~500-700 m wide and 3 km long is not located near a host rock contact, nor any obvious intraplutonic contacts. The schlieren dip steeply, and given the absence of evidence in the Sonora Pass suite for large-scale rotation, gravitational sedimentation is highly unlikely; instead, the schlieren probably record shear flow of crystal-rich magma along a subtle internal contact (Wiebe et al., 2007).

Within the study area, the rough coincidence of schlieren concentrations and felsic injections in the western margin near the “thumb” is intriguing. The felsic rocks might represent residual melts that were extracted from Kinney Lakes mush. Geochemical data are needed to test this hypothesis.

Topaz Lake granodiorite. The voluminous Topaz Lake unit is mostly homogeneous, but contains mafic enclaves, K-feldspar phenocryst accumulations, and local schlieren, magmatic tubes, and pipes. Internal contacts are not recognized, but there is a gradual coarsening of K-feldspar phenocrysts farther from the contact with

Kinney Lakes granodiorite. Many of the internal magmatic structures within the Topaz Lake granodiorite likely formed by local magma flow through crystal-mush (Weinberg et al., 2001; Paterson, 2009), in an already amalgamated magma chamber(s). The lack of internal contacts, abundance of magmatic structures, and disaggregation of mafic rocks, suggests a sizable magma chamber or chambers formed at least periodically.

Emplacement Mechanisms

Models proposed to explain how host rock accommodates magma intruded into the crust include ductile flow, stoping, assimilation, roof uplift, floor subsidence, magmatic wedging, and tectonic dilation in faults and shear zones (e.g., Buddington 1959; Pitcher and Berger, 1972; Hutton, 1988; Paterson and Fowler, 1993; Paterson and Vernon, 1995; Cruden, 1998; Žák and Paterson, 2005; Yoshinobu et al., 2009; Saint Blanquat et al., 2011). In most cases, pluton emplacement requires mechanisms to operate synchronously at different rates, times, and scales. It is likely no single mechanism operates solely to accommodate intrusion. It should be noted that within the central Sierra Nevada batholith direct evidence of material transfer processes is limited (e.g., Bateman, 1992; McNulty et al., 2000; Žák and Paterson, 2005; Petsche, 2008; Johnson, 2013; Van Dyne, 2014).

A challenge faced when determining emplacement mechanisms of plutons is that there is generally much more of the original body that has been eroded away, or is below the current exposure level, than is exposed. This applies to the Sonora Pass intrusive suite. It was emplaced at pressures of 2.0-3.5 (± 0.6) kb or ~ 4 -11 km (Macias, 1996), which is similar to emplacement depths of the neighboring Tuolumne intrusive suite (~ 4 -11 km) (Ague and Brimhall, 1988; Gray, 2003; Memeti et al., 2010a; Paterson et al., 2011). Emplacement mechanisms vary by depth, and the shallow to mid-crustal depth of the Sonora Pass rocks presumably influenced the material transfer processes that operated during emplacement.

Stoping and Assimilation

Stoping operates as a material transfer process during the emplacement of many plutons (Hutton, 1982; Paterson and Fowler, 1993; McNulty et al., 1996; Paterson et al., 1996; Clarke et al., 1998; Yoshinobu et al., 2003; Paterson et al., 2012). It is likely restricted, however, in the volume of material transferred (Glazner and Bartley, 2006).

The best evidence of stoping in the study area is within the Kinney Lakes granodiorite, where xenoliths of all of its host rock units are present. In the eastern study area, several hundred xenoliths of Snow Lake metasedimentary rocks and older quartz diorites are exposed in the outer 500 m of the granodiorite. Most of the metasedimentary xenoliths probably underwent some partial assimilation during intrusion of Sonora Pass rocks, as they have wispy contacts with the surrounding Kinney Lakes granodiorite. Foliations in the metasedimentary xenoliths are discordant with those in the Snow Lake block, providing direct evidence of stoping. The size and abundance of xenoliths within the southeastern margin of the granodiorite indicates that stoping was significant, but probably not the dominant emplacement mechanism.

Hundreds of quartz diorite xenoliths are present within the Kinney Lakes granodiorite. The angularity and brecciation of these xenoliths indicate that they behaved differently than the metasedimentary ones. Due to their isotropic fabric, it is difficult to determine if the xenoliths have been rotated.

Another example of stoping by Kinney Lakes granodiorite is in the western study area, ~500 m north of the Bummers Flat “thumb” and 1 km from the contact with the main body of the Bummers Flat granodiorite. There, a zone about 10-15-m long and 5-m wide contains both metasedimentary and plutonic xenoliths of uncertain origin. Foliations in the xenoliths differ from the magmatic foliations in the host, implying rotation. This small zone of xenoliths demonstrates stoping occurred not only at the margin, but within the interior of the Kinney Lakes granodiorite.

Stoping is apparently much less important in other plutons within the study area. No evidence of stoping was observed where the Topaz Lake granodiorite intrudes the Kinney Lakes granodiorite. The Bummers Flat granodiorite incorporates a few xenoliths of the Tom's Canyon pendant. Foliation in the xenoliths have been rotated $\sim 20^\circ$ from that in the pendant, providing evidence of minor stoping.

Ductile Flow

Ductile flow of wall rock is cited as an important material transfer process during emplacement of the Sierra Nevada batholith (Saleeby, 1990; Paterson and Vernon, 1995; Paterson et al., 1996; Žák and Paterson, 2005). Structural aureoles are typically absent, however, and if major ductile flow did occur, it was obscured or erased by stoping or other material transfer processes.

Within the eastern study area, its contact with the Kinney Lakes granodiorite, the Snow Lake block is riddled by felsic dikes, presumably related to the granodiorite. Due to the abundance of dikes, difficult access, and poor exposure, foliations were not measured within the margin of the Snow Lake block. Foliations measured by previous workers at distances ≥ 200 m from the contact are discordant to solid-state foliations within Kinney Lakes granodiorite and to the contact (e.g., Lahren and Schweikert, 1990; Wahrhaftig, 2000). These foliations constrain the limit of a ductile aureole, but given the distance measurements were taken from the contact, the formation of a narrow ductile aureole cannot be ruled out.

Strong solid-state foliations, oriented parallel to the host rock contact, are found within the margin of the Kinney Lakes granodiorite. These foliations may record ductile flow caused by emplacement of younger, more internal Kinney Lakes magmas. Metasedimentary xenoliths within the marginal granodiorite contain foliations parallel to the solid-state foliations, but discordant to the foliations within the Snow Lake block

measured ≥ 200 m from the contact by previous workers. This relationship suggests that either the xenoliths were deformed after stopping, compatible with ductile flow, or that they were rotated so that their foliation is concordant with that in the Kinney Lakes granodiorite.

Within the western study area, rocks on either side of the Kinney Lakes-host rock contact lack significant solid-state deformation. The strongest solid-state deformation in the Bummers Flat granodiorite is within the Toe Jam Lake shear zone, which is 200-500 m from the contact. Thus, it is unlikely that a structural aureole formed in the Bummers Flat granodiorite due to intrusion on the Sonora Pass suite.

Roof Uplift and Floor Subsidence

Material transfer processes commonly vary with depth of emplacement. Roof uplift and floor subsidence are two material transfer processes that are particularly depth dependent (e.g., Buddington, 1959; Paterson et al., 1996; Cruden, 1998; Cruden and McCaffrey, 2001; Yoshinobu et al., 2003).

The lack of exposure of a pluton roof within the study area precludes directly observing potential structures associated with roof uplift, such as draping of stratigraphy over the intrusion (e.g., Corry, 1988; Paterson et al., 1996; Cruden, 1998; Yoshinobu et al., 2003). Thus, this style of roof uplift cannot be ruled out. Evidence of piston-like roof uplift, primarily brittle faulting along intrusion margins, is absent in the study area. Thus, this style of roof uplift is unlikely.

Sinking or depression of the pluton floor is considered a viable mechanism for pluton emplacement, particularly in the lower to mid-crust. Sinking of host rock is accommodated by vertical and lateral ductile flow, an exchange process where host rock sinks as magma moves up to shallower levels (Cruden, 1998). Evidence for floor depression includes ductile flow along pluton walls or sagging of the pluton floor

(Cruden, 1998). At the current level of exposure, no floors of plutons are exposed within the study area and ductile flow is not widespread along walls.

Magmatic Wedging

Wedging aside of metamorphic rock has been proposed as a 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). Magmatic wedging is typically inferred to occur by intrusion along planar weaknesses in host rocks, such as foliation or bedding, resulting in isolated rafts of host rock (Hutton, 1982; Miller and Paterson, 2001; Žák and Paterson, 2005).

In the western study area, there is evidence of magmatic wedging by the felsic sheets of the Kinney Lakes granodiorite. These sheets, which range from 1 to 100s of m wide, intruded parallel to foliation and roughly parallel to the contact with the main body and “thumb” of the Bummers Flat granodiorite. Margin-parallel foliations between the two are also compatible with magmatic wedging by the felsic sheets.

Tectonically Controlled Emplacement

The concept of tectonic processes accommodating magma involves a “one-to-one” crustal transfer whereby tectonic rates equal emplacement rates. In general, however, tectonic and magmatic processes operate on timescales that differ by up to several orders of magnitude (Paterson and Tobisch, 1992; Saint Blanquat et al., 2011). Therefore, for plutons constructed over time periods of more than one million years, regional tectonic processes may act as an important material transfer process.

In the study area, there is minimal evidence for tectonically controlled emplacement, as large faults and shear zones were not observed to cut the Sonora Pass intrusive suite. Most, if not all shear zones located within the study area are concentrated within the Bummers Flat granodiorite, and are not localized next to the Kinney Lakes granodiorite.

During the Cretaceous, intrabatholithic, dextral, strike-slip faults, such as the Mojave-Snow Lake fault (Fig. 9), were active in the Sierra Nevada region (Busby-Spera and Saleeby, 1990; Kistler, 1993). Memeti et al (2010b) concluded the Mojave-Snow Lake fault was active between ~145 Ma and 102 Ma, which predates intrusion of the Kinney Lakes granodiorite by at least 7 Ma. Thus, it is unlikely that the Sonora Pass intrusive suite was emplaced via dilation during faulting.

Summary of Emplacement

The field evidence for definitively distinguishing different material transfer processes in the study area is weak, and the documented material transfer processes are insufficient to accommodate emplacement. For example, the volume of stoped host rock is relatively minor, a ductile aureole within the host rocks is absent, and there is no evidence of significant assimilation.

The best documented material transfer processes are for the Kinney Lakes granodiorite. These processes include minor stoping, ductile flow, and magmatic wedging. Evidence of stoping is preserved along the entirety of the host rock contact of the Kinney Lakes granodiorite in the eastern study area. The volume of stoped xenoliths, however, is relatively small in comparison to the amount of granodiorite. Solid-state foliations within the marginal Kinney Lakes granodiorite in the eastern study area may record ductile flow caused by more internal, subsequent intrusions of the granodiorite. Late felsic sheets of the Kinney Lakes granodiorite intrude parallel to foliations within Bummers Flat granodiorite, compatible with magmatic wedging as a viable emplacement mechanism.

Emplacement of the Topaz Lake granodiorite is particularly enigmatic. The pluton and its host, the Kinney Lakes granodiorite, lack evidence of material transfer processes that may have facilitated emplacement.

Development of Magmatic Foliation

Magmatic foliation is present in all plutons in the study area and is defined by early-forming tabular minerals, which include plagioclase, hornblende, and biotite. Several foliation patterns exist, and are attributed to strain during internal chamber processes and post-emplacement regional tectonic strain (e.g., Paterson et al., 1998; Žák and Paterson, 2005; Žák et al., 2007), as discussed below.

Bummers Flat Granodiorite

Two dominant magmatic foliation orientations formed in the Bummers Flat granodiorite (Plate 1). Some foliations strike NE to E, and dominantly dip steeply (65-90°). Foliations with these strikes are mostly localized, and show no specific spatial relationships to contacts. These foliations are best preserved within and near magmatic structures, such as schlieren and dynamic magma zones. The second, more prominent set of foliation strikes N-NNW and mostly dips steeply. These foliations are parallel to the contact with the Kinney Lakes granodiorite and the regional Sierran strike.

The NE- to E-striking foliations are attributed to localized strain fields from internal magmatic chamber processes. The second foliation orientation may reflect regional NE-SW shortening (e.g., Žák and Paterson., 2005) during intrusion of the Bummers Flat granodiorite. Alternatively, the NW-striking foliations may result from flow parallel to the walls of the elongate pluton. More work is needed at the ends of the pluton (outside of the study area) to determine whether the contact is parallel to the regional strike and discordant to the contact, or vice versa.

Kinney Lakes Granodiorite

Magmatic foliation is highly variable in orientation within the Kinney Lakes granodiorite, especially in the eastern study area, but several domains display consistent orientations (Plate 1). Perhaps the most notable pattern is near the contact with Topaz

Lake granodiorite in the eastern study area. Here, the foliation has consistent NNW strikes and steep dips ($75-90^{\circ}$), and lineation plunges steeply. Žák et al (2007) mapped similarly oriented foliations within the Kuna Crest granodiorite of the Tuolumne intrusive suite, which is coeval with the youngest part ($\sim 93-92$ Ma) of the Kinney Lakes granodiorite. They interpreted the foliation in the Kuna Crest granodiorite to record regional ENE-WSW shortening. Foliations in the Kinney Lakes rocks may also have formed by regional ENE-WSW shortening and this strain field may have characterized at least the central part of the Sierra Nevada batholith at that time. Alternatively, the NNW strike is parallel to the long axis of the Kinney Lakes granodiorite and may result from flow parallel to its contacts. The distance that these NNW-striking foliations extend inward from the margin of the Kinney Lakes granodiorite supports the regional strain interpretation.

A more complex foliation orientation in the Kinney Lakes granodiorite is located within the schlieren-rich area in the eastern study area and $\sim 50-200$ m east of the Bummers Flat “thumb” in the western study area. These foliations also mostly strike NW to NNW and dip steeply ($65-90^{\circ}$), but local E-W foliations also occur. The E-W foliations probably result from local convective perturbations.

Topaz Lake Granodiorite

Magmatic foliation within the Topaz Lake granodiorite is variable in orientation. The majority of foliations strike NW and dip steeply ($65-89^{\circ}$), discordant to the E-W-striking contact with the Kinney Lakes granodiorite in the eastern study area, but concordant to the NW-striking contact in the western study area. A second foliation strikes ENE, dips steeply ($65-89^{\circ}$), and is discordant to the NW-striking contacts. Lineations are weak and very difficult to measure.

With the eastern study area, the discordance of the NW-striking foliation to the contact is evidence of formation in response to the regional strain field. In contrast, the E-W striking foliation likely formed by internal magmatic processes. Mafic minerals in schlieren are discordant to the foliations in the surrounding granodiorite, and probably formed during localized magma flow, whereas crystals in the host granodiorite magma likely re-oriented in response to the regional strain field (e.g., Paterson et al., 1998; Žák et al., 2007).

Development of Solid-State Foliation

Solid-state foliations occur within the Bumpers Flat granodiorite and the Kinney Lakes granodiorite in the study area. Overall, they are more widespread in the Bumpers Flat rocks.

Solid-state foliations in the Bumpers Flat granodiorite strike NNW, dip steeply (65-90°), and contain steeply plunging lineations. These foliations are interpreted to be caused by sub-horizontal WSW-ENE shortening. Undeformed dikes of the Kinney Lakes granodiorite cross-cut solid-state foliations, indicating that the foliation formed before the latest Kinney Lakes magmas.

Strong solid-state foliation in the eastern domain of the Kinney Lakes granodiorite strikes NE to NNE, dips steeply (65-90°), and is parallel to the margin. These foliations are oriented differently than the majority of foliations within the Kinney Lakes granodiorite. Here, solid-state foliations may represent a ductile aureole caused by subsequent intrusions of granodiorite, as discussed above.

Timing and Regional Significance of Shear Zones in the Bumpers Flat Granodiorite

The Toe Jam Lake shear zone and smaller ductile shear zones deform the Bumpers Flat granodiorite. These shear zones dip steeply and strike NW (see section Ductile Shear Zones in STRUCTURE). Well-defined S-C fabrics and σ -type

porphyroclasts indicate reverse sense of shear, with the west-side up in most places. High temperature microstructures in the Bummers Flat granodiorite are compatible with the shear zone forming shortly after solidification of the granodiorite.

Steep, reverse shear zones with mostly east-side up displacement have been reported to the south in plutons within the central part of the Sierra Nevada batholith (Tobisch et al., 1995; Mahan et al., 2003; Johnson, 2013). These shear zones deform plutons ranging from ~102-98 Ma. The Bummers Flat granodiorite is older (~109 Ma) than the other deformed plutons, and the shear zones in this granodiorite may be older than those to the south.

CONCLUSIONS

1. The Bummers Flat granodiorite is a compositionally and texturally diverse pluton. Schlieren, dynamic magma zones, co-magmatic mafic rocks, mafic and felsic dikes, and quartz diorite xenoliths suggest a complex constructional history.
2. The Kinney Lakes granodiorite is also texturally and compositionally heterogeneous. Subunits were recognized, but contacts are cryptic. Widespread internal magmatic features include schlieren, disaggregated enclaves, and co-magmatic mafic intrusions. These features signify that the pluton was constructed by multiple increments. The number, size, and tempo of the magmatic increments are difficult to constrain.
3. The Topaz Lake granodiorite is largely homogenous in contrast to the Kinney Lakes granodiorite. The unit does display magmatic structures such as schlieren, pipes, and minor enclaves.
4. Emplacement of plutons in the study area was facilitated by a number of processes. Emplacement of the Kinney Lakes granodiorite likely involved stoping, magmatic wedging, and minor ductile flow. Floor depression is feasible, and cannot be ruled out, whereas there is no support for tectonically-controlled emplacement. The Topaz

Lake granodiorite is mostly devoid of any evidence for its emplacement. In short, the documented material transfer for the Sonora Pass intrusive suite is insufficient to accommodate the volume of the pluton. Similar conclusions have been reached for other plutons within the central Sierra Nevada batholith.

5. Magmatic foliation within the study area records regional tectonic strain associated with ENE-WSW shortening and complex internal magmatic processes.
6. The steep Toe Jam Lake reverse shear zone deforms the ~109 Ma Bummers Flat granodiorite, but shear zones were not mapped in the ~95 Ma Kinney Lakes granodiorite. The shear zone and associated foliations likely formed during ENE-WSW shortening, similar to shear zones that were documented in 102-98 Ma Sierran plutons to the south (Tobisch et al., 1995, Žák et al., 2005).

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