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STRUCTURE AND EMPLACEMENT OF THE SOUTHERN MARGIN OF THE
TUOLUMNE INTRUSIVE SUITE

A Thesis

Presented to

The Faculty of the Geology Department

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Masters of Science

by

Ronald Alvaro Karpowicz

December 2004

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ABSTRACT

STRUCTURE AND EMPLACEMENT OF THE SOUTHERN MARGIN OF THE TUOLUMNE INTRUSIVE SUITE

by Ronald Alvaro Karpowicz

The ~ 94-85 Ma Tuolumne Intrusive Suite (TIS) is a classic zoned intrusion, yet its emplacement is still under debate. The southern margin of the TIS, which includes the Kuna Crest (Kkc) and Half Dome (Khd) granodiorites, intruded Cretaceous plutonic and older metasedimentary rock, forming generally sharp and steep contacts around the NW corner of a large host rock salient.

Along the western margin of this N-S trending contact, the Khd discordantly cuts E-W striking internal contacts between host rock and intrudes out the Kkc. Host rock xenoliths were found in the Khd and Kkc. Host rock foliation is deflected along contacts with the Khd in a narrow structural aureole. Foliations in the Khd are apparently not directly related to emplacement. These field data show that stoping and ductile host rock deformation operated as material transfer processes during emplacement of the southern TIS.

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INTRODUCTION

The Tuolumne Intrusive Suite (TIS), in the central part of the Sierra Nevada batholith, California (Fig. 1), is one of the world's classic zoned intrusive bodies (Bateman and Chappell, 1979). The TIS is part of the 80-100 Ma Sierra Crest magmatic event (Coleman and Glazner, 1997) that represents the intrusion of large volumes of magma along the continental margin of North America during the subduction of the Farallon plate. The TIS was emplaced at a depth of four to seven kilometers (Ague and Brimhall, 1988) and formed a trench-oblique, north-northwest-trending elliptical body (Tikoff and Teyssier, 1992).

Exposure of more than two vertical kilometers of the TIS makes it an ideal place to study pluton emplacement. The large size and excellent vertical exposure of the TIS and host rock allow the internal contacts to be followed, provide access to three-dimensional variations in magmatic fabric patterns and structures, and facilitate an evaluation of the structural aureole around the TIS.

There is a great deal of controversy about how the TIS was constructed and what mechanisms created the space for its emplacement. Four models for emplacement have been proposed: ballooning (Bateman and Chappell, 1979), dilation of tensional bridges via P-shears (Tikoff and Teyssier, 1992), multiple material transfer processes in host rock during emplacement of nested diapirs (Paterson and Vernon, 1995), and incremental filling via dilation analogous to crack and seal veins (Glazner et al., 2004). Support for these models is drawn from a variety of studies including those based on petrology,

Figure 1. Map of the Toulumne Intrusive Suite and host rock markers (denoted by the numbered colored lines). Study area is marked by the blue box. Inset map of California shows the Sierra Nevada batholith (green) and the Toulumne Intrusive Suite (red). Modified from Bateman (1992), Huber et al. (1989), and Paterson and Vernon (1995).

magmatic fabric patterns, structural and tectonic relations, spatial relations between the host rock and pluton, and ages of the units of the TIS. Testing each of these models by concentrating a detailed structural study on the southern margin of the TIS and adjacent host rock (Fig. 1) should further our understanding of emplacement of the TIS, and potentially of large-volume, zoned intrusions in general.

Geologic Setting

The TIS comprises four units that were sequentially emplaced into plutonic and metamorphic host rock over a period of approximately 9 m.y., from approximately 94-85 Ma (Coleman et al., 2004). These units are, from the outer margin to the core and from older to younger: 1) the Kuna Crest Granodiorite, locally called the Grayling Lake Granodiorite in the southwest corner of the TIS, and the Glen Aulin and Glacier Point Tonalites; 2) Half Dome Granodiorite, which is sub-divided into an outer equigranular and an inner porphyritic phase; 3) Cathedral Peak Granodiorite; and 4) Johnson Granite Porphyry. The Sentinel and Yosemite Creek granodiorites are considered by some to be the westernmost phases of the suite (Kistler et al., 1986).

Within the area of study, the southern part of the TIS intruded Cretaceous plutonic and older metasedimentary rock, forming generally sharp and steep contacts around the northwest corner of a large salient of host rock (Plate 1). In this area, the TIS comprises the outer Kuna Crest Granodiorite and the more internal Half Dome Granodiorite. Host rock units include, in order from oldest to youngest, the metasedimentary unit, the central

Gray Peak Granite, the Mount Clark Granite to the north, the Red Peak Granite to the south, and the Red Devil Lake Granodiorite to the northeast.

Proposed Emplacement Models for the TIS

The TIS has received considerable study; however, there is little agreement about the processes operating during magma chamber construction and pluton emplacement. Four emplacement models have been proposed, each drawing from different lines of evidence for support.

Bateman and Chappell (1979) proposed a ballooning model for emplacement of the TIS based on the concentric compositional and textural changes from the margin to the core of the pluton. The margin is characterized by granitoids that are more mafic, finer grained, and better foliated than those in the interior. These characteristics were interpreted to signify cooling of one large magma chamber from its margin to the interior accompanied by differentiation due to fractional crystallization. This interpretation led them to construct a model that is best described in their own words: “during solidification, the more fluid core magma moved episodically upward, eroding the adjacent solidifying rock and expanding the area of the magma chamber at the exposed level by crowding the wall and the roof rocks outward and upward and by breaking through the solidifying carapace into the country rocks” (Bateman and Chappell, 1979). This model for forceful emplacement does not address how the host rock accommodated the intrusion of such a large body of magma over a narrow time interval.

Tikoff and Teyssier (1992) argue that the TIS and other Cretaceous intrusive suites of the Sierra Nevada batholith were passively emplaced during an interval of transpression along the continental margin. They hypothesize that dilation across bridges between P-shears formed at low angles to major north-northwest-trending dextral shear zones and opened up space for the intruding magma.

Paterson and Vernon (1995) propose that the TIS was emplaced by multiple diapirs, which were accommodated by multiple material transfer processes, including stoping and ductile downward flow of host rock. Their calculations suggest that during emplacement the wall rock was shortened by $< 30\%$, which is insufficient to account for much of the magma chamber growth via ballooning.

Glazner et al. (2004) propose that the TIS was assembled through a series of sheet-like intrusions and that only small amounts of crystal-poor magma ($> 50\%$ melt) were present at any given time. In this model, emplacement is achieved through the opening of dikes along extensional structures that create cavities which allow the intrusion of magma. They base their interpretations on thermal modeling and on their geochronologic study of the Half Dome Granodiorite, which they infer demonstrates incremental emplacement over approximately 4 Ma (Coleman et al., 2004). Glazner et al. (2004) argue that the Half Dome Granodiorite could not have existed as a large magma chamber given inferred rapid magma cooling rates. Finally, they propose that incremental filling is analogous to crack and seal veins and that evidence for internal contacts was obscured during annealing of the dikes.

Other models of emplacement that have not been proposed for the TIS, but should be considered, include floor subsidence and roof uplift. Dike-fed, tabular, and wedged-shaped plutons may be emplaced by floor subsidence, which is thought to result from two potential mechanisms. In the cantilever model, the floor tilts about a pivot point and host rocks undergo progressive simple shear while sinking into the partial melt of the lower crust (Cruden, 1998). In the non-rotational piston model, a ductile shear zone that surrounds the edge of the pluton accommodates vertical subsidence of a horizontal floor. Both models can be accompanied by stoping of overlying host rock. Roof uplift predicts brittle, vertical shear zones at the host rock contacts to allow for lifting of the roof.

Magmatic Fabric

Patterns of magmatic fabrics, such as foliations and lineations, may reveal important information about magma processes and emplacement (e.g., Cloos, 1925; Paterson et al., 1998). The interpretation of magmatic fabrics remains controversial due to three fundamental difficulties: 1) foliation and lineation can form by multiple processes; 2) foliation may form at different stages, including magma ascent, emplacement, cooling, and syn- or post emplacement tectonism; and 3) host rock strains may be decoupled or coupled mechanically from the magmatic strains (e.g., Fowler and Paterson, 1997; Paterson et al., 1998).

Bateman (1992) identifies two main foliation orientations within the TIS. Both foliations are defined by preferred orientations of the same minerals, primarily hornblende, biotite, plagioclase, and potassium feldspar. The first foliation lies parallel to

internal and external contacts, and is interpreted to be a result of differential magma flow velocities (Bateman, 1992). The second foliation strikes approximately west-northwest, dips steeply, and is interpreted to form as a result of regional strain.

Goals of the Study

This study aims to address the controversy about emplacement of the TIS. Which emplacement models best fit the TIS? How was space created for this intrusive episode and what is the nature of the magma chamber that resulted? What is the significance of lineations and foliations in the TIS and host rocks? These questions were addressed by a study of the spatial, structural, and age relations of the TIS and host rocks in the Clark Range area in the southern end of the TIS (Plate 1).

ROCK UNITS

Metasedimentary Unit

Metasedimentary rocks are found in two areas, on Quartzite Peak and along the western slope of Gray Peak. These rocks have not been dated, but they have been correlated to rocks, (20 km SW) in the Strawberry Tungsten Mine area, which are of Jurassic age (Huber et al., 1989). My observations suggest that the metasedimentary rocks are correlative with metamorphic rocks 20 km to the north, in the May Lake area that are probably Cambrian and Late Proterozoic in age (Glazner et al., 2004). The metasedimentary body at Quartzite Peak is composed of highly folded biotite schist and quartzite. Along the western slope of Gray Peak, the metasedimentary body comprises marble, calc-silicate rocks, silicic hornfels, and biotite schist.

Folds of compositional layering in the metasedimentary rock are characterized as tight and isoclinal, with an average interlimb angle of 30° and a four-centimeter wavelength. The fold axes trend east-west and north-south, and plunge steeply. The limbs of many of these folds are boudinaged. Foliation is parallel to the axial planes of the folds and has an average orientation 188/88 (all orientations are given using the right-hand rule convention). Igneous veinlets cut across foliation, are tightly folded with wavelengths of < 1 cm, and are up to 15 cm in length. Folding of these veinlets implies that deformation was synchronous with the intrusion of adjacent plutonic rocks.

Gray Peak Granite

The Gray Peak Granite, the oldest plutonic rock in the study area, is located on the north slope of Gray Peak (Plates 1 and 2). It is intruded by the Mount Clark Granite, which split the Gray Peak Granite into three bodies; the Red Peak Granite to the south; the Red Devil Lake Granodiorite to the east; and the Half Dome Granodiorite to the west (Peck, 1980, 2002). Based on compositional and textural similarities, Gray Peak Granite is correlated with the 102-103 Ma El Capitan Granite (Stern et al., 1981; Bateman, 1992).

The Gray Peak Granite is a light gray, medium-grained, moderately foliated hornblende-biotite granite. Large, tabular potassium feldspar up to three centimeters long distinguishes this granite from other host rock units (Fig. 2). Elongate microgranitoid enclaves are ubiquitous, and widespread ductile shear zones cut the granite. Aplite and pegmatite dikes, and dikes resembling Mount Clark Granite, intrude the unit.

Enclaves in the Gray Peak Granite are typically < 50 cm in size and are elongate parallel to foliation, with aspect ratios consistently between 2:1 and 3:1. Overall, enclaves are evenly distributed throughout the unit. High concentrations of enclaves were only found at one station (213, refer to Plate 3 for locations of all stations), next to the contact with the Mount Clark Granite, where they form swarms in the Grey Peak Granite.

Aplite and pegmatite dikes are typically < 15 cm wide and extend > 10 m. There is no apparent pattern to the orientation of the dikes. One cuts the contact between the Mount Clark Granite and the northern body of Gray Peak Granite. This dike is 1.5 m wide by >10 m long, and includes a 32-cm-long fragment of the Gray Peak Granite.

Figure 2. Thin section showing typical minerals and textures of the Gray Peak Granite. Note the large potassium feldspar (some illustrated with a K) and elongate quartz.

One of the dikes similar in composition to the Mount Clark Granite is one meter wide and intrudes > 300 m into the central Gray Peak Granite body (Fig. 3). Dikes such as this one are interpreted to indicate that the Gray Peak Granite is older than the Mount Clark Granite, contrary to findings of previous scholars (Peck, 1980; Bateman, 1992).

Figure 3. Geologic map showing a dike of Mount Clark Granite composition that cuts across the Gray Peak Granite-Mount Clark Granite contact. Note the discordance of the north-south foliation to the east-west trending contacts.

Petrographic Description

The Gray Peak Granite consists of 30-40% quartz, 20-35% potassium feldspar, 20-30% plagioclase, and trace amounts of biotite, hornblende, muscovite, allanite, and oxides. Quartz is coarse-grained and many crystals are elongate parallel to foliation. The quartz commonly has subgrains and shows evidence for rotational recrystallization. Fine-grained, polygonal mosaics of quartz, plagioclase, potassium feldspar, and hornblende-biotite aggregates indicate grain-size reduction. The mosaics are elongate parallel to foliation and are bounded by large, aligned plagioclase, potassium feldspar, and elongate quartz.

Plagioclase grains are large next to the fine-grained mosaics, fine-grained inside the mosaics, and medium-grained away from the mosaics. Myrmekite is present along margins of crystals that are adjacent to potassium feldspar. Some grains are bent and have deformation twins. Biotite and hornblende are restricted to the fine-grained mosaics. Biotite grains are commonly kinked and undulose.

Structure

The foliation in the Gray Peak Granite is of moderate intensity and is defined by elongate quartz, quartz aggregates, recrystallized plagioclase, potassium feldspar, and recrystallized biotite-hornblende aggregates. Aligned elongate quartz, recrystallized quartz, and recrystallized plagioclase indicate solid-state deformation (Paterson et al., 1989). Solid-state strain presumably was not great enough to allow the rotation of euhedral potassium feldspar phenocrysts into parallelism, implying that the alignment

occurred through magmatic deformation (Paterson et al., 1998; Vernon, 2000). The alignment of potassium feldspar is interpreted to indicate that deformation of the magma chamber occurred before and after solidification.

The dominant foliation strike is approximately N-S, but, in zones up to 100 m from the contacts with the Mount Clark Granite and the Red Peak Granite, another foliation strikes approximately east-west. Both foliations dip steeply (Fig. 4A). Lineations are defined by the same minerals that define foliation, are steep (all but one are steeper than 60°), and have an average plunge and trend of 85/241 (Plate 2, Fig. 4B). Foliations and lineations both have moderate to strong intensity, suggesting that the deformation was close to plane strain.

Strain was roughly quantified by measuring the aspect ratios of elongate quartz grains and aggregates in the X-Z plane (normal to foliation) from samples evenly distributed in the plutonic host rock. The extensional strain was then calculated by taking the harmonic mean of the aspect ratios of grains within each unit. It is difficult to distinguish highly elongate aggregates that formed from a single grain than those that formed by multiple grains, thus some were omitted from the analysis. Therefore, the measurements likely understate reported extensional strain in each unit. In the Gray Peak Granite, the aspect ratio was measured in 60 grains from 5 samples and the extensional strain was calculated to be 106%.

Ductile shear zones are prominent features in this granite. They are identified in the field as strongly foliated, fine-grained zones up to three meters wide that deflect foliation. In thin section, they are characterized by fine-grained, recrystallized mosaics of

Figure 4. Equal area plots of foliations and lineations in the Gray Peak and Mount Clark Granites. (A) Poles to foliations and (B) lineations in the Gray Peak Granite. (C) Poles to foliations and (D) lineations in the Mount Clark Granite. Plotted using GEORIENT© 9.12 by Rod Holcombe.

quartz, plagioclase, potassium feldspar, and hornblende-biotite aggregates (Fig. 5). The mosaics record grain size reduction, which indicates solid-state deformation. Plagioclase recrystallization in all of the ductile shear zones indicates that deformation occurred at a minimum of 450° C (Vernon, 2000). Ductile shear zones are oriented parallel to the contacts that are nearest.

Near the contact between the northern body of the Gray Peak Granite and the Mount Clark Granite, which is oriented 071/82, dozens of ductile shear zones range up to 10 cm wide. Two larger ductile shear zones that are three meters wide and can be traced for > 10 m, and have an average orientation of 072/82. Deflection of foliation within five centimeters of the two larger ductile shear zones gives a reverse sense of motion (Mount Clark Granite side up). Ductile shear zones next to the Mount Clark Granite contact record a minimum of 101% extensional strain, based on simple calculations from aspect ratio measurements of 20 quartz grains from two samples.

Within 100 m of the north-south-trending contact between the northern body of the Gray Peak Granite and the Half Dome Granodiorite, one ductile shear zone, oriented 342/47, is three meters wide and can be traced 250 m. Deflection of foliation indicates a reverse (Half Dome Granodiorite side up) displacement.

Mount Clark Granite

The Mount Clark Granite crops out near the northwest corner of the host rock salient. This granite has not been dated, but field relations described above indicate that it is younger than the Gray Peak Granite, which is probably 102-103 Ma. The lower limit

Figure 5. High-temperature, solid-state, ductile shear zone in the Gray Peak Granite, showing elongate quartz and grain size reduction.

of its age is confined by the 95 Ma Red Devil Lake Granodiorite (McNulty et al., 1996). Contacts of the Mount Clark Granite are steep, including those with the Red Devil Lake Granodiorite to the east, the Gray Peak Granite to the north and south, and the Half Dome Granodiorite to the west.

The Mount Clark Granite is coarse-grained, compositionally homogenous, and leucocratic, containing only trace amounts of biotite and hornblende. Foliation is defined primarily by aligned, elongate quartz crystals and quartz aggregates, and to a lesser degree by large potassium feldspar crystals. Sparse enclaves were observed only at station 192. Local schlieren layers display no consistent orientation, are < 15 cm wide, are traced up to 10 m along strike, and are found only within 50 m of all contacts. Aplite dikes, ranging from 10 to 35 cm in thickness, are found throughout the unit and have no dominant orientation. Dikes resembling the Half Dome Granodiorite intrude the western margin of the Mount Clark Granite. They are < 1-m-wide and are at least 60-m-long.

Petrographic Description

The Mount Clark Granite consists of: 30-40% quartz, 35-55% potassium feldspar, 15-35% plagioclase, and minor amounts of muscovite, biotite, allanite, hornblende, and oxides. Quartz is coarse-grained and is elongate parallel to the foliation. Most of the quartz records substantial ductile strain, which is shown by undulose extinction, subgrains and rotational recrystallization.

Potassium feldspar forms large, poikilitic grains and has inclusions of fine- to medium-grained plagioclase, fine-grained quartz, hornblende, and biotite. Some large

crystals (up to three centimeters) are aligned parallel to the foliation. Many grains have been recrystallized at their margins through grain boundary migration. Recrystallized grains are fine-grained and have polygonal boundaries.

Plagioclase is fine- to medium-grained. Only a very few crystals are aligned parallel to foliation. Many grains have mechanical twinning and some of these are bent. Myrmekite is present at the margins of large plagioclase grains that are in contact with potassium feldspar. Biotite and hornblende comprise only 1% to 2% of the rock. Both are medium-sized and occur as aggregates, which are elongate parallel to foliation.

Structure

Lineations are the dominant structural feature in this granite, indicating a constrictional fabric. Lineations are steeply plunging (92% are steeper than 60°) and have an average orientation of 88/161 (Plate 2, Fig. 4B-C). They are defined by elongate quartz and, to a lesser degree, biotite and hornblende aggregates. The steeply dipping foliation strikes north-south in the central part of the unit and changes to east-west within 100 m of the northern and southern contacts with the Gray Peak Granite (Fig. 4C-D). The alignment of elongate quartz, recrystallized mosaics of quartz and plagioclase, and hornblende-biotite aggregates define the weak to moderately strong solid-state foliation (Fig. 6). As discussed above, alignment of potassium feldspar is presumably a relic magmatic foliation that is parallel to the solid-state foliation. Strain in this granite was calculated to be 125%, based on measurements of 50 quartz grains from five samples.

Figure 6. Thin section of the Mount Clark Granite showing elongate quartz grains and aggregates, which define the foliation and indicate solid-state deformation.

Ductile shear zones are sparse in the Mount Clark Granite and show no consistent orientation. They are recognized in the field as fine-grained and strongly foliated planar zones that deflect foliation. They range from 2 to 10 cm in width and extend along strike for up to 20 m. They contain fine-grained polygonal mosaics of recrystallized quartz, plagioclase, and biotite-hornblende aggregates that indicate solid-state deformation (Fig. 7).

Illilouette Creek Granodiorite

The Illilouette Creek Granodiorite is a 99 ± 0.1 Ma (Tong, 1994; Tobisch et al., 1995), light gray, medium-grained hornblende granodiorite in the southern part of the field area. Two strong foliations, one striking northwest and the other east-west, pervade this unit. Both foliations are defined by aligned hornblende, plagioclase, and biotite. The Illilouette Creek Granodiorite is isolated from all other units in the field area by > 1 km of alluvium, thus preventing a study of structural and contact relations with the other units within the area of study. For this reason, the Illilouette Creek Granodiorite will not be discussed further.

Red Peak Granite

The Red Peak Granite is the southernmost host rock unit. Its age is poorly constrained, bracketed by the 102-103 Ma Gray Peak Granite and the 95 Ma Red Devil Lake Granodiorite (McNulty et al., 1996). In outcrop, this porphyritic unit is light gray where fresh, but it is commonly weathered to shades of red because of disseminated

Figure 7. Thin section view of a solid-state ductile shear zone in the Mount Clark Granite showing elongate quartz and fine-grained polygonal mosaics of recrystallized quartz, plagioclase, and biotite-hornblende aggregates.

pyrite (Peck, 1980). Metasedimentary xenoliths were found at one station (45). Foliation is defined by elongate quartz, fine-grained aggregates of quartz, biotite and plagioclase, and large potassium feldspar grains (Fig. 8).

Petrographic Description

The Red Peak Granite consists of about: 45% potassium feldspar, 35% plagioclase, 20% quartz, and trace amounts of biotite, sphene, and oxides. Many potassium feldspar phenocrysts have marginal subgrains that record rotational recrystallization. Plagioclase occurs primarily as phenocrysts and is fine-grained in ductile shear zones. Many grains are poikilitic and have inclusions of quartz.

Mechanical twinning is present in many plagioclase grains.

Quartz is fine- to medium-grained. Some grains are elongate parallel to the foliation. Much of the quartz has subgrains and records rotational recrystallization.

Recrystallized polygonal mosaics of quartz, plagioclase, potassium feldspar, biotite and sphene are aligned parallel to the foliation. Recrystallized plagioclase and potassium feldspar in these zones indicate moderate to high temperature deformation (e.g., Voll, 1976; Tullis, 1983).

Structure

The foliation strikes approximately north-south in the central part of the unit and dips steeply (Fig. 9A). As discussed in the Gray Peak Granite and Mount Clark Granite sections, aligned potassium feldspar presumably reflects a relict magmatic foliation. The

plastic strain of quartz, plagioclase, and potassium feldspar indicates that the foliation is predominantly solid-state (Vernon, 2000). Lineations are defined by the polygonal mosaics and elongate quartz. They plunge steeply (all $> 60^\circ$) and have an average

Figure 8. Thin section view of the Red Peak Granite showing solid-state foliation defined by aligned elongate quartz, fine-grained aggregates of quartz (some are circled), biotite and plagioclase and large potassium feldspar grains (some illustrated with a K). Note the blue line is aligned parallel to foliation and not all potassium feldspar is oriented parallel to foliation.

Figure 9. Equal area plots of poles to (A) foliations and (B) lineations within the Red Peak Granite. Plotted using GEORIENT© 9.12 by Rod Holcombe.

orientation of 78/277 (Plate 2, Fig. 9B). The weak intensities of the lineations relative to foliations in the Red Peak Granite indicate a flattening fabric.

Ductile shear zones in the Red Peak Granite are concentrated only in a zone within 100 m of the contact with the Kuna Crest Granodiorite. These have a bimodal thickness distribution; the larger are up to two meters wide and can be traced for up to 50 m, whereas the smaller, more abundant ductile shear zones are centimeters wide and < 1-m-long. Lineation pitches are uniformly steep in the ductile shear zones. Deflection of the foliation at the ductile shear zones variously indicates dextral, sinistral, or reverse

kinematics (Fig. 10). The complex kinematics of these shear zones makes their interpretation difficult.

Red Devil Lake Granodiorite

The Red Devil Lake Granodiorite is a 95 ± 2 Ma unit (Tobisch et al., 1995; McNulty et al., 1996) that is the outermost part of the Washburn Lake Intrusive Sequence. It is located on the east side of the study area where it intrudes the Mount Clark Granite and the Gray Peak Granite and is intruded by the porphyritic phase of the Half Dome Granodiorite to the north (Plate 1).

In outcrop, the Red Devil Lake Granodiorite is a gray, fine- to medium-grained, equigranular, hornblende-biotite granodiorite. Two foliations of moderate intensity are found in individual outcrops and characterize the granodiorite. Both foliations are defined by aligned plagioclase feldspar, biotite and elongate quartz. Abundant enclaves are dominantly elongate in a northeast orientation.

Petrographic Description

The Red Devil Lake Granodiorite comprises approximately 35% quartz, 20% potassium feldspar, 40% plagioclase, 3% biotite, 2% hornblende, and trace amounts of muscovite. Quartz is coarse-grained and is slightly elongate parallel to foliation. Subgrains are present, but there is no evidence for recrystallization. Plagioclase is medium- to coarse-grained, and myrmekite is present at the margins of grains that are in contact with potassium feldspar. The coarse grains are aligned parallel to foliation and

Figure 10. Ductile shear zone in the Red Peak Granite on a horizontal face. Curvature of the foliation indicates a dextral slip. Penny for scale.

some of the medium-sized grains are recrystallized around their margins. Biotite is large, is elongate parallel to foliation, and shows no signs of internal deformation. Fine- to medium-grained hornblende is only present in aggregates with biotite, which are also aligned parallel to foliation.

Structure

One foliation strikes approximately northeast and dips steeply to the northwest and the other strikes approximately northwest and dips steeply to the north (Plate 1, Fig. 11). The same minerals define both foliations. These foliations are magmatic as they are defined by aligned plagioclase and biotite, and weakly elongate quartz (Fig. 12). The Red Devil Lake Granodiorite has a flattening fabric, as lineations were not observed.

Figure 11. Equal area plot of poles to foliations in the Red Devil Lake Granodiorite. Note two dominant foliation orientations.

Figure 12. Thin section view of the Red Devil Lake Granodiorite, showing two magmatic foliations at the same outcrop. Foliation (A) is oriented 307/70 and foliation (B) is oriented 145/73. The dashed line is parallel to foliation in both pictures. Note that plagioclase, quartz, and biotite are aligned parallel to both foliations.

Kuna Crest Granodiorite

The Kuna Crest Granodiorite, which is approximately 93 Ma (Coleman et al., 2004), is the outermost and oldest unit of the Tuolumne Intrusive Suite. This unit is discontinuous, but was probably continuous around the margin of the intrusive suite prior to the emplacement of younger units (Fig. 1). The granodiorite intrudes the Red Peak Granite in the south-central part of the field area.

The dominant rock in the unit is a dark gray, fine- to medium-grained, well-foliated, mafic biotite-hornblende granodiorite, but monzodiorite, quartz diorite, and tonalite are also present (Peck, 1980; Huber, 1989; my observations). Foliation is defined by alignment of hornblende, plagioclase, and biotite-hornblende aggregates (Fig. 13). Enclaves, schlieren, and dikes are ubiquitous in this unit.

Enclaves in the Kuna Crest Granodiorite are elongate, and their lengths range from one centimeter to one meter. They are fine-grained, spheroidal masses containing abundant hornblende and biotite. Enclave aspect ratios vary from 2:1 to 6:1, and the long axes are parallel to foliation. Enclaves are unevenly distributed, with no apparent pattern. In some areas, hundreds are grouped together in clusters and are 2 to 30 m² in area.

Schlieren layering is commonly found near high concentrations of enclaves. Biotite and hornblende define the schlieren, which are oriented parallel to the elongate enclaves and foliation. These layers are typically < 10 cm thick, but can range up to 50 cm in thickness.

Aplite and pegmatite dikes intrude all parts of the Kuna Crest Granodiorite, and have mostly planar contacts. The dikes range in thickness from 2 to 100 cm and show no

Figure 13. Thin section view of the Kuna Crest Granodiorite showing a magmatic foliation (parallel to the yellow line) defined by aligned hornblende, plagioclase, and biotite.

consistent orientation. An aplite dike near the contact with the Red Peak Granite (station 22) is probably co-magmatic with the granite, as the dike displays irregular cusped-lobate contacts.

Petrographic Description

The Kuna Crest Granodiorite approximately 60% plagioclase, 10-15% quartz, 2-15% potassium feldspar, 17-18% biotite, 6-9% hornblende, and trace amounts of clinopyroxene, allanite, igneous and secondary sphene, secondary muscovite, epidote, and chlorite. Plagioclase varies from fine- to coarse-grained. Large plagioclase grains are aligned parallel to the foliation, show oscillatory zoning, and have mechanical twinning; some grains are bent. Very few crystals show evidence for recrystallization.

Quartz is mostly small and anhedral, likely as a result of being a late-forming phase. Most quartz has subgrains and undulose extinction, and a small number record rotational recrystallization, indicating that quartz underwent a relatively small amount of strain. Only a small percentage (< 10%) of grains are elongate parallel to foliation.

Potassium feldspar is fine- to coarse-grained, and anhedral, and probably was a late forming phase. Many of the large crystals are poikilitic and have inclusions of hornblende and plagioclase. Hornblende is fine- to medium-grained and is aligned parallel to foliation. Hornblende is most commonly found in elliptical aggregates with biotite and oxides. The grain size of the biotite and hornblende does not vary in the aggregates. Aggregates are aligned parallel to foliation, but individual crystals within the aggregates are not aligned. Clinopyroxene is present in the cores of a small percentage (<

10%) of hornblende in a few samples. Biotite is medium- to coarse-grained. Most crystals lack internal deformation, but a few are bent.

Structure

Foliation within the Kuna Crest Granodiorite has a medium to strong intensity (easily visible from standing position) with a mean principal orientation of 208/86 (Fig. 14 A). Alignment of hornblende, plagioclase, and biotite, and the weak strain of quartz, indicate that the foliation is magmatic. Two foliations at individual outcrops were observed at two stations (station 68 and 74). Lineations invariably plunge steeper than 60° and have an average plunge and trend of 80/255 (Plate 2, Fig. 14B). Lineations and foliations are equally intense, indicating a plane strain-type fabric.

Figure 14. Equal area plots of (A) poles to foliations and (B) lineations in the Kuna Crest Granodiorite. Plotted using GEORIENT© 9.12 by Rod Holcombe.

Ductile shear zones generally strike parallel to the north-south-striking contact with the Red Peak Granite, but have a shallower dip. They typically have reverse, TIS-side-up, displacements and are identified in the field by strongly foliated, fine-grained zones that deflect foliation (Fig. 15A). These zones, typically two to five centimeters thick and > 10 m long, are characterized by recrystallized polygonal mosaics of fine-grained plagioclase and quartz, formed by grain boundary migration, which supports moderate- to high-temperature deformation (e.g., Vernon, 2000). Enclaves are commonly stretched by the ductile shear zones (Fig. 15B).

Half Dome Granodiorite

The Half Dome Granodiorite consists of an outer equigranular phase and an inner porphyry phase. Intrusion of the 91 ± 1 Ma equigranular granodiorite (Coleman et al., 2004) removed the Kuna Crest Granodiorite around the host rock salient (Bateman, 1992). This phase intrudes the metasedimentary rock on Quartzite Peak, the Mount Clark Granite, Gray Peak Granite, and Red Devil Lake Granodiorite.

In outcrop, the equigranular Half Dome Granodiorite is light gray, medium-to coarse-grained, hornblende-biotite granodiorite. Large (up to 1.5 cm), euhedral hornblende, biotite books, and conspicuous sphene crystals comprise 10% of this unit. The porphyritic Half Dome Granodiorite is compositionally similar to the equigranular phase, but it contains potassium feldspar phenocrysts, up to three centimeters in length. Mafic minerals define two weak foliations at the outcrop scale that intensify from the core to the margin of both phases of the Half Dome Granodiorite. Ductile shear zones are

Figure 15. Field photos of ductile shear zones in the Kuna Crest Granodiorite. (A) Sheared elongate enclaves in a ductile shear zone. Note the high aspect ratio of the enclaves, which are aligned parallel to foliation. (B) The bottom portion of an enclave is drawn out in a ductile shear zone. Ductile shear zones in both A and B give reverse (top to the left) displacement.

strikingly absent in both units. Enclaves and aplite dikes are found throughout both phases and schlieren were observed in 12% of the stations, concentrated close to contacts with host rocks.

Enclaves in both units of the Half Dome Granodiorite are elliptical, fine-grained and tonalitic. They are commonly < 10 cm, but they can range up to 1.5 m long. In areas where there are two foliations in the same outcrop, enclaves are typically equally elongate in each foliation (Fig. 16). Enclave aspect ratios range from 1:2 to 1:8. The spacing between enclaves typically ranges from < 5 cm to > 10 m. Enclave swarms range from 4 m² to 90 m² in area, are irregular in shape, and are typically adjacent to multiple schlieren layers. Schlieren are equally developed in both phases of the Half Dome Granodiorite and have no apparent preferred orientation.

Aplite dikes have scattered orientations (Fig. 17) and they are ubiquitous in both phases of the Half Dome Granodiorite. The dikes range from 0.4 to 80 m in width and 10 to 200 m in length and are typically < 1 m wide. The largest aplite body observed is 80 m by 300 m, is wedge-shaped in map view, and forms sharp contacts that are stepped in areas. This aplite body contains several screens of Half Dome Granodiorite that range up to 15 m thick. Field observations indicate that the aplite dikes formed late relative to internal features of the Half Dome Granodiorite. Contacts of the aplite dikes are sharp and planar; however, some contacts display mingling as large hornblende crystals, characteristic of the Half Dome Granodiorite, are two centimeters inward from the margin of the dikes. Where multiple dikes are present, one set typically is oriented

parallel to enclaves and schlieren, and another set cuts across the schlieren and enclaves. Neither set of dikes shows a consistent pattern of orientations.

Figure 16. Photo of the equigranular Half Dome Granodiorite showing enclaves elongate in different orientations. The larger enclave is parallel to the foliation oriented 305/78 and the smaller enclave is parallel to the foliation oriented 224/78. Pen for scale.

Figure 17. Map showing orientations of dikes in the Half Dome Granodiorite with an inset of an equal area plot of poles to dikes.
Petrographic Description

Petrographic Description

The Half Dome Granodiorite consists of 35-40% plagioclase, 25-35% quartz, 20-25% potassium feldspar, 3-8% biotite, 2-8% hornblende, up to 1% sphene, and trace amounts of muscovite, zircon, and oxides. Plagioclase is medium- to coarse-grained. Crystal-plastic strain indicators, including deformation twins, bent crystals, and recrystallization resulting from grain boundary migration, occur only in a small percentage of plagioclase crystals.

Quartz is medium- to large-grained and experienced mild strain, which is recorded by subgrains and undulose extinction; evidence for recrystallization is sparse. Some medium-grained crystals have spherical to euhedral inclusions of hornblende, plagioclase and sphene. Potassium feldspar forms medium to large euhedral grains. Poikilitic phenocrysts of potassium feldspar have subhedral to spherical inclusions of plagioclase, hornblende, biotite, and sphene. Hornblende is seriate and ranges up to 1.5 cm long and do not show internal deformation. Biotite grain size ranges from fine to coarse and shows no internal deformation, although some are bent. Crystals of all of these igneous minerals are parallel to each foliation.

Structure

Two steeply dipping foliations are found within the Half Dome Granodiorite. One strikes northwest and has a mean principal orientation of 317/83, and the other strikes approximately northeast and has a mean principle orientation of 047/83 (Fig. 18A). Both foliations are weak (require close observation for identification) and intensify towards the

margin of the unit. They are identified by the alignment of subhedral to euhedral hornblende, biotite, plagioclase and (to a lesser degree) potassium feldspar. Grains aligned in each foliation are equal in size (Fig. 19 A-B). The lack of evidence for plastic strain and internal deformation in the igneous minerals aligned parallel to each foliation demonstrate that these foliations are magmatic (Paterson et al., 1998). Lineations plunge steeply and are weaker than foliations, which indicates a flattening fabric (Fig. 18B).

Figure 18. (A) Contoured equal area plot of poles to foliations in Half Dome Granodiorite. Note the red contours illustrate the maxima that indicate the orientations of two foliations. (B) Equal area plot of lineations in the Half Dome Granodiorite. Plotted using GEORient© 9.12 by Rod Holcombe.

Figure. 19. Thin section view of the Half Dome Granodiorite showing two foliations at an individual outcrop, with foliation (A) oriented 319/74 and foliation (B) oriented 178/80. The yellow line is aligned parallel to each foliation. Aligned hornblende, plagioclase, and biotite define both foliations.

CONTACT RELATIONS

Contacts of the Host Rocks

The Mount Clark Granite-Gray Peak Granite contact is the contact between host rock units that was studied in the most detail, and is emphasized in the following description. Mount Clark Granite intrudes the Gray Peak Granite, separating it into three bodies (Plate 1). The contacts between these units trend east-west and are steep, with an average dip of 80° (Plate 4). Dikes of Mount Clark Granite, ranging up to one meter in width, are found up to 100 m from the contact in the northern Gray Peak Granite body and up to 300 m from the contact in the central body of Gray Peak Granite (Fig. 3). Some areas along the contact show mingling between the two units in zones < 1 -m-wide. In these zones, the Mount Clark Granite is fine-grained.

Contacts of the Kuna Crest Granodiorite

The Kuna Crest Granodiorite cuts the Red Peak Granite-metasedimentary rock contact at an angle of approximately 70° (in map view) with little deflection. The contact between the Kuna Crest Granodiorite and the metasedimentary rocks was observed at one station (42), where it trends approximately north-south, but in detail is irregular in strike. The axial-planar foliation in the metasedimentary unit and the magmatic foliation in the Kuna Crest Granodiorite are both parallel to the contact (Fig. 20) in a zone extending at least 10 m from the contact. The contact-parallel foliation in the metasedimentary rock

Figure 20. Photo showing the stepped (note the small step in the upper left corner) metasedimentary unit (ms)-Kuna Crest Granite (Kkc) contact. The magmatic foliation in Kuna Crest Granodiorite and the axial planar foliation in metasedimentary unit are parallel to the contact. Pen for scale.

may have formed by 1) ductile host-rock deformation during the emplacement of the TIS, 2) older strain of another orientation followed by rotation of the metasedimentary block, or 3) intrusion of the Kuna Crest Granodiorite concordant with an older foliation in the metasedimentary rock.

Figure 21. Map of the Kuna Crest Granodiorite-Red Peak Granite contact. Note the highly stepped, irregular contact.

The contact between the Kuna Crest Granodiorite and Red Peak Granodiorite trends approximately north-south and dips steeply (Plate 5, CD-1.1). This irregularly shaped contact has steps that range from 10 m to 55 m in length (Fig. 20). A 125-m² xenolith-rich zone is well exposed in the Kuna Crest Granodiorite next to the stepped contact. The xenoliths are angular, range in size from 1 x 0.5 m to 3 x 3 m, and have randomly oriented long axes. Foliations within the xenoliths are also randomly oriented. For example, a biotite schist xenolith has a foliation oriented 208/49, and the foliation in a Red Peak Granite xenolith is oriented 055/76. The most abundant xenoliths are quartzite, biotite schist and calc-silicate metasedimentary rock, followed in decreasing abundance by Red Peak Granite, layered tonalite, volcanic breccia, and silicic hornfels in (Fig. 22 A-C). The Kuna Crest Granodiorite, comprises just approximately 30% of the zone, and has a chaotic foliation that is not deflected at the margins of the xenoliths (Fig. 23).

Tonalite xenoliths up to 1.5 m across have hornblende-defined comb layers, which are 2-12 cm thick and span entire tonalite xenoliths (Fig. 22A). Comb layering in the tonalite fragments is interpreted to result from cumulate processes during early stages of crystallization of the Kuna Crest magma. Pegmatite dikes are abundant in the zone of xenoliths and have cusped lobate contacts with the Kuna Crest Granodiorite. Mirolitic cavities in the zone of xenoliths are one to two centimeters wide. They are filled with plagioclase, quartz, potassium feldspar, and secondary epidote and are evidence for abundant volatiles.

Figure 22. Xenolith-rich zone in the Kuna Crest Granodiorite. (A) Comb layering in a fragment of tonalite, presumably of an early crystallized part of the Kuna Crest Granodiorite. (B) Xenolith of the Red Peak Granite. Note on the right side, the fragment with a two-centimeter wide reaction zone. (C) Xenolith of a calc-silicate metasedimentary rock. Rock hammer and field book for scale.

Figure 23. Calc-silicate metasedimentary xenolith in the Kuna Crest Granodiorite. Foliation in the Kuna Crest Granodiorite is not deflected at the margin of the xenolith. Pen is for scale and is parallel to foliation in the Granodiorite.

Half Dome Granodiorite Contacts

Based on the map pattern, the metasedimentary unit of Quartzite Peak was hypothesized to be a remnant of the roof of the TIS; however, close examination of this contact revealed that it dips steeply (Plate 5, CD File 1). The Kuna Crest Granodiorite was presumably continuous around the margin of the TIS based on the map pattern (Fig. 1) that shows this granodiorite cropping out along the margin of the TIS on all sides of the study area and for many km along the eastern and western margins of the TIS as a whole; it is also found along a large part of the margin of the TIS in the study area. Along the western side of the host rock salient, the equigranular Half Dome Granodiorite cuts out the Kuna Crest Granodiorite and forms a steep contact with the Mount Clark Granite (Plate 1, Fig. 24). The irregular contact has steps up to 15 m long. The contact varies from sharp and planar to cusped-lobate, which implies localized partial assimilation of the Mount Clark Granite (Barnes et al., 2003), as the crystallization ages of these bodies differs by at least 10 m.y.

The equigranular Half Dome Granodiorite truncates the east-west-trending Mount Clark Granite-Gray Peak Granite contact (Plate 1). Furthermore, the north-south foliation in the Mount Clark Granite is not deflected next to the east-west-trending contact with the equigranular Half Dome Granodiorite (Fig. 24). Foliation in the equigranular Half Dome Granodiorite is parallel to the contact only within 20 m of the contact.

A xenolith of Mount Clark Granite is enclosed in the equigranular Half Dome Granodiorite approximately 20 m from the contact between these two units (Fig. 24).

Figure 24. Geologic map of the equigranular Half Dome Granodiorite-Mount Clark Granite contact. The solid-state foliation in the Mount Clark Granite is not deflected at the contact. Note the discordance between the foliation in the xenolith and that of the main body of Mount Clark Granite.

The foliation in the equigranular Half Dome Granodiorite is oriented approximately east-west at the northern and southern margins of the block, which is parallel to the contacts of the block. Within the block, a moderately strong solid-state foliation is oriented 260/54, and a lineation of similar intensity has a plunge and trend of 50/321. This solid-state foliation likely formed when the block was attached to the Mount Clark Granite, and thus was probably initially oriented N-S, implying that the foliation in the xenolith was rotated $\geq 80^\circ$ relative to the main body. The long axis of the block has been rotated into subparallelism with the foliation in the equigranular Half Dome Granodiorite. Close to this block, smaller (1 m²) Mount Clark Granite xenoliths, were found within 10 m from the equigranular Half Dome Granodiorite-Mount Clark Granite contact (Fig. 25).

Within two meters of the contact, on the equigranular Half Dome Granodiorite side, irregularly shaped felsic bodies resembling the Mount Clark Granite are 30 cm wide and two meters long. Across the contact, in zones up to one meter wide, are irregularly shaped bodies of Half Dome Granodiorite composition. These wispy bodies provide further evidence for localized partial assimilation of the leucocratic Mount Clark Granite, as discussed above.

The northern margin of the Red Devil Lake Granodiorite forms a sharp and steep contact with the porphyritic Half Dome Granodiorite (Plate 4). The two centimeter wide contact is lined with abundant large, euhedral biotite and hornblende grains that are aligned parallel to the contact on the porphyritic Half Dome Granodiorite side, whereas plagioclase and potassium feldspar are aligned parallel to the contact on the Red Devil Lake Granodiorite side (Fig. 26). This contact cuts internal layering of the Red Devil

Lake Granodiorite at a high angle. Foliations that are subparallel to this contact are observed up to 500 m from the contact in the Red Devil Lake Granodiorite. This foliation may imply that the structural aureole of the southern TIS ranges up to 500-m-wide; however, the foliation is magmatic and if it was rotated by the emplacement of a younger (probably by 4 m.y.) pluton, then more solid-state deformation than observed seems likely.

Figure 25. A Mount Clark Granite xenolith in the equigranular Half Dome Granodiorite. The chaotic foliation is illustrated by the long axes of the enclaves. Compass for scale.

Figure 26. Red Devil Lake Granodiorite- porphyritic Half Dome Granodiorite contact. The foliation in both granodiorites is contact-parallel. Pen for scale.

DISCUSSION OF STRUCTURE AND EMPLACEMENT

Structure of the Host Rocks

Foliations and lineations are solid-state within the metasedimentary unit, Gray Peak Granite, Mount Clark Granite, and Red Peak Granite. Aligned potassium feldspar in the granites of Gray Peak and Mount Clark, which are interpreted to have rotated while melt was present, indicate that foliation and lineation development initiated before complete solidification of the magma chamber. The Red Devil Lake Granodiorite displays two magmatic foliations. In all of these host rock units, foliation dip and lineation pitch are uniformly steep (Plates 1 and 2).

The north-south-striking foliation that pervades the Gray Peak Granite, Mount Clark Granite, and Red Peak Granite is found throughout the Sierra Nevada batholith (e.g., Bateman, 1992; McNulty et al., 1996). This north-south foliation is parallel to the western contacts with the equigranular Half Dome and Kuna Crest granodiorites. Three observations indicate that this concordance did not form as a result of emplacement of the TIS: 1) the east-west-trending contacts between the host rock are not deflected by the TIS; 2) the foliation is found more than two kilometers away from the contact, which exceeds the < 500-m-wide structural aureole of the TIS (see above); and 3) the foliation does not intensify as the TIS contact is approached. The north-south foliation is discordant to the east-west-trending contacts between host rock units. Based on these observations, I infer that the foliation indicates east-west regional shortening.

An east-west-striking foliation is found in the Gray Peak Granite, Mount Clark Granite, and Red Peak Granite in zones extending up to 250 m from each of the east-west-trending internal host rock contacts (Plate 1). This contact-parallel foliation is likely related to emplacement and is discussed in the following section.

The northwest-striking foliation in the Red Devil Lake Granodiorite is subparallel west-northwest-striking foliation in the Half Dome Granodiorite, which has been interpreted to have formed by regional strain (Bateman, 1992; Teruya and Miller, 2000). The rotation of foliation from north-south in the Red Peak Granite to north-northwest in the Red devil Lake Granodiorite suggests that regional shortening may have shifted from east-west to northeast-southwest between 98 Ma and 95 Ma, after the emplacement of the Red Peak Granite and before crystallization of the Red Devil Lake Granodiorite. The northewat-striking foliation may have formed by internal magma chamber processes, as it is not parallel to inferred regional strain.

Plane strain fabric is observed in the Gray Peak Granite, constrictional fabric in the Mount Clark Granite, and flattening fabric in the Red Peak Granite. This fabric variation indicates that either the strain field changed with time or that strain was partitioned differentially among the three bodies. The latter is less likely given the similarity in composition of the granites. Insufficient data are available to completely understand the cause of the fabric variation.

Some of the strain in the metasedimentary unit may be related to the emplacement of the TIS. The north-south-striking axial-planar foliation in this unit is parallel to contacts with the TIS. Granite veinlets are tightly folded and the axial planes are parallel

to the contact, implying east-west shortening. If these folds and the foliation formed during or after the emplacement of the Kuna Crest Granodiorite, then ductile shortening of the metasedimentary unit may have accommodated space for the intruding TIS. Alternatively, the folds and foliation in the metasedimentary unit may have formed earlier and rotated to their present orientations by emplacement of the TIS, or the Kuna Crest Granodiorite may have intruded concordantly to the structure in the metasedimentary unit.

Shortening in the Gray Peak Granite was accommodated in part by ductile shear zones. Orientations and kinematics of ductile shear zones proximal to the contact with the equigranular Half Dome Granodiorite imply east-west shortening, which is compatible with the N-S foliation found in all of the host rocks. This east-west shortening may be associated with the emplacement of the TIS and/or regional strain. Near the contact with the Mount Clark Granite, E-W trending ductile shear zones are contact-parallel, are discordant to the north-south foliation, and formed at high temperature. These observations imply north-south shortening which may have resulted from emplacement of the Mount Clark Granite. Alternatively, but probably less likely, the ductile shear zones may have formed by strain partitioning next to a rheological discontinuity during regional shortening.

Structure of the Tuolumne Intrusive Suite

The magmatic foliation in the Kuna Crest Granodiorite generally strikes north-northeast (Fig. 14A) and is parallel to the stepped contact with the Red Peak Granite (Fig.

21). The foliation may have formed due to emplacement of younger pulses of magma of the TIS, flow along the wall of the TIS, east-west regional shortening, or some combination of these processes.

Ductile shear zones in the Kuna Crest Granodiorite have the proper orientation (approximately north-south-striking and steep) and kinematics to operate as a material transfer during intrusion of the Half Dome Granodiorite and/or more internal pulses of the Kuna Crest Granodiorite. However, the paucity, small size, and minor displacement of the shear zones indicate that they accommodated only a minor amount of space for the intrusive suite. Higher-strain ductile shear zones, which experienced more substantial ductile deformation may have been removed by stoping along the margin of the Kuna Crest Granodiorite (Paterson et al., 1996; Yoshinobu et al., 2002), or may lie beneath alluvium.

The Half Dome Granodiorite contains two magmatic foliations at single outcrops throughout the study area, one generally striking northeast-southwest and the other striking northwest-southeast. The mechanism that formed foliations of two different orientations at individual outcrops is not well understood (e.g., Teruya and Miller, 2000; Paterson et al., 2003). Enclave shape and orientation relative to the two foliations at can help distinguish the relative timing of their formation (Paterson et al., 2004). At one enclave (station 172) in the equigranular Half Dome Granodiorite, one magmatic foliation overprints the other (Fig. 27). If this area is representative, then the northeast foliation formed before the northwest foliation, which indicates at least two strain increments in the magma chamber. These different strain orientations may have been due

Figure 27. Photo of an enclave in the Half Dome Granodiorite. The enclave is aligned parallel to the northeast-southwest foliation and it is intruded by a finger of the Half Dome Granodiorite that has a foliation parallel to the northwest-southeast foliation in the Half Dome Granodiorite. The pencil is aligned parallel to the northwest-southeast foliation and the field book is aligned with the northeast-southwest foliation.

to a transition from differential flow in the magma chamber during emplacement to tectonic shortening, shortening caused by separate tectonic events, or tectonic strain overprinted by strain reflecting late crystallization and elastic recovery (Paterson et al., 2004).

I propose that the two foliations formed as a result of a transition from differential flow in the magma chamber to tectonic shortening. The northeast-striking foliation formed early, is concordant to the contact between the equigranular Half Dome Granodiorite and the Mount Clark Granite, and thus may be related to flow along the wall of the TIS or internal chamber processes. The northwest-striking foliation is discordant to contacts and internal layering, and formed after northeast-striking foliation, thus suggesting that the northwest-striking foliation records tectonic strain.

Deflection of the foliation in the equigranular Half Dome Granodiorite around the large stoped block of Mount Clark Granite indicates that magma of the Half Dome Granodiorite must have been viscous enough to suspend the block of granite, yet enough melt was still present to record a magmatic foliation. This implies that the foliation formed during a late stage of magma chamber evolution, either during emplacement or shortly after emplacement as the magma cooled (Fowler and Paterson, 1997; Paterson and Miller, 1998).

Evidence for Mechanisms of Emplacement

The east-west-striking foliations in the granites of Gray Peak, Mount Clark, and Red Peak may be related to emplacement. I propose that each of these host rock units

were emplaced by the intrusion of multiple pulses of magma, as are many plutons (e.g., Miller and Paterson, 2001; Hirt and Hatton, 2004). The first, outer pulses of each unit solidified before the younger pulses of each unit intruded. The east-west solid-state foliation formed at the margin of each unit by strain related to the intrusion of younger pulses. At the margins of the plutons, emplacement-related strain dominated, whereas at the core of the plutons, the E-W regional shortening dominated. This shortening was active during the emplacement of each of these older host rock units, and formed the north-south foliations.

Stoping and contact-parallel ductile shear zones in host rocks provide evidence for vertical transport of host rock via multiple material transfer processes during emplacement of the TIS. Multiple lines of evidence show that stoping was active during the emplacement of the TIS, as described below, including: 1) truncation of contacts between host rock units, 2) removal of the Kuna Crest Granodiorite, and 3) rotation of xenoliths in the Half Dome and Kuna Crest granodiorites. The E-W-trending Mount Clark Granite-Gray Peak Granite contact is truncated at a high angle by the equigranular Half Dome Granodiorite (Plate 1). The porphyritic Half Dome Granodiorite truncated the north-south-trending Gray Peak Granite-Red Devil Lake Granodiorite contact at a high angle (Plate 1). The Kuna Crest Granodiorite was presumably continuous around the southern margin of the TIS before the emplacement of the Half Dome Granodiorite as discussed above, and its absence around the northwest corner of host rock salient probably is a result of stoping during the emplacement of the Half Dome Granodiorite.

Incorporation of xenoliths of Mount Clark Granite, Red Peak Granite, tonalite, and metasedimentary rocks in the TIS provide further evidence for stoping.

Contact-parallel, reverse ductile shear zones in the Gray Peak Granite along the contact with the Half Dome Granodiorite may indicate that ductile deformation of country rock occurred during the emplacement of the TIS. These ductile shear zones record vertical flow of the host rock and may have accommodated material transfer process during emplacement. Contact-parallel axial-planar foliation and folds in the metasedimentary unit adjacent to the Kuna Crest Granodiorite also may have accommodated the intruding TIS. Crude calculations imply that ductile deformation in the host rock created only 1-2% of the space needed to accommodate the TIS. These calculations assume 50% strain over the thickest part of the structural aureole results in approximately 200 m of space, which is 2% of the 20 km radius of the TIS. Steeply plunging lineations in the TIS and all host rock units are consistent with vertical flow of host rock (Plate 2).

Evidence for localized assimilation of host rock is found in the Mount Clark Granite, in zones up to one meter from the contact with the equigranular Half Dome Granodiorite. The highly localized evidence for assimilation suggests that it acted as a very minor material transfer process during the emplacement of the TIS.

Evaluation of Proposed Emplacement Models for the TIS

Nested Diapir Accommodated by Multiple Material Transfer Processes

Stoping and ductile host rock deformation in the study area show that multiple material transfer processes accommodated the intrusion of the TIS. Ductile deformation in the host rock did not accommodate a large percent of the intrusion of the TIS. Data from this study do not constrain mechanisms of magma ascent, so the hypothesis that this pluton was constructed by multiple nested diapirs (Paterson and Vernon, 1995) cannot be evaluated.

P-Shear Model

No evidence was found to support the “P-shear” emplacement model. This model predicts that fractures on small scale faults strike north-northwest. These structures are inferred to be in P-shear orientations relative to the main shear zones in the Sierra Nevada (Tikoff and Teyssier, 1992). No prominent faults were found in the TIS and host rock units. Ductile shear zones in the Kuna Crest Granodiorite do not strike north-northwest, and ductile shear zones did not form in the Half Dome Granodiorite. Although steeply plunging lineations can form in a transpressional setting (e.g., Robin and Cruden, 1994; Tobisch and Cruden, 1995), ductile shear zones in the host rock are not dominantly oriented north-northwest and they mainly record a reverse motion. Furthermore, P-shears are minor structural features. It is probably unlikely that dilation along structurally minor features could have created space to accommodate the emplacement of the TIS, which crops out over a 1,500 km² area (Bateman, 1992).

Ballooning Model

No evidence was found to support the ballooning model (Bateman and Chappell, 1979) for the emplacement of the TIS. The ballooning model predicts a strain gradient in the magma chamber during intrusion and a large flattening strain in the host rock. The increase in the intensity of steeply dipping foliations and steeply plunging lineations in the TIS from the core to the margin indicate an increasing strain gradient toward the margin, however, the steeply dipping lineations at the margin of the TIS are not compatible with *in situ* expansion. Furthermore, ductile deformation of the host rock created a small amount of space, which is contrary to predictions of the ballooning model. My conclusions are in agreement with the isotopic by Kistler et al. (1986) that attributed compositional zoning of the TIS resulted from multiple batches of magma that were derived from different mixtures of parent magmas.

Incremental Filling

The incremental filling model (Glazner et al. 2004) is incompatible with the data from this study for several reasons. 1) Stoping is not predicted in the incremental filling model. Host rock inclusions are viewed as interconnected septum that were isolated by dikes and did not rotate with respect to the host rock from which they were separated (Glazner et al, 2004). In contrast, in the southern part of the TIS, the orientation of foliation within xenoliths clearly indicates that they have been rotated relative to the body from which they were derived. 2) The presence of two foliations at individual outcrops in the Half Dome Granodiorite is incompatible with the incremental filling model. If small batches of magma cooled rapidly and formed the Half Dome Granodiorite, only

small amounts of magma would have been above the solidus at any given time; thus, magmatic foliations would have formed rapidly. The northeast-southwest foliation could have formed by strain associated with the emplacement of the small batches of magma, but second foliation in this model is not easily explained if emplaced by small batches of magma that would be above the solidus for a short time. 3) The increasing intensity of foliations from the core to the margin of the TIS are difficult to explain with small magma batches that presumably would have remained above their solidi only for short time intervals. Margins of plutons typically undergo more regional strain than their cores and record foliations of greater intensity (e.g., Paterson et al., 1998). Increasing foliation intensity from the core to the margin of the Half Dome Granodiorite is more compatible with the presence of a relatively large, long-lived magma body rather than ephemeral magma bodies that solidified rapidly upon emplacement.

Floor Subsidence

It is difficult to evaluate floor subsidence models (Cruden and McCaffery, 2001) because the base of the TIS is not exposed in the study area. Downward folding of wall rocks is consistent with floor subsidence. The rotation in the cantilever model would create radial stretching deformation fabrics that are related to the down-dropping of one side of the pluton floor. Conversely, piston-style emplacement will form flat floors with vertical sides that are related to faults, ductile shear zones, and bordering dikes. Evidence for ductile downward flow of host rock is found only in the Gray Peak Granite and cannot solely accommodate the down-dropping of the floor of the TIS.

Roof Uplift

Roof uplift is proposed for plutons at shallow crustal levels (< 5 km), in a variety of tectonic settings (Acocella and Mulugeta, 2001). Roof uplift typically domes of host rock above a pluton; however, it is difficult to find evidence for surface doming in most plutons because the overlying host rock layers are quickly eroded during uplift and emplacement (Acocella and Mulugeta, 2001). Roof uplift also predicts brittle, vertical shear zones at the host rock-pluton contacts to allow for lifting of the roof. No evidence for this model is found in the study area.

CONCLUSIONS

The following are conclusions drawn from the research of this thesis:

1. Foliation dips and lineation pitches are uniformly steep in all units in the study area.
2. The N-S-striking foliation in the metasedimentary unit, Gray Peak Granite, Mount Clark Granite, and the Red Peak Granite formed by E-W regional shortening.
3. The N-S-striking foliation in the Kuna Crest Granodiorite may be related to strain from the intrusion of younger magmas of the TIS.
4. Two magmatic foliations at outcrop scale in the Half Dome Granodiorite formed late, are discordant to contacts, and are not related to strain from emplacement.
5. Stopping and ductile host rock deformation accommodated, in part, the emplacement of the southern part of the Tuolumne Intrusive Suite.
6. General implications the P-shear, incremental filling, and ballooning models of emplacement are not compatible with data from this study.

REFERENCES CITED

- Acocella, V., and Mulugeta, G., 2001, Surface deformation induced by pluton emplacement: The case of Amiata (Italy): *Physics and Chemistry of the Earth, Part A, Solid Earth and Geodesy, Part A*, v. 26, p. 355-362.
- Ague, J.J., and Brimhall, G.H., 1988, Magmatic arc asymmetry and distribution of anomalous plutonic belts in the batholiths of California: Effects of assimilation, crustal thickness, and depth of crystallization: *Geologic Society of America Bulletin*, v. 100, p. 912-927.
- Bateman, P.C., 1992, Plutonism in the central part of the Sierra Nevada batholith, California: U.S. Geologic Survey Professional Paper 1483, 186 p.
- Bateman, P.C., and Chappell, B.W., 1979, Crystallization, fractionation, and solidification of the Tuolumne Intrusive Series, Yosemite National Park, California: *Geologic Society of America Bulletin*; Part 1, v. 90, p. 465-482.
- Barnes, C.G., Dumond, G., Yoshinobu, A.S., and Perstvik, T., 2003, Asymmetric zoning of a middle crustal pluton in the Norwegian Caledonides: Selective assimilation of host rocks: *Geological Society of America Abstracts with Programs*, v. 35, no. 6, p. 92
- Coleman, D.S., and Glazner, A.F., 1997, The Sierra Crest magmatic event: Rapid formation of juvenile crust during the late Cretaceous in California: *International Geology Review*, v. 39, p. 768-787.
- Coleman, D.S., Gray, W. and Glazner, A.F., 2004, Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California: *Geology*, v. 32, p. 433-436.
- Cloos, H., 1925, *Einführung in die tectonische Behandlung magmatischer Erscheinungen*: pt 1: *Das Riesengebirge in Shlesien*. Gebr., Borntraeger, Berlin, 194 quoted in R. Balk, 1937.
- Cruden, A.R. and McCaffrey, K.J.W, 2001, Growth of plutons by floor subsidence: implications for rates of emplacement, intrusion spacing and melt-extraction mechanisms: *Physics and Chemistry of the Earth, Part A, Solid Earth and Geodesy*, 26, 303-315.
- Cruden, A.R., 1999, Magnetic fabric evidence for conduit fed emplacement of a tabular intrusion: Dinkey Creek Pluton, central Sierran Nevada batholith, California: *Journal of Geophysical Research*, v. 104, p. 10511-10530.

- Cruden, A.R., 1998, On the emplacement of tabular granites: *Journal of the Geological Society, London*, v. 155, p. 853-862.
- Fowler, T.K., and Paterson, S. R., 1997, Timing and nature of magmatic fabrics from structural relations around stoped blocks: *Journal of Structural Geology*, v. 19, p. 209-224.
- Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., and Taylor, R.Z., 2004, Are plutons assembled over millions of years by amalgamation from small magma chambers?: *GSA Today*, v. 14, no. 4/5, p. 4-11.
- Hirt, W. H., and Hatton, J. R., 2004, Thermal modeling of a composite felsic intrusion: Implications for the origin of compositional zoning within members of the Mount Whitney Intrusive Suite, Sierra Nevada, California: *Geological Society of America Abstracts with Programs*, v. 36, no. 4, p. 71.
- Huber, N.K., Bateman, P.C., and Wahrhaftig, C., 1989; *Geologic Map of Yosemite National Park and Vicinity: U.S. Geologic Survey Map I-1874*, scale 1:125000.
- Kistler, R.W., Chappell, B.W., Peck, D.L., and Bateman, P.C., 1986, Isotopic variation in the Tuolumne Intrusive Suite, central Sierra Nevada, California: *Contributions to Mineralogy and Petrology*, v. 94, p. 205-220.
- Miller, R.B., Paterson, S.R., 2001, Construction of mid-crustal sheeted plutons: Examples from the North Cascades, Washington: *Geological Society of America Bulletin*, v. 113, no. 11, p. 1423-1442.
- McNulty, B.A., Tong, W., Tobisch, O.T., 1996, Assembly of a dike-fed magma chamber: The Jackass Lakes pluton, central Sierra Nevada, California: *GSA Bulletin*, v. 108, p. 926-940.
- Paterson, S.R., Vernon, R.H., and Tobisch, O.T., 1989, A review of the criteria for the identification of magmatic and tectonic foliations in granitoids, *Journal of Structural Geology*, v. 11, p. 349-363.
- Paterson, S.R., and Vernon, R., 1995, Bursting the bubble of ballooning plutons: A return to nested diapirs emplaced by multiple processes: *Geologic Society of America Bulletin*, v. 107, p. 1356-1380.
- Paterson, S.R., and Fowler, T.K., 1996, Local displacement of diapir contacts and its importance to pluton emplacement study: Discussion: *Journal of Structural Geology*, v. 18, no. 5, p. 711-712.

- Paterson, S.R., Fowler, K.T., Schmidt, K., Yoshinobu, A., and Yuan, S., 1998
Interpreting magmatic fabric patterns in plutons: *Lithos*, v. 44, p. 53-82.
- Paterson, S.R. and Miller, R.B. 1998. Stopped blocks in plutons: paleo-plumb bobs, viscometers, or chronometers? *Journal of Structural Geology*, v. 20, p. 1261-1272.
- Paterson, S.R., Pignotta, G.S., and Vernon, R.H., 2004, The significance of microgranitoid enclave shapes and orientations: *Journal of Structural Geology*, v. 26, p. 1465-1481.
- Paterson, S.R., Onezime, J., and Teruya, L., Zak, J., 2004, Quadruple-pronged enclaves: their significance for the interpretation of multiple magmatic fabrics in plutons: *Journal of the Virtual Explorer*, v. 11.
- Peck, D.L., 2002, Geologic map of the Yosemite quadrangle, central Sierra Nevada, California: U.S. Geologic Survey Map I-2751, scale 1:62,500.
- Peck, D.L., 1980, Geologic map of the Merced Peak quadrangle, central Sierra Nevada, California: U.S. Geologic Survey Map GQ-1531, scale 1:24,000.
- Ratajeski, K.R., Glazner, A.F., and Miller, B.V., 2001, Geology and geochemistry of mafic to felsic plutonic rocks in the Cretaceous intrusive suite of Yosemite Valley, California: *Geological Society of America Bulletin*, v. 113, no. 11, p. 1486-1502.
- Robin, P.-Y.F., and Cruden, A.R., 1994, Strain and vorticity patterns in ideally ductile transpression zones: *Journal of Structural Geology*, v. 16, p. 447-466.
- Stern, T.W., 1981, Isotopic U-Pb ages of zircon from the granitoids of the central Sierra Nevada: U.S. Geological Survey Professional Paper 1185, p.17.
- Teruya, L.A., and Miller, R. B., 2000, Significance of multiple magmatic fabrics at two internal contacts within the Tuolumne Intrusive Suite, Sierra Nevada batholith, California: *Geological Society of America Abstracts With Programs*, v. 32, p. A-231.
- Tikoff, B., and Teyssier, C., 1992, Crustal-scale, en-echelon "P-shear" tensional bridges: A possible solution to the batholith room problem: *Geology*, v. 20, p. 927-930.
- Tobisch, O.T, and Cruden, A.R., 1995, Fracture-controlled magma conduits in an obliquely convergent continental magmatic arc: *Geology*, v. 23, no. 10, p. 941-944.

- Tobisch, O.T, Saleeby, J.B., Renne, P.R., McNulty, B.A., and Tong, W., 1995, Variations in deformation fields during development of a large volume magmatic arc, central Sierra Nevada, California: Geological Society of America Bulletin, v. 107, p. 148-166.
- Tong, W., 1994, Nature, physical conditions and time constraints of ductile deformation and pluton emplacement in the Quartz Mountain area, Sierra Nevada, CA, and within the Changle-Nanao shear zone, Dongshan area, southeast China [Ph.D. thesis]: Santa Cruz, University of California, 182 p.
- Tullis, J.A., 1983, Deformation of feldspars, Mineralogical Society of America Reviews in Mineralogy, v. 2, p. 297-323.
- Vernon, R.H., 2000, Review of Microstructural Evidence of Magmatic and Solid-State Flow: Electronic Geosciences, ISSN 1436-2511.
- Voll, G., 1976, Recrystallization of quartz, biotite and feldspar from Erstfeld to the Leventina Nappe, Swiss Alps, and its geological significance, Schweizerische Mineralogische und Petrographische Mitteilungen, v. 56, p. 641-647.
- Yoshinobu, A.S., et al., 2002, A view from the roof: magmatic stoping in the shallow crust, Chita pluton, Argentina: Journal of Structural Geology, v. 25, p.1037-1048.

APPENDIX

Procedure For GIS Work: How I Drafted My Geologic Map Using ArcGis

Part 1) Gather the necessary files, format them into an ArcGis friendly format, and place the files into one folder. ArcGIS 7.0 software or above must be installed on the computer.

- 1) The first step is to organize all of the field data into an excel database that can be imported into ArcGis. My database includes station numbers, their coordinates in latitude/longitude decimal degree NAD 27, structural data and other field observations. There must not be any spaces between letters in each column of the first row.
- 2) This spreadsheet must be saved as a <Comma-Delimited> spreadsheet so that it can be imported into ArcGIS. Place this spreadsheet in a folder called MyGIS. You will place all files that will be used to construct this GIS in this folder.
- 3) Download the Digital Raster Graphic (DRG) of the Merced Peak Quadrangle. This can be found at <http://casil.ucdavis.edu/casil/gis.ca.gov/drg/> and it is labeled <o37119f4>. Save these files in the MyGIS folder.

Part 2) Add the Merced Peak Quadrangle to the GIS and set the coordinate system.

- 1) Add data by clicking on <File>, <Add Data>, and scroll to the MyGIS folder and select <o37119f4.tiff>. You now should see the map displayed in GIS.

- 2) This map is georeferenced with the NAD 27 lat/long coordinate system. The coordinate system in the data frame needs to be set to the same as the map coordinate system. To do this right click anywhere in the data frame. Then select <Properties> then select <Coordinate System>, in the dialog box under <Select a Coordinate System> select <Predefined>, select <Geographic Coordinate System>, then select <North America>, and finally <North America Datum 1927>. The coordinate system of the map and data frames should now be the same.
- Part 3) Add the excel data, plot and label all of the foliations.
- 1) Add the excel spreadsheet containing the foliation data by clicking on <File>, <Add Data>, and scroll to the MyGis folder and select the foliation excel file, which is in <csv> format.
 - 2) Once the excel file appears in the Table of Contents on the left side of the screen, right click on it and select <Display XY Data>. The X field should be set to <longitude> and the Y field should be set to <latitude>. In the Spatial Reference section press the <Edit> button to select a coordinate system. Then press <Select> to choose the coordinate system as done for the Data Frame. Select <Geographic Coordinate System>, then select <North America>, and finally <North America Datum 1927> and press <OK>. Now all of the stations are plotted as dots on the Merced Peak Quadrangle.

- 3) Now the dots must be converted into properly oriented foliation symbols. To do this, right click on the foliations layer in the Table of Contents. Select <Properties>, then select the <Symbology> tab. Double click on <Symbols>, this will prompt a Symbol Selector dialog box. In order to be able to display geological data, select <more symbols> and make sure there is a check by <Geology 24K>. Now in the Symbol Selector dialog box, scroll down to the symbol <inclined foliation in a layered gneiss, showing strike and dip>. Then set the symbol size to 50 and press <OK>.
- 4) Next, the foliation strike must be set. To do this press the <Advanced> button in the Symbol box and select <Rotation...>. Then under <Rotate Points by angle in this field>, scroll down to <Strike>, select <Geographic> under <Rotation Style>, and press <OK>. Now all of the foliations should be displayed showing strike and dip direction.
- 5) To label the dip of the foliations right click the foliations layer in the table of contents and select Properties. Next select the <Labels> tab. Make sure to check box next to <Label Features in this layer>. In the Text String box select <foliation strike>. To ensure that all of the foliations will be labeled you must press the <Label –placement Options> button. Next select the <Conflict Detection> tab and at the bottom left side of this box, check the box next to <Place overlapping labels> and hit ok.

Part 6) Create a 3-D geologic map.

119°30'

119°27'30"

Plate 1. Geologic Map of the Southern Margin of the Tuolumne Intrusive Suite and Host Rocks

Explanation	
	Qal-Quaternary Alluvium
	Khde-Equigranular Half Dome Granodiorite
	Khdp-Porphyritic Half Dome Granodiorite
	Kkc-Kuna Crest Granodiorite
	Krd-Red Devil Lake Granodiorite
	Kil-Illilouette Creek Granodiorite
	Krp-Red Peak Granodiorite
	Kmc-Mount Clark Leucogranite
	Kgp-Grey Peak Granite
	ms-Undifferentiated Metasedimentary rock
	Solid-State foliation, showing strike and dip
	Magmatic foliation, showing strike and dip

Produced by Karpowicz, R.A., 2003-2004; data for NW corner and central north section from Miller, R.B., and Miller, J.S., 2002. Base from U.S. Geologic Survey, 1992, Lambert Conformal Conic projection, 1927 North America datum, 10,000 foot grid based on California coordinate system, zone 3

SCALE 1:24000

CONTOUR INTERVAL 40 FEET

GRID AND 1994 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

- 1) Add the JPEG final map to the GIS. Georeference and rectify this map.
- 2) Obtain Digital Elevation Model (DEM) of the Merced Peak Quadrangle. This can be found at the following url
<http://data.geocomm.com/catalog/US/61069/1533/group4-3.html>>. This DEM is scaled to 1:24000 with a 10 meter resolution and it is in SDTS format. You need to download the SDTS translator from the website to convert this file into a format that ArcGIS can read. Follow the websites instructions on how to do this.
- 3) Add the Merced Peak DEM to the GIS. Georeference and rectify the DEM as done in Part 4.3.
- 4) Open ArcScene and add the rectified final map and the rectified DEM.
- 5) Activate the 3D Analyst extension by clicking <Tools> then <Extensions>. Then click on the <3D Analyst> tab and scroll down to <Convert>, then select <raster to tin...>.
- 6) In the Convert Raster to Tin dialog box be sure to select the input raster as the rectified DEM, then press <OK>. This will create a TIN, which is a 3D image of the Merced Peak Quadrangle.
- 7) In order to convert the rectified final map into a 3D image right click on it and select <Properties>. Next select the base heights tab and choose <Obtain heights for layer from surface:>. Make sure the Tin that you just created is selected in this box. Press <OK> and now the geologic map is 3D.

119°30' 119°27'30" 119°22'30"

Plate 2. Map of Lineations in the Southern Margin of the Tuolumne Intrusive Suite and Host Rocks

Mapped by Kurpovitz, R.A., 2003-2004; data for RW corner and central-north sliver from Miller, R.B., and Miller, J.S., 2002. Base from U.S. Geologic Survey, 1992, Lambert Conformal Conic projection, 1927 North America datum, 10,000 foot grid based on California coordinate system, zone 3

GRID AND 1994 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

Plate 3. Stations Map

Base from U.S. Geological Survey
Merced Peak Quadrangle, 1992

Scale 1:48000

- Khd-Half Dome Granodiorite
- Kkc-Kuna Crest Granodiorite
- Krd-Red Devil Lake Granodiorite
- Ki-Illilouette Creek Granodiorite
- Krp-Red Peak Granodiorite
- Kmc-Mount Clark Leucogranite
- Kgp-Gray Peak Granite
- ms-Metasedimentary rocks

Plate 5. E-W cross-section. Note the dashed lines are foliations that were measured at the surface and extrapolated at depth.