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Structure, Construction, and Emplacement of Jurassic and Cretaceous Plutons in the Keiths Dome-Echo Lake Area, Southwest of Lake Tahoe, California

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STRUCTURE, CONSTRUCTION, AND EMPLACEMENT OF JURASSIC AND CRETACEOUS
PLUTONS IN THE KEITHS DOME-ECHO LAKE AREA, SOUTHWEST OF LAKE TAHOE,
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

by

Pamela Jamie Clay

December 2014

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A Designated Thesis Committee Approves the Thesis Titled
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APPROVED FOR THE DEPARTMENT OF GEOLOGY

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December 2014

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ABSTRACT

STRUCTURE, CONSTRUCTION, AND EMPLACEMENT OF JURASSIC AND CRETACEOUS PLUTONS IN THE KEITHS DOME-ECHO LAKE AREA, SOUTHWEST OF LAKE TAHOE, CALIFORNIA

By Pamela Jamie Clay

Jurassic (Keiths Dome) and Cretaceous (Echo Lake, Glen Alpine) plutons and their host rocks were investigated, and structural and petrographic analyses were conducted, to elucidate the nature and timing of pluton construction and emplacement, deformation, and related tectonic regimes. Evenly distributed enclaves and a lack of internal contacts suggest pluton construction via thorough mixing of multiple increments of magma. Ductile flow of conglomerate host rocks, stoping of volcanic host rocks, and possibly other processes, facilitated emplacement. In Cretaceous plutons, margin-parallel magmatic foliations may record internal processes, whereas the Keiths Dome pluton contains foliations that are discordant to contacts and likely record regional strain. The Keiths Dome pluton contains NW-striking, steeply dipping ductile shear zones, and steeply dipping microdiorite dikes that are deformed by some shear zones. The inferred strain field from foliation, lineation, dikes, and ductile shear zones is one of regional transpression that likely changed or weakened prior to intrusion of the Cretaceous plutons. Emplacement of the Keiths Dome pluton and subsequent ductile shear may have occurred during the Late Jurassic Nevadan orogeny, as other syntectonic dike swarms in the Sierra Nevada batholith are 158-148 Ma. Geochronologic data are needed to further constrain the timing of deformation.

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INTRODUCTION

Much advancement in our understanding of plutons has been made in recent years, but the complexity of these systems continues to drive debate regarding the size of magmatic increments and existence of large, relatively long-lived magma chambers. Many researchers (e.g., Clemens and Mawer, 1992; Paterson and Vernon, 1995; Clarke and Clarke, 1998; Wiebe and Collins, 1998; Barbey et al., 2008; Paterson et al., 2011) suggest that plutons may be assembled by large pulses, or by many increments of magma spaced close enough in time to maintain a steady-state chamber, and others (e.g., Coleman et al., 2004; Michel et al., 2008) have proposed that incremental construction by small batches of magma takes place on timescales of thousands to millions of years and no sizable magma chamber forms.

Many models supporting the presence of a magma chamber emphasize that dynamic processes, including stoping and recycling of older phases, may obscure contacts between pulses (e.g., Bergantz, 2000; Zak and Paterson, 2005; Paterson et al., 2008). In addition, internal contacts in a chamber may be obscured if the contrast between magma increments is subtle, or if the crystal network is destabilized (Matzel et al., 2006; Horsman et al., 2009; Huber et al., 2009; Burgisser and Bergantz, 2011; Miller et al., 2011). In the alternative model of construction, via small increments separated by enough time such that magma interaction is limited (Glazner et al., 2004; Bartley et al., 2006), thermal annealing obscures internal contacts. Both styles of construction

have been supported by geochemical data (e.g., Vernon and Paterson, 2008; Zak et al., 2009; Miller et al., 2011).

Interpretation of construction and emplacement requires an evaluation of structural data with respect to mass transfer processes (MTPs). Most MTPs allow the crust to accommodate the addition of magma via redistribution of material without changing the crustal volume (e.g., stoping, ductile flow, magmatic wedging, assimilation, extension, and floor subsidence). Other MTPs, such as roof uplift, may be capable of changing crustal volume (Paterson and Vernon, 1995). Numerous studies infer that pluton emplacement requires multiple processes operating at different rates, times, and scales (e.g., Paterson et al., 1996; McNulty et al., 2000; Miller and Paterson, 2001; Zak and Paterson, 2005; Miller et al., 2009).

Structural data collected from granitoid plutons and their host rocks are useful in determining the magmatic and tectonic evolution of magmatic arcs. As magma is emplaced and cools, plutons and their host rocks record a variety of structures from which magmatic flow dynamics, mass transfer processes, construction and emplacement mechanisms, tectonic strain fields, and relative timing of magmatic events and deformation may be interpreted. More powerful yet, data collected from adjacent plutons with ages spanning a significant period of time may record temporal changes in tectonic regime and the potential impact of these regimes on construction and emplacement.

Geologic Setting

One exhumed magmatic arc that illustrates the importance of plutons for understanding magmatic and tectonic processes is the ~640-km-long, Mesozoic Sierra Nevada batholith. This batholith has been host to numerous recent studies of plutons, most concentrating on the highly accessible and well-exposed Tuolumne Intrusive Suite and its host rocks (e.g., Ratajeski et al., 2001; Coleman et al., 2004; Albertz et al., 2005; Albertz, 2006; Miller et al., 2007; Burgess and Miller, 2008; Gray et al., 2008; Solgadi and Sawyer, 2008). The northern part of the Sierra Nevada has received much less attention. This thesis investigates the structure of Jurassic and Cretaceous plutons southwest of Lake Tahoe, California, and the adjacent metamorphosed sedimentary and volcanic rocks of the Early Triassic-Middle Jurassic Mount Tallac pendant. The study area is ~45 km² and is located ~10 km southwest of Lake Tahoe (Fig. 1).

The study area was previously examined by Loomis (1961, 1983) as part of his mapping of the Fallen Leaf Lake 15-Minute Quadrangle. The Mount Tallac pendant was mapped and interpreted by Fisher (1989). Approximately 5 km west of the study area, Wiebe et al. (2002) conducted very detailed research on part of the Pyramid Peak Granite, interpreting dynamic magma interactions between mafic and felsic magma during construction of the intrusion. With ~865 m of topographic relief and excellent accessibility via a network of trails that include the Pacific Crest National Scenic Trail, the exposure is ideal for collecting structural data and interpreting construction and

Figure 1. Simplified geologic map of study area modified from Loomis (1983). Dashed line delineates study area. Inset shows the location of the study area relative to the rest of the Sierra Nevada batholith.

emplacement mechanisms, the temporal evolution of tectonic strain fields, and the regional deformational history.

The study area contains both Jurassic (Keiths Dome quartz monzonite and Desolation Valley granodiorite) and Cretaceous (Echo Lake, Bryan Meadow, and Glen Alpine granodiorites) plutons. Within the study area, the Keiths Dome, Echo Lake, and Glen Alpine plutons intrude sedimentary and volcanic host rocks of the mostly NE-dipping, Middle Jurassic Tuttle Lake Formation, the youngest portion of the Triassic-Jurassic Mount Tallac pendant. The Lower-Middle Jurassic Sailor Canyon Formation underlies the Tuttle Lake Formation, and a portion of this formation is thrust over the volcanic rocks of the Tuttle Lake Formation, forming small outcrops that lie within the boundaries of the study area. These rocks have been metamorphosed mostly to the greenschist facies (Loomis, 1983). The Keiths Dome pluton is deformed by numerous solid-state shear zones and is inferred to be the oldest pluton in the area (Loomis, 1983). It is cut by steeply dipping microdiorite dikes that intrude other Jurassic plutons in the study area (Loomis, 1983; Sabine, 1993).

Issues with K-Ar dating and overprinting of Early Jurassic deformation have hindered interpretation of timing of deformation in the northern part of the batholith (Ward, 1995). Analysis of paleomagnetic apparent-polar-wander data supports a change in tectonic environment in the Late Jurassic at ~150 Ma, in which the North American plate makes a dramatic change in absolute motion at the J2 cusp (May and Butler, 1986). This event has been linked to the Nevadan orogeny (Wolf and Saleeby,

1992), a Late Jurassic period of contractional deformation, which is estimated to have peaked in intensity between 154 and 150 Ma (Schweikert et al., 1984; Burchfiel et al., 1992).

East-dipping thrust sheets in the western Sierra Nevada metamorphic belt, and a NW-striking, NE-dipping, slaty, phyllitic, and crenulation cleavage in the Sailor Canyon and Tuttle Lake Formations of the Mount Tallac pendant were originally attributed to shortening during the Nevadan orogeny (Schweikert, 1984; Edelman et al., 1989; Girty et al., 1993; Ward, 1995). More recently, Girty et al. (1995) inferred that these structures are older (175-166 Ma) than the Nevadan deformation event based on fossil assemblages in the Sailor Canyon Formation and the rotation of cleavage near the 168-166 Ma Emigrant Gap and Haypress Creek plutons.

A number of syntectonic dike swarms were emplaced from 158-148 Ma, during and subsequent to the Nevadan orogeny, including those of the Owens Mountain dike swarm-shear zone, the Sonora mafic dike swarm, and the Independence mafic to felsic dike swarm (Sharp, 1980; James, 1989; Wolf and Saleeby, 1992; Carl and Glazner, 2000). The tectonic regime inferred from these studies is one of transtension-transpression (Wolf and Saleeby, 1992, 1995). The microdiorite dikes in the Keiths Dome pluton and other Jurassic plutons in the Fallen Leaf Lake quadrangle may, speculatively, have also formed during the Late Jurassic (Wolf and Saleeby, 1992, 1995).

Methods

Mapping at a 1:24,000 scale over a $\sim 45 \text{ km}^2$ area was performed and a detailed structural analysis was conducted. Orientations of magmatic and solid state foliations and lineations, contacts, dikes, and ductile shear zones were measured. Magmatic and solid state foliation and lineation data were used to investigate internal magmatic flow and regional strain. Measurements and observations of contacts with host rocks, along with foliation and lineation orientations in the plutons and host rocks, were used to identify material transfer processes active during emplacement. Dikes helped constrain the relative timing of plutons and extension directions during dike injection, and ductile shear zone orientations and microstructures allowed for the interpretation of solid-state kinematics and deformation temperatures. Magmatic features, such as schlieren and enclaves, were examined to study magma dynamics. Thin sections were analyzed to determine approximate modes, textures, and microstructures. In the following, I describe the units in the study area and associated structures, and I discuss the implications of the structures with respect to the construction and emplacement of the plutons and the proposed tectonic regimes.

ROCK UNITS AND FIELD RELATIONSHIPS

Jurassic Rocks

Mount Tallac Pendant

The ~4,400 m-thick Mount Tallac pendant (Fisher, 1990) is exposed west of Fallen Leaf Lake (Plate 1) and is composed of three stratigraphic units: unnamed Upper Triassic(?) limestone, the Lower and Middle Jurassic Sailor Canyon Formation, and the Middle Jurassic Tuttle Lake Formation. The pendant extends ~16 km in an east-west direction and is 2.5-5 km wide. The sedimentary and volcanic rocks of the Tuttle Lake Formation are exposed over ~6 km² in the northernmost part of the study area (Plate 1). The sedimentary rocks of the Sailor Canyon Formation unconformably underlie the conglomerate of the Tuttle Lake Formation northwest of the study area. The Sailor Canyon Formation is thrust over the Tuttle Lake Formation and ~0.4 km² of the Sailor Canyon rocks are exposed in the study area near Fallen Leaf Lake (Plate 1) (Loomis, 1983). Although all of the rocks of the Mount Tallac pendant are at least weakly metamorphosed, they will be referred to herein by their primary sedimentary and volcanic rock names.

The Tuttle Lake Formation consists of interbedded diamictite and pebble-cobble conglomerate that are conformably overlain by intercalated unstratified tuff-breccias,

tuffaceous sandstones, and basalt and pyroxene andesite flows referred to as the “intercalated volcanic sequence” (Fisher, 1990). This sequence is composed of generally unstratified tuff-breccias, tuffaceous sandstones, and basalt and pyroxene andesite flows (Fisher, 1990). A portion of the Sailor Canyon Formation is thrust over the volcanic rocks and is composed of alternating beds of bluish-gray and white sandstone that are inversely graded (Fig. 2). Ammonites from various stratigraphic levels of a correlative body near the North Fork of the American River define the Early-Middle Jurassic age of the Sailor Canyon Formation (Clark et al., 1962; Imlay, 1968; Fisher, 1990).

The rocks of the Tuttle Lake Formation are interpreted to have been syntectonically deposited in a marine, fault-bounded trough in a locally extensional setting (Fisher, 1990). The conglomerate contains clasts of quartzofeldspathic sandstone, siltstone, and pelite, which are derived from the Sailor Canyon Formation (Fisher, 1990). Tuff-breccia dikes and clasts have been identified in the upper portion of the conglomerate, and conglomeratic clasts also appear in the lower portion of the volcanic sequence (Loomis, 1983). These observations, and the conformity of the contact between the sequences, suggest that volcanism occurred penecontemporaneously with deposition of the conglomeratic portion of the Tuttle Lake Formation (Loomis, 1983; Fisher, 1990).

Figure 2. Inversely graded layers in sandstone near Fallen Leaf Lake. Photomicrograph is under cross-polars.

Within the study area, the southern margin of the Mount Tallac pendant is intruded by the Jurassic Keiths Dome quartz monzonite, two bodies of the Jurassic(?) Undifferentiated granodiorites, and the Cretaceous Glen Alpine granodiorite. The Mount Tallac rocks have been contact metamorphosed to actinolite-hornfels to hornblende-hornfels facies near these plutons (Loomis, 1983). The conglomeratic portion of the Tuttle Lake Formation is exposed west of the Glen Alpine intrusion, and

the volcanic sequence is exposed on the east (Plate 1). Pluton-host rock contact relationships vary with host rock lithology, as discussed below.

Matrix composition and clast size vary throughout the weakly stratified conglomerate of the Tuttle Lake Formation (Fisher, 1990). Microscopic analysis of conglomerate from south of Grass Lake shows a fine-grained matrix of subhedral plagioclase, anhedral quartz, subhedral hornblende, apatite, and secondary anhedral epidote and oxidized hematite. Clasts of quartzofeldspathic sandstone, quartzite, siltstone, and tuff-breccia, 0.5 mm-1.5 cm long, define a weak foliation that becomes stronger as intrusive contacts are approached. Larger clasts are typically quartzofeldspathic sandstones, siltstones, and quartzites. Quartz in these clasts contains subgrains and shows recrystallization by bulging. Smaller tuff-breccia clasts typically consist of embayed plagioclase, subhedral hornblende, tremolite, and biotite, and secondary epidote.

Andesitic tuff-breccias comprise ~65% of the volcanic sequence in the study area. Rounded or subangular pyroxene andesite and basalt clasts are common and are 1-20 cm in length (Fig. 3). Most samples have phenocrysts of subhedral hornblende and recrystallized plagioclase, and a fine-grained matrix composed primarily of plagioclase, subhedral biotite, clinopyroxene, minor tourmaline, and secondary epidote. Rarely, clinozoisite replaces plagioclase and hornblende is replaced by actinolite.

Tuffaceous sandstones make up ~25% of the volcanic sequence within the study area, and are interbedded with the tuff-breccias. The presence of cross-bedding and

lack of fossil foliage, soil, and erosional structures led Loomis (1981) to conclude that these clastic and volcanic rocks were deposited in a subaqueous environment. The tuffaceous sandstones are composed of fine-grained clinopyroxene, plagioclase, and hornblende, and minor actinolite and epidote.

Figure 3. Subangular pyroxene andesite and basalt clasts (dark) in tuff-breccia. Compass is 10 cm wide.

Basalt and pyroxene andesite flows comprise ~10% of the volcanic sequence in the study area. Flows contain minerals similar to those of the tuff-breccias and tuffaceous sandstones, including a fine-grained matrix of plagioclase laths, subhedral

hornblende, rare anhedral quartz, and secondary epidote. Phenocrysts of subhedral to euhedral plagioclase, and subhedral hornblende that is replaced by actinolite are also common in the flows (Fig. 4). Flows are easily distinguished from the other units of the volcanic sequence by abundant 1-4-cm-long, spheroidal, silica-filled amygdules.

Figure 4. Representative texture of basalt and pyroxene andesite flows. Note euhedral plagioclase phenocryst in the center. Photomicrograph is under cross-polars.

Keiths Dome quartz monzonite

The Jurassic Keiths Dome pluton is a quartz monzonite exposed over ~17 km² in the central portion of the study area. The rectangular exposure trends N-NW, and in the north, the pluton intrudes the southern margin of the Mount Tallac pendant. The Keiths Dome pluton is intruded by younger, less deformed plutons on all sides and appears to be the oldest intrusion in the study area, according to Loomis (1983). Most outcrops of the quartz monzonite are heavily fractured and weathered to deep orange in color. Millimeter- to meter-scale ductile shear zones are common throughout the body, as discussed in detail below. Fine-grained, angular, dioritic enclaves in the quartz monzonite are typically small (<2 cm long) and less common than those in the younger, surrounding plutons. These enclaves have sharp and diffuse boundaries and their long-axes have no preferred orientation. Less abundant, 5-10-cm-long enclaves are porphyritic, containing 1-2-mm-long plagioclase phenocrysts. The porphyritic enclaves have sharp boundaries and are elongate vertically. Modal abundances suggest that the Keiths Dome pluton is a low-silica granite rather than a quartz monzonite, but the Loomis (1983) name for the unit is retained.

A Jurassic age has been previously estimated by Loomis (1983), who included the quartz monzonite in the “Early Granitic Group.” This group also includes the Desolation Valley granodiorite, which is in contact with the western margin of the Keiths Dome pluton (Plate 1), and the Pyramid Peak Granite and Camper Flat granodiorite. According

to Loomis (1983), plutons in the Early Granitic Group all intrude older diorites and gabbros west of the study area, and are intruded by steeply dipping mafic dikes and surrounding plutons. The Keiths Dome quartz monzonite has not been dated; however, a Jurassic age for the pluton is also supported by cross-cutting relationships, and my observations of the distribution of ductile shear zones.

The Keiths Dome pluton intrudes the southern margin of the volcanic sequence of the Tuttle Lake Formation, east of the Glen Alpine pluton (Plate 1). Some of the rocks near the irregularly shaped contact are mixed igneous and metamorphic rocks, and it is unclear if they formed from partial melting. These rocks are referred to herein as migmatites. Metatexite migmatites with schollen (Fig. 5) extend ~10 m from the contact. Farther east, southwest of Lily Lake, phlebite migmatites contain two sets of leucosome veins that strike N-NW and N-NE (Fig. 6). The pluton margin interfingers with the tuff-breccia along steep ($>70^\circ$) contacts southeast of Lily Lake (Fig. 7), and 3-5-cm-long xenoliths of metamorphosed porphyritic andesite occur in the Keiths Dome pluton within centimeters of the contact.

The Keiths Dome pluton is intruded by less deformed plutons on all other sides. The Jurassic Desolation Valley granodiorite intrudes the quartz monzonite to the west, along a poorly exposed contact (Plate 1). To the east, the N-NW-striking contact with the Echo Lake pluton (Evernden and Kistler, 1970) is sharp and generally well exposed, as is the E-NE-striking contact between the quartz monzonite and the Cretaceous Bryan

Meadow granodiorite to the south. Where intruded by the Glen Alpine pluton, the contacts are also sharp.

Figure 5. Metatexite migmatite with schollen. Migmatite developed in tuff-breccia host rock ~5 m from contact with the Keiths Dome pluton. Marker is 14 cm long and the capped end points NW.

Figure 6. Phlebite migmatite with N-NW and N-NE-striking leucosome veins. Migmatite developed in tuff-breccia host rock. Field book is 18 cm long.

Figure 7. Keiths Dome quartz monzonite interfingering with tuff-breccia. Marker is 14 cm long and the capped end points NW.

Internal contacts are rare in the pluton, with the exception of those of a 20-m-wide, ~400-m-long sheet-like body of quartz diorite north of Ralston Lake (Plate 1). The mostly sharp, N-NW-striking western contact of the quartz diorite dips steeply. Biotite and hornblende coarsen in the quartz monzonite as the quartz diorite is approached from the east, defining the gradational eastern contact of the quartz diorite (Fig. 8).

Figure 8. Representative texture of quartz diorite sheet in the Keiths Dome pluton. Photomicrograph is under cross-polars.

Basalt dikes and porphyritic microdiorite dikes that strike N-S, W-NW, and E-NE, and dip steeply ($>77^\circ$), intrude the Keiths Dome quartz monzonite. Basalt dikes are 0.5-1.5 m wide, and extend up to 50 m. The microdioritic dikes contain plagioclase phenocrysts up to 3 mm long. These dikes are 0.5-10 m wide, extend 1- ≥ 100 m, are typically aphanitic in their margins and have sharp contacts. Some of the microdioritic dikes in the Keiths Dome pluton are deformed or cut by ductile shear zones (Fig. 9).

Similar microdioritic sheets intrude the other Jurassic plutons of the Early Granitic Group and have been described by others (i.e. Loomis, 1983; Sabine, 1993; Wiebe, 2002).

Figure 9. Microdiorite dike deformed by ductile shear in the Keiths Dome pluton. Arrows show small component of dextral strike-slip determined from curved foliation defined by plagioclase phenocrysts. Marker is 14 cm long and the capped end points NE.

The Keiths Dome pluton is texturally homogeneous, medium-grained, and has little modal variability. Modal abundances are approximately 35% plagioclase, 25% alkali feldspar (mostly microcline), 20% quartz, 10% hornblende, and 10% biotite.

Allanite is a common accessory mineral. Plagioclase forms subhedral laths that are 0.5-2 mm long. Plagioclase is generally weakly sericitized and fragmented, and commonly contains biotite inclusions. Interstitial potassium feldspar grains typically exhibit micrographic intergrowths with quartz (Fig. 10). Hornblende and biotite are 0.5-2 mm long, define a N-NW-striking foliation, and commonly form “clots” that are 3 mm-1 cm in diameter. These clots may be parts of disaggregated enclaves. Fractured tourmaline, 30-300 μm long, is concentrated in some mylonites south of Tamarack Lake (Fig. 11) (Plate 1).

Figure 10. Micrographic texture in Keiths Dome quartz monzonite. Photomicrograph is under cross-polars.

Figure 11. Tourmaline in a mylonitic ductile shear zone in the Keiths Dome pluton. Shear is top-to-right as shown by foliation curvature defined by biotite. Photomicrograph is under plane-polarized light.

The Keiths Dome quartz monzonite records moderate- to high-temperature deformation. Outside of shear zones, the dominantly igneous fabrics are overprinted by abundant recovery and recrystallization microstructures in quartz and plagioclase. In quartz these structures include chessboard subgrains, and irregularly shaped lobate grain boundaries associated with grain boundary migration recrystallization (cf. Jessel, 1987; Hirth and Tullis, 1992; Stipp et al., 2002). Plagioclase displays deformation twins,

bulging of grain boundaries and small, recrystallized grains surrounding larger grains, (Fig. 12). Abundant myrmekite in the Keiths Dome may also be evidence of dynamic recrystallization, but more likely represents a magmatic texture (Phillips, 1974). Overall, these microstructures imply deformation at temperatures of 400- $\geq$ 500 °C (cf. Jessel, 1987; Hirth and Tullis, 1992; Pryer, 1993; Ji, 1988a, b; Shigematsu, 1999; Stipp et al., 2002).

Ductile shear zones in the Keiths Dome pluton vary in deformation intensity, and temperatures estimated in shear zones range from 300 °C to $\geq$ 550 °C. Fragmented feldspar porphyroclasts (200-675 μ m long), bent and fractured biotite grains, and small (40-85 μ m long), recrystallized quartz characterize the moderately deformed, lower-temperature shear zones (cf. Wilson, 1980; Lister and Snoke, 1984; Bell et al., 1986b; Tullis and Yund, 1987; Stipp et al., 2002) (Fig. 13). In higher-temperature zones, aggregates of polygonal plagioclase containing grain boundary mobility structures (i.e. pinning, window, and dragging) suggest recrystallization by grain boundary migration (cf. Jessel, 1987) (Fig. 14). Larger plagioclases are 50-360 μ m long, and smaller grains are 5-10 μ m long. Fractured hornblendes, 20-320 μ m long, are not recrystallized indicating temperatures of <600 °C for these zones (cf. Allison and LaTour, 1977; Nyman et al., 1992; Babaie and LaTour, 1994; Berger and Stünitz, 1996; Imon et al., 2002, 2004).

Figure 12. Representative texture of the Keiths Dome pluton. Note quartz with irregularly shaped grain boundaries and micrographic texture. Photomicrograph is under cross-polars.

Figure 13. Lower-temperature ductile shear zone in the Keiths Dome pluton. Shear is top-to-right as shown by foliation curvature defined by biotite. Note bent and fractured biotite, fractured feldspar porphyroclasts, and recrystallized, polygonal quartz. Photomicrograph is under cross-polars.

Figure 14. Higher-temperature ductile shear zone in the Keiths Dome pluton. Note recrystallized aggregates of plagioclase and elongate aggregate of recrystallized sphene. Photomicrograph is under cross-polars.

Desolation Valley granodiorite

The Jurassic Desolation Valley granodiorite is exposed over $\sim 4 \text{ km}^2$ in the westernmost part of the study area (Plate 1). Outcrops of the Desolation Valley pluton are much less fractured than those of the Keiths Dome pluton, forming massive, jointed boulders with relatively fresh surfaces. A few mm-scale, NW-striking ductile shear zones cut the granodiorite, but are much less abundant than in the Keiths Dome pluton.

Porphyritic, dioritic enclaves with quenched margins are common in the granodiorite, and are grouped into two types: angular, fine-grained enclaves with biotite phenocrysts (1-2 mm long), and subangular, fine-grained enclaves with plagioclase phenocrysts (2-3 mm long). Enclaves are elongate parallel to foliation, typically have aspect ratios of 2:1, and are up to 20 cm in length.

Steeply dipping mafic dikes that intrude the Desolation Valley pluton near its southernmost margin led Loomis (1983) to include the granodiorite in the Early Granitic Group. In addition, it is deformed by NW-striking ductile shear zones that are also present in great amounts in the Jurassic Keiths Dome pluton, and are not found in the younger plutons. No radiometric age data currently exists for the Desolation Valley granodiorite; however, the dikes and the presence of NW-striking ductile shear zones suggest that the pluton is Jurassic in age.

Within the study area, the Desolation Valley pluton intrudes the Keiths Dome pluton and is intruded by the Bryan Meadow pluton (Plate 1). Outside the study area, the Desolation Valley pluton intrudes the Pyramid Peak pluton. The poorly exposed contact with the Keiths Dome pluton strikes NW. Limited exposure of the E-W-striking contact with the Bryan Meadow pluton suggests that the contact is sharp. Plutonic xenoliths and internal contacts were not observed in the pluton.

The Desolation Valley pluton is a texturally homogenous, medium-grained granodiorite, averaging ~40% plagioclase, 30% quartz, 15% alkali feldspar (microcline), 10% biotite, and 5% hornblende. Accessory minerals include allanite and zircon.

Plagioclase forms twinned, zoned, subhedral laths, 0.3-2 mm long; some grains contain potassium feldspar inclusions (Fig. 15). Myrmekite is common. Biotite, 2-3 mm long, and euhedral, 0.2-1.6-mm-long hornblende grains define a strong, N-NW-striking foliation.

Figure 15. Representative texture of the Desolation Valley granodiorite. Note aligned hornblende grains. Photomicrograph is under cross-polars.

Microstructures imply that modest solid-state deformation of the Desolation Valley pluton occurred at temperatures of $>450^{\circ}\text{C}$. These include chessboard subgrains

in quartz, patchy extinction in plagioclase, bulging of plagioclase grain boundaries, and small, recrystallized grains along those boundaries (cf. Borges and White, 1980; Gapais, 1989; Gates and Glover, 1989; Tullis and Yund, 1991; Hirth and Tullis, 1992; Lloyd and Freeman, 1994; Shigematsu, 1999; Stipp et al., 2002).

Undifferentiated granodiorites

The Undifferentiated granodiorites are exposed in three separate bodies; two bodies are in contact with the northern margin of the Keiths Dome pluton, and the third is juxtaposed with the southern margin of the Keiths Dome quartz monzonite. Two of these bodies were previously mapped and designated as “Miscellaneous granitic rocks” by Loomis (1983). The granitic bodies are assumed to be Jurassic based on contact relationships with the Keiths Dome pluton and because they contain NW-striking ductile shear zones found in other Jurassic rocks in the study area. A genetic relationship between the two northern bodies is suggested by shape, modal similarities, and gradational contacts with the Keiths Dome pluton (see below). The undifferentiated bodies cover $\sim 0.5 \text{ km}^2$ in the study area and vary in shape, color index, and intensity of deformation. Modal percentages of plagioclase, microcline, and quartz suggest that these bodies are mostly granodiorites, ranging locally to granites. Dioritic and microgranitoid enclaves are common, and typically 1-4 cm long, except within $\sim 20 \text{ m}$ of

the Keiths Dome pluton, where dioritic enclaves reach 6-10 cm in length and are more angular.

Undifferentiated granodiorites in contact with the northern, mostly E-W-striking (within the study area) margin of the Keiths Dome pluton are exposed in curvilinear-shaped bodies (map view) east and west of the Glen Alpine intrusion (Plate 1). The northwestern granodiorite is in gradational contact with the Keiths Dome pluton. This contact is defined in the Keiths Dome pluton by an increase in quartz content, a lower color index, and larger hornblende as the Undifferentiated granodiorite is approached. This granodiorite is in sharp contact with the Glen Alpine granodiorite and the conglomerate of the Tuttle Lake Formation. The northeastern body of Undifferentiated granodiorite is elongate parallel to the curvilinear margin of the Keiths Dome pluton. This body also grades into the quartz monzonite, and the contact is defined by the same changes in the quartz monzonite as observed near the northwestern body. The contact with amygdaloidal andesite flows of the volcanic sequence is marked by incorporation of these rocks into the granodiorite as mm-to-m-scale xenoliths (Fig. 16). Xenoliths are found as far as ~15 m from the contact.

The southern body of Undifferentiated granodiorite is located south of Cup Lake (Plate 1) and is in sharp contact with the southern margin of the Keiths Dome pluton. Slopes of talus obscure contacts with the Bryans Meadow pluton on the west and south. The body contains porphyritic, microdioritic enclaves up to 50 cm long, and is cut by

ultramylonitic ductile shear zones that are 5-20 m wide. Some zones are folded in places and the folds have hinge lines that trend N-NE and plunge steeply.

Figure 16. Tuff-breccia xenolith in Undifferentiated granodiorite. Note xenolith is in northwestern body of Undifferentiated granodiorite. Marker is 14 cm long and points E.

The granodiorites are medium-grained and typically contain ~40% plagioclase, 25% alkali feldspar, 25% quartz, 5% biotite, and 5% hornblende. Accessory minerals include sphene, zircon, and apatite. Quartz content is higher than typically found in the texturally similar Keiths Dome pluton, and color index varies slightly between the three

bodies. The granodiorites are porphyritic, and contain well-zoned plagioclase phenocrysts that are 0.2-4 mm long. Myrmekitic texture is common. Hornblende, 1-6 mm long, and smaller biotite grains, 0.5-3 mm long, define a N-NW-striking magmatic foliation.

Microstructures indicating moderate-to-high deformation temperatures (≥ 450 °C) include plagioclase with tapering deformation twins, flame perthite, and bulging grain boundaries with small, recrystallized grains along those boundaries (cf. Pryer, 1993; Ji, 1998a, b; Shigematsu, 1999). Quartz contains chessboard subgrains and has lobate grain boundaries indicating recrystallization by grain boundary migration (cf. Jessel, 1987; Hirth and Tullis, 1992; Stipp et al., 2002) (Fig. 17).

Figure 17. Representative texture of the Undifferentiated granodiorites. Note chessboard subgrains in quartz, lobate quartz grain boundaries, and new recrystallized plagioclase grains along old grain boundaries. Photomicrograph is under cross-polars.

Cretaceous Rocks

Echo Lake granodiorite

The Cretaceous Echo Lake granodiorite is exposed over $\sim 10 \text{ km}^2$ in the eastern portion of the study area (Plate 1) where in map view it forms a curvilinear, N-NW-striking body, that is ~ 5.5 by 1.5 km . More outcrops of Echo Lake granodiorite are

exposed ~5 km east of the study area, and are separated from the main mass by glacial outwash (Loomis, 1983). The pluton body may be roughly equant in shape if outcrops south of the outwash are also taken into account.

The coarse-grained granodiorite forms massive, jointed boulders and domes. Dioritic and microgranitoid enclaves are more abundant in this pluton than in the other intrusions in the study area. Most enclaves are 3-4 cm long with diffuse margins, but rare, larger enclaves are up to 22 cm long, have quenched margins, and possess a higher color index than the smaller ones. The Echo Lake pluton is one of two radiometrically dated plutons in the study area; Evernden and Kistler (1970) obtained K-Ar cooling ages of 87.8 Ma (biotite) and 91.4 Ma (hornblende) from the granodiorite (age uncertainties were not reported). The use of modern decay constants (Steiger and Jaëger, 1977) would result in older ages.

The Echo Lake pluton intrudes the eastern margin of the Keiths Dome quartz monzonite and the Sailor Canyon Formation south of Fallen Leaf Lake (Plate 1). The granodiorite is intruded by the Bryan Meadow pluton in the south, and covered by glacial outwash on the east. The well-exposed contact with the Keiths Dome pluton is sharp, strikes N-NW, and is wavy on the map-scale (1:24,000). The poorly exposed contact with Sailor Canyon Formation is also sharp, and no xenoliths of host rock were identified near this contact. A gradational contact with the Bryan Meadow pluton is defined by an increase in abundance of large sphene (2-3 mm long) and an increase in the size of hornblende grains upon crossing into the Bryan Meadow pluton. Internal

contacts are extremely rare in the Echo Lake granodiorite. The exceptions are the sharp contacts of a 1-m-wide, NE-striking, shallowly dipping ($\sim 40^\circ$) sheet of medium-grained granodiorite, ~ 200 m north of the southern tip of Lower Echo Lake (Fig. 18).

The Echo Lake granodiorite is coarse-grained and locally grades to quartz monzonite. Modal abundances for the pluton are $\sim 40\%$ plagioclase, 30% quartz, 20% alkali feldspar (typically microcline), 8% biotite, and 2% hornblende. Accessory minerals include apatite and zircon. Plagioclase forms zoned subhedral crystals, 1.5 - 7 mm long, which have been sericitized (Fig. 19). Microcline is poikilitic, and encloses plagioclase. Myrmekitic texture and perthite are common. Hornblende grains, 0.3 - 1.3 mm long, and biotite grains, 0.2 - 1.5 mm long, define a subtle, mostly N-NW-striking foliation. Many of the smaller grains of hornblende and biotite form ~ 1.5 -mm-long mafic “clots” that are interpreted as disaggregated enclaves.

Figure 18. Contact of medium-grained granodiorite sheet within Echo Lake pluton. Marker resting on eroded contact surface dips 45° toward the east.

Figure 19. Zoned, sericitized plagioclase in the Echo Lake granodiorite. Photomicrograph is under cross-polars.

The Echo Lake granodiorite records low-to-moderate (300-450 °C) deformation temperatures. Bent biotite, subgrains and deformation lamellae in quartz, and patchy extinction in plagioclase grains support lower temperatures (cf. Wilson, 1980; Lister and Snoke, 1984; Bell et al., 1986; Tullis and Yund, 1987; Hirth and Tullis, 1992; Stipp et al., 2002) (Fig. 20). Moderate temperatures are inferred from the presence of kink bands in

microcline, tapered deformation twins in plagioclase, and subgrains and deformation lamellae in quartz (cf. Hirth and Tullis, 1992; Pryer, 1993; Ji, 1998a, b).

Figure 20. Microstructures in the Echo Lake granodiorite. Note bent biotite and subgrains in quartz. Photomicrograph is under cross-polars.

Bryan Meadow granodiorite

The Bryan Meadow granodiorite (Evernden and Kistler, 1970) is a heterogeneous pluton exposed over $\sim 2.5 \text{ km}^2$ in the southern part of the study area. The granodiorite forms steep, narrow summits (Talking Mountain and Becker Peak) that erode into

angular cobbles and boulders. It contains swarms of 3-10-cm-long, plagioclase-phyric enclaves that are elongate E-W, parallel to a strong magmatic foliation. Evernden and Kistler (1970) reported biotite K-Ar cooling ages of 87.4 and 87.1 (age uncertainties were not reported) for the Bryan Meadow granodiorite, but the use of modern decay constants (Steiger and Jaëger, 1977) would result in older ages.

Along its E-NE-striking northern contact, the Bryan Meadow pluton sharply intrudes the Keiths Dome and Desolation Valley plutons, and the southernmost body of Undifferentiated granodiorites. In contrast, the contact with the Echo Lake pluton is gradational, as described above. The color index of the Bryan Meadow pluton varies gradually, but no internal contacts were identified in the pluton.

The Bryan Meadow granodiorite is coarse-grained and has modal abundances of ~40% plagioclase, 25% quartz, 20% alkali feldspar, 10% biotite, and 5% hornblende. Primary accessory minerals include sphene and apatite, and minor chlorite replaces hornblende. Plagioclase, 0.3-2.5 mm long, forms normally zoned, subhedral grains. Poikilitic grains of potassium feldspar enclose plagioclase, and myrmekite is common. Euhedral sphene grains, 1-3 mm in length, distinguish the granodiorite from others in the study area (Fig. 21). Biotite, 0.5-1.3 mm long, and hornblende, 0.2-2 mm long, define a foliation that strikes NW-to-NS away from contacts, and E-W within 2-3 m of the contact with the Keiths Dome and Echo Lake plutons.

In the Bryan Meadow pluton, quartz contains subgrains and displays “sweeping” undulose extinction, and recrystallization of quartz by bulging is rare. Plagioclase

commonly exhibits patchy undulose extinction, and small fractures. These microstructures are interpreted to record deformation temperatures of 300-400 °C (cf. Tullis and Yund, 1987; Hirth and Tullis, 1992).

Figure 21. Distinctive euhedral sphene in the Bryan Meadow granodiorite. Photomicrograph is under cross-polars.

Glen Alpine granodiorite

The Glen Alpine granodiorite is exposed over $\sim 2 \text{ km}^2$ in the northern part of the study area (Plate 1). The weakly elliptical (in map view) granodiorite sharply intrudes

the conglomerate and volcanic rocks of the Tuttle Lake Formation, and the northern margin of the Keiths Dome quartz monzonite. Most outcrops exhibit subvertical jointing. Subvertical, 1-10-cm-wide aplitic dikes commonly intrude the granodiorite. The pluton contains dioritic and microgranitoid enclaves that average 8 cm in length, and are commonly rounded with quenched borders. Enclaves are more abundant, and typically larger (10-15 cm long) in the interior of the pluton. The Glen Alpine pluton is inferred to be the youngest pluton in study area because solid-state deformation is minimal, and because it has a margin-parallel foliation pattern that contrasts with the discordant, N-NW-striking foliation exhibited by the Jurassic Keiths Dome pluton and volcanic host rocks.

The granodiorite intrudes a ~0.7-km-wide body of quartz diorite that rims the eastern and northeastern margins of the pluton, separating the Glen Alpine pluton from the volcanic host rocks (Plate 1). The contact relationships, location, and shape of quartz diorite suggests that it is an early pulse in the same episode of magmatism that created the granodiorite, and Loomis (1983) included it as a phase of the Glen Alpine pluton. The quartz diorite is homogenous and does not contain enclaves or readily recognized foliation.

The contact between the granodiorite and the tuff-breccia of the volcanic sequence is sharp and stepped in places. Subvertical dikes of the granodiorite extend 1-3 m from the contact into the volcanic sequence, and a few 3-4-cm-long metavolcanic xenoliths are present near the contact. The tuff-breccias are migmatized within ~10 m

of the contact. The sharp contact with the Keiths Dome quartz monzonite does not appear to be stepped in contrast to the contact with the volcanic sequence. The southernmost part of the contact was not examined in detail due to accessibility issues.

Internal contacts were not found in either phase of the Glen Alpine pluton. Angular xenoliths of the quartz diorite are abundant in the granodiorite near the contact with the early, quartz diorite phase of the pluton (Fig. 22). The contact is stepped where the quartz diorite intrudes volcanic host rocks, and volcanic xenoliths 5-10 cm in diameter occur in the quartz diorite north of Soda Springs.

Figure 22. Xenoliths of quartz diorite in the Glen Alpine granodiorite. Pencil for scale is 15 cm long and points NW.

The medium-grained, equigranular granodiorite has modal abundances of ~50% plagioclase, 25% quartz, 10% potassium feldspar, 10% biotite, and 5% hornblende. Accessory minerals include sphene, apatite, and zircon. Subhedral, 0.3-1.3-mm-long plagioclase is commonly zoned and enclosed in interstitial, poikilitic microcline. Quartz content is greatest near the western margin of the pluton, at ~30%, and decreases gradually toward the eastern margin, where it is ~20%. Aggregates of biotite grains, 0.1-1.5 mm long, define the margin-parallel, steeply dipping magmatic foliation (Fig. 23). Low-to-moderate (300-450 °C) deformation temperatures in the Glen Alpine pluton are inferred from the combination of subgrains, and “sweeping” undulose extinction in quartz, bulging quartz grain boundaries, and tapering deformation twins in plagioclase (cf. Hirth and Tullis, 1992; Pryer, 1993; Ji 1998a, b; Stipp, 2002).

Figure 23. Representative texture of the Glen Alpine granodiorite. Note biotite aggregate in the bottom left-hand corner. Photomicrograph is under cross-polars.

STRUCTURE OF ROCKS IN THE STUDY AREA

Structure of the Host Rocks

The Triassic-Middle Jurassic Mount Tallac pendant is composed of an unnamed Upper Triassic(?) limestone, the Lower and Middle Jurassic Sailor Canyon Formation, and the Middle Jurassic Tuttle Lake Formation. The Tuttle Lake Formation comprises the majority of the host rock in the study area and a small portion of the Sailor Canyon Formation is exposed in the hanging wall of a thrust, outcropping ~0.5 km west of Fallen Leaf Lake. The host rocks are folded on a km-scale and the folds have N-NW-trending hinge lines (Loomis, 1983). Within the study area, the sedimentary host rocks and the overlying volcanic rocks form an ~4.5 km long, N-NE-dipping, eastern limb of an anticline (Plate 1).

Structure of Sedimentary Host Rocks of the Sailor Canyon and Tuttle Lake Formations

Thin-bedded sandstones and siltstones comprise the youngest unit of the Sailor Canyon Formation that is thrust over the Tuttle Lake Formation near Fallen Leaf Lake (Loomis, 1983) (Plate 1). A strain gradient was not observed near the thrust fault. Bluish-gray and white alternating beds dominantly strike N-NW and dip >75° E-NE. Steeply dipping joints are typically oriented at a high angle to bedding, striking E-W.

Boudinage and pinch-and-swell structures are common in the deformed beds. Sub-isoclinal-to-isoclinal, parallel chevron folds deform rare E-NE-striking, steeply dipping ($>85^\circ$) beds and have hinge lines that trend N-NW and plunge $>70^\circ$ (Fig. 24). The folds have variable wavelengths and amplitudes ranging from 5 cm-1.5 m.

Figure 24. Sub-isoclinal-to-isoclinal, parallel, chevron folds in sandstone. Located near Fallen Leaf Lake. Pencil is 14 cm long and points SE.

The conglomerates of the Tuttle Lake Formation in the study area show little evidence of bedding aside from minor changes in average clast size and poorly

developed sorting. Away from contacts with plutons, clasts in the conglomerate are rounded and weakly flattened, defining a subtle foliation that dominantly strikes N-NE and dips 15-50° W-NW. Clasts gradually increase in aspect ratio from 1.5:1 to 3:1 over 150-300 m as contacts with intrusions are approached, defining a steeply plunging lineation. Lineation is stronger than foliation. Foliation dip also steepens to nearly vertical in these 150-300-m-wide structural aureoles.

Structure of Tuttle Lake Volcanic Host Rocks

The volcanic rocks conformably overlie the conglomerates rocks in the eastern limb of the regional anticline. Loomis (1983) mapped two west-side down, N-NW-striking, steeply dipping faults 0.5-1.5 km west of Fallen Leaf Lake (Plate 1). These faults cut the volcanic rocks, but terminate at contacts with the Keiths Dome pluton and the Dicks Lake granodiorite (~4 km north of the study area). Rare bedding defined by interlayering of basalt and pyroxene andesite flows strikes N-NW and dips >45° E-NE. Foliations in the volcanic host rocks dominantly strike N-NW, and dip steeply. A strong, steep lineation is defined by elongate volcanic clasts and plagioclase phenocrysts in tuff-breccias. NW-striking ductile shear zones that typically dip >45° E-NE are subparallel to the foliation. Lineations in the 3-15-mm-wide ductile shear zones were not well exposed, but plunge >70° in steeply dipping zones.

The shear zones in basalt and pyroxene andesite flows commonly contain mantled plagioclase porphyroclasts, 0.5-1.2 mm long, with σ -type wings that indicate normal motion (Fig. 25). Recrystallized, polygonal plagioclase grains containing patchy extinction are concentrated in the mantles of the porphyroclasts, suggesting deformation at $>450^\circ\text{C}$ (cf. Pryer, 1993; Ji, 1998a, b; Shigematsu, 1999). S-, C-, and C' surfaces, best defined by mica fish, are well developed.

Figure 25. Ductile shear zone in a basalt flow. Note σ -type mantled plagioclase porphyroclasts and mica fish indicating top-to-right motion. Photomicrograph is under cross-polars.

Contact Relationships

The conglomerate of the Tuttle Lake Formation is sharply intruded by a body of Undifferentiated granodiorite, the Keiths Dome quartz monzonite, and the Glen Alpine granodiorite. Outside of ductile aureoles, weakly flattened clasts define a foliation that dips mostly 15-50° W. As contacts with all those intrusions are approached, foliation gradually rotates into parallelism with contacts and dips steepen to nearly vertical over a distance of 150-300 m. Aspect ratios of clasts gradually increase from 1.5:1 outside of the ductile aureole to 3:1 inside of the aureole. Angular, 10 cm-1-m-long conglomerate xenoliths are more common in the Undifferentiated granodiorite than in the other intrusions. Variably striking, steeply dipping, 1-1.5-m-wide dikes of the Glen Alpine granodiorite are rare and extend from that pluton into the conglomerate near contacts.

The rocks of the volcanic sequence of the Tuttle Formation are migmatized in places for distances extending up to ~10 m from the contact with the northeastern body of Undifferentiated granodiorite and the Keiths Dome quartz monzonite (see Rock Units). The few volcanic xenoliths found in these intrusions are 2 cm-2 m long. Sharp, stepped contacts dominate where the volcanic sequence is intruded by the Cretaceous Glen Alpine pluton. Small quantities of 3-4-cm-long xenoliths are present in the intrusion near the contacts. Subvertical, variably striking, 1-2-m-wide dikes of the Glen Alpine granodiorite intrude the volcanic sequence for short distances (1-3 m) from the pluton contact.

Nearly all well-exposed contacts between intrusive units are between the Keiths Dome pluton and younger plutons. Most of these contacts strike roughly N-NW and E-W; the semi-circular contact between the Glen Alpine and Keiths Dome plutons is an exception. The contact between the Undifferentiated granodiorites and the Keiths Dome pluton is gradational and defined by an increase in quartz content, a lower color index, and larger hornblende in the quartz monzonite as the granodiorite bodies are approached. The remaining contacts of the Keiths Dome pluton are typically sharp, steep, and sinuous on the outcrop scale, but linear to curvilinear on the map scale.

In contrast to those of the Keiths Dome quartz monzonite, a 5-m-wide gradational contact that extends >300 m separates the Echo Lake and Bryan Meadow plutons in the southeastern portion of the study area. This contact is marked by the gradual increase in abundance of sphene and size of hornblende in the Echo Lake pluton as the Bryan Meadow pluton is approached.

Xenoliths are extremely rare near all contacts between plutonic rocks. Dikes of Echo Lake pluton intrude the Keiths Dome pluton, but otherwise, dikes do not extend into older plutons.

Magmatic Fabrics

Magmatic foliations occur in all plutonic rocks in the study area, are of weak-to-moderate intensity, and are primarily defined by aligned, subhedral hornblende and

biotite grains. The Keiths Dome, Desolation Valley, and Echo Lake plutons contain two sets of magmatic foliations; a moderately intense, dominant foliation strikes N-NW and dips steeply, and a weak foliation strikes N-NE and dips steeply (Fig. 26). The weak foliation appears locally in outcrops with the dominant foliation. Magmatic foliations in all units do not typically intensify near contacts with the Tuttle Lake Formation or plutonic host rocks. The N-NW-striking foliation transgresses the northern contact between the Keiths Dome quartz monzonite and the volcanic host rocks (Plate 1). The northernmost contact of the Desolation Valley pluton was not observed; however, the N-NW-striking foliation transgresses the contact between the Desolation Valley and Keiths Dome plutons east of Lake of the Woods, and a W-NW-striking foliation transgresses this contact west of Ralston Peak (Plate 1). The Cretaceous Glen Alpine plutons, and possibly the Echo Lake pluton, have steep foliations that mimic the shape of the intrusions (“onion-skin” pattern) (Plate 1). In the limited area examined in the Bryan Meadow pluton, the foliation strikes N-NW to N-S, and dips steeply. The foliation strikes parallel to the contact between the Bryan Meadow and Echo Lake plutons within 2-3 m of the contact.

Strong magmatic lineations occur in all plutonic rocks in the study area, plunging steeply ($>60^\circ$) and trending variably (Fig. 27). Subhedral hornblende and biotite define the lineations, and mafic enclaves are generally elongate parallel to lineation (Fig. 28). Magmatic lineations do not typically intensify near contacts with the Tuttle Lake Formation or plutonic host rocks. Lineations are more pronounced than foliations in all

plutons except for the Bryan Meadow granodiorite, where these fabrics are equally, moderately intense.

Figure 26. Poles of magmatic foliations in all plutons. Poles projected onto a lower-hemisphere stereonet. Contour interval is 2 sigma using the method of Kamb (1959). Data plotted using Stereonet software, version 8.9.2 (Allmendinger et al., 2013; Cardazo and Allmendinger, 2013).

Figure 27. Poles of magmatic lineations in all plutons. Poles projected onto a lower-hemisphere stereonet. Contour interval is 2 sigma using the method of Kamb (1959). Data plotted using Stereonet software, version 8.9.2 (Allmendinger et al., 2013; Cardazo and Allmendinger, 2013). Note, much fewer lineation than foliation measurement reflects difficulty in measuring lineation in plutonic rocks.

Figure 28. Enclaves with long-axes parallel to steep lineation. Located in the Keiths Dome pluton. Note nearly equant shapes on top surface.

Dikes

Felsic and mafic dikes intrude the plutonic units with mostly sharp contacts.

Felsic dikes dominantly strike NE and dip steeply ($>60^\circ$), but show considerable variability in orientation (Fig. 29). Most of these dikes are 3 cm-1 m wide, and are continuous for up to 50 m. Pegmatite dikes are typically >1 m wide, and are less continuous than other felsic dikes (<30 m). Pegmatite dikes are most abundant in the Glen Alpine and Keiths Dome plutons, and a few undeformed pegmatites are spatially associated with the ductile shear zones in the quartz monzonite.

N-S, W-NW, and E-NE-striking, steeply dipping ($>77^\circ$), basalt and plagioclase-phyric microdiorite dikes intrude the conglomerate host rocks and the Keiths Dome pluton (Fig. 30). The basalt dikes are 0.5 cm-1 m wide and extend for up to 50 m. The microdiorite dikes are 0.5-10 m wide, average 1.5 m in thickness, and typically extend ≥ 100 m. Ductile shear zones deform many of the microdiorite dikes in the Keiths Dome pluton (Figs. 8 and 31). Similar plagioclase-phyric dikes intrude other Jurassic plutons of the Early Granitic Group and have been described by Loomis (1983), Sabine (1993), and Wiebe (2002).

Figure 29. Poles of felsic dikes. Poles are projected onto a lower-hemisphere stereograph. Contour interval is 2 sigma using the method of Kamb (1959). Data plotted using Stereonet software, version 8.9.2 (Allmendinger et al., 2013; Cardazo and Allmendinger, 2013).

Figure 30. Poles of basalt and plagioclase-phyric microdiorite dikes. Poles are projected onto a lower-hemisphere stereograph. Data plotted using Stereonet software, version 8.9.2 (Allmendinger et al., 2013; Cardazo and Allmendinger, 2013).

Figure 31. Microdiorite dike offset left-laterally by ductile shear zone. Located in the Keiths Dome pluton. Rock hammer is 38 cm long and the handle points N.

Ductile Shear Zones

Ductile shear zones are abundant in the Keiths Dome pluton, less common in the volcanic host rocks, Desolation Valley pluton, and Undifferentiated granodiorites, and rare in the Echo Lake, Bryan Meadow, and Glen Alpine plutons. Ductile shear zones in the volcanic rocks, and the Keiths Dome and Desolation Valley plutons dominantly strike NW, and dip $>70^\circ$, mostly to the west (Plate 1). Lineations in the zones typically plunge $>45^\circ$, and average 53° NW. West-side up, reverse motion is dominant, whereas the

smaller strike-slip component is inconsistent. The zones are 5 mm->45 m wide and extend 1-100 m. S-C fabrics are defined by grain size reduction, recrystallized quartz, biotite and hornblende, and less common *C'* surfaces are also defined by biotite. Deformation temperatures for ductile shear zones in these units are estimated to range from 300 °C->450 °C based on recovery in quartz and dynamic recrystallization of quartz and feldspar (see Rock Units).

Ductile shear zones in the Undifferentiated granodiorites north of the Keiths Dome pluton are 1 mm-2 cm wide, strike NW and dip steeply. The southern body of Undifferentiated granodiorite contains ultramylonitic ductile shear zones that are 5-20 m wide. Some of these zones are folded in places and the folds have hinge lines that trend N-NE and plunge steeply. Rare, E-W-striking, ductile shear zones in the Echo Lake and Bryan Meadow plutons are 2-15 mm wide, are continuous for only a few centimeters, and do not transgress contacts. These shear zones have sinistral separation on gently dipping surfaces. Vertical rock faces normal to foliation and parallel to lineation could not be found near these relatively small zones; thus, vertical separation was not determined.

Ductile Shear Zones in the Keiths Dome Pluton

The Keiths Dome pluton is the most heavily deformed unit in the study area, containing abundant mylonitic to ultramylonitic ductile shear zones that are 5 mm->45

m in width and typically extend 1-100 m. Approximately 75% of all zones measured in the quartz monzonite strike NW and dip $>70^\circ$ (Fig. 32). Analysis of foliation curvature, asymmetric porphyroclasts, and S-C fabrics indicates that NW-striking, W-side up reverse motion is dominant with a small component of sinistral slip (Fig. 33). Some of the shear zones are spatially associated with undeformed pegmatites, suggesting that that shear was localized next to strong pegmatite sheets. Lineations in the ductile shear zones plunge moderately NW (Fig. 34).

Ductile shear zones are distributed throughout the quartz monzonite. A large concentration of cm-to-m-scale zones occurs between Tamarack Lake and Upper Echo Lake (Plate 1). Most ductile shear zones in this area do not extend >15 m; however, a ~ 2.8 -km-long, N-S-striking, mylonitic ductile shear zone transects the quartz monzonite ~ 350 m west of Upper Echo Lake (Plate 1). This zone is >30 m wide and is composed of individual shear zones that record normal or reverse slip in approximately equal proportions (Fig. 35). Mylonite in the zones contain plagioclase porphyroclasts that are 0.5-1.5 mm long, and has biotite-defined, S- and C-surfaces in some places (Fig. 36).

Ductile shear zones in the Keiths Dome pluton are estimated to have formed at temperatures of 300°C - $>550^\circ\text{C}$. Moderately strong, lower-temperature shear zones are characterized by fragmented plagioclase, bent and fractured biotite grains, quartz grains with undulose extinction, and small, recrystallized quartz (cf. Wilson, 1980; Lister and Snoke, 1984; Bell et al., 1986; Tullis and Yund, 1987; Hirth and Tullis, 1992; Pryer, 1993; Ji, 1998a, b) (Fig. 13). In higher-temperature zones, aggregates of polygonal

plagioclase contain pinning, window, and dragging structures, suggest recrystallization by grain boundary migration (Jessel, 1987) (Fig. 14). Quartz and plagioclase grains are reduced from 0.5-2 mm long outside of ductile shear zones, to as small as 5-10 μm long in the zones.

Figure 32. Poles of ductile shear zones in the Keiths Dome quartz monzonite. Poles projected onto a lower-hemisphere stereograph. Contour interval is 2 sigma using the method of Kamb (1959). Data plotted using Stereonet software, version 8.9.2 (Allmendinger et al., 2013; Cardazo and Allmendinger, 2013).

Figure 33. S-C fabrics and mica fish in a ductile shear zone. Located in the Keiths Dome pluton. Shear is top-to-right. Photomicrograph is under cross-polars.

Figure 34. Poles of lineations in ductile shear zones in the Keiths Dome pluton. Poles are projected onto a lower-hemisphere stereograph. Contour interval is 2 sigma using the method of Kamb (1959). Data plotted using Stereonet software, version 8.9.2 (Allmendinger et al., 2013; Cardazo and Allmendinger, 2013). Note, much fewer lineation than ductile shear zone measurements reflects difficulty in measuring lineation in these zones.

Figure 35. Portion of the large N-S-striking shear zone composed of smaller zones. Shear zone extends for >2.8 km (see text).

Figure 36. Mantled plagioclase porphyroblast. Note biotite-defined strain shadows showing δ -type wings. Shear is top-to-right. Sample from N-S-striking, >30-m-wide ductile shear zone located ~0.5 km west of Indian Rock. Photomicrograph is under cross-polars.

The timing of deformation in the Keiths Dome quartz monzonite can be constrained by: (1) the deformation by the ductile shear zones of plagioclase-phyrical, microdioritic dikes that intrude the other Jurassic plutons of the Early Granitic Group; and (2) the lack of shear zones in the ~91 Ma Echo Lake granodiorite (Evernden and Kistler, 1970). These relationships suggest a lower age limit for deformation of ~91 Ma.

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

Most plutonic units show very weak-to-moderate solid-state deformation outside of ductile shear zones. In the Keiths Dome pluton, deformation microstructures include chessboard subgrains in quartz, lobate quartz grain boundaries, deformation twins in plagioclase, and bulging of grain boundaries in plagioclase, indicating temperatures of 400- $\geq$ 500°C (cf. Jessel, 1987; Hirth and Tullis, 1992; Pryer, 1993; Ji, 1998a, b; Shigematsu, 1999; Stipp et al., 2002). Other plutons show similar microstructures away from shear zones (see Rock Units).

Solid-state foliations defined by aligned biotite and elongate quartz grains are most evident in the Keiths Dome pluton near large concentrations of ductile shear zones, particularly in the area between Tamarack Lake and Upper Echo Lake. These foliations may thus be related to the deformation that formed the shear zones. The foliation dominantly strikes N-NW and dips steeply ($>70^\circ$) to the SW. Solid-state lineations are stronger than foliations, plunge steeply ($>70^\circ$), and trend variably. Lineations are defined by biotite and elongate quartz.

DISCUSSION

Construction of the Keiths Dome, Echo Lake, and Glen Alpine Plutons

Interpretations of thermal models and geochronological data have spawned debate amongst researchers regarding the construction of plutons, including the existence, size, and sustainability of magma chambers. It is commonly accepted that most plutons are constructed by multiple increments; however, the size, number, and amount of time between the increments remain contentious. Many studies (e.g., Clemens and Mawer, 1992; Paterson and Vernon, 1995; Clarke and Clarke, 1998; Wiebe and Collins, 1998; Solgadi and Sawyer, 2008; Barbey et al., 2008) suggest that plutons are constructed by multiple pulses intruded close enough in time to maintain a steady-state chamber capable of mechanical movement of magma. Others (e.g., Coleman et al., 2004; Glazner et al., 2004) contend that plutons are constructed by small dikes and sills separated by long enough time periods to inhibit the formation of a magma chamber.

These questions are evaluated below for the construction of the Keiths Dome, Echo Lake, and Glen Alpine plutons. Construction and emplacement of the Desolation Valley and Bryan Meadow granodiorites could not be adequately evaluated, as they were investigated in less detail. Outcrop- and hand sample-scale textural evidence and petrographic analyses suggest that these plutons were constructed by multiple pulses

intruded close enough in time to form a magma chamber capable of mechanical movement of magma, as discussed below.

Homogeneity of Plutons

Homogenization of different magma increments requires that pulses exhibit physical and chemical properties that promote mixing, and that the convective stirring be somewhat turbulent (e.g., Huber et al., 2009). Chemical properties that promote mixing include similar density, temperature and viscosity, with a SiO₂ difference of <10% (Sparks and Marshall, 1986; Frost and Mahood, 1987; Philpotts and Ague, 1990). In addition, increments must be intruded close enough in time and proximity to prevent solidification and allow for mixing. These conditions would suggest that the interacting pulses capable of creating a homogenous pluton might come from a single source, or from thorough mixing of multiple sources similar enough to avoid unmixable chemical heterogeneities (Huber et al., 2009).

Rock texture, mineralogy, internal contacts, and dynamic structures were analyzed in the Keiths Dome, Echo Lake, and Glen Alpine plutons to interpret the construction of these intrusions. These plutons are markedly homogeneous at the hand sample and outcrop scale, and thin-section analysis shows no obvious magmatic disequilibrium textures. Uniformly distributed, dioritic and microgranitoid enclaves are common, but dominant shape, size, and texture vary between the plutons. Internal

contacts and schlieren are rare, and other magmatic structures such as pipes, tubes, ladder dikes, and flame structures were not found. These observations support the interpretation that the Keiths Dome, Echo Lake, and Glen Alpine plutons were constructed from one or multiple pulses intruded close enough in time and proximity to allow for thorough mixing in a chamber. More geochronological and geochemical data are clearly needed to test this interpretation.

Mafic Enclave Distribution and Dispersal. Enclaves represent injection and mingling of mafic magma into host magma. High contrast in composition and physical properties between the two magmas prevents mixing and may result in distinctive textures, such as quenched margins (Sparks and Marshall, 1986; Frost and Mahood, 1987; Philpotts and Ague, 1990). Common dioritic and microgranitoid enclaves in the Echo Lake and Glen Alpine plutons were probably distributed evenly throughout the plutons by convection. Some of the larger enclaves exhibit quenched margins, supporting a significant temperature contrast between the magmas.

In contrast to these younger plutons, the Keiths Dome pluton has only minor mafic enclaves. The quartz monzonite more commonly contains 3 mm-1-cm-diameter mafic “clots” of fine-grained, intergrown biotite and hornblende, which may represent extensively disaggregated mafic enclaves. A small temperature contrast between the mafic and felsic magmas is required to mechanically break the enclaves up, suggesting that the mafic and felsic magmas were intruded closer in time than inferred for the Echo

Lake pluton, or that a large mafic increment slowed the crystallization of the host quartz monzonite, limiting the temperature contrast.

The Keiths Dome pluton contains less quartz than the Echo Lake and Glen Alpine plutons (Loomis, 1983). The presence of well-formed enclaves in the Echo Lake pluton versus clots in the Keiths Dome pluton may be related to the degree of SiO₂ variation between the interacting felsic and mafic magmas; however, the lack of obvious chemical disequilibrium textures in both plutons suggests that interaction between the felsic and mafic magmas was mostly mechanical, and that chemical interaction was limited. Additional variables, including volume of mafic versus felsic magma, and the degree of crystallinity of the felsic magma (i.e. rheology) could also explain this contrast.

Internal Contacts and Dynamic Structures. Three sheet-like bodies are identified in the study area. The first body is a 20-m-wide, N-NW-striking, steeply dipping quartz diorite that is in both sharp and gradational contact with the Keiths Dome quartz monzonite and is cut by NW-striking ductile shear zones, suggesting that it is an internal sheet. The quartz diorite can be found as round enclaves in the nearby quartz monzonite indicating that the two are contemporaneous. The second body is a NE-striking, medium-grained granodiorite sheet that sharply intrudes the Echo Lake pluton, cuts mafic enclaves, and contains xenoliths of the Echo Lake pluton, suggesting that it is a dike formed after the main pluton had crystallized. The third body is a NE-striking quartz diorite that extends ~425 m along the northeastern contact of the Glen

Alpine pluton with its volcanic host rocks. The body intrudes the host rocks sharply, and xenoliths of it are incorporated into the Glen Alpine granodiorite. The quartz diorite is homogenous and does not contain enclaves or foliation. The marginal location and curvilinear shape of the sheet-like body suggest that it originates from the same episode of magmatism that generated the Glen Alpine pluton.

Dynamic structures, such as well-developed schlieren zones, ladder dikes, and flame structures, are not present in the plutons. Rare schlieren were found in the Keiths Dome pluton, but are so faint that flow direction could not be adequately determined. The rarity of internal contacts, lack of dynamic structures, and even distribution of mafic enclaves and/or clots casts doubt on a model of construction by dikes separated by long intervals of time. These observations support the development of a chamber, or multiple ephemeral chambers, capable of homogenizing multiple pulses of magma, distributing enclaves, and erasing evidence of internal contacts.

Emplacement of the Keiths Dome, Echo Lake, and Glen Alpine Plutons

Emplacement of plutons requires space to be made, or material redistributed via mass transfer processes (MTPs) in the crust to accommodate large volumes of ascending magma. Within the study area, the Jurassic Keiths Dome and Cretaceous Glen Alpine plutons are in contact with meta-supracrustal host rocks, and the Glen Alpine pluton intrudes the Keiths Dome quartz monzonite and the northwestern body of

Undifferentiated granodiorite, allowing for interpretation of the effects of time and regional stress on MTPs. In addition, the host rock type is different to the east of the Glen Alpine pluton than to the west, aiding in analysis of the effect of host rock type and rheology on MTPs.

Ductile Flow

Host rock transfer via ductile flow dominated in the conglomerate of the Tuttle Lake Formation near contacts with the Keiths Dome, Undifferentiated granodiorite, and Glen Alpine plutons. A ductile structural aureole, 150-300 m wide, is defined by the increase in strain of clasts as the contacts with the plutons are approached. Aspect ratios of clasts are as high as 3:1 near the contacts, whereas they are typically 1.5:1 outside of the aureole. The clear transition from a shallow-to-moderately dipping, weakly deformed conglomerate outside of the aureole, to the nearly vertical, highly deformed conglomerate inside of the aureole indicates vertical flow of the conglomerate at the current level of exposure.

The Keiths Dome pluton, Undifferentiated granodiorites, and Glen Alpine pluton contain strong, steeply plunging magmatic lineations that are typically stronger than magmatic foliations, and elongate enclaves with long axes parallel to lineations. These constrictional fabrics are consistent with vertical motion related to diapiric ascent, regional strain, or some other complex internal flow. The spherical shape of the Glen

Alpine pluton could be explained by ballooning of a magma chamber; however, structures in the aureole surrounding the granodiorite indicate constriction dominated over flattening.

Stoping and Assimilation

Brittle transfer dominated in the strong, weakly anisotropic tuff breccia and porphyritic andesite near contacts with the Keiths Dome pluton, Undifferentiated granodiorites, and Glen Alpine pluton. Sharp, stepped contacts and rare xenoliths of volcanic host rock in the plutons indicate that stoping played at least a minor role in material transfer. Significant density contrast between the volcanic rocks and the magmas is supported by a lack of deflection in the magmatic fabrics surrounding the xenoliths (Paterson and Miller, 1998). This contrast may have allowed stoped blocks to sink, and could explain the scarcity of xenoliths exposed at the current crustal level (Pignotta and Paterson, 2007). Minor amounts of stoped blocks may have been assimilated upon descent; a lack of chemical data limits evaluation of assimilation as a significant MTP. Brittle transfer suggests that the temperature contrast between the volcanic rocks and the intruding magma was great enough to allow for fracturing, and/or that the volcanic rocks were strong enough to resist ductile deformation.

Roof Uplift/Floor Subsidence

Research suggests that marginal faulting and bending and draping of roof rocks are evidence of piston-like motion associated with roof uplift (e.g., Pollard and Johnson, 1973; Corry, 1988). Marginal faults were not found in the host rocks, and the roofs of the plutons have been removed by erosion; thus, any draping could not be observed. In short, evaluation of roof uplift as a MTP is difficult due to the lack of roof preservation, but piston-like uplift by faulting is unlikely.

Similarly, floor subsidence is difficult to evaluate because the pluton floors are not exposed. Evidence supporting floor subsidence includes shearing along pluton walls and downward folding of host rock (e.g., Bridgewater, 1974; Corry, 1988; Cruden, 1998; Cruden and McCaffrey, 2001). Ductile shear in the Keiths Dome quartz monzonite is distributed throughout the pluton, rather than near the pluton walls, and strikes of shear zones are typically at a high angle to these contacts. Downward-directed ductile flow of host rocks has been discussed as a mechanism involved in floor subsidence (e.g., Cruden, 1998). The NE dip of the conglomerate next to the Keiths Dome and Glen Alpine plutons is due to pre-emplacement folding of the Mount Tallac rocks (Loomis, 1981), and is probably not related to floor subsidence. The vertical ductile flow suggested by structures in the conglomerate may be related to floor subsidence, but the expected width for a ductile aureole involved in floor subsidence has yet to be well defined by researchers, further complicating its evaluation.

Magmatic Wedging

Wedging aside of host rocks during emplacement may preferentially occur along pre-existing anisotropies in the host rocks. Regional foliation strikes N-NW and map-scale folding hinge lines have a similar trend. The long axes of the Keiths Dome and Desolation Valley plutons are also N-NW and this relationship suggests that these plutons may have exploited regional structures during emplacement. In addition, the Glen Alpine pluton obscures the conformable contact between the conglomerate and the volcanic host rocks and may have utilized that anisotropy during emplacement, although its shape in map view does not support wedging. Host rock rafts, separating different magmatic sheets, are taken as evidence of wedging (e.g., Hutton, 1988; Miller and Paterson, 2001), but were not observed. The Keiths Dome pluton is intruded on all sides by younger plutons, obscuring the original shape and hindering evaluation of this mechanism (Plate 1).

Dilation Associated with Regional Faulting/Shearing

Some researchers (e.g., Hutton, 1988; Petford and Atherton, 1992; Tikoff and Teyssier, 1992; Grocott et al., 1994; Tobisch et al., 1995) have proposed that emplacement of some plutons is facilitated by dilation resulting from regional episodic extension or strike-slip faulting/shearing in the host rocks. Variably striking, map-scale

dip-slip faults cut the folded Tuttle Lake Formation beyond the study area, and cross-cutting relationships indicate that faulting pre-dated pluton emplacement (Loomis, 1981). These faults may have served as anisotropies that focused magma emplacement, but their apparently older ages imply that they did not act as a MTP. The NW-striking ductile shear zones in the Keiths Dome pluton were active after emplacement. Motion synchronous with emplacement cannot be ruled out, but most of the shear zones recorded reverse, rather than normal shear (see Tectonic Implications, below). It is therefore unlikely that much, if any, magma was focused in or along dilational spaces created by regional faulting or shearing.

Effect of Host Rock Type/Rheology on MTPs

Stoping and vertical flow are inferred near the Keiths Dome, Undifferentiated granodiorite, and Glen Alpine contacts, and the dominance of one over the other reflects the host rock type. This relationship suggests that host rock rheology exerted control on brittle versus ductile behavior. Elevation differs little between the exposures; thus, it is unlikely that the behavior of the volcanic and conglomerate rocks is depth-dependent. Similar rheological responses are described in the South Mountain batholith, Nova Scotia, where granite intrudes sandstone that has structures probably reflecting downward flow, and also intrudes slate along a discordant contact (Culshaw and Bhatnagar, 2001). Host rocks to both the Jurassic and Cretaceous plutons in the

study area contain evidence of brittle and ductile processes, suggesting that time, and a possible change in tectonic regime did not play a significant role in controlling the dominant mass transfer process.

Development and Tectonic Implications of Structures

Analyses of syn- or post-emplacement structures (e.g., magmatic and solid-state foliations and lineations, and ductile shear zone orientations, and kinematics) and cross-cutting relationships are used to infer the tectonic regime active during emplacement of most of the plutons in the study area. N-NW-striking, steeply dipping magmatic foliations in the Keiths Dome and Desolation Valley plutons are discordant to E-W-striking contacts and roughly concordant to regional foliation (Plate 1), indicating that the foliations resulted from tectonic strain rather than emplacement. In contrast, the steeply dipping foliation that mimics the shape of the Glen Alpine and Echo Lake plutons was likely formed as a result of internal magmatic processes during emplacement. Magmatic lineations in all plutons in the study area plunge steeply and are typically of greater intensity than the foliations, indicating that lineations formed during significant subvertical stretching resulting from emplacement (Glen Alpine, Echo Lake plutons) and/or tectonic strain (Keiths Dome, Desolation Valley plutons).

In the Keiths Dome pluton, ductile shear zones are approximately concordant to the N-NW-striking regional foliation, and discordant to pluton contacts in some places

(Plate 1), indicating that they formed as a result of tectonic strain. Kinematic analysis of the ductile shear zones indicates reverse, west-side up motion dominated, with a small component of sinistral and dextral strike-slip. Volcanic host rocks also contain similarly oriented ductile shear zones, but in much smaller sizes and quantities. Ductile shear zones in the Keiths Dome pluton do not transgress the pluton-host rock contacts, suggesting that these zones did not form during the same episode of deformation that deformed the volcanic host rocks, or that those rocks did not deform as easily as the pluton. In the latter case, ductile shear zones may have developed in the quartz monzonite shortly after solidification when the pluton was still relatively hot, or the ductile shear may have been more distributed in the host rock than in the quartz monzonite, possibly occurring along foliation planes.

The strain field inferred from the N-NW-striking foliations, steeply plunging lineations, several E-NE-striking mafic dikes, and NW-striking, reverse (W-side up) shear zones is one of E-NE-to-NE contraction combined N-NW subvertical extension (from dikes) with subvertical stretching (from lineations). This is compatible with regional transpression, a tectonic regime that has been proposed for the arc in both the Middle and Late Jurassic (e.g., Lallemand and Oldow, 1988; Edelman and Sharp, 1989; Wolf and Saleeby, 1992; Girty et al., 1993; Girty et al., 1995; Wolf and Saleeby, 1995; Pachell et al., 2003; DeCelles, 2004).

Timing of Deformation

A domainal, N-NW-striking slaty, phyllitic, and crenulation cleavage is present in the Sailor Canyon Formation and can be traced into the Tuttle Lake Formation (Girty et al., 1995). Bajocian and Bathonian fossil assemblages in the Sailor Canyon Formation provide an upper age limit for cleavage formation, and the 168 $\pm$ 2 Ma oldest phase of the Emigrant Gap composite pluton and the 166 $\pm$ 3 Ma Haypress Creek pluton bracket the lower age of cleavage formation (Girty et al., 1995). The cleavage is rotated into parallelism with the margin of the Emigrant Gap pluton and is not present in the undeformed Haypress Creek pluton (Girty et al., 1995). The ductile shear zones in the volcanic rocks of the Tuttle Lake Formation are roughly concordant to the regional cleavage, and thus, may have formed at 175-166 Ma. Alternately, shear in these rocks may have occurred later, concentrating along the cleavage anisotropies.

The ductile shear zones in the Keiths Dome pluton likely formed during or slightly after emplacement of steeply dipping ($\geq 77^\circ$), plagioclase-phyric, microdiorite dikes, as some of the dikes are deformed by the shear zones, whereas others are not. Regionally, other syntectonic dikes, including those of the Owens Mountain dike swarm-shear zone, the Sonora mafic dike swarm, and much of the Independence mafic to felsic dike swarm, were emplaced from 158-148 Ma (Sharp, 1980; James, 1989; Wolf and Saleeby, 1992; Carl and Glazner, 2002; Glazner et al., 2008). The syntectonic microdiorite dikes in the

Keiths Dome pluton may have formed in response to the same period of oblique convergence inferred in the formation of the above-mentioned Late Jurassic dike swarms (Wolf and Saleeby, 1992; Wolf and Saleeby, 1995), and if this correlation is accurate, would represent the farthest known northern extent of these Late Jurassic dikes. Consequently, the ductile shear zones in the Keiths Dome pluton may have also formed during the Late Jurassic.

The Echo Lake intrusion truncates the ductile shear zones, suggesting that motion in the shear zones weakened or ceased by the Late Cretaceous. The contact-parallel foliation of the Glen Alpine pluton implies that a weakening of the inferred transpressive tectonic regime may have occurred prior to the intrusion of the granodiorite, or that the stresses generated by magma expansion overwhelmed the regional tectonic stress.

Summary of Construction, Emplacement and Tectonic Implications

Structural and petrologic evidence suggests that the Keiths Dome, Echo Lake, and Glen Alpine plutons were each constructed by multiple increments of compositionally similar magma intruded close enough in time to allow for mixing and thorough homogenization. Construction and emplacement of the Desolation Valley and Bryan Meadow granodiorites could not be adequately evaluated, as they were investigated in less detail. MTPs involved in emplacement include ductile flow and

stoping; both MTPs were controlled by host rock rheology during emplacement of the Keiths Dome and Glen Alpine plutons. Mass transfer by roof uplift, floor subsidence, and magmatic wedging may have also played a role in emplacement. Major focusing of magma along dilational fault/shear zones is unlikely due to the lack of regional fault zones in the rocks and the evidence supporting a period of transpression during emplacement. This evidence includes the orientations of regional foliation, ductile shear zones, and mafic dikes. Although temporal resolution is limited by a lack of geochronologic data, emplacement of, and deformation in, the Keiths Dome pluton may have occurred during the Late Jurassic Nevadan orogeny.

CONCLUSIONS

1. The Keiths Dome, Echo Lake, and Glen Alpine plutons were each probably constructed by multiple increments of magma. These plutons are mostly homogenous on the outcrop- and hand-sample-scale and contain well-distributed mafic enclaves. Internal contacts and dynamic structures are rare. These properties suggest that chambers formed that were capable of thoroughly homogenizing multiple increments of compositionally similar magma, distributing enclaves, and erasing internal contacts.
2. Ductile flow and stoping facilitated the emplacement of the Keiths Dome, Echo Lake, and Glen Alpine plutons. A steeply dipping ductile aureole in the conglomerate host rocks supports ductile flow as a significant MTP, and rotated xenoliths of volcanic host rock in the Keiths Dome pluton and in the northeastern body of Undifferentiated granodiorite support stoping as a MTP. Magmatic wedging may have occurred along N-NW anisotropies created by regional foliation and pre-emplacement, map-scale folds in, and contacts between, the host rocks. The original shapes of the Keiths Dome and Desolation Valley plutons are obscured, hampering evaluation of magmatic wedging with respect to these intrusions.
3. Brittle and ductile MTPs are consistently restricted to different host rock types (conglomerate versus volcanic rocks), suggesting that host rock rheology exerted control on brittle versus ductile behavior. Elevation differs little between the

exposures, and thus this contrasting behavior is not depth dependent. Host rocks to Jurassic and Cretaceous plutons contain evidence of brittle and ductile processes, suggesting that time, and a possible change in tectonic regime did not play a significant role in controlling the dominant mass transfer process.

4. The strain field inferred from the N-NW-striking regional foliation, NW-striking ductile shear zones, several E-NE-striking mafic dikes, and steep lineations is compatible with regional transpression. This regime is inferred to have been active during the emplacement of the Keiths Dome pluton. Magmatic foliation patterns in the Glen Alpine and Echo Lake plutons suggest that the transpressive regime may have weakened or ceased before emplacement of these granodiorites, or that magma expansion overwhelmed the tectonic stress. Geochronologic data are needed to further constrain timing of deformation in the Keiths Dome pluton, but evidence suggests that emplacement of the quartz monzonite and the microdiorite dikes that intrude the pluton, and the related deformation may have occurred during the Late Jurassic Nevadan orogeny.

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