Fault development in the Cathedral Peak Granodiorite, 
Sierra Nevada batholith: 
Evidence for directional emplacement of the Johnson Granite Porphyry

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ABSTRACT
This study focuses on the development of mineralized fractures in the Cathedral Peak Granodiorite, proximally to the Johnson Granite Porphyry, Sierra Nevada batholith, California. The observed fractures exhibit epidote and chlorite mineralization, and are associated with a cm-scale bleached zone surrounding the fracture. Lineations, slickenside steps and microstructures on some fracture groups suggest shear has occurred; slip indicators show these groups to be sinistral faults with a small component of dip-slip movement. Based on similarities in orientation and mineralization between Cretaceous age Sierra Nevada fracture sets and the observed minor faults, I infer that these faults are also Cretaceous features. The orientation and slip direction of the observed faults are, however, incompatible with the bulk dextral tectonic regime. I suggest that these minor faults formed to accommodate vertical and northerly translation of Cathedral Peak Granodiorite blocks as a result of directional emplacement of the Johnson Granite Porphyry into the Cathedral Peak Granodiorite. Although other models exist for the facilitation of the Johnson Granite Porphyry’s intrusion (e.g., dilatational forces, structural emplacement, and stoping), a translational model for emplacement, which has not previously been suggested, best explains the observed minor faults.

Keywords: left-lateral, faults, plutons, Cathedral Peak Granodiorite, Johnson Granite Porphyry, Sierra Nevada batholith.
INTRODUCTION

Recognizing the mechanisms controlling pluton emplacement in the upper crust is a fundamental prerequisite for understanding the dynamics of pluton development. Plutons, which can consist of hundreds of km$^3$ of material, are known to crystallize at shallow crustal levels (i.e., < 5 km). However, at these crustal levels there are no open spaces on the hundreds of km$^3$ scale. Therefore, a ‘space’ issue needs to be addressed; how are plutons emplaced where there is no open space for the pluton?

To solve this problem, authors have increasingly proposed models that rely on regional extension (e.g. Glazner, 1991; Hamilton, 1981; Tobisch et al., 1986). These models are limited in that they explain intrusion only at tectonic rates. Other authors have called upon mechanisms such as pull-apart structures (Tikoff and Teyssier, 1992), tensional cracks (Hutton, 1982), and shear zone terminations (Hutton, 1988; Titus, 2005), all of which rely on tectonically controlled translation to make room for intrusions. There are plutons, however, for which no tectonic process seems to accompany intrusion (Tikoff et al., 1999). This has led some to conclude that plutons can be emplaced forcefully and that this emplacement is not directionally limited to vertical motion (Tikoff et al., 1999). Forceful emplacement has not been a popular solution to pluton emplacement due to the observation that the amount of strain surrounding a pluton is insufficient to create the space needed for intrusion. However, this issue is resolved if the far-field translation of a system by faulting is included in the strain calculations (Tikoff et al., 1999).

This study examines the development of minor faults in the Cathedral Peak Granodiorite, Sierra Nevada batholith to investigate the role of minor faulting in pluton
emplacement. The minor faults, which are inferred to be mid-Cretaceous, are anomalous given the dextral transpression that occurred in this region during the Cretaceous. I argue that these faults formed due to the intrusion of the Johnson Granite Porphyry into the Cathedral Peak Granodiorite and can be viewed as indicators of far-field translation that occurred during the directional, forceful emplacement of the Johnson Granite Porphyry.

**GEOLOGIC SETTING**

**Sierra Nevada batholith**

The Sierra Nevada batholith is composed of Mesozoic age rocks that were emplaced due to subduction of the Farallon plate under the western margin of the Paleozoic North American margin (Engebretson et al., 1985). The batholith is a near continuous NNW-SSE body of plutonic rocks, with an estimated volume of ca. \(8 \times 10^5\) km\(^3\) (Bateman, 1992). Due to Cenozoic exhumation (Renne et al., 1993; Saleeby, 1999) and multiple glaciations in the last 100 ka (Huber, 1987), the batholith is well exposed at high (> 2500 m) elevations.

The Sierra Nevada batholith exhibits several notable trends. First, within the Cretaceous age plutons, older Cretaceous rocks lie to the west and younger rocks to the east. Second, within eastern plutons, Sr-isotope ratios increase from west to east (Bateman, 1992), indicating a corresponding increase in crustal mixing. Third, the batholith becomes increasingly felsic to the east. All of these trends suggest an eastward migration of magmatism through the Cretaceous, accompanied by stronger crustal mixing of magma (Bateman, 1992).
Although the batholith was emplaced throughout the Mesozoic, the dominant phase of magmatism (> 50% of total batholith volume) occurred during the Cretaceous (Chen and Moore, 1982), with the last major pulse of magmatism occurring during the Late Cretaceous (98 to 82 Ma; Chen and Moore, 1982; Coleman and Glazner, 1997; Kistler et al., 1986; Stern et al., 1981; Tobisch et al., 1995). This pulse is termed the Sierra Crest magmatic event and was responsible for several late intrusive suites, including the Tuolumne Intrusive Suite.

**Tuolumne Intrusive Suite**

The Tuolumne Intrusive Suite is located in the east-central portion of the Sierra Nevada batholith (Fig. 1). It is the best-known and most extensively studied plutonic complex in the Sierra Nevada due to its superb exposures and ease of access.

Based on Al-in-hornblende geobarometry, the Tuolumne Intrusive Suite crystallized at upper crustal depths (< 4 km; ~1–3 kbar; Ague and Brimhall, 1988). The Suite is a classic example of normally zoned, nested plutons, where the oldest, most mafic plutons are at the margins of the suite and the youngest, most felsic plutons at the center (Fig. 1) (Bateman and Chappell, 1979; Kistler et al., 1986; Piccoli and Candela, 1994; Reid et al., 1993; Segall and Simpson, 1986). The older, distal plutons include the tonalite of Glen Aulin, Kuna Crest Granodiorite, and Half Dome Granodiorite (ages vary from 92.8 ± 0.2 Ma at the outer margins to 88.8 ± 0.8 Ma near the center; Coleman et al., 2004). The younger, proximal plutons are the Cathedral Peak Granodiorite (88.1 ± 0.2 Ma; Coleman and Glazner, 1997) and the Johnson Granite Porphyry (85.4 ± 0.1 Ma; Coleman and Glazner, 1997). Further distinctions that can be made between the younger and older plutons include decreases in the strength of foliation towards the center of the
Figure 1. Map of the Tuolumne Intrusive Suite and the regional shear zones. Modified from Titus et al. (2005)
suite, as well as texture and composition variations that suggest either an increase in water content, a decrease in crystallization temperature, or both (Bateman, 1992).

**Cathedral Peak Granodiorite & Johnson Granite Porphyry**

The two youngest plutons of the Tuolumne Intrusive Suite, the Cathedral Peak Granodiorite and the Johnson Granite Porphyry, are the focus of this study. The Cathedral Peak Granodiorite is coarse grained, consisting of plagioclase (45%), potassium feldspar (25%), quartz (20%), and biotite (9%) (Tikoff et al., 2005), as well as trace amounts of hornblende. The most diagnostic feature of the Cathedral Peak Granodiorite is the presence of potassium feldspar megacrysts. Megacrysts are typically 2-4 cm in length, but can be up to 5-8 cm. Megacrysts vary in size and abundance, generally decreasing towards the interior margin of the pluton (Bateman, 1992). Aplitic dikes cross-cut the Cathedral Peak Granodiorite and range in length from 10s to 100s of meters. These dikes generally trend NE-SW (P. Riley, personal communication) and increase in abundance towards the contact with the Johnson Granite Porphyry.

Nested within the south-central portion of the Cathedral Peak Granodiorite is the Johnson Granite Porphyry, an elongate NS-trending pluton. The Johnson Granite Porphyry is a leucocratic fine- to medium-grained granite with an aplitic, equigranular mass. Biotite is the only mafic mineral found within the Johnson Granite Porphyry, with increasing concentrations (< 5%) to the north (Bateman and Chappell, 1979). Many sub-rounded xenoliths of coarse-grained granodiorite with K-feldspar megacrysts were also observed. These xenoliths are interpreted as partially digested pieces of Cathedral Peak.
The contacts between the Johnson Granite Porphyry and Cathedral Peak Granodiorite are generally sharp (Bateman and Chappell, 1979); however, local sheeting, stoping, mutually intrusive relationships, gradational/lobate margins, and stoped blocks of Cathedral Peak Granodiorite are present in Johnson Granite Porphyry (Riley, 2009; Titus et al., 2005; Zak and Paterson, 2005). I observed gradients between the two units as well as numerous intrusions and dikes of Johnson Granite Porphyry into the Cathedral Peak Granodiorite. Evidence of stoping appeared in some small outcrops in Tuolumne Meadows that were not easily classified as Johnson Granite Porphyry or Cathedral Peak Granodiorite. In other areas of the Johnson Granite Porphyry, round phenocrysts were found to contain large feldspars that originated in the Cathedral Peak Granodiorite.

**Regional Deformation**

The Tuolumne Intrusive Suite is near several large NW trending shear zones, including the Gem Lake shear zone (Greene and Schweickert, 1995), the Cascade Lake shear zone (Tikoff et al., 2005), and the Bench Canyon shear zone (McNulty, 1995) (Fig. 1).

The Gem Lake shear zone and the Cascade Lake shear zone are part of the larger dextral Sierra Crest shear zone system that parallels the Tuolumne Intrusive Suite and was active in the Late Cretaceous (Tikoff and Greene, 1997). One model for the emplacement of the Tuolumne Intrusive Suite and other late Cretaceous plutons of the Sierra Nevada posits that space was created via dilation/transcurrent structures caused by motion along the Sierra Crest shear zone (Glazner, 1992; Tikoff et al., 1999; Tikoff and Teyssier, 1992).
The Bench Canyon shear zone is a 20 km long structure that parallels the Sierra Crest shear zone (McNulty, 1995) and is truncated by the Half Dome Granodiorite at the southern border of the Tuolumne Intrusive Suite (Fig. 1). The Bench Canyon shear zone trends N30°W and dips ~40° W and was active from ~ 101-78 Ma (Tobisch et al., 1993). The bulk shear on the Bench Canyon shear zone is estimated at ~N21° W and has resulted in a maximum thrust displacement of ~ 4.6 km (McNulty, 1995). The early-stage deformation (~101-95 Ma) was characterized by extensional deformation; the main-stage of deformation (95-90 Ma) by a ductile thrust regime; the late-stage deformation (90-78 Ma) also exhibited thrust sense and showed weak, fluid-enhanced ductile deformation to the south and brittle deformation to the north (McNulty, 1995).

Regionally Observed Fractures

Epidote lined fractures are common in granodiorites throughout the Sierra Nevada batholith. Cloos (1936), Mayo (1941), Moore (1963), and Bateman (1965) all note that minor strike-slip faulting has occurred along many of these fractures and that cumulative offset along these fractures is extensive.

Lockwood (1979) used aerial photographs to complete extensive mapping of fractures in an 8,000 km² area of the Sierra Nevada batholith. He noted several general characteristics of the fractures: 1) most fractures show no offset, 2) fractures occur in conjugate sets, 3) mineralization is common, and 4) fault planes often vary in dip along strike. The faults that Lockwood (1979) observed in the Tuolumne Meadows quadrant with left-lateral offset trended N30°E, whereas the associated right lateral faults had an average trend of N24°W. He concluded that these faults were first formed by late
Cenozoic extension, likely related to the regional extension of the Great Basin, and were later reactivated by strike-slip motion.

Cretaceous fractures, both shear and opening-mode, are hypothesized to have originated as discrete joints in response to thermal contraction (Bergbauer and Martel, 1999) and to have been locally reactivated as strike-slip faults (Pachell and Evans, 2002). Segall and others (1984; Segall and Pollard, 1983a, b; Segall and Simpson, 1986) reported that most fractures have zero shear displacement and are dilatational in nature. Fractures typically range in length from 1 m to 70 m and have an estimated maximum offset of up to ~ 2 m (Martel et al., 1988). Many of the fractures are bound by a lighter, altered granodiorite rim of 3 to 4 cm in width (Segall, 1983b).

FIELD OBSERVATIONS

I measured the orientation and documented the characteristic behavior of chlorite/epidote-lined fractures at two locations within the Cathedral Peak Granodiorite: Lembert Dome and Budd Lake (Fig. 2). Differences exist between the two sets of fractures, but all fractures in this study are surrounded by a ‘bleached zone’ that extends 0.9 - 2.2 cm on each side of the fracture (Fig. 5a). This bleached zone has been hydrothermally altered, reducing the mafic quantities of the granodiorite. This has reduced the quantity of mafics available for oxidation, resulting in a band of rock without iron staining.
Figure 2. General map of the study area including landmarks. Inset of the Budd Lake faults is included. Contact information taken from Bateman (1983).
Lembert Dome

Fractures at Lembert Dome are mineralized by epidote/chlorite, which typically covers 30-40% of the fracture surfaces. Some of the fracture planes are lineated with partial remnants of epidote mineral growth, but the lineations are not parallel to each other (Fig. 3a). The fractures are parallel, with a best-fit strike of 175°. The fractures exhibit a wide range of dips to the west, from 20° W to 70° W (best fit = 48° W) (Fig. 3a). Steeply dipping fractures cross-cut gently dipping fractures (Fig. 4a). No shear offset is observed in the form of offset crystals or joints across any of the fractures.

Budd Lake

The fractures at Budd Lake are divided into two groups based on geographic location and differences in fracture orientation. The first group consists of gently dipping fractures found at the southern end of the outcrop; the second group consists of steeply dipping fractures found at the northern end of the outcrop (Fig. 2).

Group 1

The fractures observed in the southern part of the Budd Lake outcrop have a consistent, N-S strike and dip gently to the west (Fig. 4b), with a best fit orientation of 185°/21° W (Fig. 3b). These fractures range in length from ~ 1 m to ~ 113 m (Fig. 4c). Bleached zones are more competent and substantially lighter than the surrounding rock (Fig. 5a). Mineralization is observed on all exposed fracture surfaces, many of which exhibit nearly 100% epidote/chlorite mineralization coverage. Those fracture surfaces that have less mineralization appear to be heavily weathered. Due to weathering on the fracture planes and the homogeneity of the rock, it was often difficult to assess movement
Figure 3. Fault orientations from Lembert Dome fractures (a), Budd Lake Group 1 faults (b) along with directionality indicated by step-down structures (c), and a rose diagram of pop-out structures indicated directionality from Group 1 (d). Budd Lake Group 2 orientation (e) and stress analysis from Group 2 (f).
Figure 4. (a) Cross-cutting fractures from Lembert Dome. Pen for scale. (b) Looking down dip of Budd Lake Group 1 faults. (c) Looking along strike of a Budd Lake Group 1 fault. (d) Heavily weathered fault surface. Field notebook for scale.
Figure 5. (a) Cross section of a Budd Lake group 1 fault with altered zone bracketed. Pen for scale. (b) Sample of fault surface from group 1. Random orientation of fine epidote crystals, as well as slickensides (indicated by red line) upon the chlorite surfaces. (c) Step-down structures found on group 1 faults. Sharpie for scale. (d) Same picture (c) with interpreted slip direction. Sharpie for scale.
Figure 6. (a) Pop-out structures with arrows indicating interpreted movement direction. Pen for scale. (b) Fracture offset by left lateral motion of fault (offset = 2 mm). (c) Slickensides from Budd Lake Group 2 faults; chattermarks can be seen as shadows. Pen for scale. (d) Group 2 slickensides with arrow to indicate movement direction. Pen for scale.
along the fractures in Group 1. Therefore data was collected to establish if shear occurred on the fractures and whether shear was dextral or sinistral.

Some of the fracture planes are lineated with epidote mineral growth, but it is not clear whether the mineral fibers are partial remnants due to weathering, partial remnants due to movement along the fracture planes, or slickenfibers that formed during fault motion. Some of the fracture surfaces have mineral growth lineations while others have clear slickensides on polished, finely ground epidote surfaces (Fig. 5b). Measurements of these data were not grouped (Fig. 3b).

Along exposed fracture planes, systematic step-downs were observed. These step-downs connect parallel fracture planes that effectively have the same strike and dip, but are offset by < 1cm. The direction and orientation of the step-downs is consistent. These step-downs could be interpreted as similar in origin to slickenside steps on a larger scale (Fig. 5 c,d). Based on these observations, the measurements indicated sub-parallel, systematic features consistent with left-lateral motion with a small component of oblique divergence on the exposed fracture planes (Fig. 3c).

I also measured tetrahedral forms that were fractured out of feldspars. These structures are similar to pop-out structures found in association with glaciers. The observed ‘pop-out’ structures are non-equilateral and have a preferred orientation, which I measured using the line that intersects the most acute vertex of the tetrahedron perpendicular to the opposite side of the tetrahedron (Fig. 6a). These ‘pop-out’ structures cannot have been glacially formed, as might normally be inferred, because of the undisturbed, fine, elongate epidote crystals on the fracture surfaces.
At one locality along a Group 1 fracture, an offset joint was observed. The fracture is preserved on a sheltered, vertical face. The 2 mm of left-lateral offset was observed on a 6.65 m fracture with a cross-cutting joint 0.42 m from the end of the fracture (Fig. 6b). This observation suggests that other, longer fractures likely have similar offsets that were unobservable due to weathering.

**Group 2**

Group 2 fractures are found in the northern part of the Budd Lake outcrop (Fig. 2). Group 2 fractures strike NNE and dip approximately 75° W (Fig. 3e). The fractures are pervasively lineated due to the formation of slickensides on the fracture plane. Slickensides are sub-horizontal, with plunges of 15°-30°, and trend NNE (Fig. 3d). The lineated surfaces are accompanied by clear slickenside steps (Fig. 6c, d). This intense strike-slip movement appears to have worn away much of the epidote precipitate, which, unlike in Group 1 fractures, covers less than 10% of the fracture surface.

**ANALYSIS**

**Fracture Formation**

Differences are present between the Budd Lake and Lembert Dome fractures. First, the Budd Lake fractures have clustered orientations, while greater variance exists among the Lembert Dome fracture orientations. Second, Budd Lake fractures are planar (Fig. 4 b-d); in contrast, Lembert Dome fractures change orientation along strike (Fig. 4a). Lineations are found on both Lembert Dome and Budd Lake fractures, but lineations at Lembert Dome are not sub-parallel. The Lembert Dome lineations are likely due to
radial mineral growth and not shear movement on the fracture plane. Budd Lake fractures have sub-parallel lineations, which suggest shear movement.

Budd Lake fractures and those found at Lembert Dome differ in map-view fault distribution, as well. In order to quantify this difference, aspect ratios were calculated for the observed fault areas. This was done by measuring the length of the area along strike where faults were observed and comparing it to the width of the same area. Group 1 fractures at Budd Lake have an aspect ratio of ~5:1 (along-strike: perpendicular-to-strike) and Group 2 fractures have an aspect ratio of ~6:1. Lembert Dome fractures have an aspect ratio of 4:6. Furthermore, Budd Lake fracture orientations in both groups have a high concordance with the elongate boundaries of the fracture zones.

These Budd Lake observations contradict what others have found elsewhere in the Sierra Nevada, where fracture areas are large and usually not confined to mapable outcrops. Of the few fully mapable fracture sets, nearly complete fracture sets were mapped by Segall, which had aspect ratios of 3:5, 5:2, and 9:5 (1984, 1983a), and Martel (1988) mapped a similarly complete fracture set that had an aspect ratio of 7:9. These large, wide fracture areas indicate both a uniform rock and a regional, dilatational force (Segall and Pollard, 1983a).

The differences between Lembert Dome and Budd Lake fractures suggest they formed under different conditions. Lembert Dome fractures are similar to fractures observed in the Mt. Abbot area (Segall and Pollard, 1983a) and are inferred to have formed under similar conditions. Budd Lake fractures, however, require a different explanation.
Fault Movement

Due to the variability in orientations, non-planar nature, and lack of evidence for shear along Lembert Dome fractures outlined above, no attempt to derive offset was made. However, both groups of fault data from the Budd Lake outcrops exhibit consistent with shear offset.

Group 1

In the field, it was difficult to distinguish the nature of offset across the fractures. Most of the observed fracture planes contain lineations defined by both elongate mineral growth and slickensides. The mineral growth component of the lineation data causes the same confidence problems as those caused by the Lembert Dome lineations since it is not clear whether the mineral elongation is due to mineral weathering, preferential preservation, or slickenfiber growth (Fig. 3b for orientation). Based on lineation data, it cannot be confidently stated whether these are shear (i.e., small fault) or extensional fractures. If we include other fault movement indicators, fault movement direction becomes clear. Fault step-down structures, tetrahedral pop-out structures, and the single fault offset marker all indicated left-lateral motion with a small component of oblique divergence to the SW, consistent with the lineation data (Fig. 3). The possibility of these structures being attributable to glacial forces is negated by the nature of the surfaces, the delicate mineral precipitate present, and the disagreement between the orientation of step-downs and the down-slope movement of a glacier.

Group 2

Slickensides on the Group 2 faults are pervasive and are accompanied by incontrovertible slickenside steps, pointing towards left-lateral motion to the SSW (Fig.
3d). Although the steps could possibly be caused by the movement of glaciers over the rock surface, this interpretation is highly unlikely due to 1) the steeply dipping nature of the fracture planes, and 2) the disagreement between the orientation of steps and the down-slope movement of a glacier.

**Paleostress Analysis on Group 2 Faults: Stress methods and results**

Paleostress was estimated using Andersonian faulting theory. This theory requires that faulting have occurred at a shallow depth. Since the Cathedral Peak Granodiorite crystallized at shallow depths, we can assume that this condition holds on the Budd Lake faults. The theory also requires principle stresses be either parallel or perpendicular to the earth’s surface, which necessitates that the faults dip vertically. For this reason stress analysis was only performed on the Group 2 faults, which dip sub-vertically. Andersonian fault theory then uses the Mohr-Coulomb criteria to determine paleostress. The Mohr-Coulomb criteria dictates that shear fracture planes contain $\sigma_2$ and that the angle between the fracture plane and the principle stress direction ($\sigma_1$) is $45^\circ$. Shear stress ($\sigma_3$) is assumed to be parallel to slip direction on the fault plane. Using this Andersonian fault theory, paleostress analysis was performed on the Budd Lake Group 2 faults, which returned a NNE principal stress direction ($\sigma_1$) (Fig. 3f).

**Fault Zone Alteration and Petrography**

Mineralized fractures were observed using transmitted light microscopy under both plane and cross-polarized light. Budd Lake Group 1 fractures are shown in Figure 7. At the macro-scale, epidote crystals can clearly be observed on the fracture planes, but at
the micro-scale it is apparent that the fracture planes are dominated by two phases: epidote and chlorite (Fig. 7b). Fracture surfaces consist of large (0.5-1.0 mm) epidote crystals embedded in a fine-grained chlorite matrix. The chlorite has a preferred \( \sim 45^\circ \) orientation (as indicated by elongate crystals) to the fracture plane, an orientation that defines a foliation within the mineralization (Fig. 7b). The epidote crystals are predominantly aligned either with the foliation defined by chlorite elongation or with the fracture walls. Epidote crystals are heavily fractured, and these fractures form rough conjugate sets within the crystals (Fig. 7b). The total epidote/chlorite precipitate is approximately 3 mm wide, with a 1-mm band of chlorite and a \( \sim 250-\)um band of heavily deformed chlorite that is defined by the most elongated chlorite crystals. The observed angle of chlorite foliation to the fracture plane is \( \sim 45^\circ \), providing further evidence of left-lateral motion on the Group 1 fractures (Fig. 7b).

Figure 7b shows that the \( \sim 250-\)um band of heavily deformed chlorite crystals does not extend all the way through the precipitate. One interpretation of this observation is that the fractures first formed by extension, epidote and chlorite then precipitated into the fracture aperture, and fractures were finally reactivated as shear fractures. Another interpretation is that the fractures formed due to shear, reducing the grain size of host rock crystals (biotite, feldspar) along the fracture plane. The reduced grain size would then lead to preferential alteration of host rock minerals to chlorite and epidote, and reactivation of the shear fracture would cause the observed chlorite elongation. A third interpretation is that continuous movement occurred on the fracture plane (leading to the precipitation of chlorite and epidote in a preferred orientation) but did not deform.
Figure 7. (a) Cross-section photomicrograph of a fault wall from a Group 1 fault; 3 mm wide precipitate zone is bracketed. (b) Enlarged area of the left-bottom of (a) showing chlorite precipitate zone with area of deformation and angled epidote grains.
precipitate grains. Given the previously stated evidence that Budd Lake faults are not formed by extension, either of the latter two interpretations is superior to the first as an explanation of the Budd Lake faults mineralization.

Walls of the Budd Lake Group 1 faults show preferential deformation; in hand sample, chlorite precipitate shows more deformation than epidote precipitate (Fig. 5b), with lineations appearing on the chlorite precipitate. I attribute this to the chlorite grains’ weakness, which would cause chlorite to preferentially accommodate slip as well as to exhibit deformation more readily. Alternatively, it could be inferred that preferential slip on chlorite precipitate indicates a second, shear stage of deformation, which would require there to have been an opening mode with epidote precipitation and a shear mode with chlorite precipitation. However, the intergrowth between the chlorite and epidote does not indicate separate stages in precipitation. Furthermore, previously discussed field observations make implausible the argument for independent opening and shear deformation.

DISCUSSION

One of the major debates in current geologic literature centers on how room is created during the emplacement of large plutonic bodies (Bowen, 1948; Buddington, 1959). Previous studies have focused on the role of tectonic-scale structures (D'Lemos et al., 1992; Hutton and Brown, 1988; Tikoff and Teyssier, 1992), incremental assembly (Coleman et al., 2004), forcible emplacement (Tikoff et al., 1999), and stoping (Paterson references; Titus et al., 2005). Of these models,
only the model proposed by Tikoff et al. (1999) suggests that host rock surrounding an intruding pluton will record strain.

Specific to the Johnson granite porphyry is the mechanism of pluton emplacement due to a fault zone termination (Titus et al., 2005). This model is based primarily on the overall N-S trend of the Johnson Granite Porphyry and on gravity data that suggests the intrusion continues below surface exposures to the south, toward the termination of the Bench Canyon shear zone (Fig. 9). These data indicate that the Johnson Granite Porphyry is: 1) elongate in the N-S direction; and 2) located deeper in the south than in the north.

**Origin of Mineralized Faults**

Data recorded in this study indicate there are sinistral, mineralized faults in the Cathedral Peak Granodiorite. During the mid-Cretaceous, the Sierra Nevada batholith underwent dextral transpression, as recorded by the Sierra Crest shear zone system (Tikoff et al., 2005; Tikoff and Greene, 1997). Given the strike (NNE) and shear sense (sinistral) of the faults in this study, it is possible they formed as R’ shears within a larger zone of dextral shear, and are tectonic in origin. This model fits a model proposed by Tikoff and Teyssier (1992), in which emplacement of mid-Cretaceous Sierra Nevada plutons occurs in a P-shear/R-shear context. However, the R’ shear model does not fit the fault data well. While the steeply dipping group 2 faults are dipping steeply enough to by R’ shears, they strike NNE rather than the ENE predicted be the R’ shear model. Even if Group 2 Budd Lake fractures did conform perfectly to this hypothesis, the gently dipping Budd Lake fractures are
incompatible with this model due to their gentle dip and oblique-normal motion. Therefore, a more unifying theory that fits all of the observed structures is proposed.

A non-tectonic formation model is presented for the mineralized fractures at Budd Lake in which they formed in response to directional emplacement above the intruding Johnson Granite Porphyry. This interpretation furthers the models proposed by Tikoff et al. (1999), whereby host rock surrounding a pluton records strain (fig. 8), and by Titus et al. (2005), whereby the Johnson Granite Porphyry is hypothesized to be a deeper crustal feature in its southern extent due to deep origination at the terminus of the Bench Canyon shear zone. The proposed model furthers these past emplacement models by suggesting that there is a directional component to emplacement that may be recorded by the host rock.

Several lines of evidence suggest that these faults are related to the intrusion of the Johnson Granite Porphyry. First, there is a spatial correlation to the Johnson Granite Porphyry; mineralized structures over 100 m long are not observed elsewhere in the Cathedral Peak Granodiorite (P. Riley, personal communication). Second, these structures are likely mid-Cretaceous in age, based on their similarities to fractures studied in the Mt. Abbot area of the Sierra Nevada batholith (Segall et al., 1990). Third, the faults strike sub-parallel to the overall trend of the Johnson Granite Porphyry.
Figure 8. Example of translation from the emplacement of the Mono Creek bulge. Horizontal contraction caused material to elongate vertically or horizontally. MC, Mono Creek Granite; RV, Round Valley Peak Granodiorite; M, Marble of Wheeler Crest Septum; WC, Wheeler Crest Granodiorite. Modified from Tikoff et al. (1999).

Figure 9. Bouger anomaly map imposed on a UTM grid map of the Johnson Granite Porphyry. Contours of inversions are 0.5 km in depth. From Titus et al. (2005).
Directional Emplacement Model

The proposed model posits two stages of deformation. The first stage of deformation involved the forceful intrusion of the Johnson Granite Porphyry upward in a diapir-like structure (Fig. 10a). Evidence for this first stage of intrusion can be seen in the lower gravity anomaly shown in Figure 9. I posit that this stage of intrusion resulted in the translation of Cathedral Peak Granodiorite vertically and slightly northward, forming the gently dipping faults in the Budd Lake area (Fig. 11a). This vertical intrusion was likely aided by a fault termination structure but not by a pull-apart structure, since known movement on the Bench Canyon shear zone would not facilitate a pull-apart structure (McNulty, 1995). This model seems to be contradicted by the absence of internal magmatic fabrics parallel to the pluton margin (Titus et al., 2005). However, if diapirism were responsible for the intrusion of the Johnson Granite Porphyry only at depth (i.e., below the current exposure), the observed translation of the wall rocks would be the only expected evidence for the existence of diapirism.

I propose that a second stage of deformation was dominated by forceful emplacement to the north (Fig. 10b), a hypothesis supported by the gravity data, which suggests that the Johnson Granite Porphyry is relatively shallow in areas of surface exposure (Fig. 9) (Titus et al., 2005). This hypothesis is consistent with the Titus et al. (2005) theory that the Johnson Granite Porphyry originated in a shear zone termination structure to the south and propagated northward. This intrusion resulted in a block of the Cathedral Peak Granodiorite being translated northward, forming the steeply dipping faults with sinistral motion at the Budd Lake outcrop (Fig. 11b). This model is further
Figure 10. Model for the intrusion of the Johnson Granite Porphyry in an episode of vertical motion (a), followed by northward propagation (b), and the final form of the Johnson Granite Porphyry along with resultant faults (c).
Figure 11. (a) Cross section of the translation resulting from vertical intrusion of the Johnson Granite Porphyry. (b) Map view of translation resulting from northward intrusion of the Johnson Granite Porphyry.
supported by the paleostress analysis calculations, which indicate a primary stress direction of NNE (Fig. 3f): a direction of intrusion of the Johnson Granite Porphyry consistent with the orientation of the pluton.

This two-stage intrusion of the Johnson Granite Porphyry does not contradict patterns of precipitate seen in thin section and is supported by the two groupings of fault movement data (one group indicating WSW and the other SW movement). Two stages of intrusion would also explain the differences in dip and slip between the two groups at the Budd Lake outcrop. This hypothesis places Budd Lake fault formation before the crystallization of the Johnson Granite Porphyry (85.4 Ma) and (given that fluid flow was evidently still present) before complete solidification of the Cathedral Peak Granodiorite.

CONCLUSION

This study focuses on a group of small left-lateral faults in the Cathedral Peak Granodiorite. Data were collected on orientation and slip movement in order to better understand these faults. Two fault groups were distinguished in the Budd Lake study area, the first striking NS and gently dipping to the west and the other striking SSW and steeply dipping to the west. These faults proved to be particularly interesting because they were determined to be dissimilar in both their forms and formation to other epidote/chlorite-lined fractures found elsewhere in the Sierra Nevada. These faults were therefore hypothesized to have been formed by an area stress that was in opposition to regional stress.

This paper argues that fault development at Budd Lake can be divided into early and late stages of deformation. The first stage of intrusion was characterized by a vertical
force and the second dominated by a northward force. I contend that these stresses were caused by the forceful intrusion of the Johnson Granite Porphyry. Specifically, the Johnson Granite Porphyry intruded into the Cathedral Peak Granodiorite, possibly at the Bench Canyon shear zone termination, resulting in a diapir or laccolith structure. This first intrusion laterally translated mass above the Johnson Granite Porphyry, resulting in the observed gently dipping faults. A second stage of forceful intrusion to the north then occurred, causing northward translation of local Cathedral Peak Granodiorite, which resulted in the second group of observed steeply dipping faults.

In the current literature, a forceful intrusion of the Johnson Granite Porphyry has not been considered because little strain is seen in the immediate area of the Johnson Granite Porphyry. If translation is included in space calculations, however, forceful intrusion becomes a possibility. Far-field translation is likely often associated with regional tectonics, making the two stresses indistinguishable in most cases (Tikoff, 1999). However, the observed faults, because they contradict regional tectonic stress, allow isolated study of translation, making them a powerful tool for generating a novel translational model that describes a forceful intrusion of the Johnson Granite Porphyry.

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