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Translation and the resolution of the pluton space problem

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Abstract

The Late Cretaceous Mono Creek granite has a pronounced NW–SE elongate shape, 60 km long by 10 km wide, characteristic of plutons from the eastern Sierra Nevada batholith. An 8 km-wide bulge exists on the NE side of this pluton, which exhibits evidence of forceful emplacement (or in-situ ballooning), such as deflection of metamorphic wallrock and igneous foliation, and the orientation of fracture patterns. Three-dimensional strain analysis indicates that wallrock strains do not provide enough volume to accommodate the emplacement of the bulge, a recurring problem in studies of plutonic terranes.

We suggest that emplacement of the Mono Creek bulge was accommodated by all components of the three-dimensional displacement field—including translation, rotation, and pure strain (shape change)—of the surrounding units. Classical strain analysis only addresses the rotation and pure strain components, and is incapable of quantifying the translation component. However, our analysis suggests that translation plays the dominant role in the emplacement process. A shell model of translation of the surrounding igneous and metamorphic units is proposed for the Mono Creek bulge, which suggests that the translation component decreases dramatically away from the intrusion, consistent with the observed geology and finite strain analysis. We propose that translation is the solution to the recurring pluton 'space' problem, either through tectonically controlled (passive) or magmatically controlled (active) movement of the wallrocks. Translation is generally the neglected component of the displacement field, but it may often be evaluated through judicious use of finite strain analysis and tectonic reconstruction.

1. Introduction

In the structural geology literature, there is a recurring theme of a 'space problem' or 'room problem' for emplacement of large plutonic bodies (Bowen, 1948; Buddington, 1959). This problem has been partially obviated by studies which indicate that faults, shear zones, large-scale tension fractures, folds, or extensional tectonics facilitate pluton emplacement (e.g. Hutton, 1988; Karlstrom, 1989; D'Lemos et al., 1992; Tikoff and Teyssier, 1992). In these cases, the tectonically controlled translation facilitates emplacement of the plutons ('passive' emplacement). Translation may also facilitate 'forcefully' emplaced plutons that have the form of laccoliths, by lifting the wallrock roof above the intrusion (e.g. Jackson and Pollard, 1988), even at mid-crustal depths (Morgan et al., 1998).

However, some plutons show forceful emplacement with a horizontal motion, including sub-vertical foliation in the surrounding wallrock and no evidence of a structural control of emplacement mechanism. For these plutons, the choices for an emplacement mechanism are few: stoping or forceful emplacement. The mechanism of stoping is typically not a viable option, since it requires incorporation of large volumes of wallrocks, which are not recognized either structurally or geochemically. Moreover, at a large scale, stoping is thermally inefficient (e.g. Marsh, 1982). The common problem concerning horizontal forceful emplacement is based on the observation that the amount of strain surrounding a pluton is insufficient to allow for the

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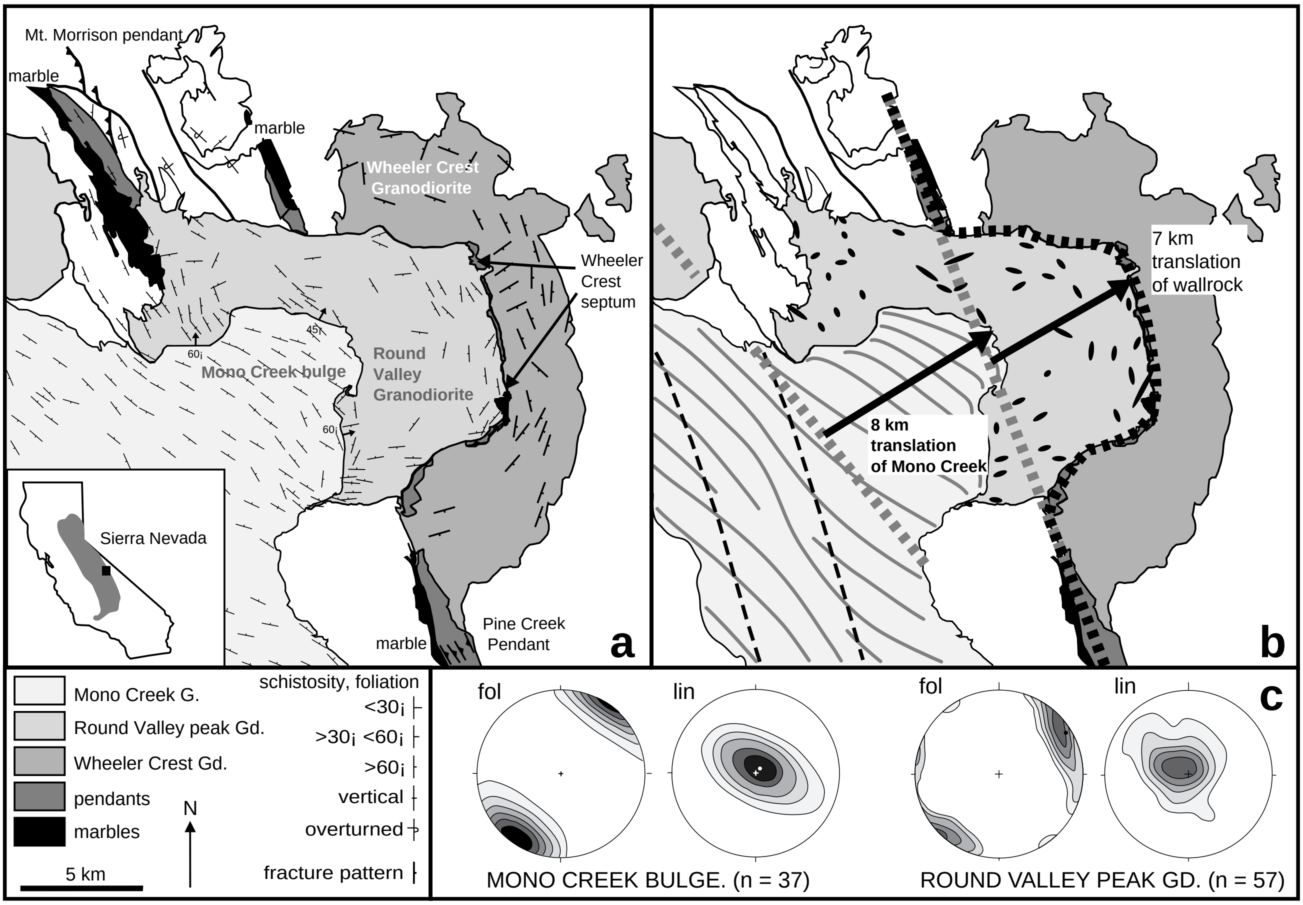

Fig. 1. (a) Geological map of Mono Creek bulge. From W to E across the bulge is the Mono Creek granite (MCG), Round Valley granodiorite (RVG), Wheeler Crest septum, and Wheeler Crest granodiorite. Foliation is from AMS (Mono Creek and Round Valley) and field observation (other units). (b) Predicted offsets of units, three-dimensional strain analyses (xenos) in RVG, and AMS foliation trajectories in MCG. (c) Stereonet of foliation and lineation in the MCG bulge and RVG. Note subvertical foliations and lineations. Equal area, contours = 2, 6, 10 s. Some data from Mayo (1941) and Bateman (1965).

volume increase due to magma emplacement (Paterson and Vernon, 1993, 1995).

We have studied the bulge of the Mono Creek granite in order to address the strain problem associated with forceful emplacement. This bulge locally deflects metamorphic wallrock by up to 7 km from their strike in the eastern Sierra Nevada batholith, in an orientation inconsistent with regional deformation (Bateman, 1965, 1992). Using stratigraphy, three-dimensional analyses, AMS (anisotropy of magnetic susceptibility), and structural trends, we independently derive the translation, rotation, and pure strain components of deformation. Our analysis suggests that translation of the surrounding units is the major component of deformation induced by forceful emplacement of the Mono Creek bulge. Thus, the pluton space/strain problem is solved in this case by considering the role of translation. The problem of the ultimate accommodation of the volume increase due to magma emplacement is greatly diminished by the proposed shell model. The total emplacement-related deformation is distributed from the pluton outward and may combine with regional deformation, producing indiscernible strain at reasonable distances (~2–3 times the original radius of the intrusion) from the pluton.

2. Geological setting

The Cretaceous Sierra Nevada batholith was emplaced between 123 and 83 Ma, and lies along the western edge of the North American craton, as evidenced by preserved Paleozoic stratigraphy and high $^{87}Sr/^{86}Sr$ ratios within the easternmost granitoids (Bateman, 1992). The Mono Pass, Tuolumne, and Whitney Intrusive Suites constitute most of the youngest magmatism within the Cretaceous Sierra Nevada batholith (92–83 Ma, Bateman, 1992). Emplacement of the Mono Pass intrusive series is thought to be upper-crustal and shallow, approximately 1–2 kbar, based on regional studies (e.g. Hirt, 1989; Tikoff and de Saint Blanquat, 1997). The two youngest plutons of the Mono Pass series, the Mono Creek granite and the Round Valley Peak granodiorite, outcrop along the eastern edge of the batholith, adjacent to the Paleozoic stratigraphy and an older Triassic pluton (Wheeler Crest granite; Fig. 1). The U/Pb ages obtained from zircons within these plutons are 87 Ma for the Round Valley Peak granodiorite (Stern et al., 1981; note that errors were not reported) and 86 ± 1 for the Mono Creek granite (B. Carl, pers. comm., 1996). Structural studies indicate that these plutons have magma-mixed at their boundaries (Sherlock and Hamilton, 1958), indicating a close temporal tie between the plutons. The forceful intrusion of the bulge of the Mono Creek granite has affected the following units, from West to East: the Round Valley Peak granodiorite, the Wheeler Crest pendant, and the Triassic Wheeler Crest granodiorite (Fig. 1).

2.1. Mono Creek granite

The Mono Creek pluton is the youngest pluton of the Mono Pass intrusive suite, as determined by both structural studies and isotopic dating. It is primarily a biotite granite with a porphyritic texture throughout, consisting of 3–4 mm quartz and plagioclase crystals and 10–40 mm K-feldspar crystals. Trace amounts of magnetite are found within the pluton, which control its magnetic fabric. The main part of the Mono Creek pluton was probably emplaced into a tensional bridge between en échelon dextral shear zone (Tikoff and Teyssier, 1992) and shows no evidence for forceful emplacement. The bulge of the pluton is distinct from the main part of the Mono Creek granite, both petrologically and structurally. The bulge contains a higher percentage of mafic minerals and a slightly lower percentage of alkali feldspar (Lockwood, 1975). A possible internal contact is revealed on the edge of the bulge by the presence of an abundance of K-feldspar megacrysts, as similar abundances are only observed at the edges of the pluton (Lockwood, 1975). Despite these differences, no discrete contact was observed between the bulge and the main part of the Mono Creek granite.

Structurally, the field-measured foliation within the bulge is vertical and approximately concordant with its boundary, similar to other examples of forcefully emplaced plutons. This is in contrast to the NW-trending field foliation throughout the rest of the pluton. The same pattern is revealed by the magnetic foliation, determined through AMS: concordant foliation in the bulge and NW-trending foliation in the main part of the pluton (Fig. 1a). The magnetic lineation determined with AMS exhibits a sub-vertical trend in the bulge (Fig. 1c), but a sub-horizontal trend within the main mass of the pluton. Microstructurally, the foliation in the bulge is magmatic and only shows high-temperature solid-state deformation along its northern boundary (de Saint Blanquat and Tikoff, 1997).

2.2. Round Valley Peak granodiorite

The Round Valley Peak granodiorite is a fine- to medium-grained, equigranular hornblende–biotite granodiorite containing abundant mafic enclaves (Bateman, 1992). Most structural relations indicate that it is older than the Mono Creek granite, although magma-mixing occurred locally along the contact (Sherlock and Hamilton, 1958). It is an arcuate-shaped body surrounding the bulge of the Mono Creek pluton. The foliation within the pluton is vertical and parallels the main arcuate shape of the pluton (Fig. 1), and it is typically strongest near the Mono Creek contact. The foliation decreases towards the middle of the pluton, but is again visible on its outside contact with the surrounding wallrocks (Bateman, 1992). Microstructures indicate that deformation in the pluton is mainly high-temperature solid-state.

The mafic enclaves within the Round Valley Peak granodiorite provide a useful measure of the finite strain. Measurements were taken at 41 locations, by measuring a minimum of 20 elongate xenoliths on each of three individual planes and taking a harmonic mean. These data were transformed into a three-dimensional ellipsoid using a program from Schultz-Ela (1988) based on the method of Owens (1984). The enclaves show a dominantly flattening fabric, often with the maximum stretching axis in a steeply-plunging orientation. The enclave data (Fig. 1b) show two low-strain zones at the NW and S ends of the pluton, with increasing strain outboard of the Mono Creek bulge. Within these zones of lower strain, the foliation is parallel to the regional NW strike.

The enclave data are corroborated by the AMS analyses on the Round Valley Peak pluton. The AMS signal, controlled by the shape-preferred orientation of magnetite crystals (Grégoire et al., 1995; Launeau and Cruden, 1998), indicates a flattening fabric. Furthermore, the magnetic lineation generally parallels the long axis of the mafic enclaves, which is subvertical (Fig. 1c).

2.3. Wallrock: Wheeler Crest septum

The Wheeler Crest septum is a thin, arcuate wallrock pendant that locally separates the Round Valley Peak and Wheeler Crest granodiorites (Fig. 1). The Wheeler Crest septum contains grayish, fine-grained marble and reddish siliceous argillite. These units correlate with the Mt Baldwin and Bright Dot formation (D. Greene, pers. comm., 1994; Stevens and Greene, in press). The Wheeler Crest septum is considered to be the northward continuation of the Pine Creek pendant and the southern continuation of the Mt Morrison pendant, both of which contain the Mt Baldwin and Bright Dot formations. It is primarily on the basis of the arcuate offset of the distinctive Mt Baldwin marble that the forceful emplacement of the Mono Creek bulge was initially suggested (e.g. Mayo, 1941; Bateman, 1965).

Recent mapping indicates a previously unrecognized section of Mt Baldwin Marble on the east side of the Mt Morrison pendant, resulting from Jurassic thrusting (Greene et al., 1997). Because the marble in the Wheeler Crest may have originally been part of the eastern Mt Morrison pendant, previous estimates of the amount of displacement are slightly reduced, from ~13 km (Bateman, 1965) to ~7 km. As suggested by Bateman (1965), the offset of these units cannot be explained by a regional deformation, indicating a local forceful emplacement.

The Wheeler crest septum is highly discontinuous. Foliation in the septum is generally sub-parallel to foliation in the adjacent Round Valley Peak granodiorite. Chocolate-tablet boudinage of the marble and argillite adjacent and immediately within the Round Valley granodiorite supports the notion of dominantly flattening strains.

2.4. Wheeler Crest granodiorite

The Wheeler Crest granodiorite is one of a series of Triassic granitoids along the eastern edge of the Sierra Nevada batholith. The eastern edge of the Wheeler Crest granodiorite is defined by normal faults of the eastern escarpment of the Sierra Nevada. The present outcrop shape of the pluton is arcuate around the Mono Creek bulge (Fig. 1). Compositionally, the Wheeler Crest pluton is a medium-grained, megacrystic body that generally lacks good foliation.

Deformation within the Wheeler Crest pluton is characterized by conjugate and sub-vertical fractures, which rotate in orientation around the edge of the arcuate shape of the pluton (Mayo, 1941; Fig. 1). This pattern indicates a horizontal radial shortening direction centered from within the Round Valley Peak granodiorite. There is also a weak foliation developed on the western side of the pluton, leading to a locally granoblastic texture (Bateman, 1992). The arcuate geometry, location of shearing, and the brittle–ductile style of deformation suggests that these deformations occurred during emplacement of the Mono Creek bulge.

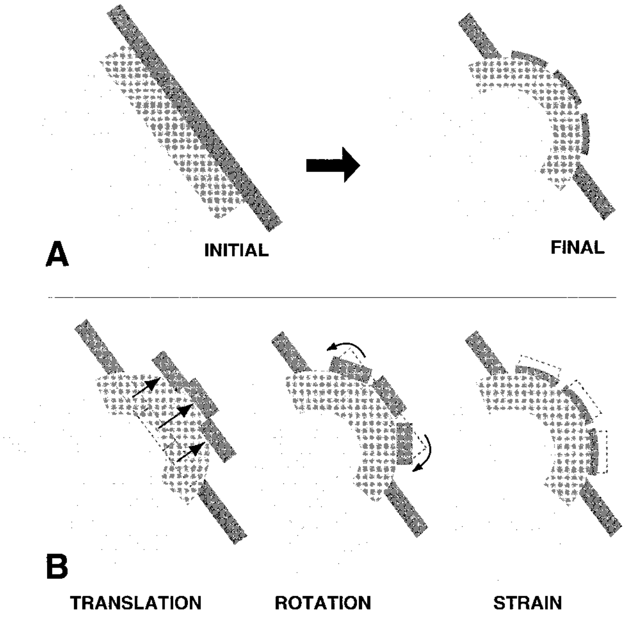

Fig. 2. The components of the displacement field—translation, rotation, and pure strain (shape change)—which occur simultaneously during the emplacement of the Mono Creek bulge.

3. Structural analysis

Deformation requires the unique specification of its three components: pure strain (shape change), rotation, and translation (Fig. 2). Classical strain analysis only provides information about pure strain and rotation. A good example is thrust sheets, where strain analysis indicates little distortion and rotation even though tens of kilometers of translation may be involved. However, because the regional geometry of the eastern Sierra Nevada batholith is well known, we can independently determine each of the components of deformation.

Translation is determined by using the original geometry of the sedimentary and plutonic units prior to intrusion of the bulge (Fig. 2). The metamorphic wallrocks of the eastern Sierra Nevada batholith show a regionally consistent NW-trend, resulting primarily from Permian–Triassic tectonism (e.g. Stevens and Greene, in press), except where altered by forceful pluton emplacement (Bateman, 1992). Likewise, the Cretaceous plutonic rocks of the Mono Pass intrusive suite show a pronounced NW-trend (Bateman, 1992), which probably correlates with their mode of intrusion (P-shear hypothesis; Tikoff and Teyssier, 1992). The continuity between the Mt Morrison and Pine Creek pendants through the Wheeler Crest septum is consistent with the NW structural grain. Therefore, we assume that contacts which do not strike NW are related to local effects, such as ballooning, and that the western contact of the Round Valley Peak granodiorite has moved 8 km to the NE and the wallrocks of the

Wheeler Crest septum have moved 7 km to the NE (Fig. 1b). Because the wallrocks have sub-vertical dips, the map pattern offsets result from horizontal translation.

The rotation of the surrounding rocks, as a result of bulge emplacement, is visible in the arcuate-shaped pattern in map view (Fig. 1). Before intrusion of the Mono Creek bulge, it is assumed that the wallrocks had a NNW-trending orientation, consistent with wallrocks throughout the rest of the eastern Sierra Nevada batholith (Bateman, 1992). If this assumption is correct, rotations of up to 90° are recorded by the foliations within the Round Valley Peak pluton and the metamorphic wallrocks of the Wheeler Crest septum. The subvertical orientations of foliation in both the Wheeler Crest septum and adjacent pendants indicates predominantly vertical axis rotation. Since the Wheeler Crest pluton behaves primarily in a brittle fashion, the rotation of the material occurred primarily between faults and is more difficult to evaluate.

The strain caused by the emplacement of the Mono Creek bulge is evaluated for each of the affected units. Strain is heterogeneous in both the Wheeler Crest granodiorite and the Wheeler Crest septum and cannot be quantified. In both cases, there is a bulk thinning of material around the arcuate shape of the Round Valley Peak pluton (Fig. 1a). However, strain can be quantified in the Round Valley Peak pluton, by using AMS fabrics and the shape of the mafic enclaves. These data illustrate flattening fabrics which are concentrically oriented around the Mono Creek bulge, consistent with the forceful emplacement.

In the absence of a translation component, it is expected that the strain within the Round Valley Peak pluton must accommodate the intrusion of the Mono Creek bulge. In this case, as with most cases of strain analyses around forcefully emplaced plutons, the strain in the Round Valley Peak pluton is insufficient to accommodate the intrusion. However, because we can make informed geological assumptions concerning the original orientation of both its western contact (8 km translation from the geometry of the Mono Creek pluton and wallrocks) and eastern contact (7 km translation from the geometry of the eastern Mt Morrison–Wheeler Crest septum–Pine Creek pendant), we can evaluate both strain and translation. Thus, the strain in the Round Valley Peak pluton only accommodates 1 km of the emplacement of the bulge. The classic space problem—that the recorded strain is insufficient to allow the observed emplacement—is not a problem at all. Translation, although unrecognized by strain techniques, may have a significant role in the emplacement of plutonic bodies, in this case accommodating ~7/8 of the displacement field. Identical results are proposed on the basis of three-dimensional numerical simulations (Guglielmo, 1994) and porphyroblast studies (Morgan et al., 1998).

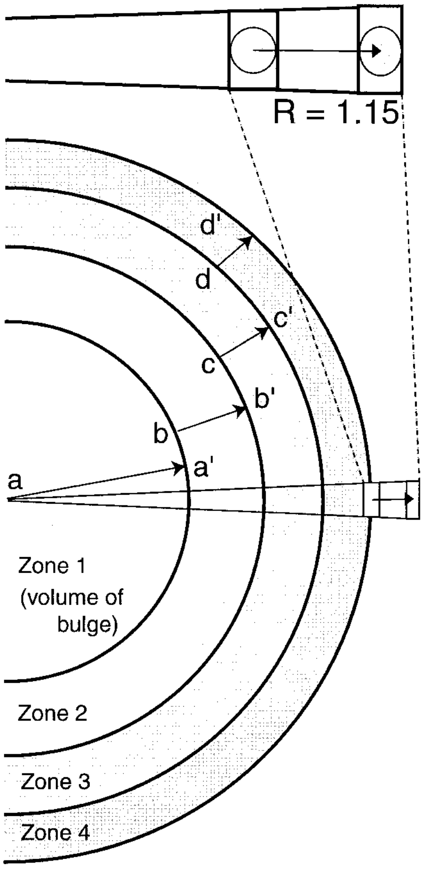

Fig. 3. Cross-section through cylindrical shells. Each grey zone (1–4) contains the same area. If an intrusion fills Zone 1, then all the material that was originally in Zone 1 must move to Zone 2, etc. Thus, point a moves to point a′, b to b′, etc. The inset demonstrates that the amount of strain results from the amount of translation, so strain at point a′ is larger than that at point b′, etc. Indistinguishable strain (< 5%) is expected at distances of 2–3 times the original radius of the intrusion.

4. Shell model

Unlike a laccolith, the translation of the Mono Creek pluton is not pushing upwards to the free surface of the earth. Rather, since the main push is horizontal, we must evaluate how the translation of wallrocks is ultimately accommodated far from the pluton contact. In order to do so, we have constructed a very simple two-dimensional geometric model, based on the principle of area balance (this geometry is cylindrical in three dimensions; Fig. 3). Each of the circular shells in Fig. 3 contains an equal area. Therefore, an initial circular intrusion (Zone 1) can be accommodated by moving all the material that was in Zone 1 into Zone 2. The material that was in Zone 2 moves to

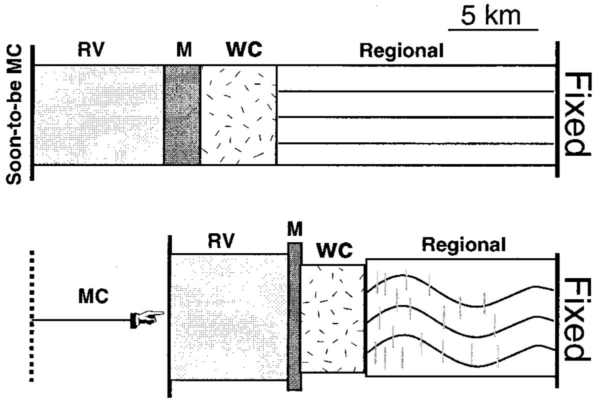

Fig. 4. Deformation of the wallrocks resulting from emplacement of the Mono Creek bulge. In response to horizontal contraction, the material may elongate vertically or horizontally (out-of-the-page). MC, Mono Creek granite; RV, Round Valley Peak granodiorite; M, Marble of Wheeler Crest septum; WC, Wheeler Crest granodiorite.

Zone 3, and so on. However, now evaluate the movement of material points that were initially on the border between the two areas. Point a moves the entire distance of the intrusion, while points b, c, and d move only 41%, 33%, and 26% of that movement, respectively.

One can also make a three-dimensional model, based on a spherical shell geometry with volume balance, which is perhaps more appropriate for the three-dimensional bulge. In this case, the outward movement decreases even more drastically: Points b, c, and d move only 26%, 18%, and 15% of the movement imposed by bulging.

Thus, during emplacement of the Mono Creek bulge, rocks are being ‘stretched’ around the bulge, while at the same time being translated outward. Therefore, the shape change (e.g. strain) is intimately associated with the amount of translation: The more translation, the more strain. Field structures indicate that high magma pressures existed on the NW and SE corners of the Round Valley peak pluton, yet the deformation is relatively low. Conversely, strain is very high within the NE part of the Round Valley Peak pluton at the location of maximum translation. Using a shell model, one can compare the line length before and after intrusion, as point a moves to the initial orientation of point b, and so on. The amount of strain at any point is the difference in line length, caused by moving a point from a shell of radius R_1 to another shell of larger radius R_2. The volume between the two shells—which depends on cylindrical, spherical, or other three-dimensional geometries—should equal the original volume of the forceful intrusion.

Using either the cylindrical or spherical geometries, non-discernible strain values ($<5\%$) are expected at distances of 2–3 times the amount of original magma displacement (the Mono Creek bulge in this case). Thus, the translation caused by horizontal forceful magma emplacement is distributed in a volume, which is approximately 27 (3^3) times the volume of the intrusion. This large volume explains why the strain at any point is relatively small. An additional consequence of this distribution of diffuse displacement is that forceful emplacement of large batches of magma may ultimately have the appearance of a regional contractional event, regardless of the overall tectonic setting (Fig. 4).

5. Discussion

We have shown that accounting for the role of translation explains that the observed strain does not record the total emplacement strain. Rather, the emplacement strain is primarily a result of translation, itself caused by push of magma. In this way, the common observation of insufficient strain to accommodate pluton emplacement (e.g. Paterson and Vernon, 1995) simply reflects a combination of unknown translation and a two-dimensional cross-section through a three-dimensional geometry, but not necessarily a space problem.

While we have potentially helped to clarify the role of translation, this approach does lead directly to two important questions: How is the translation accommodated? And how large is the magma pressure?

5.1. *How is the translation accommodated?*

The possibilities for accommodating the translation component include distributing it widely in the three dimensions, by pushing up, down, and sideways. Translation upward is an option, because, as noted by Morgan et al. (1998), an apparent horizontal bulge may develop even if emplacement is predominantly by vertical motion. Owing to a lack of kinematic markers in the Mono Creek granite, we cannot constrain the three-dimensional geometry of the body. However, the metamorphic wallrocks have sub-vertical dips throughout the eastern Sierra Nevada (e.g. Stevens and Greene, in press), a geometry which requires horizontal movement to modify the map pattern.

The outward translation caused by the Mono Creek bulge is accommodated by regional horizontal contraction. This regional contraction will necessarily lead to either horizontal extension, parallel to the arc of the shells, and/or vertical extension. The outward movement of the bulge may be accommodated by vertical movement, through a regional deformation (Fig. 4). Thus, although the bulge is translated outward, material around the area of the bulge may move upward or downward (e.g. Glazner, 1997). In this respect, it is interesting to note that both the Mono Creek bulge and the Round Valley Peak pluton, although showing flattening fabrics, record subvertical stretching from AMS lineation pattern (mean plunge of 84° and 75°, respectively) and three-dimensional strain measurements.

5.2. How large is the magma pressure?

As evidenced by field, microstructural, and AMS studies (Tikoff and Teyssier, 1992; Tikoff and de Saint Blanquat, 1997; de Saint Blanquat et al., 1998), the main body of the Mono Creek pluton was emplaced in a pull-apart setting. However, the pluton comprises a forcefully emplaced bulge, which deflects the surrounding foliation and displaces metamorphic wallrocks from their regional trend. Therefore, the Mono Creek pluton was emplaced by both forceful and passive mechanisms, although possibly separated in time. The location of the forceful intrusion on the east side of the Mono Creek pluton is explained by examining regional structural weaknesses. The area of the bulge is the only location along the eastern edge of the Mono Creek granite where it was in direct contact with the Round Valley Peak granodiorite without intervening wallrock. The evidence that the Mono Creek and Round Valley Peak plutons are magma mingled in the area of the bulge (Sherlock and Hamilton, 1958), and that the Round Valley Peak rarely records a medium to low temperature solid-state fabric, suggests that this pluton was incompletely crystallized during emplacement of the Mono Creek bulge. Thus, the magmatic bulge pushed out an incompletely crystallized pluton (one could make an apt, but very biological, analogy to an aneurysm).

Although the Mono Creek bulge indicates a translation of 8 km, it only locally records solid-state deformation along its NE edge. Thus, translation was certainly facilitated by shells of gradually increasing rheological strength that surrounded the pluton. The magmatic Mono Creek pushes a more solidified Round Valley Peak, which in turn pushes an easily-deformable (at high T conditions) carbonate and a thermally weakened granite wallrock (granoblastic fabrics and secondary foliation in the Wheeler Crest granodiorite). It is often proposed that magma cannot deform wallrock, because of the large differences in viscosities (Ramberg, 1970). However, within an arc setting with high thermal gradients and pre-existing weaknesses, both thermal and structural gradients in rheology may exist that can enhance the effect of magma pressure.

The amount and the cause of magma overpressuring are of critical importance. In the case of relatively thin laccoliths, the magma pressure is only required to exceed the lithostatic load in order to lift its roof. Exceeding lithostatic load could be accomplished by buoyancy forces. However, horizontal forceful intrusion implies much greater magma forces and the necessity of high magma driving pressures. Particular geodynamic settings, such as transpression, can generate strong tectonic pressure gradients in the crust. When these tectonic models are incorporated with magma dynamics, it is possible that the tectonics could contribute significantly to the magma driving pressure (Robin and Cruden, 1994; Hutton, 1997; de Saint Blanquat et al., 1998), and could help to resolve this problem. The exact source of the magma pressure and its evolution through time remain exciting questions in the study of granite intrusions.

5.3. The role of translation in geological analysis

Translation apparently plays a critical role in pluton emplacement, a result reached by other numerical (e.g. Guglielmo, 1994) and field-based (e.g. Morgan et al., 1998) studies. The broader implications for interpreting rock deformation, ranging from thin section to orogenic scales, are primarily two-fold. First, translation, although not evaluated by finite strain analysis, may be the dominant component of the deformation. Second, translation is the most difficult of the three components of deformation to quantify, particularly in areas with poor markers.

Workers in thrust sheets understand these difficulties and, consequently, undertake palinspastic reconstructions rather than rely only on finite strain data. However, finite strain analysis does provide clues about the amount and sense of translation, as finite strain reflects gradients in the displacement field not accommodated by translation. Two obvious ways to develop large displacement gradients, and consequently recognizable finite strain, are large translations or pinned boundary conditions. The former results because small differences in trajectory are amplified by large offsets. The latter results because there is no translation at the pinned boundaries. A no-slip basal condition for a thrust sheet illustrates the latter, in which case the displacement of the top of the thrust sheet is obtainable by integrating the deformation from the lower part of the sheet. The emplacement of the Mono Creek bulge also exemplifies a pinned boundary condition as the bulge apparently cannot translate the wallrocks adjacent to the Mt Morrison or Pine Creek pendants. The consequent radial symmetry of the bulge, with fixed NW and SE endpoints, provides the observed relation between translation and finite strain. Thus, although the translation component of deformation is lost, it is not forgotten. A combination of palinspastic reconstructions and finite strain trajectories/gradients can provide crucial information on translation, even in igneous terranes.

6. Conclusions

With the recent observations that structural features very often facilitate and/or control pluton emplacement, the classical question about the space problem is now limited to ballooning or forcefully emplaced plutons. Our study of the Mono Creek bulge demonstrates that forceful emplacement was accommodated by all components of the deformation, including translation, rotation, and pure strain (shape change) of the surrounding units. Classical strain analysis can only address the rotation and internal strain, and is incapable of directly quantifying the translation component. However, our analysis suggests that translation plays the dominant role in the emplacement process.

We propose a shell model, in which the deformation caused by forceful intrusion is dispersed into low strains ($< 5\%$) on a regional basis. Thus, the shell model differs significantly from a laccolith model, because the shell model does not require a free-surface. The emplacement of the Mono Creek bulge highlights the amount of regional deformation that is ultimately caused by magmatic processes. Forcefully emplaced magma can have the appearance of a regional contractional event and, thus, magma emplacement and regional tectonics are potentially indistinguishable. How the translation is acommodated and the source of necessarily high magma pressure remain critical questions for studies of pluton emplacement.

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