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15.PROBLEMS WITH THE MAGMATIC MODEL FOR THE ORIGIN OF THE HALL CANYON MUSCOVITE GRANITE PLUTON, PANAMINT MOUNTAINS, CALIFORNIA

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Introduction

Mahood et al. (1996) described zoning patterns of mineral, rock, and isotopic compositions in the Hall Canyon pluton (Fig. 1) in a ~800 m vertical cross-section of the top of a supposed magma chamber. On the basis of these patterns upper and lower zones of the pluton are alleged to form from two different source rocks and crystallize from two different magmas, although the lower and upper zones are gradational to each other. These investigators also suggest that a third magma has been injected a sills in the bottom of the upper zone in the form of mushes *before* the upper zone was totally crystallized. The greater thickness (600+ m) of the lower granodiorite zone supposedly permits convection which results in a nearly constant composition. The lesser thickness and nearly constant temperature of the upper granite zone (150-180 m) are posited to prevent convection and allow the upper zone to be fractionated, causing gradational chemical and mineralogical changes from bottom to top. The emplacement of this pluton was suggested to be by stoping of overlying Precambrian metasediments.

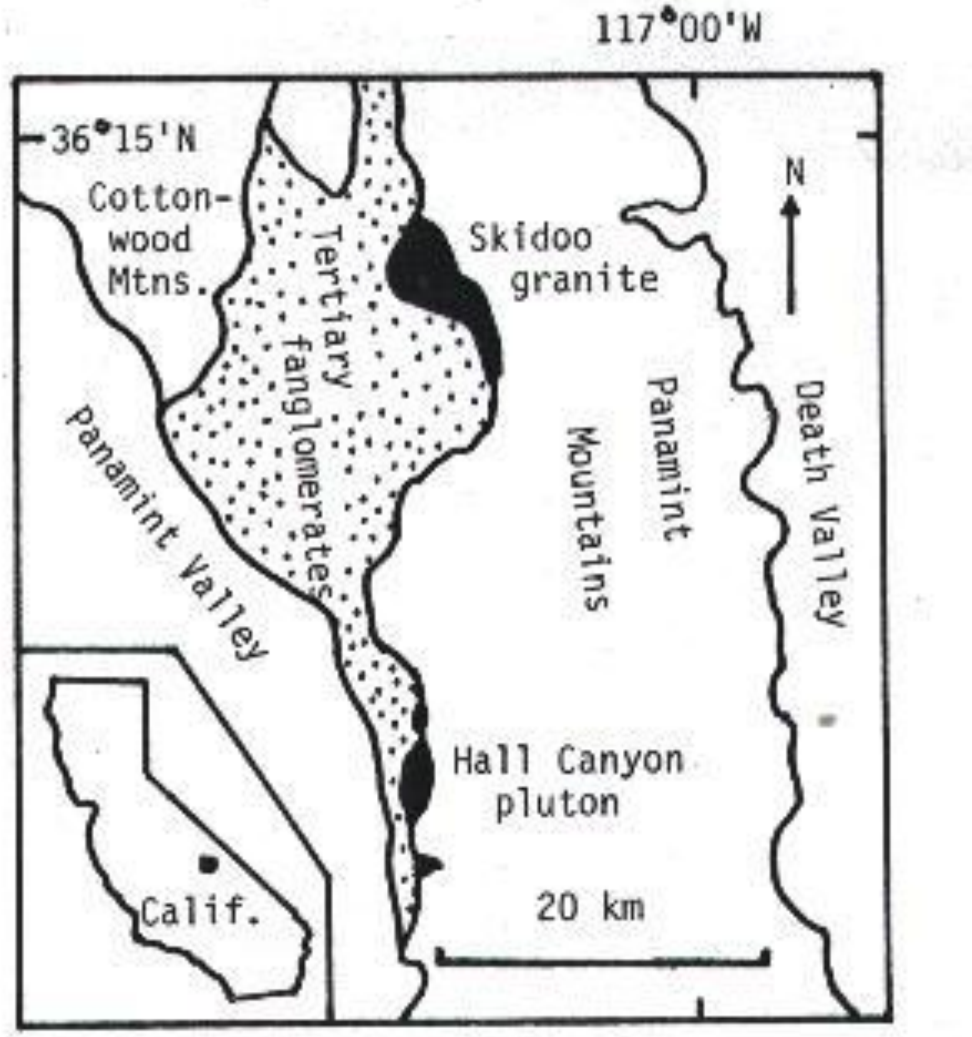

Fig. 1. Map showing location of the Hall Canyon and Skidoo muscovite granite plutons. Map is modified after Fig. 1 of Mahood et al. (1996).

The magmatic genesis of the original granitic rocks in the Hall Canyon pluton is unquestioned. The biotite-bearing granodiorite in the lower zone contains strongly zoned plagioclase, indicating crystallization of magma at shallow depths. The magmatic interpretation, proposed by Mahood et al. (1996), however, results in a number of problems which require explanations that are illogical or require improbable interpretations. These problems include explaining: (1) why MgO and TiO_2 contents behave in parallel fashion in celadonitic muscovite when normally they exhibit antithetical behavior in hydrothermal muscovite (Zen, 1988), (2) why dense garnet crystals do not settle in a hydrous granite magma, (3) why the upper zone contains no xenoliths and xenocrysts and no reactions with the wall rocks or stoped blocks when such features would be expected to occur in an intruding hot magma that is emplaced by stoping, (4) how crystal mushes of biotite-muscovite granite can be injected as sills into fractures in biotite-free muscovite granite that *also* consists of crystal mushes, and (5) why compositions of the peraluminous granitic rocks neither fit a mantle source nor a metapelite source. This presentation provides evidence that these problems can be resolved if the original magmatic rock were modified by K- and Si-metasomatism.

Celadonitic muscovite and biotite

One of the problems noted by Mahood et al. (1966) was that MgO and TiO_2 contents behave in parallel fashion in celadonitic (Mg- and Fe-bearing) muscovite when normally these oxides exhibit antithetical behavior in hydrothermal muscovite (Zen, 1988). These investigators suggested that the coherent behavior of the Mg and Ti in the muscovite reflected "the control of melt composition on muscovite composition." Inclusions of biotite in the muscovite were explained by these investigators as forming by exsolution. Because biotite is enclosed in muscovite, it is just as logical to suggest that the relatively large muscovite crystals and their parallel Mg- and Ti-bearing compositions result from different degrees of replacement of former biotite, leaving some biotite remnants as inclusions. Movements upward of fluids from lower levels carrying displaced Al from replaced plagioclase would provide the Al to change the biotite into the Mg-, Fe-, and Ti-bearing celadonitic muscovite.

Garnet relationships

Mahood et al. (1996) reported garnet throughout the upper zone but noted that concentrations of tiny garnet (almandine-spessartine) crystals occurred in the top 20-30 m of the upper zone. This relationship is perplexing because the supposed fluid nature and low density of the hydrous granite magma in the upper zone should have allowed the denser garnet crystals to settle 1 m per day. For example, settling of garnet crystals resulted in "line" granite consisting of alternating layers of garnet and plagioclase in the Pala pegmatite (Jahns, 1954). A simple explanation of the concentration of garnet in the upper part of the upper zone is that a residual enrichment in Fe and Mn and low fO_2 caused the garnet crystals to form, as suggested by Mahood et al. (1996), but these garnet crystals resulted from replacement processes --- *not magmatic* --- and could not settle because they were formed in solid but deformed rocks.

Xenocrysts, xenoliths, and reactions with wall rocks

Mahood et al. (1966) noted that the muscovite granite in the upper zone contains no xenoliths or xenocrysts and shows no reactions with the wall rocks or stoped blocks as might be expected for a hot magma that is intrusive into metapelites or carbonates. If the muscovite granite were formed from a melt, the absence of xenoliths and xenocrysts could be because the magma melted and assimilated these foreign fragments. If assimilation occurred, however, the carbonate fragments should have changed the muscovite granite melt into a more mafic composition. Assimilated metapelite fragments should have enriched the original melt in biotite. None of these characteristics is found. On the other hand, if the upper zone were a former biotite granodiorite, which likely contained such fragments, it is logical to explain the Mg- and Fe-content of the biotite partly because of assimilation of these fragments and partly to the original Mg- and Fe-content of the magma. Then, the absence now of xenoliths or xenocrysts of metapelite and carbonate wall rocks can be explained because metasomatic fluids, moving through the upper zone and roof zone, would have strongly removed any Ca, Mg, and Fe from the rocks. In this way the original Ca-bearing minerals and ferromagnesian silicates in xenoliths, xenocrysts, and the primary granodiorite would have been destroyed as they were replaced by minerals rich in K, Si, Al, and Na. *Therefore, no xenoliths or xenocrysts would remain*.

Sills in the upper zone

Tabular biotite-muscovite granite layers are interpreted by Mahood et al. (1966) to be sills of magma (crystal mushes) that were injected into fractures in biotite-free muscovite granite (also crystal mushes). *Fractures in crystal mushes make no sense*. For fracturing to occur, the upper zone must have been solid. It is more logical to assume that the upper zone was formerly a solid biotite granodiorite, subjected to increasing degrees of deformation from bottom to top. If this deformation were accompanied by lateral translation along multiple shear zones, then layers that now have the appearance of sills could actually be parallel, tabular zones of less sheared or unsheared rocks. On that basis, *the absence* of truncated crystals in adjacent muscovite granite layers (as noted by Mahood et al. 1996) would be expected. Otherwise, truncation should have been produced if supposed biotite-bearing sills were injected into these layers along fractures, and veins of biotite-bearing granite should extend from the sills into the adjacent muscovite granite in former smaller fractures. Instead, contacts between these rocks range from relatively sharp to diffuse, and no truncation or veins occur. Therefore, it is the rock adjacent to the supposed sills which was strongly deformed, replaced, and recrystallized to become the biotite-free muscovite granite. This same reasoning in regards to increasing degrees of deformation and changes in composition applies to the gradational changes between the lower and upper zones of the Hall Canyon pluton.

Source rocks

Mahood et al. (1996) observed that the compositions of the granitic rocks neither fit a mantle source nor a metapelite source. That is, the high $^{87}Sr/^{86}Sr$ initial ratios (0.719-0.723) and enrichment in Nd make the mantle an unlikely source for the granites in the Hall Canyon pluton. Moreover, because the granitic rocks are weakly peraluminous with molar $Al_2O_3/(CaO + Na_2O + K_2O)$ values averaging 1.14 in the upper zone and 1.10 in the lower zone, these values and relatively high Ca contents in the lower zone are *not consistent* with the granitic rocks being anatectic melts of metapelites, which would have produced much higher peraluminous values (Patino Douce and Johnston, 1991). Mahood et al. (1996) were unable to find a source rock in the area with the need characteristics. It is possible that the high radiogenic strontium-content and the enrichment in Nd may result from metasomatic processes; see discussion in presentation 14 in this web site. Furthermore, the lack of correlation of the Hall Canyon pluton with a metasedimentary source rock is *not unexpected*. This realization becomes readily apparent when comparing the Hall Canyon muscovite-garnet granite with the Waldoboro muscovite-garnet granite.

Comparison of Hall Canyon and Waldoboro granites

The Waldoboro granite complex along the southeastern coast of Maine (Barton and Sidle, 1994) is likely a good analogue for the Hall Canyon granitic rocks because replacements in both terranes result in muscovite-garnet granite; see discussion of the Waldoboro rocks at http://www.csun.edu/~vcgeo005/Nr6Waldoboro.pdf. Barton and Sidle, (1994) plotted chemical data from the Waldoboro rocks on a triangular diagram (Fig. 7 with 15 x Al_2O_3%, 300 x TiO_2%, and Zr ppm at the corners (hereafter called Al-Ti-Zr).

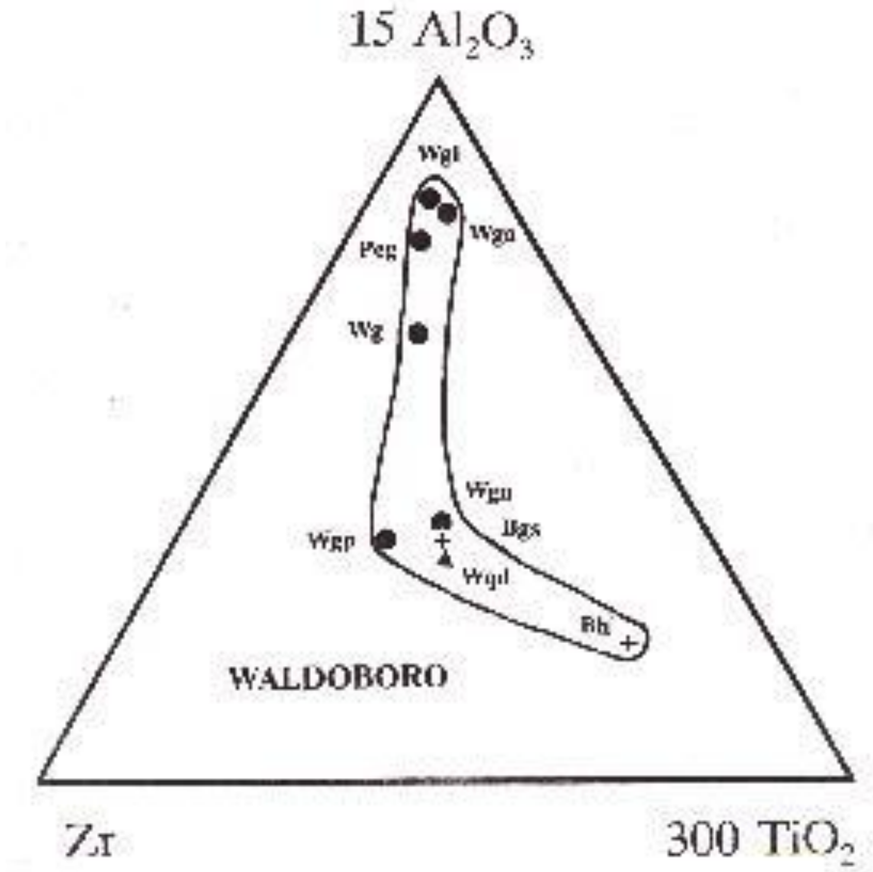

Fig. 7 in article about the Waldoboro rocks. Example in the Al-Ti-Zr projection of seven granitoid units from the Waldoboro Pluton Complex in mid-coastal Maine and two adjacent country rocks from the Bucksport Formation and Benner Hill sequence (Baron and Sidle, 1994). Data points represent average values. Granitic rocks (solid circles; including WGp granite porphyry, Wng granodiorite gneiss, WG granite, Wga aplite, Wgl leucogranite, and Peg pegmatite); quartz diorite (solid triangle); and country rock (pluses; including Bgs Bucksport Formation and Bh Benner Hill sequence).

This diagram shows that the peraluminous granites in the Waldoboro terrane do not project to the aluminous shales, and, therefore, cannot be derived by melting of metapelites. When Al-Ti-Zr data from the Hall Canyon pluton are plotted for comparison (Fig. 2), the field of these data plot in a peraluminous trend and to the left of the trend for the Waldoboro granites, and, thus, far from any projection to metapelites. This relationship gives strong support to the hypothesis that the Hall Canyon granites are derived by a replacement of a magmatic rock in the calc-alkalic series and *NOT from metasediments*.

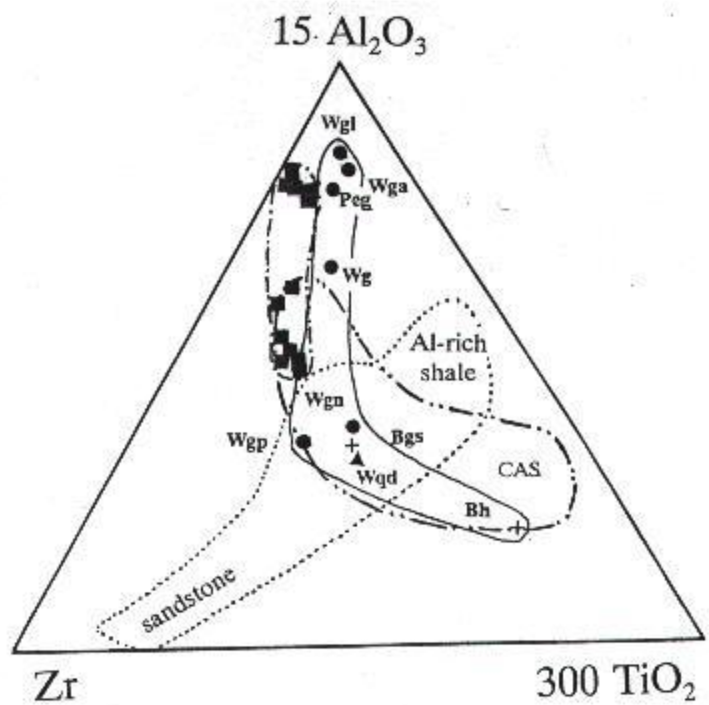

Fig. 2. Example in the Al-Ti-Zr projection (Garcia et al., 1994) of granitic rocks from Hall Canyon (Mahood et al., 1996), seven granitoid units from the Waldoboro Pluton Complex in mid-coastal Maine, and two adjacent country rocks form the Bucksport Formation and Benner Hill sequence (Barton and Sidle, 1994). Data points for the Waldoboro Pluton Complex represent averaged values. Granitic rocks, solid circles, including granite porphyry (Wgp), granodiorite gneiss (Wgn), granite (Wg), aplite (Wga), leucogranite (Wgl), and pegmatite (Peg); quartz diorite, solid triangle; and country rock, pluses, including Bucksport Formation (Bgs) and Benner Hill sequence (Bh). Data points for the Hall Canyon granitic rocks are shown in the field containing solid black squares.

Metasomatic model

In the metasomatic model, variations and enigmatic features of the Hall Canyon pluton can be explained if the crystallized rocks were once a magmatic biotite granodiorite that was strongly deformed, causing cataclasis and lateral shearing. This deformation would have been an older event, separate from that associated with a detachment fault which extends through the lower part of the lower zone. Nevertheless, the detachment fault could represent a younger continuation of the forces that permitted the muscovite-bearing granites in the Hall Canyon pluton to form, but the detachment fault would have occurred at much lower temperatures than that present when the older deformation helped to produce the metasomatic granites. Metasomatic fluids, moving through the ancestral, deformed, biotite granodiorite, are suggested to convert this rock in the lower zone into a myrmekite-bearing, biotite-muscovite granodiorite (containing more K-feldspar than initially there) and in the upper zone, to a biotite-free muscovite granite. In that process, K-metasomatism would have converted relatively-calcic plagioclase into microcline, more sodic plagioclase, and myrmekite, and K-, Al-, and Si-metasomatism would have changed biotite into garnet, quartz, and muscovite.

Statistical analyses of chemical data

Statistical analyses of the published chemical data for the rocks (Mahood et al., 1996; Table 2) were done by Michael DePangher, using two computer programs (SCREEN and CONSERVE) in order to check the plausibility of this metasomatic model versus a magmatic model. These programs have been used by economic geologists as aids in exploring for metallic ore deposits in volcanic rocks and give data that help evaluate whether the volcanic rocks have been altered and affected by metasomatic fluids. The same programs can also reveal any metasomatic modifications that might have occurred in plutonic igneous rocks because plutonic and volcanic rocks should have corresponding, common, chemical, differentiation trends. Although the total number of rock analyses published by Mahood et al. (1996) is small (only 17) and far less than is normally used in such statistical analyses, such computer programs may show whether the granitic rocks in the Hall Canyon pluton have only magmatic characteristics or whether there is evidence for metasomatism.

The program SCREEN performed a systematic comparison of the Hall Canyon data with a data-base of 1,133 unaltered volcanic rocks to assess *altered* versus *unaltered* compositions. The program CONSERVE performed an analysis of the data for *conserved components and protolith affinities*. These two methods are completely independent techniques. SCREEN compares compositions with a reference data-base, whereas CONSERVE analyzes internal patterns within the analyses themselves (no data-base).

The results from SCREEN are interpreted by Michael DePangher as follows:

1. Compositions from the lower zone and sills show *no departure* from the reference data-base, and, therefore, *probably represent unaltered igneous compositions*. Sample 1-6-B is a modest exception, showing slight departure from the data-base with respect to MgO and/or Ca.

2. All compositions from the upper and roof zones show *no departure* from the reference data-base for SiO_2, Al_2O_3, Na_2O, and K_2O, suggesting that these components have probably been conserved.

3. All compositions from the upper and roof zones show *significant departure from the reference data-base* with respect to MnO, Fe_2O_3, TiO_2, MgO, CaO, and P_2O_5, suggesting that *some or all of these components have been gained or lost by metasomatic process*.

The results from CONSERVE are interpreted by Michael DePangher as follows:/

1. All 17 analyses are derived from a single protolith composition by conservation of SiO_2, Al_2O_3, Na_2O, and K_2O and possibly P_2O_5, Y, and Nb.

2. All other chemical components have been gained or lost in a post-magmatic metasomatic process.

3. The protolith composition is probably best represented by an average of all samples from the lower zones and sills.

The absolute gains and losses for each component and the actual alteration reactions and their stoichiometries by Pearce element ratio (PER) analysis have not yet been done. However, Michael DePangher suggests that the fact that the lower zone compositions are unaltered *and* form a linear trend on many PER plots strongly suggests that all of the observed variation within the lower zone has been caused by *a single normal igneous process*, probably fractionation of one or more ferromagnesian crystalline phases.

On that basis, the conversions of a former magmatic biotite granodiorite to biotite-muscovite granodiorite and biotite-free muscovite granite by metasomatism are quite plausible. The metasomatic modifications in the lower zone could have been slight enough (nearly isochemical) that most of its magmatic chemical characteristics, as indicated by the SCREEN and CONSERVE program analyses, were still preserved.

Microscopic evidence

1. *Interior replacements*.

Evidence for K-metasomatism and early stages of the conversion of biotite granodiorite to biotite-muscovite granodiorite is indicated by the interior replacement of plagioclase by K-feldspar (Figs. 3 and 4).

Fig. 3. Replacement of albite-twinned plagioclase (gray and light-gray) by irregular islands of K-feldspar (black and cross-hatched pattern) along microfractures.

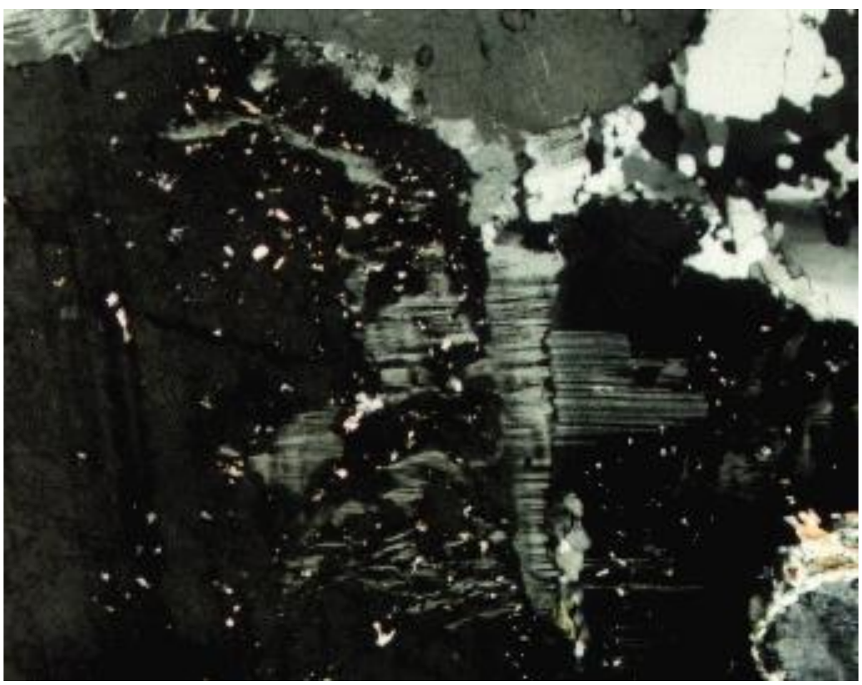

Fig. 4. Replacement of albite-twinned plagioclase (dark gray and black) by irregular islands of K-feldspar (light-gray cross-hatched pattern) along microfractures.

2. *Myrmekite and K-feldspar*.

Although it is difficult to separate the effects of the early deformation (because of recrystallization) from mineral alterations in the later detachment fault zone, *a clue to this former deformation and the extensive K-metasomatism is myrmekite* (Collins, 1988; Hunt et al., 1992). Myrmekite comprises less than 1.0 vol. % of the lower zone and is less abundant in the upper zone, but *its presence is the significant point --- not the abundance*. The thickness of the quartz vermicules correlate with the composition of the primary plagioclase. In the lower zone the maximum thicknesses of the quartz vermicules in the myrmekite have tiny sizes (Fig. 5) and correlate with the associated plagioclase An_{25-28} composition, whereas in the upper zone the maximum thicknesses of the quartz vermicules are so narrow that the vermicules are difficult to see, even under high power magnification, and correlate with the associated plagioclase An_{2-15} composition (Collins, 1988). The upward progressive change in vermicule sizes suggests that the metasomatic processes were on-going and repeated with renewed deformation, recrystallization, and subsequent modifications.

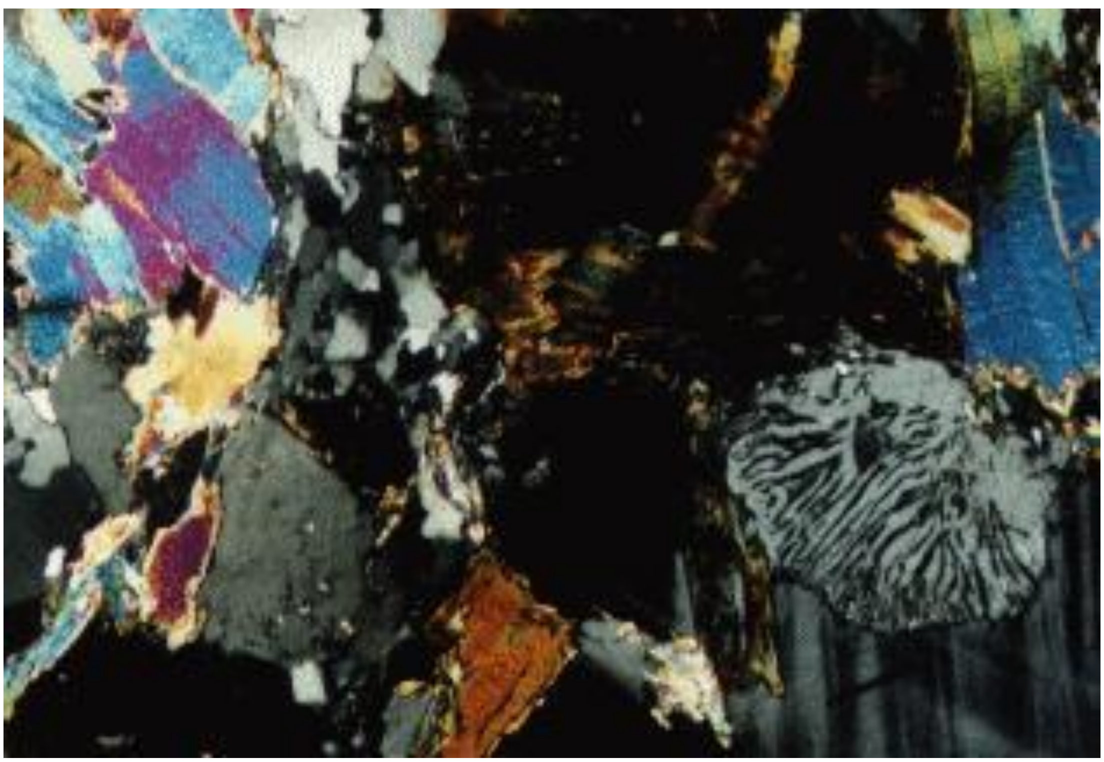

Fig. 5. Wartlike myrmekite with tiny branched quartz vermicules enclosed in microcline (gray cross-hatched pattern). Biotite (brown), muscovite (bright colors), and quartz (white and gray) are coexisting minerals. Photo is from a sample in the lower zone of the Hall Canyon pluton.

3. ***Ghost myrmekite*.**

The replacement of plagioclase by K-feldspar is further supported by the presence of ghost myrmekite (quartz bleb clusters) in the K-feldspar (Fig. 6). If these K-feldspar-quartz intergrowths were formed by simultaneous crystallization of quartz and K-feldspar from a melt (solution), then the quartz should have runic shapes in micrographic-granite textures instead of oval shapes. Moreover, in micrographic-granite textures, the quartz has a common optic orientation throughout the K-feldspar. In the ghost myrmekite (Fig. 6), however, each region of oval quartz clusters has quartz whose common optic orientation is different from that in adjacent regions, supporting the hypothesis that the quartz in these places is from former myrmekite on the borders of the K-feldspar crystal. The plagioclase of this myrmekite has been replaced by K-feldspar, and the K-feldspar has grown slightly beyond its original boundary to enclose the ghost myrmekite completely.

Fig. 6. Ghost myrmekite in K-feldspar (black and gray with cross-hatched pattern). Note that the ghost myrmekite area in the middle contains clusters of ovoid quartz islands (black) that occur between two ghost myrmekite areas with clusters of ovoid quartz islands (white), indicating different optic orientations of the quartz in these three different quartz clusters in the K-feldspar. Biotite (brown), muscovite (bright colors), and quartz (white, gray) are on the margin of the K-feldspar.

See examples of ghost myrmekite in a similar relationship in the Rubidoux Mountain leucogranite in http://www.csun.edu/~vcgeo005/Nr13Rubidoux.pdf.

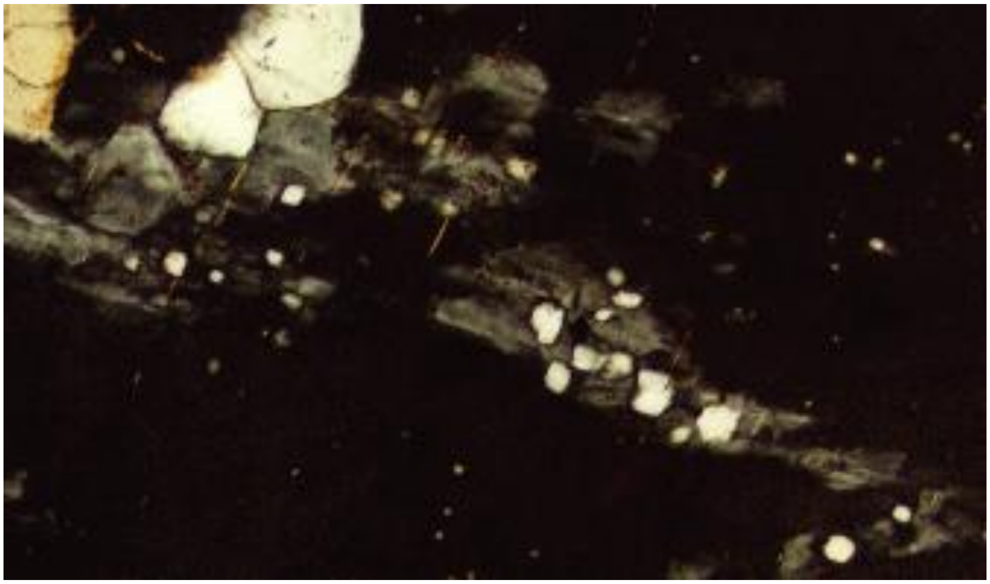

Fig. 6 in Rubidoux article. Isolated island myrmekite (ghost myrmekite). Albite (gray), K-feldspar (black), quartz blebs (white), and quartz crystal inclusions (white and cream).

Partial melting and Na enrichment

Mahood et al. (1996) indicated that the top 10-30 m of the roof zone is enriched in Na rather than K. In myrmekite-bearing rocks formed by metasomatism, the Na_2O content remains nearly constant. When altered plagioclase crystals are replaced by K to form microcline, both Na and Ca are displaced, but some of the Na tends to remain behind in other plagioclase crystals that now recrystallize as a more-sodic plagioclase. Nevertheless, much Na is displaced and could have been carried upward to be concentrated at the top of the Hall Canyon pluton where Na_2O wt.% became greater than K_2O wt.%. This Na enrichment has experimental support. Orville (1963) demonstrated that in low-temperature regions K-feldspar coexists with increasingly Na-rich fluids.

Although the aforesaid metasomatic processes in the major part of the Hall Canyon pluton must have occurred below melting temperatures in deformed solid rocks, following the replacements undoubtedly temperatures rose in the very top of the pluton. Likely, temperatures eventually became sufficiently high that partial melting took place. This possibility is supported by the presence of albite-rich aplite and pegmatite dikes that extend into the roof rocks. Anatectic melts (or hot plastic solids) could have been squeezed out by deformational forces, and these melts (or hot plastic solids) penetrated overlying cracks and fractures in the Kingston Peak Formation.

Conclusions

The upward coherent behavior of Mg and Ti in the muscovite, the lack of settling of dense garnet crystals in a presumed granite magma of low density, the absence of xenoliths and xenocrysts, the improbability of producing fractures in crystal mushes into which other crystal mushes could be injected to form sills, and the lack of any nearby source rocks which had the proper chemical and isotopic compositions are enigmatic problems in a magmatic model for the origin of the Hall Canyon pluton. All of these puzzling features, however, can be readily explained if only one primary magmatic rock was intruded in the crust, and it crystallized as a biotite granodiorite. Later, if this solidified granodiorite were strongly deformed and modified by metasomatic fluids, the different compositions in the sills and lower and upper zones can be formed without creating the aforesaid problems. Forming the Hall Canyon pluton from three different magmas is not necessary.

The mineralogical and chemical characteristics of the upper and lower zones and the sills in the lower part of the upper zone in the Hall Canyon pluton suggest that the K- and Si-metasomatism must have occurred in a compositional gradient because of progressively increasing degrees of deformation at higher levels in the pluton. Greater mineral and chemical changes became increasingly possible upward because of the progressive intensity and duration of the deformation upward.

The metasomatic model offers a simpler interpretation and logically explains more of the data and observations than those presented by Mahood et al. (1996).

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