K-, Na-, and Ca-metasomatism – characteristics of replacement textures associated with feldspars and ferromagnesian silicates and the formation of coexisting rim, wartlike, or ghost myrmekite

Lorence Gene Collins¹

¹Department of Geological Sciences, California State University Northridge, Northridge, CA 91330

Barbara Jane Collins²

²Department of Biology, California Lutheran University, Thousand Oaks, CA 91360

¹email: <u>lorencec@sysmatrix.net</u>

Date: January 15, 2012

Key words: metasomatism, K-feldspar, granite, myrmekite

ABSTRACT

Petrologists generally agree that granitic rocks form by crystallization from magma. Some granitic bodies, however, have been modified by alkali metasomatism at subsolvus temperatures (300-550°C). Myrmekite offers a petrographic means to detect the occurrence and conditions of alkali metasomatism in granitic rocks. Because metasomatic minerals inherit the hypidiomorphic textures of the former magmatic rocks, K-, Na-, and Ca-metasomatism may go unrecognized were it not for the additional presence of myrmekite in combination with other textural and mineralogical features, including microfractures, parallel alignments of silicate lattices and feldspar twin planes, quartz sieve-textures in ferromagnesian silicates, and sizes of quartz vermicules. Deformation is a precursor for myrmekite formation, but recrystallization may obliterate the deformation textures, so that myrmekite is the only remnant of prior deformation history. The loss of displaced Ca, Mg, Fe, and Al on a plutonic scale causes shrinkages as the residue becomes more granitic. The maximum width of the quartz vermicules in myrmekite correlates with the An content of the primary plagioclase being replaced and in the surrounding non-myrmekite-bearing relatively more-mafic rock. Examples of the use of wartlike and ghost myrmekite as clues for metasomatism are illustrated for the Bonsall tonalite near Temecula, California, the Papoose Flat pluton, and the Twenty Nine Palms pluton. myrmekite forms in granitic rocks where deformation is at a minimum. Contrasting these textural and mineralogical features that occur during K-metasomatism is a second type of wartlike myrmekite formation by Na- and Ca-metasomatism in many granitic plutons in Finland, Iran, New York, China, and other localities.

INTRODUCTION

Metasomatism (replacement) of feldspars in granitic rocks can occur because of the introduction of K, Na, or Ca ions in hydrothermal fluids. Na-metasomatism has been welldocumented during the process of fenitization (Winter, 2001). Surrounding carbonatite-alkaline silicate complexes are wide Na-metasomatic halos where quartz and feldspars in wall rock gneisses are converted into aegerine (Na-pyroxene), alkali amphiboles (arfedsonite and riebeckite), nepheline, phlogopite, alkali feldspars, and carbonates. In some places pseudosyenites are formed that are difficult to distinguish from an igneous rock. Temperatures of fenitization are >450°C but below the subsolvus (e.g., Pearson and Taylor, 1996). In other geologic terranes, relatively-calcic plagioclase in plutonic igneous bodies is albitized along shear zones by Na-metasomatism and at temperatures below the subsolvus (e.g., Engvik et al, 2008; Morad et al., 2010; and Pluemper, 2009). In both types of geologic environments the Nametasomatism is not doubted by the geologic community because the formation of Na-rich minerals is easily recognized as not being present in the metamorphic wall rocks surrounding the carbonatite-alkaline silicate complexes or in unsheared granitic plutons before the metasomatism occurred. Also, the metasomatism occurs across a zone in which gradual changes in mineral compositions are observed or in which veins of albite can be seen to extend into microfractured relatively more-calcic plagioclase.

K has chemical properties that are similar to that of Na, and, therefore, K-metasomatism should also be expected. For example, in the temperature range of 25-350°C, sodic and calcic plagioclase feldspars are altered to sericite mica by weathering processes and at temperatures of about 100°C, mobilized K has formed metasomatic authigenic adularia (a low-temperature polymorph of K-feldspar) in Precambrian gneisses and overlying Paleozoic rocks, extending across thousands of square kilometers throughout Missouri, Wisconsin, Iowa, Illinois, Indiana, and Ohio (Liu et al., 2003). However, in the temperature range of 350-550°C (below the subsolvus), no large-scale K-metasomatism is reported in the refereed geologic literature. At temperatures above the subsolvus, other high-temperature polymorphs of K-feldspar (orthoclase and sanidine) are known to crystallize, but below the subsolvus K-feldspar (microcline or orthoclase) formed by K-metasomatism is not reported on a plutonic scale. The reason for this unusual reporting gap is because most granite petrologists consider all granite bodies of plutonic size to have formed entirely by magmatic processes on the basis of earlier experimental work of Tuttle and Bowen (1958) and because the mineralogical changes that occur during Kmetasomatism in this temperature range produce replaced and recrystallized mineral products that are stable in this range and look as if the rock crystallized from magma. Hence, there is no reason to suspect that large-scale K-metasomatism has occurred at temperatures in the range of 350-550°C. However, it should seem unusual to have a gap in a temperature range in which nothing occurs. Putnis et al. (2007) demonstrated internal elemental changes in feldspar lattices which this kind of metasomatism produces in this temperature range in granites from Finland, Brazil, Sweden, and near Temecula, California (described in this article), but did not provide further elaborations about external changes that accompany these changes.

This article provides mineralogical and textural evidence that large-scale K-metasomatism occurs in the range of 350-550°C. It also contrasts this style of metasomatism with another style in which Na- and Ca-metasomatism occur. Forty-eight images have been selected from more than thirty-one different geologic terranes and are used in this article to illustrate the differences in textural styles for the two styles of metasomatic processes. Other images can be seen in website articles listed at http://www.csun.edu/~vcgeo005/index.html. Only a few photomicrographs of thin sections have a scale-bar, but they are all photographed at low magnification (40x). Therefore, their scales are comparable.

I. TEXTURES ASSOCIATED WITH AND FORMED DURING K-METASOMATISM

Three different kinds of textural features provide evidence that large-scale K-metasomatism occurs in many plutonic igneous terranes. These include (a) K-feldspar replacements along fractures, (b) parallel alignments of silicate lattices and feldspar twin planes, and (c) quartz sieve-textures in ferromagnesian silicates.

A. K-feldspar Replacements Along Fractures

Evidence that the K-metasomatism occurs at temperatures below the subsolvus exists in places (a) where K-feldspar projects into microfactures in adjacent primary plagioclase (Figure 1) and (b) where broken plagioclase crystals are surrounded by the K-feldspar so that plagioclase islands are created in parallel optic continuity with the adjacent, larger, unbroken plagioclase crystal (**Appendix**: Microfracturing, Figures 12 and 18).

In early stage of K-feldspar replacement of plagioclase, the K-feldspar occurs interstitially as the K-feldspar replaces albite-twinned and zoned plagioclase along broken grain-boundary seals and as veins penetrating fractures that cut the plagioclase crystals.

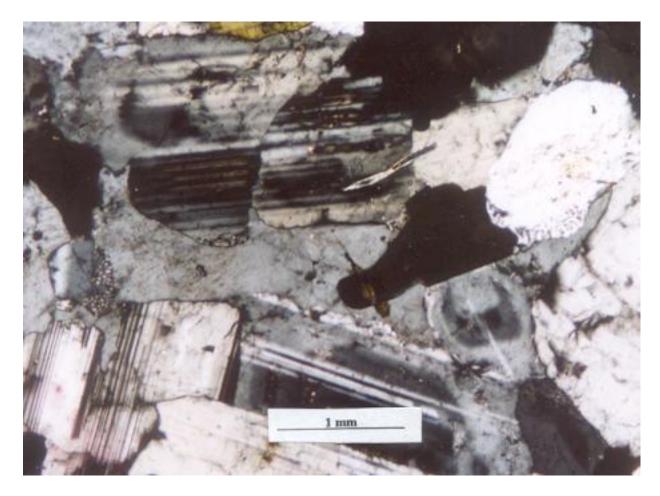


Figure 1. K-feldspar (light gray; extending from left to right through center of photo); albitetwinned and zoned plagioclase (black, white, gray) above and below the K-feldspar. Note curved fracture that extends upward through a plagioclase crystal above the top edge of the K-feldspar and K-feldspar penetrating the plagioclase along this fracture. Source: Collins (2003, Figure 6).

In addition to the existence of fractures that are necessary as a prior condition before wartlike myrmekite can form is the evidence that where K-feldspar begins to replace the interiors of microfractured primary plagioclase, this replacement is in parallel alignments of silicate lattices with feldspar twin planes.

B. Parallel Alignments of Silicate Lattices and Feldspar Twin planes

Where secondary K-feldspar forms by K-metasomatism of primary plagioclase, Ca, Na, and some Al are extracted from the plagioclase silicate lattice prior to the introduction of K to form K-feldspar. Because the former lattice of the plagioclase crystal is still present, (a) one twin-plane of the grid-twinning in microcline is inherited from the albite twin-plane of the plagioclase or (b) the Carlsbad twin-plane of orthoclase or microcline is inherited from the Carlsbad-twin plane of the plagioclase. Therefore, the replacement-K-feldspar has parallel

alignments of one of its twin planes with twin planes of the former plagioclase crystal that is being replaced (Figures 2 and 3; **Appendix**: Parallel alignment, Figures 6 and 8). Because in some places microcline commonly forms, it may not first be orthoclase that converts to microcline.

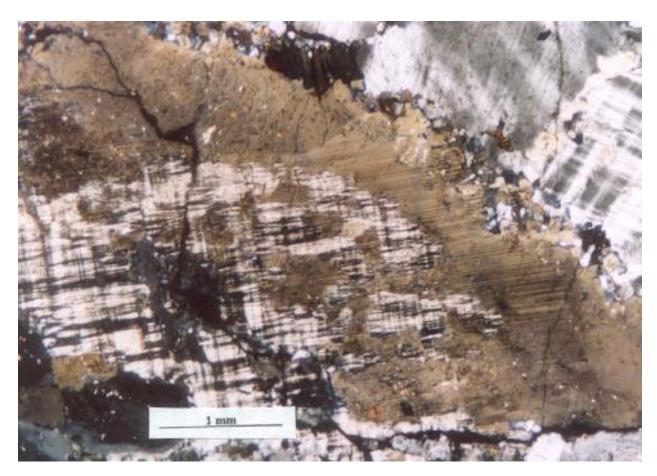


Figure 2. Microcline (black and white; grid-twinned; lower left side) is in the process of replacing the interior of an albite-twinned plagioclase crystal (tan) toward the right. Microcline (upper right) also occurs in the upper right. A twin-plane of the microcline parallels the albite twin-planes of the host plagioclase. Myrmekite and cataclastic fragments of remnant plagioclase occur along the border between the microcline and the plagioclase. Source: Collins (2003, Figure 20).

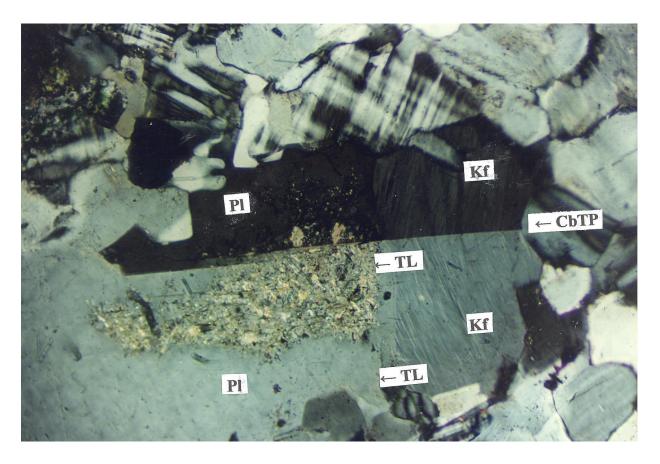


Figure 3. A Carlsbad-twinned plagioclase (Pl) with sericitized calcic core is replaced by K-feldspar (Kf). The plagioclase crystal occurs in the massive, pink Cape Ann granite several meters from the contact with the Salem diorite and is similar in size and shape to Carlsbad-twinned plagioclase crystals in the diorite. At the right end of the plagioclase crystal, its calcic core is truncated (vertical line, TL) and replaced by orthoclase whose Carlsbad twin plane (CbTP) is inherited from the former plagioclase lattice that once filled this space. Source: Collins (1997c, Figure 6).

C. Quartz Sieve-Textures in Altered Ferromagnesian Silicates

Commonly where relatively-mafic rocks are being microfractured and/or deformed such that K and Si can be introduced to cause K-metasomatism, the coexisting biotite and hornblende are also affected by Si-metasomatism to produce secondary quartz blebs as Fe and Mg are removed from their lattices by through-going metasomatic fluids (Figure 4; **Appendix**: Quartz sieve-textures, Figures 7 and 31).

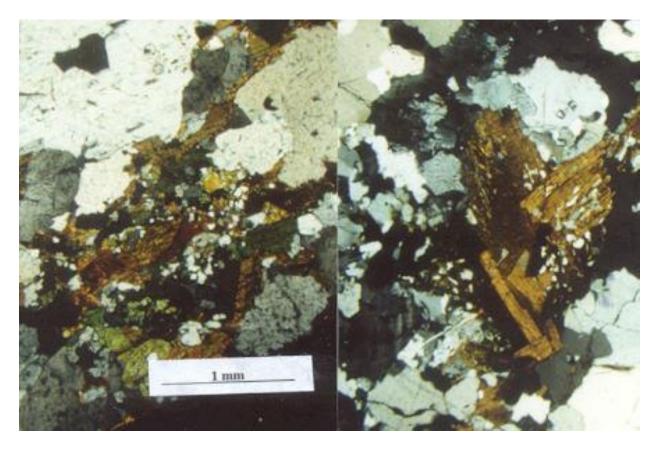


Figure 4. Left side. Hornblende (brown and olive green) replaced in the interior by tiny grains of quartz (white). Plagioclase (white, cream, gray). **Right side**. Biotite (brown) replaced in interior by tiny quartz grains. Source: Collins (2002, Figure 10).

With this background preparation, we are now ready to look at wartlike myrmekite.

II. WARTLIKE MYRMEKITE AND ITS CHARACTERISTICS

Wartlike myrmekite (a two-mineral intergrowth of plagioclase and vermicular quartz) is usually seen projecting into K-feldspar so that the area that is myrmekitic is between two pincers of the K-feldspar on either side. The quartz vermicules taper toward the K-feldspar, and the plagioclase An-content of the plagioclase in the myrmekite adjacent to the quartz vermicules becomes more sodic, the narrower the quartz vermicule. In some kinds of wartlike myrmekite, the quartz vermicules narrow still further and disappear toward the K-feldspar where a quartz-free (Na-rich) albite rim may occur against the K-feldspar (Figure 5; **Appendix**: Wartlike myrmekite, Figures 2 and 24).



Figure 5. Myrmekite (center, with branched vermicules) bordering a K-feldspar megacryst (gray, upper left). Quartz is light gray and white. Biotite is brown. At the outer edge of the myrmekite against the K-feldspar, the quartz vermicules become narrower until they disappear where the plagioclase of the myrmekite forms an outer albite rim. Source: Collins (1997e, Figure 5).

Quartz vermicules in myrmekite are not always oriented so that their long wormy-lengths are visible. In some places the long axis of each vermicule may be oriented perpendicular to the plane of the thin section. Therefore, under cross-polarized light they may appear black or gray because the view is down the c-axis of the quartz. An example occurs in the Vrådal pluton in Norway (Figure 6).

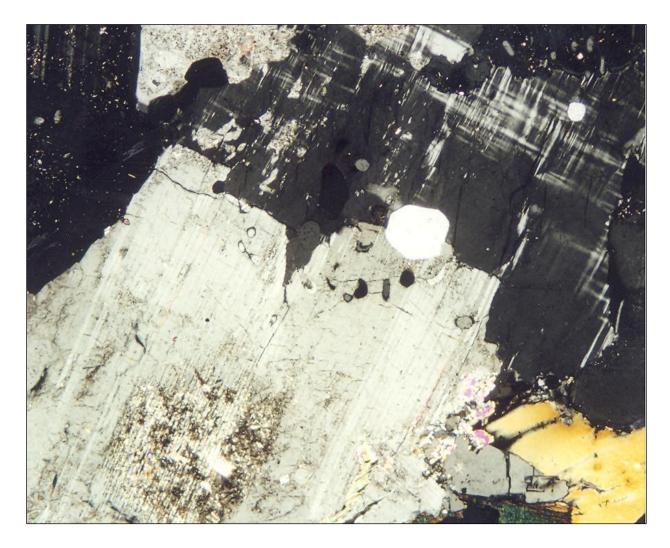


Figure 6. Myrmekite is in two places: (a) in the center of the image below the white quartz grain and the grid-twinned microcline (top; black) and (b) to the left of the black wedge of microcline that projects into the plagioclase (gray). Quartz-free, albite-twinned plagioclase with a speckled core occurs in the bottom left quadrant, and its albite-twin planes are optically continuous with the albite twinning of the plagioclase in the myrmekite. One plane of the grid-twinning of the microcline is parallel to the albite twin-planes of the plagioclase (light gray). Biotite (tan; lower Source: Vrådal pluton southern Norway. right). in See: http://www.csun.edu/~vcgeo005/metasomatism_Collins.pdf and http://www.csun.edu/~vcgeo005/Abstract%20Vradal2.htm.

A. Sizes of Quartz Vermicules

From many different geologic terranes, it can be deduced that the maximum sizes of the quartz vermicules in wartlike myrmekite vary with the An content of the former primary plagioclase. For example, myrmekite in the Cottonwood Creek S-type granite in Australia has vermicules that are very tiny where the primary plagioclase averaged about An₂₄ (Figure 7).



Figure 7. Tiny white vermicules in myrmekite, Cottonwood Creek pluton. Plagioclase (black) in the upper left and upper right quadrants. Primary plagioclase averaged about An_{24} . Source: Collins (1997a, Figure 2).

In comparison, myrmekite at Temecula, California, has primary plagioclase that averages about An_{30} and contains vermicules that are slightly thicker than in the Cottonwood Creek pluton (Figure 8).

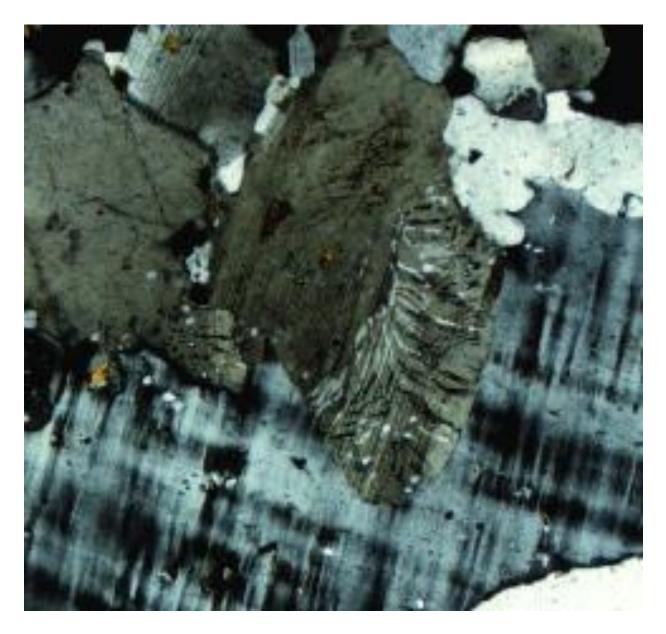


Figure 8. Myrmekite at Temecula, California. Primary plagioclase averaged about An₃₀. Source: Collins (1997a, Figure 3).

In contrast, is myrmekite with coarse vermicules that occurs in a deformed biotite-orthopyroxene gabbro layer (30-50 mm wide and 20 km long) near Split Rock Pond, New Jersey. Here, the An-content of the former primary plagioclase is An_{80} .

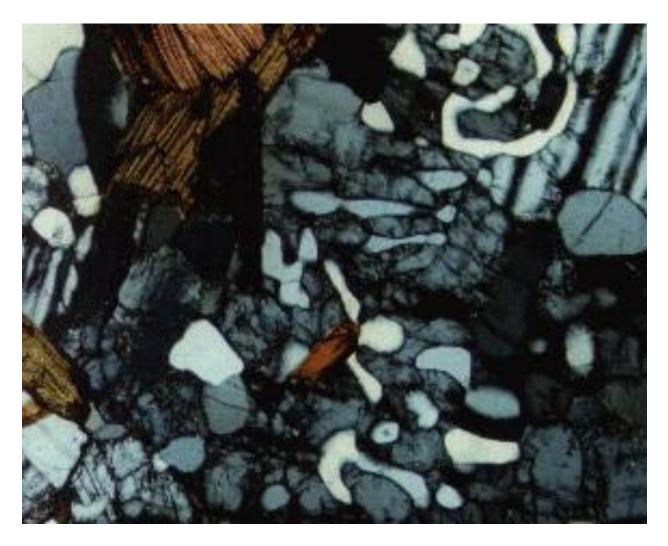


Figure 9. Myrmekite in deformed biotite-orthopyroxene gabbro layer near Split Rock Pond, New Jersey. Former primary plagioclase is An80. Source: Collins (1997a, Figure 6).

As a general observation, in rocks that have a total mineralogical and chemical makeover during K-metasomatism, the An content of the quartz-free recrystallized plagioclase that coexists with the myrmekite generally has an An content about half that of the An content of the original plagioclase in the rock that was replaced, and the quartz content of the vermicules in the myrmekite is proportional to the reduced An content. This is diagrammatically illustrated in Figure 10.

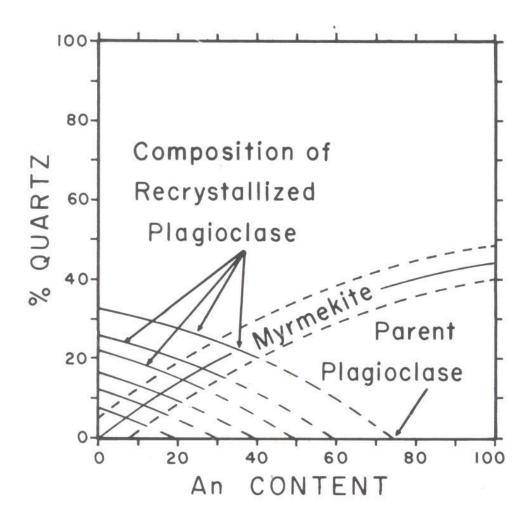


Figure 10. Source: Collins (1988, Figure 14).

In this diagram the An content of the parent (primary) plagioclase is plotted against the percent quartz in vermicules of the myrmekite, and the An content of the recrystallized plagioclase of the myrmekite (after the rocks have been affected by K-metasomatism) is plotted within the curved field. That is, in Figure 9 the former primary plagioclase An₈₀ in the Split Rock Pond area has been converted to recrystallized plagioclase An₄₀ with coarse quartz vermicules, and in Figure 8 the former primary plagioclase An₃₀ has been converted to recrystallized plagioclase An₁₂₋₁₅ for the recrystallized plagioclase at Temecula with correspondingly smaller quartz vermicules. In comparison, the generally accepted models for forming myrmekite (a) by exsolution of Na, Ca, Al and Si ions from primary K-feldspar or (b) by Na- and Ca-metasomatism of outer rims of primary K-feldspar would not predict such a relationship. Moreover, these two models would not provide any basis for correlating maximum widths of quartz vermicules in wartlike myrmekite with An contents of primary plagioclase in relatively-mafic plutonic masses many meters outside myrmekite-bearing granite. On the other

hand, the K-metasomatic model provides an explanation as to how the maximum sizes of the vermicule widths correlate with the An-content of primary plagioclase because the greater the left-over Ca and Al in altered plagioclase lattices prior to the recrystallization to form myrmekite, the greater is the volume of quartz in the vermicules. If total make-over of the mineralogy and chemistry in a rock does not occur during K-metasomatism, there still is a correlation between the maximum widths of the quartz vermicules and the An-contents of the primary plagioclase, but the An-contents of recrystallized plagioclase need not be at half-values.

B. Rim Myrmekite

If the amount of deformation in granitic rocks is very minor and if the amount of available introduced K is minimal, rim myrmekite may form on the outer edges of primary zoned plagioclase crystals (Figure 11).



Figure 11. Rim myrmekite (center) occurs on the outer edge of a zoned plagioclase crystal in a Sierran pluton (photographed by Bill Richardson). In some places the adjacent secondary K-feldspar (black) may be so narrow that it is not noticeable but is visible here. The tiny quartz vermicules correlate with sodic plagioclase with low An content which occurs in the outer rim of the zoned crystal. Source: Collins (1988, Figure 12).

Where rim myrmekite is found, the amount of K-metasomatism is nearly isochemical. However, rocks containing rim myrmekite may grade into rocks that contain wartlike myrmekite. On that basis, the conversion to rocks having only rim myrmekite to rocks containing wartlike myrmekite occurs where increased deformation and increased amounts of K are available to form secondary K-feldspar. This secondary K-feldspar can be in addition to any primary K-feldspar that may also be present.

C. Ghost Myrmekite

In some places after wartlike myrmekite is formed on the margins of K-feldspar crystals, renewed deformation and microfracturing may occur to open the system again so that the plagioclase of the myrmekite is replaced by additional K-feldspar, leaving remnant quartz ovals of the former vermicules. This additional replacement produces a trace remnant of the former myrmekite, called "ghost myrmekite." An example of ghost myrmekite in early stages of being formed occurs in the Wanup pluton where remnants of the original myrmekite are still present (Figure 12). The K-feldspar can be seen growing around some of the former coarse quartz vermicules. (See other examples of ghost myrmekite in **Appendix**: Ghost myrmekite, Figures 10, 16, and 19.)



Figure 12. Myrmekite with coarse quartz vermicules (white and cream), enclosed in microcline (grid pattern, light gray). Plagioclase of myrmekite (center, dark) with coarse quartz vermicules (mostly oriented perpendicular to the plane of the thin section) is speckled brown (sericite alteration). Source: Collins (2001b, Fig 18).

Another early stage of forming ghost myrmekite is also seen in Figure 13 where the sizes of the vermicules of the former myrmekite are a bit smaller because the An content of the primary plagioclase is less than that in Figure 12.

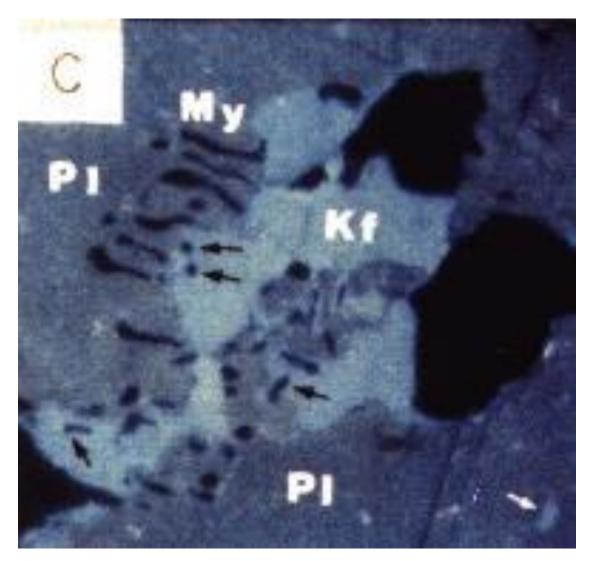


Figure 13. Cathodoluminescence image with quartz blebs (black) in microcline (Kf, light blue) in which the quartz blebs are the same size as in the adjacent quartz vermicules in myrmekite My) bordering plagioclase against the microcline. Source: Hopson and Ramseyer (1990a) and Collins (1997g, Figure 9).

Hopson and Ramseyer (1990a) argued that the myrmekite in Figure 13 results from replacement of primary K-feldspar by Ca- and Na-bearing fluids which react with the K-feldspar to form the quartz vermicules (equations (1-2). Then, these investigators suggest a reversal in the replacement direction (3-4). That is, K-replacement of the plagioclase in the myrmekite then takes place, so that quartz is left behind as islands (quartz blebs) in the K-feldspar (Figure 13).

Ca- and Na-metasomatism

$$KAlSi_3O_8 + Na^{+1} \rightarrow NaAlSi_3O_8 + K^{+1}$$
. (1)
 $2KAlSi_3O_8 + Ca^{+2} \rightarrow CaAl_2Si_2O_8 + 4SiO_2 + 2K^{+1}$. (2)
potassium feldspar myrmekite

Reversed reactions

3
NaAlSi $_3$ O $_8$ + K $^{+1}$ \rightarrow KAlSi $_3$ O $_8$ + Na $^{+1}$. (3) 4 CaAl $_2$ Si $_2$ O $_8$ + 4SiO $_2$ + 2K $^{+1}$ \rightarrow 2KAlSi $_3$ O $_8$ + Ca $^{+2}$. (4) plag. in myrmekite quartz potassium feldspar

It is unreasonable for a chemical reaction to reverse itself inside a crystal when no logical chemical gradient exists there to cause a reversal. Once the first Ca- and Na-replacement occurs, how can K be re-introduced to drive the reaction in the opposite direction? If the reactions were reversed and the reactions proceeded in the way proposed by Hopson and Ramseyer (1990ab; Collins, 1990) in the balanced mass-for-mass equations, why does quartz remain in the K-feldspar when reversals of the equations should consume it?

The absence of K-feldspar and myrmekite in undeformed Bonsall tonalite in the Rubidoux area, the gradual appearance of K-feldspar and myrmekite in the Bonsall tonalite (where the tonalite is first deformed), and the equal volumes of K-feldspar and myrmekite at first deformation sites suggest that both K-feldspar and myrmekite are formed simultaneously. Also, the equal size of quartz vermicules in myrmekite in the Bonsall tonalite and in myrmekite in the leucogranite supports the hypothesis that myrmekite in both places were produced from primary plagioclase with the same An content.

The seeming appearance of primary K-feldspar replacing plagioclase in Figure 13 is visually misleading. It is actually a one-directional but incomplete K-replacement of primary plagioclase that forms the myrmekite in the first place but renewed deformation opens the system so that continued replacement of some of the plagioclase followed by continued K-replacement that leads to the textures seen in Figures 12 and 13. Ultimately, where replacement of the plagioclase of the myrmekite is more complete, the result is *ghost myrmekite* that is in Figure 14 where some quartz is left behind as tiny blebs in the secondary K-feldspar because the silica cannot be incorporated into its composition.



Figure 14. Ghost myrmekite in Rubidoux Mountain leucogranite. At the extinction position for microcline (black), clusters of quartz blebs (white) occur in faint traces of remnant plagioclase or as isolated oval islands in the microcline. The maximum sizes of the quartz blebs in the microcline match the maximum diameters of quartz vermicules in myrmekite (left side) where plagioclase is white and quartz vermicules are gray. Source: Collins (1997b, Figure 11)

On the basis of these characteristics of myrmekite and ghost myrmekite and the evidence that replacement features occur in granitic bodies on a plutonic scale, this information is applied to three different areas – the first of which is near Temecula, California.

III. APPLICATIONS OF CHARACTERISTICS IN SECTIONS I AND II

A. Temecula, California

The following nine figures (Figure 15 to Figure 23) are representative images of what has been observed from (a) thin section studies under cross-polarized light, (b) electron-microbe

analyses of 80 different feldspar crystals, (c) cathodoluminescent studies of several altered grains, and (d) scanning-electron analyses. These images come from thin sections of rocks in a transition from undeformed Bonsall biotite-hornblende tonalite through a zone of deformation to myrmekite-bearing granite, near Temecula, California (Collins, 2002). In undeformed and unaltered biotite-hornblende tonalite the primary zoned plagioclase has cores of An_{39} and rims of An_{18} (Figure 15).

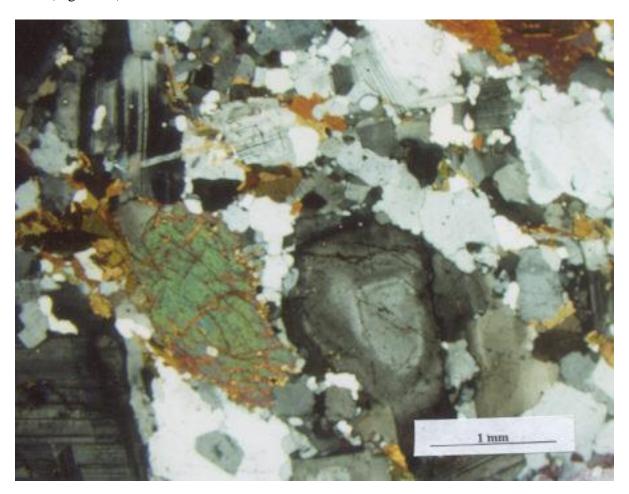


Figure 15. Photomicrograph of Bonsall tonalite with unaltered hornblende (green); biotite (brown); zoned plagioclase (rims, An_{20} , dark gray and cores, An_{39} , light gray); albite twinned plagioclase (black, and light gray; left side); quartz (white and mottled gray). Source: Collins (2002, Figure 5).

The first stage of alteration of primary plagioclase crystals during earliest deformation history have plagioclase cores with compositions of An_{39} which are chemically altered to become cores of An_{18} to An_{20} while the rims remain the same, An_{18} to An_{20} (Figure 16). Therefore, Ca and Al have been lost from the cores. Microfractures in the plagioclase are not visible under cross-polarized light.

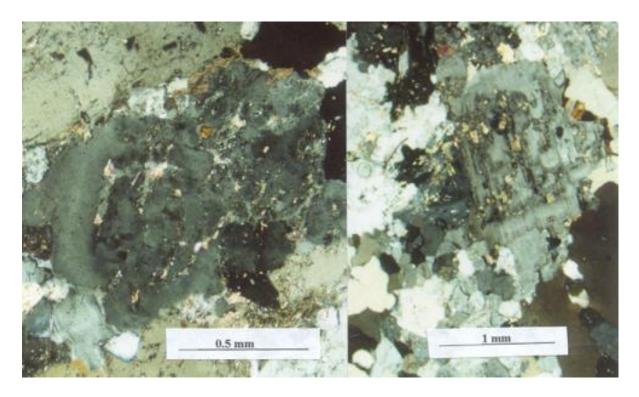


Figure 16. Left side. Normally zoned plagioclase (with outer sodic rim, An_{18} to An_{20} ; light gray) in which the core (darker gray, mottled) is microfractured and in the process of losing Ca. **Right side**. Rims and cores have equal An-content of An_{18} to An_{20} . Source: Collins (2002, Figure 8).

Under cathodoluminescence chemical alterations, microfractures, and the first appearance of K-feldspar in the core along microfractures that cannot be seen under cross-polarized light images become visible (Figure 17).

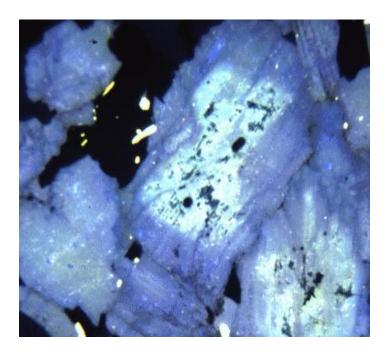


Figure 17. This cathodoluminescent image has two plagioclase crystals with remnant zoning. The inner plagioclase cores were once rectangular in outline and were relatively calcic (greenish white) and graded to an outer more sodic rim (blue). Microfractures (dark blue veins) extend from the edge of the crystals to the relatively calcic cores. The dark blue indicates that Ca has been removed, leaving Na in the lattice. Locally, K-feldspar islands (faint light blue) occur inside the core area where loss of Ca is most advanced and where both Ca and Na have been subtracted. Source: Collins (1997b, Figure 3). Karl Ramseyer provided the image.

In a more-advanced stage of replacement K-feldspar has started to replace the plagioclase in the interior of the former primary plagioclase crystal (Figure 18).

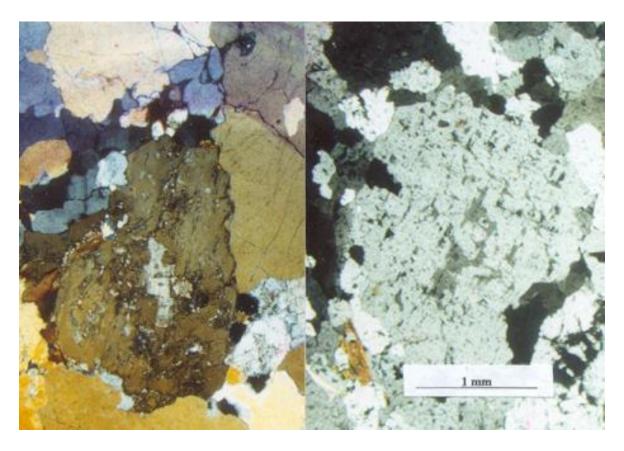


Figure 18. Left side. Plagioclase crystal (center; tan) replaced in its core by microcline (gray; grid-twinned). One twin plane of the microcline grid-twinning is parallel to the albite twinning of the plagioclase, but this albite twinning is barely noticeable in this orientation. **Right side**. The plagioclase grain (whitish gray) has lost its normal zoning and albite twinning. Plagioclase (light gray) is replaced in the interior by irregular islands of microcline (dark gray). Most nearby plagioclase grains lack these microcline islands even though they may be equally microfractured. The absence of visible microcline is just a matter of chance for K-bearing fluids to reach these other grains but as the metasomatism progresses, they would be expected also to be modified. Source: Collins (2002, Figure 11).

Other nearby crystals have greater degrees of microfracturing and chemical alteration. Cores and rims of many grains have equal An contents An_{18-20} (Figure 19).

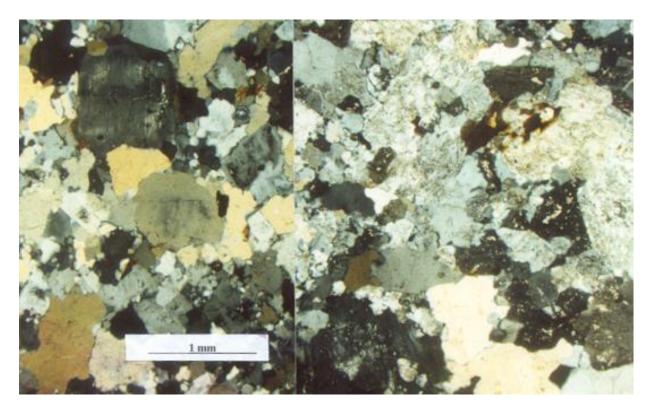


Figure 19. Left side. Plagioclase grains (shades of gray), many of which have lost their albite twinning and normal zoning. Cores are An_{25-30} ; rims are An_{18-20} . Quartz (cream, white). **Right side**. Plagioclase crystals (whitish gray) are speckled. Some have cores An_{18-20} ; rims An_{18-20} . Others have reversed zoning with cores An_{15} ; rims An_{18-20} . Some have tiny islands of K-feldspar which cannot be seen in thin section in plane or cross-polarized light but can be seen in a cathodoluminescent image in Figure 17. Source: Collins (2002, Figure 12).

Eventually, across the zone of deformation, reversed zoning in the plagioclase occurs with Na-rich cores of An_5 and rims of An_{18-20} . Where this occurs, holes in the silicate lattice are revealed as is seen in Figure 20 - a scanning-electron microphotograph (magnified 1,600x).

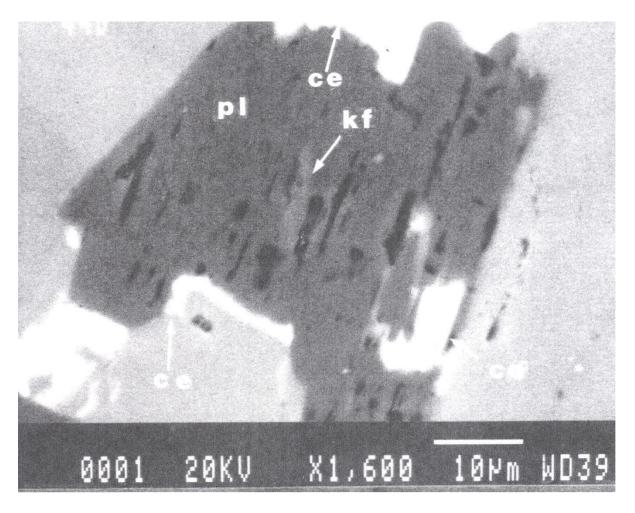


Figure 20. Scanning-electron microphotograph (magnified 1,600x). Plagioclase (pl, dark gray) is full of holes (black) with angular boundaries parallel to the plagioclase crystal lattice. Many holes are bordered by concentrations of K (lighter gray, incipient K-feldspar, kf) which are beginning to replace the plagioclase lattice along the walls of the holes. Locally, Ba is concentrated in celsian (barium feldspar; ce, white), and in some places the celsian occurs on hole walls adjacent to the K concentrations. Because the Ba +2 ion is about the same size as the K +1 ion, introduced Ba commonly substitutes in the lattice in the same places where K is replacing the Na and Ca. The identification of element concentrations is confirmed by microprobe studies.

In more advanced hole-formation in altered plagioclase crystals, where holes are larger and where K-introduction produces visible K-feldspar, rosettes of tiny hematite crystals line holes in the K-feldspar to make the K-feldspar pink (Putnis et al., 2007). The iron in the hematite logically comes from the iron that is released as quartz forms sieve-textures in nearby hornblende and biotite (Figure 5), which is simultaneous with the plagioclase alterations.

A key to understanding how myrmekite is formed is revealed where myrmekite first appears (Figure 21). Speckled crystals on the left side have reversed zoning with Na-rich cores of An_{18-20} . Toward the right side a few of the grains of the same size are

beginning to recrystallize to form myrmekite with tiny quartz vermicules (first fuzzy in appearance but then more distinct). Farther along the transition, quartz vermicules are more distinct and obvious (Figure 22).

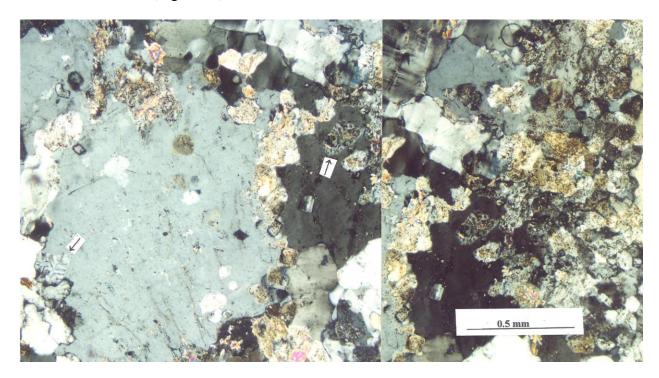


Figure 21. Left side. Microcline (large light gray grain) has now completely replaced a former plagioclase crystal like what is in early stages of replacement in Figure 18. Speckled granules of plagioclase surround the microcline. The speckling is sericite and clay alteration because of the ease at which these grains are weathered. Arrows (left side and right top center) point to early-stage myrmekite formation. The same image is on the right side but the image is at a different optic orientation. The microcline (black) in the right image is the same as microcline (dark gray) in the left image. Source: Collins (2002, Figure 13).

Because the holes in the lattice (Figure 20) make many crystals structurally weaker, the crystals are easily broken during shearing to form a cataclastic aggregate of small grains. At both places (indicated by arrows) the reversed-zoned plagioclase crystal is beginning to form myrmekite. As recrystallization occurs, the quartz vermicules are formed because there is more silica in the reversed-zoned plagioclase lattice than can combine with residual proportions of Ca, Na, and Al to form only plagioclase, so silica is left over to form quartz vermicules. Thus, it is clear here that the myrmekite *did not form by Ca- and Na-metasomatism of primary K-feldspar or by exsolution of Ca, Na, Al, and Si from primary K-feldspar*.

With continued deformation and with the addition of more K-bearing fluids, locally some of the tiny myrmekite grains are engulfed and much of their plagioclase content is replaced to form ghost myrmekite (Figure 22).

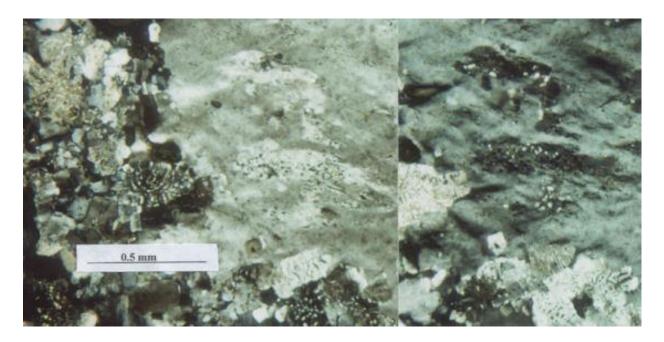


Figure 22. Ghost myrmekite in microcline (light gray). Images on the left and right are the same areas but in a slightly different optic orientation. All myrmekite granules now have lost the speckled appearance that is seen in Figure 21 because the residual lattice has recrystallized without any holes and is less easily weathered. Source: Collins (2002, Figure 14).

In other parts of the transition zone, former plagioclase crystals are not so thoroughly granulated, but the coarser crystals still exhibit reversed zoning with Na-rich cores of An₅ and rims of An₁₈₋₂₀. In some places a part of an altered reverse-zoned crystal can become wartlike myrmekite that projects into adjacent microcline while being attached to non-quartz-bearing plagioclase, as in Figure 23.

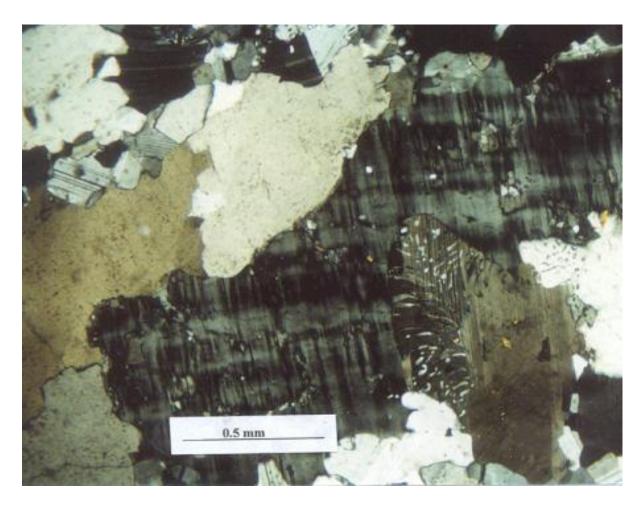


Figure 23. Wartlike myrmekite projecting into microcline (dark gray; grid-twinned). Source: Collins (2002, Figure 19).

In most places where K ions come into altered (reverse-zoned) plagioclase lattices from one side to form K-feldspar, the interior Na and Ca ions, displaced by the K ions, can readily escape out the other side. However, in some places an escape route is prevented either because the adjacent plagioclase forms a crystal seal against the K-feldspar which is not broken by later fracturing or because Na ions came into an altered plagioclase crystal from the opposite direction and filled the escape routes. When either condition occurs, the residual amounts of Na, Ca, Al, and Si ions in the altered plagioclase lattice may not be in the proper ratios to recrystallize only as more-sodic plagioclase, and silica is left over to form quartz vermicules. The way in which the myrmekite is formed results in the wartlike myrmekite projecting into the microcline on one side while being attached to the non-quartz-bearing, recrystallized sodic plagioclase on the other side. Because escape routes are rarely blocked, generally no more than 0.5 vol. % of the newly formed granite is myrmekite. In some geologic terranes, myrmekite may range up to 2 vol. %, but the abundance of myrmekite is not important. Its presence should be noted because it is a clue that significant chemical and mineralogical changes have occurred in the rock.

Note that the albite twinning in the myrmekite with tiny quartz vermicules (white) is continuous with albite twinning in the non-quartz-bearing plagioclase and is also parallel to one of the twin planes of the grid-twinning in the microcline. As suggested for Figure 2, this parallelism strongly suggests that the microcline is not primary orthoclase that inverted to microcline but is **secondary replacement-microcline** that has inherited its lattice from a former altered plagioclase lattice as in the scanning-electron image (Figure 20); see (Collins, 1998a).

Other many small reverse-zoned plagioclase crystals, instead of being replaced by K-feldspar, are recrystallized as plagioclase without holes. This recrystallization occurs because Na that has been displaced from other sites by introduced K has entered these crystals and converted them into secondary plagioclase crystals with albite-twinning (upper left corner of Figure 23; white and black), and these crystals have compositions of An₁₂₋₁₅. Moreover, the volume of secondary quartz has also increased (from 5 to 25 vol. %) because of the simultaneous Simetasomatism of much of the former primary biotite and hornblende in the Bonsall tonalite to form quartz sieve-textures (Figure 4). Eventually, the quartz blebs coalesce to form scattered anhedral quartz grains. By looking at the granite in thin section, one would not recognize that this quartz was mostly secondary and not primary or that the plagioclase (An₁₂₋₁₅) was also secondary. The hypidiomorphic texture looks as if it formed by crystallization from magma since the K-feldspar inherits its crystal outline from the primary plagioclase crystals.

In most other granitic rocks in other geologic terranes that contain wartlike myrmekite, all the above sequential alteration stages (Figures 15 to 23) are missing, and what is observed is the final recrystallization product of just wartlike myrmekite and/or ghost myrmekite being present. Therefore, the textural changes that are observed in the Temecula rocks become a clue to what occurred prior to the formation of wartlike myrmekite and ghost myrmekite in these other terranes.

On the basis of this understanding of how wartlike myrmekite is formed as one of the consequences of K-metasomatism of primary plagioclase, we can now look at wartlike myrmekite and other replacement features and textures in the Papoose Flat pluton.

B. Papoose Flat Pluton

Application of the model for wartlike myrmekite being formed by K-replacements of primary plagioclase crystals is appropriate for the concentrically-zoned orthoclase megacrysts in the Papoose Flat pluton in California. The megacrysts in this pluton are thought by most granite petrologists to be phenocrysts. An example of concentrically-arranged small plagioclase inclusions occurs in an interior corner of a large orthoclase crystal, 2.5 cm long (Figure 24). The regular pattern of aligned small plagioclase crystals is certainly suggestive that they nucleated on faces of a growing orthoclase crystal in magma. But appearances can be deceiving if not looked at carefully.

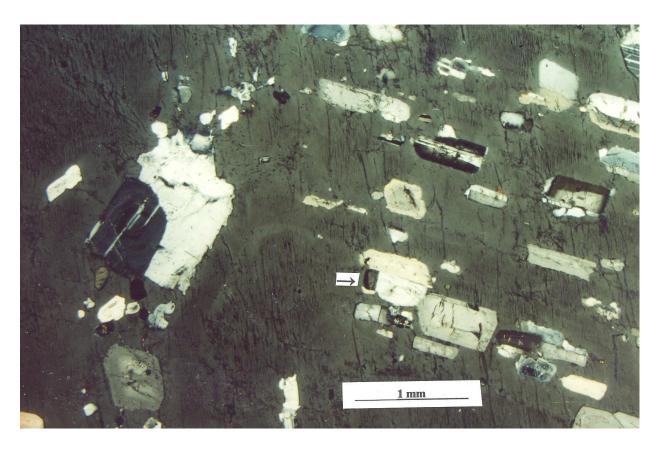


Figure 24. An inner corner of a Ba-zoned orthoclase megacryst has well-developed concentric banding of tiny parallel plagioclase inclusions and a change of orientation of the inclusions at the border. Many inclusions have sodic rims. At least one plagioclase inclusion coexists with an adjacent tiny plagioclase inclusion (gray and black, arrow; center; about 1 mm above left end of scale line) whose orientation is at right angles to the Ba-K layering. Source: Collins and Collins (2002, Figure 11).

The Ba-zonation need not be related to magmatic processes because at different stages of K-feldspar replacement of microfractured plagioclase crystals and the growth of the megacrysts, different amounts of Ba ions may come in with K ions during the metasomatic processes as indicated by the deposition of celsian (Figure 20).

At those localities in the Papoose Flat pluton where orthoclase is first beginning to form crystals, the orthoclase does not begin with a small euhedral crystal that eventually presumably grows into a large euhedral phenocryst as expected by magmatic theory but instead begins where it is replacing primary plagioclase along microfractures and between grain boundaries (Figures 25 and 26).

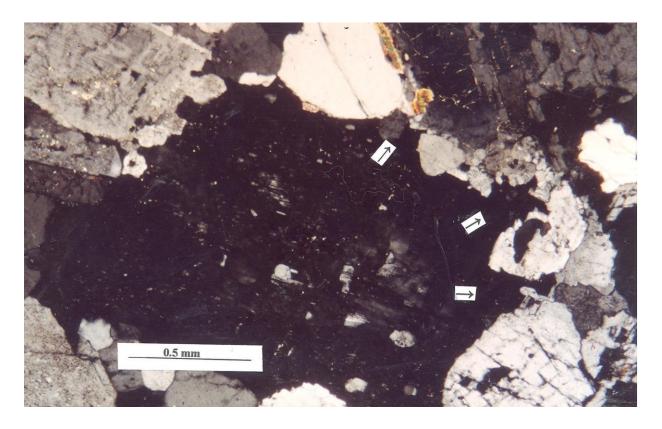


Figure 25. Orthoclase (black) with tiny remnant plagioclase inclusions. The orthoclase forms scalloped edges against adjacent plagioclase crystals (light gray; right side and upper left), which would not occur in magma where euhedral rectangular orthoclase would form. Tiny quartz vermicules (barely visible) occur in myrmekite that borders the three orthoclase fingers (black; arrows) that project into the plagioclase along former fractures or broken grain-boundary seals (right side). The tiny vermicules correlate with the primary sodic plagioclase that has low Ancontent. Source: Collins and Collins (2002, Figure 5). See Figure 4 in this same website article for another example of early stage replacements.

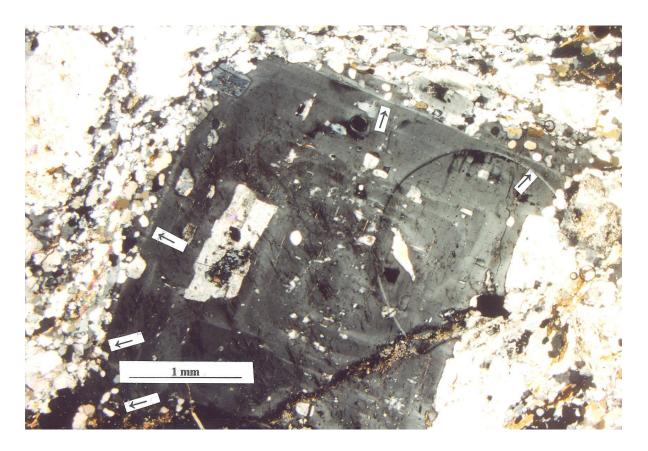


Figure 26. In this image the growing zoned orthoclase crystal (light gray) is not perfectly rectangular but has irregular growth on different faces of the crystals. In its outer border, the orthoclase encloses tiny inclusions of the ground mass (left side and top edge; arrows). Note that the orthoclase extends beyond its corner (upper right; arrow) to penetrate and enclose rounded inclusions of the ground mass, and that this part of the orthoclase is optically continuous with the main crystal and has not resulted from deformation of the orthoclase to form a "tail." Thus, such K-feldspar megacrysts are subsolvus and post-magma. One elongate plagioclase inclusion (left side) is parallel to the zoning. Source: Collins and Collins (2002, Figure 8). See also Figure 7 in this same article for a similar early replacement stage.

The same kind of granulation of ground mass minerals occurs in Figure 31, but this figure has shearing that extends around the corner of an orthoclase megacryst, but the shearing does not extend through the megacryst and off-set the corner.

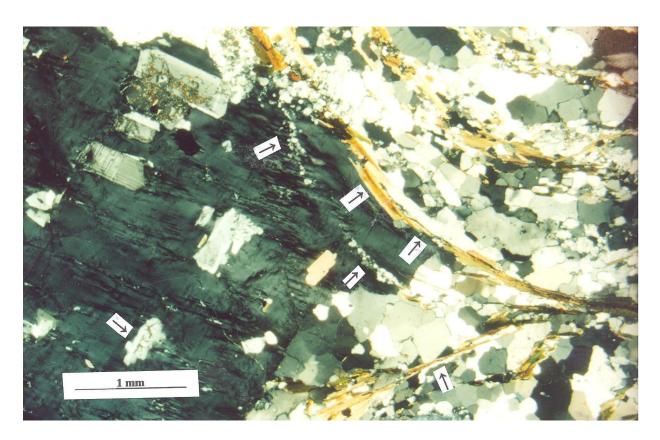


Figure 27. Shearing directions (arrows; top center and lower right) of the ground mass is revealed by the alignments of biotite crystals (tan) around the corner of an orthoclase megacryst (light gray; partly inverted to microcline). A myrmekitic inclusion occurs in the lower left (arrow; above the scale), but the quartz vermicules are not visible in this orientation. Quartz (white, gray, black) occurs on right edge of the megacryst. Source: Collins and Collins (2002, Figure 18).

An examination of the orientation of ground mass crystals relative to the orientation of crystal inclusions in an orthoclase megacryst is instructive because it reveals the degree of replacement of ground mass minerals that occur in a megacryst as inclusions (Figure 28). Many plagioclase inclusions in the outer edge of the orthoclase crystal have scalloped borders (arrows). Scalloping certainly suggests that these inclusions are being replaced and that they have not nucleated on the face of a growing megacryst crystallizing in magma. Five elongate plagioclase crystals (gray, white, black) in the groundmass (right side) have crystallized against each other in parallel alignment (synneusis) and are parallel to the zoning in the megacryst, but some are inclined. It is logical that if the megacryst had continued to grow by K-replacement processes, those crystals in the ground mass aligned parallel to a possible orthoclase face might have been enclosed without replacement and those that were inclined might be replaced. Thus, the concentric zoning of plagioclase inclusions can be explained. Remnants of inclined grains are commonly scalloped in Figure 28, in Figure 24, and in many images in the Papoose website article (not included here). Note that the outer face of the orthoclase megacryst has projections of K-feldspar that extend around individual quartz grains (gray, white, cream) of the ground

mass and that continued replacement of these quartz grains would cause them to become smaller rounded remnants like the small oval quartz (bright cream) remnant in the upper left quadrant.

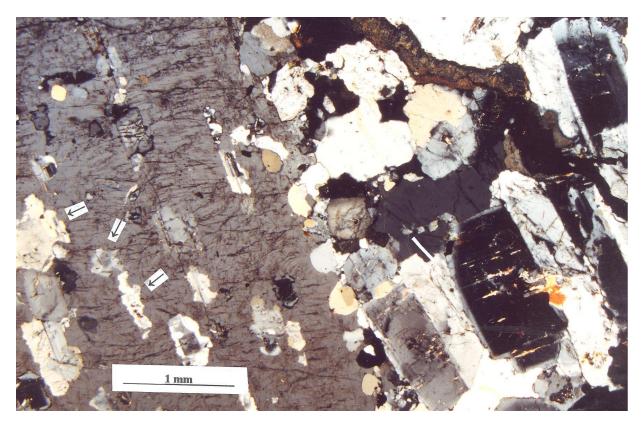


Figure 28. Outer edge of a large orthoclase megacryst (left side). Five elongate plagioclase crystals (gray, white, black) in the groundmass (right side) have crystallized against each other in parallel alignment (synneusis) and are parallel to the zoning in the megacryst, but some are inclined. Source: Collins and Collins (2002, Figure 15). See Figure 10 in this same website article for remnant ground mass grains inside a megacryst.

Some particular features of the zoned orthoclase crystals in the Papoose Flat pluton which negate a magmatic origin of the megacrysts are (a) the crystal inclusions that are found at interior corners of the crystals and (b) the occurrence of wartlike myrmekite. For example, a large segment of an aggregate of ground mass minerals is at an interior corner (Figure 29. top center). This aggregate mass of normally-zoned plagioclase crystals have their longer dimensions parallel to each other and are right angles to the inclusions in the megacryst. Two plagioclase grains at the right corner of the aggregate mass adjacent to the myrmekite are parallel to the plagioclase inclusions. The myrmekite has very tiny quartz vermicules (black and white) and is in the right lower corner of the aggregate mass (arrow; left of two white quartz inclusions). Many orthoclase megacrysts contain aggregates of ground mass minerals at interior corners because at corners the potential lattice (-201) crystal face there does not provide a surface on which inclusions can be easily aligned. Moreover, if the orthoclase megacrysts were growing in magma, the aggregates of crystals would occur in random places in the crystals as inclusions and not be mostly restricted to interior corners.

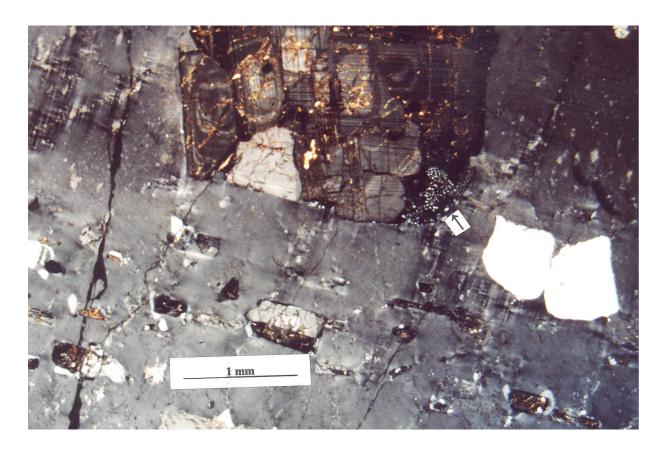


Figure 29. A large segment of an aggregate of ground mass minerals is at an interior corner (top center) of a zoned megacryst. Quartz (white; right side). Source: Collins and Collins (2002, Figure 17). See Figures 20 and 21 in this same article for other examples of remnant wall rock mineral grains in the corner of a megacryst.

If the tiny plagioclase inclusions in K-feldspar megacrysts had formed by nucleation on outer faces of growing crystals in magma, then everywhere in the pluton, the parallel arrangement of the long dimensions of the inclusions with possible faces should be found. Instead, only where the ground mass crystals exhibit synneusis does this parallel arrangement occur. In that part of the pluton where the ground mass minerals have random orientation, then the plagioclase inclusions also have random orientation with little to no alignments of long dimensions parallel to possible crystal faces (Figure 30). See also Collins and Collins (2002, Figure 30). This evidence is consistent with the model that the K-feldspar megacrysts grew post-solidification of magma.

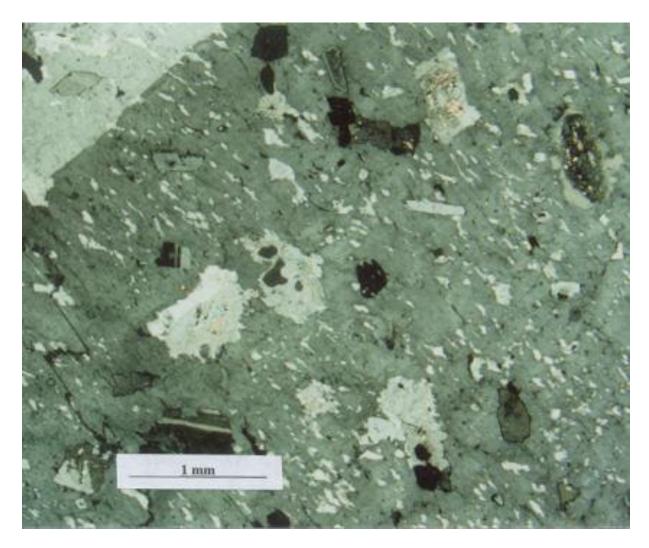


Figure 30. Interior of Carlsbad-twinned orthoclase megacryst (light gray and dark gray). Disoriented plagioclase inclusions occur along Ba-K growth zones that extend from lower right to upper left. None of the inclusions is aligned parallel to the growth zones, and many have borders that are strongly scalloped. Source: Collins and Collins (2002, Figure 31)

The ground mass surrounding the megacrysts contain 15 to 20 percent quartz. But quartz inclusions in the orthoclase are scarce, and those that are present exist as tiny ovals, as in Figure 28. If the megacrysts had formed by crystallization from magma, this quartz should have formed as crystals with outlines typical of a granophyric texture. This expectation is particularly true when the ground mass surrounding the orthoclase megacrysts contains 15 to 20 vol. % quartz and at the eutectic both K-feldspar and quartz should crystallize simultaneously. An example of such a granophyric texture occurs in the Dunan granite, Isle of Skye (Figure 31).



Figure 31. Granophyric texture. Source: Collins (1997m, Figure 22)

However, at corners of zoned orthoclase crystals large quartz grains are not as easily consumed (Figure 32).

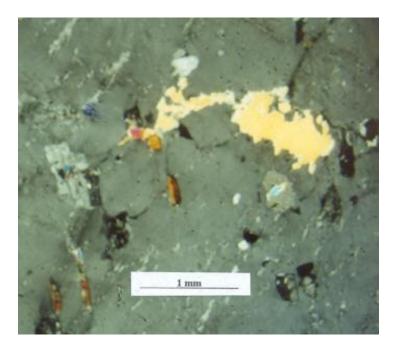


Figure 32. A large former quartz crystal (yellow) mostly remains at an interior corner as a scalloped crystal. Source: Collins and Collins (2002, Figure 22).

Moreover, let's look again at the balanced mass-for-mass equations. In the reactions, plagioclase is replaced by potassium feldspar and silica (quartz) is consumed in the transformation to K-feldspar (equation 4).

$$NaAlSi_3O_8 + K^{+1}$$
 \rightarrow $KAlSi_3O_8 + Na^{+1}$. (3) $CaAl_2Si_2O_8 +$ $4SiO_2 + 2K^{+1} \rightarrow 2KAlSi_3O_8 + Ca^{+2}$. (4) plag. in ground mass quartz potassium feldspar

This requirement is even more clearly demonstrated when it is understood that the transformation in the rocks in the Papoose Flat pluton is not mass-for-mass but volume-for-volume, the low density of the K-feldspar crystal structure (G=2.56) in comparison to plagioclase (G=2.62 to 2.66 for An_{10-30}) also requires more silica for the space in which the K-feldspar forms. Therefore, it is logical that the quartz grains in the ground mass are consumed or nearly so as the K-feldspar grows and replaces the plagioclase in the ground mass (Figures 32 and 36).

The fact that K-feldspar consumes quartz when it replaces plagioclase also explains why in those places where K-feldspar replaces plagioclase in myrmekite the quartz vermicules are mostly replaced in their narrower parts but leave behind round or oval blebs in ghost myrmekite (Figure 12; and **Appendix**: Ghost myrmekite, Figures 10, 16, and 19).

Myrmekite occurs along the edge of a megacryst (Figure 33), in an interior inclusion (Figure 28), and in the earliest stage of K-metasomatism (Figure 26). Myrmekite cannot have crystallized from magma at the same time that magmatic orthoclase was crystallizing because from melts, quartz-plagioclase intergrowths can form only as granophyric or micrographic textures (Figure 31). The occurrence of myrmekite along edges of the orthoclase megacrysts explains why an orthoclase crystal, forming as a K-replacement product of some of the disoriented primary plagioclase crystals in the ground mass, could grow around myrmekite so that it is enclosed in the interior of the crystal (Figure 29).



Figure 33. Myrmekite with very tiny quartz vermicules along edge of orthoclase megacryst (gray). Source: Collins and Collins (2002, Figure 24). Another example of myrmekite that occurs in the interior of a megacryst occurs in Figure 26 of this same article.

Finally, in the Campito sandstone (arkose) that is an adjacent wall rock of the Papoose Flat pluton are isolated zoned orthoclase crystals with oriented tiny plagioclase crystals in concentric zones, similar to the concentric pattern that occurs in the orthoclase megacrysts in the pluton (Figure 34). In one such megacryst tiny biotite inclusions occur in the corner, and these inclusions match similar-sized biotite flakes in the adjacent ground mass of the sandstone. In other places plagioclase inclusions match ground mass mineral sizes and appearances. Therefore, these megacrysts cannot have formed by dragging primary orthoclase megacrysts from granitic pegmatite dikes that extend into the wall rocks during shearing of the sandstone (Vernon and Paterson, 2002; Vernon, 1991) or by crystallization in igneous dikes (Brigham, 1984). The megacrysts had to grow in place and at sites completely isolated from granite magma in the pluton. That is, the same K-bearing fluids that moved through microfractures inside the Papoose Flat pluton also moved through fracture openings in the Campito sandstone outside the

pluton and produced the same kinds of metasomatic alterations of plagioclase crystals. The idea that the orthoclase megacrysts in the Campito sandstone were formed by metasomatic processes and not from magmatic fluids was originally proposed by Frank Dickson (Dickson, 1966; Collins and Collins, 2002).

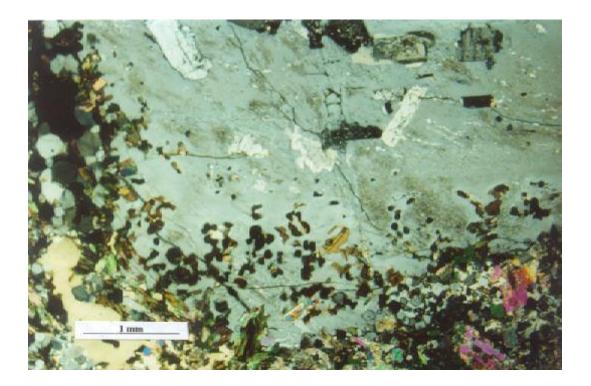


Figure 34. Orthoclase megacryst (light gray) in Campito sandstone contains remnant biotite grains of the sandstone enclosed in the border of the megacryst. Tiny plagioclase inclusions aligned in the megacryst are the same size as plagioclase grains in the sandstone. Some inclusions are inclined to the Ba-K concentric layers in the megacryst and would not be expected to nucleate in that position on the face of an orthoclase crystal growing in magma. Source: Collins and Collins (2002, Figure 44).

A final point that needs to be made is that the K-feldspar megacrysts in the Campito sandstone are not the result of contact metamorphism from the heat of the crystallizing pluton because they form only locally and not along all portions adjacent to the pluton contact. This relationship is consistent with the model that the K-feldspar megacrysts are post-crystallization of the pluton from magma.

The observations of the K-replacement textures in the Papoose Flat pluton are not meant to suggest that all orthoclase megacrysts in other geologic terranes, which have concentric zoned inclusions, are formed by K-replacement processes, but the evidence in the Papoose Flat pluton and adjacent wall rocks certainly supports such a conclusion. See Collins and Collins (2002)

that adds many more illustrations that support a K-replacement origin for the orthoclase megacrysts.

C. Twenty Nine Palms

The Twenty Nine Palms quartz monzonite contains K-feldspar megacrysts as much as 16 cm long, and like the megacrysts in the Papoose Flat pluton, the Twenty Nine Palms megacrysts also contain inclusions of granulated ground-mass grains in many places. For these megacrysts to be formed by K-metasomatic processes, then prior to their growth, the former host Gold Park diorite that became the megacrystal quartz monzonite had to be cataclastically deformed. This deformation was observed across 50 meters in a transition zone from the Gold Park diorite into the megacrystal granite (Collins, 1997f). The earliest stage of introduction of K-feldspar in microfractured diorite is illustrated in Figure 35. Here the felsic hornblende diorite has a cataclastic texture the broken groundmass matrix consists of hornblende, quartz, and plagioclase. In early stages of replacement microcline engulfs the ground mass fragments along irregular borders and contains minor wartlike myrmekite with tiny quartz vermicules. Here, microcline is 1 to 5 vol. % of the rock. Normal, undeformed, felsic Gold Park diorite has crystals of hornblende and plagioclase all about the same size.

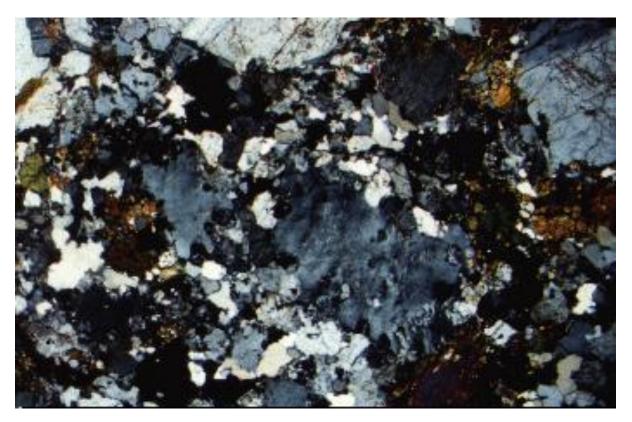


Figure 35. Felsic hornblende diorite with cataclastic texture. Hornblende (brown and green), quartz (clear-white and gray), and plagioclase (gray and dark gray). Two microcline crystals (dark gray; center and left of center) with irregular borders against the granulated groundmass. Myrmekite occurs on microcline borders. Source: Collins (1997f, Figure 5).

Where cataclasis of the Gold Park diorite was first modified by metasomatic fluids, the ferromagnesian silicate minerals (mostly hornblende but minor biotite) were replaced by quartz to form a quartz sieve-texture (Figure 36).

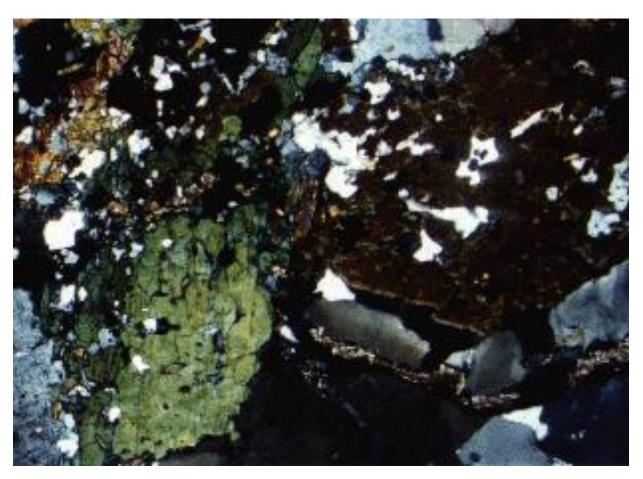


Figure 36. Felsic diorite with quartz sieve-texture in hornblende (brown and green). Microcline (gray; less than 1 vol. %). Quartz (white, gray, and cream). Albite-twinned plagioclase (white and gray; upper left). Source: Collins (1997f, Figure 6).

In the transition to where the megacrysts become 3-5 cm long, the K-feldspar megacrysts first begin to make their appearance as 1-cm-sized crystals. Here, commonly wartlike myrmekite is formed (Figure 41).

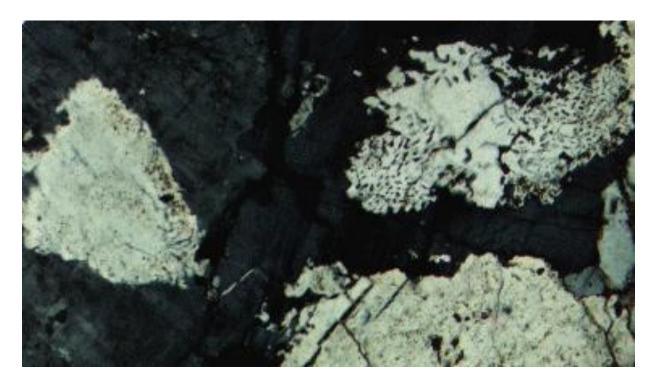


Figure 37. Microcline (black) encloses, penetrates in veins, and replaces plagioclase (creamgray, light gray). Large plagioclase islands are optically continuous with adjacent tiny islands (blebs) of plagioclase in microcline. Large plagioclase islands are locally myrmekitic, containing elongate-oval cross-sections of quartz vermicules (black to gray). Source: Collins (1997f, Figure 10).

Convincing evidence that the K-feldspar megacrysts in the quartz monzonite pluton were formed by K-replacement processes is the fact that many megacrysts contain more than 50 percent granulated ground mass minerals (Figure 38). In some places the scattered inclusions are so abundant that the K-feldspar of the megacrysts is difficult to see. In the field, however, these abundant inclusions cannot be seen on the exterior faces of the megacrysts. In other places the inclusions are less abundant (5 to 20 vol. %), and they are not in concentric zones of aligned inclusions as occur in megacrysts in the Papoose Flat pluton. However, tiny euhedral titanite crystals that occur in the ground mass remain in the megacrysts because they are not easily replaced.

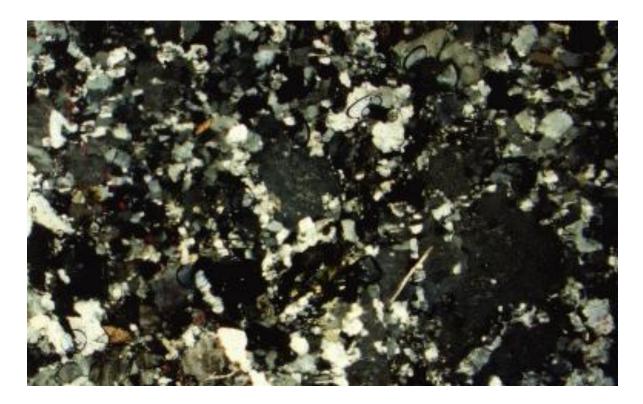


Figure 38. The entire field of view is a small portion of a microcline megacryst, 2 to 3 cm long with more than 50 vol. % ground mass inclusions. Quartz and plagioclase (gray and white). Microcline (gray) can hardly be seen. Tiny sphene (titanite) crystals (brown). Hornblende is absent and presumably replaced by quartz and/or microcline. Source: Collins (1997f, Figure 11).

In one place, a thin section of a megacryst has a band of granulated ground-mass mafic grains that extends from outside the megacryst on one side and then through the megacryst where it continues out the opposite side into the granulated ground mass without any offset of the megacryst or the band. This relationship is too large to photograph under the microscope but is readily apparent in the thin section.

Because of the above evidence, it is clear that the K-feldspar megacrysts have grown under subsolvus conditions in cataclastic broken rock that provided an open system through which metasomatic fluids carrying large volumes of K ions could have moved freely and converted the Gold Park hornblende diorite into the Twenty Nine Palms hornblende quartz monzonite on a plutonic scale. The ground mass surrounding the megacrysts is dominantly plagioclase (45-65 vol. %) and hornblende (10-20 vol. %), but the amount of hornblende in the Gold Park diorite is generally greater than 20 vol. %.

Most plutonic igneous rocks that contain such large K-feldspar megacrysts in great abundance (25 to 50 volume percent) would be expected to be biotite rich on the basis of (a) the large amounts of K needed to produce such large volumes of K-feldspar and (b) the richness of Fe and Mg in the diorite which would be expected to react with K to make abundant biotite. But

that is not the case here. Generally, only 1 to 5 vol. % biotite is present, and in most places it is only 1 vol. %. The absence of much biotite in the Twenty Nine Palms quartz monzonite that replaced the diorite is logically explained by the absence of much biotite in the original magmatic Gold Park diorite. Therefore, the K-metasomatic origin of the K-feldspar megacrysts in the Twenty Nine Palms quartz monzonite is a logical conclusion. Nevertheless, the production of such large volumes of K-feldspar megacrysts must require the addition of much K from an outside source in order for the K-metasomatism to occur. Locally, the pluton has xenoliths of biotite schists in which the tiny biotite flakes are as much as 90 vol. %. Therefore, such schists (carried up from metasedimentary rocks below) suggest that a deep source of K is present.

IV. EVIDENCE AGAINST AN EXSOLUTION MODEL FOR THE ORIGIN OF WARTLIKE MYRMEKITE

Figure 39 comes from a sample of diorite which grades to myrmekite-bearing granodiorite at Monterey, California. In this place wartlike myrmekite projects into K-feldspar, and the volume of myrmekite exceeds or is equal to the volume of the adjacent K-feldspar. Therefore, the myrmekite cannot have formed by Ca- and Na-exsolution from the small volume of K-feldspar. Such myrmekite-abundance greater than K-feldspar-abundance is common in rocks that are in the earliest stages of the first appearance of K-feldspar formed by K-replacement



Figure 39. Wartlike myrmekite (center, top and bottom) on borders of albite-twinned plagioclase (whitish gray and gray) and projecting into microcline (black). Microcline penetrates and replaces plagioclase along cracks where diorite is in early stages of being replaced by K-

feldspar to convert the rock into granodiorite. The volume of the myrmekite is greater than the volume of the microcline. Source: Collins (2001a, Figure 14).

V. CONSEQUENCES OF K-METASOMATISM

One aspect of K-metasomatism that has not been mentioned so far relates to the balanced mass-for-mass equations that are generally used in explaining how wartlike myrmekite forms, either (a) by Na- and Ca-metasomatism of primary K-feldspar or (b) by Na, Ca, Al, and Si exsolution from primary K-feldspar. These balanced equations tend to restrict the modeler to a narrow view, particularly when the volume of myrmekite in the rock is generally less than 0.5 vol. %. (1) How can something as small as 0.5 vol. % have any major effects on the chemical composition of the whole rock? The answer is usually thought to be zero if the host granite is also considered to be totally magmatic in origin, and, therefore, wartlike myrmekite is commonly ignored.

A second matter to consider is that during K-metasomatism, the fluids that allow the metasomatism to occur create holes in the lattices as elements (Ca, Na, Al, Fe, and Mg) are dissolved out and carried away. The hole formation may be assisted by microfracturing but not necessarily so. Nevertheless, if these holes are plugged by introduced elements (K and Si), (2) how can the metasomatism continue? Once the holes are plugged, then the system should no longer be open to any further metasomatic changes.

The answers to questions (1) and (2) involve several factors. First, the K-metasomatism is not mass-for-mass but volume-for-volume, and not even at equal volume. When biotite and hornblende (density 3.0) are replaced by quartz (density 2.65) to form a quartz sieve-texture and eventually only quartz (except for remnants of biotite), the space occupied by the quartz is generally less than the space once occupied by the biotite and hornblende. Thus, shrinkages in local volume occur which then put stress (added pressure) on adjacent primary plagioclase crystals, causing them to be microfractured. Second, microfracturing of these plagioclase crystals allows subtraction of more Ca, Na, and Al and the creation of more holes in the lattices into which K can be introduced to form K-feldspar. However, even though the density of Kfeldspar (G = 2.56) is lower than the density of primary plagioclase (G = 2.61 to 2.66 or higher), the expanded K-feldspar lattice that is created by the introduced K need not fill all the space once occupied by the plagioclase, and, again, local shrinkages can occur. Therefore, additional stress is created locally on adjacent primary biotite, hornblende, and plagioclase, causing further microfracturing. On that basis, during the replacement processes, the system is not plugged but is constantly being re-opened for more metasomatic fluids to come in so that more elements can move out in escaping fluids. Thus, K- and Si-metasomatism continues and spreads to increase the volume in which metasomatism occurs. Once K- and Si-metasomatism begins, it is almost self-perpetuating. Only when sources of K and Si are depleted in introduced fluids is the metasomatism stopped.

Although the volume losses (shrinkages) are small, when considered on a plutonic scale, as former relatively more-mafic rocks become more granitic, the shrinkages may be significant. Such shrinkages are consistent with what would be expected in rocks that are being sheared under high pressure. Certainly, expansion under high confining-pressure is not a possibility. Such shrinkages are more readily identified in metasedimentary rocks interlayered with igneous layers (sills) than in an igneous intrusion of nearly uniform composition where there is no structure to use as a reference base that could reveal that shrinkages have occurred. For example, on limbs of anticlinal-synclinal structures where rocks are being compressed to tighten the fold and where these rocks in foliated layers slide past each other as the folding progresses, granulation or microfracturing of crystals can occur. The granulation and microfracturing opens the system to movements of metasomatic fluids. Because in noses of the folds no movement or granulation occurs, only in the limbs does metasomatism modify the compositions of the rock layers. In that metasomatic process, rocks in the limbs become both more granitic and smaller in volumes. These two consequences in turn make it possible for the anticlinal-synclinal structure to become more tightly folded and eventually, as metasomatism continues, become isoclinal. These combinational relationships were observed where wartlike myrmekite is found in rocks in such isoclinal structures that occur (a) in the Gold Butte area in Nevada (Collins 1997f and (b) in the Split Rock Pond area in New York (Collins 1997kl; Collins, 1988).

In the Gold Butte area, an igneous layered intrusive body occurs in which more felsic layers are at the top, and then toward the bottom other layers become progressively more mafic. All these layers are folded such that one limb of the fold is bent underneath the other limb to produce an overturned fold. In that folding process, the rock layers in the underlying limb are stretched (sliding past each other) such that microfracturing allows hydrous fluids to come in and change the rocks metasomatically. In contrast, the rocks in the overlying limb are not stretched and remain unaffected. The metasomatism in the underlying limb converts each layer into more granitic compositions progressively away from the nose of the fold as shrinkages in volume also occur. The shrinkages are aided because the primary ferromagnesian silicates are recrystallized as andradite garnet (G = 3.84), packing some of the residual Ca, Al, Fe and Mg into smaller volumes. Garnet is absent in each of the layers in the overlying limb. If the garnets had formed by dynamothermo-metamorphism, then they should occur in both limbs, and that is not the case.

Because the more felsic layers at the top are affected differently from the more mafic layers at the bottom, contrasting wartlike myrmekite types are formed with the predicted coarser vermicules in the more mafic rocks where the primary plagioclase has higher An content and less coarse vermicules are formed in the more felsic layers where the primary plagioclase has lower An content. The final results of the tight folding and metasomatism cause the rocks in the inner tightest part of the fold to form a massive granitic residue in which much of the original Ca, Al, Mg, and Fe have been extracted in escaping fluids.

On that basis, other structural relationships involving shrinkages should be looked for in other terranes that contain wartlike myrmekite. For example, shrinkages are described in the Isabella pluton at the southern end of the Sierra Crest Shear Zone in California (http://www.csun.edu/~vcgeo005/Nr49Isabella.pdf). Here, the several hundred parallel granitic pegmatite dikes do not represent places where late-stage granite magma was injected into open fractures or where relatively low-pressure sites existed into which eutectic granitic melts

migrated but where high-pressure (but open) shear zones occurred along which large volumes of Ca, Al, Fe, and Mg were subtracted during metasomatism to leave granitic residues that recrystallized as pegmatite dikes.

Potentially, shrinkages could occur in igneous rocks in metamorphic core complexes that are modified by K-metasomatism, Such a metamorphic core complex exists in eastern California and western Arizona where igneous rocks are commonly mylonitized and granulated along horizontal thrust sheets (Davis et al., 1980; Anderson et al., 1979). In an unpublished master's thesis Podruski (1979) described K-metasomatism to form K-feldspar megacrysts (bordered by wartlike myrmekite) in the Whipple Mountains in the Parker Dam granite that occurs within this core complex. Therefore, not only were the igneous rocks granulated along the contact between upper and lower plates, they also likely shrank in volume from loss of elements in escaping fluids moving through the contact between the plates as these rocks were converted to a moregranitic composition by K-metasomatism.

Another locality is in the Alps in Switzerland where rock layers have been thrust past each other during plate tectonics and where fracturing likely accompanied these movements. For example, the Bergell granite (Wenk, 1982; Schmid, et al., 1996) that occurs there contains megacrysts of K-feldspar bordered by wartlike myrmekite, and, therefore, a zone of shrinkage could have occurred as a former igneous pluton was converted into the more-granitic Bergell granite body by K-metasomatism.

An additional consequence is the consideration to the kinds and abundances of elements that are extracted by escaping metasomatic fluids and the problem of where do these elements go? Where do large volumes of Ca, Na, and Al ions go that are displaced by introduced K that forms secondary K-feldspar? The places where these ions have gone has been almost impossible to find because where the metasomatized granitic rocks can be observed, the overlying rocks into which the escaping fluids could have moved have been eroded away. Perhaps, they have produced metasomatic quartz-bearing anorthosites as occurs in the Komaki District of southwestern Japan (Takagi et al., 2007). Granitic rocks immediately adjacent to the Komaki District contain secondary K-feldspar and myrmekite. Of course, the connection with deep-seated K-metasomatic granite below the plagioclase-quartz rock which would supply Ca, Na, and Al to the anorthosite cannot be demonstrated without extensive drilling. Nevertheless, the introduced Ca, Na, and Al into anorthosite must come from somewhere, and the circumstantial evidence suggests that the connection to myrmekite-bearing granite as a source could be possible.

Another possibility of where the Ca, Na, and Al go is in the production of concentrations of secondary epidote. For example, in some places in the Cargo Muchacho Mountains in southeastern California (Collins, 1988) and in the megacrystal quartz monzonite at Twenty Nine Palms, California (http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf) more epidote is present in large volumes in the host rocks than can logically be explained by derivation of the Ca and Al from altered primary minerals in the original rock. A simple relatively-closed-system alteration

to produce epidote will usually have a single generation of epidote. A complicated open-systemalteration to produce epidote during metasomatism will have multiple generations of epidote because K-metasomatism requires the system to be kept open by repeated episodes of deformation (Barth and Ehlig, 1989).

Where do displaced Mg and Fe go that are released from biotite and hornblende as these minerals are replaced by quartz? Notably, Mg moves out preferentially over Fe, because of the greater solubility of Mg and because Fe tends to remain behind in hematite and magnetite. Both iron oxides have densities (G = 5.2) greater than the densities of ferromagnesian silicates (G = 3.0) that are replaced by quartz, so the formation of residual hematite and/or magnetite contributes to the shrinkage of the rocks during metasomatic processes. If Fe is abundant, concentrations of magnetite may be produced, such as magnetite enrichments in the outer shell of the Vrädal pluton in Norway (http://www.csun.edu/~vcgeo005/Abstract%20Vradal2.htm). and the magnetite iron ore deposits in the limbs of the Split Rock Pond anticline in New York (Collins, 1988). Because soluble Mg moves out in escaping hydrothermal fluids preferentially over Fe, the escaping Mg could be the means for causing overlying limestones to be converted into dolomites. It is has always been a problem as to where the Mg comes from in limestones that cause progressive conversions to dolomite in layers buried far below Mg-bearing oceanic waters.

Another possibility is lamprophyre dikes that have a puzzling association with granitic rocks (Hyndman, 1972; Bowes and Wright, 1976). Their high Fe- and Mg-contents make no geologic sense if they are derived from granites, and, therefore, a deep mantle source is usually postulated as to where their Fe- and Mg-rich compositions come from. On the other hand, if these dikes represent deposition from hydrous fluids enriched in Fe and Mg that were escaping from rocks undergoing K- and Si-metasomatism, a deep mantle source is not necessary and makes geologic sense (Collins, 1988).

If biotite and hornblende contain small percentages of Cu, Pb, Mo, and/or Zn in their lattices, these metallic elements could be released into the hydrothermal fluids to form sulfide ore deposits in wall rocks. Likewise, Au and U could be released to form local ore concentrations. At any rate, mostly where elements go that are extracted from rocks that undergo K- and Si-metasomatism has to be speculation because it is almost impossible to connect any granitic sources containing wartlike myrmekite with the final destination of where escaping fluids go.

Unlike rocks affected by K-metasomatism, rocks affected by Na- and Ca-metasomatism, described in the next section, generally do not have coexisting great losses in volume because Na- and Ca-metasomatism mostly affect small volumes in outer rims of primary K-feldspar or plagioclase in which the replacements cause little to no shrinkage.

VI. SECOND STYLE: TEXTURES FORMED BY Ca- AND Na-METASOMATISM

In contrast to textures that are formed where K-metasomatism modifies primary plagioclase to produce secondary K-feldspar and wartlike myrmekite are textures that are produced where Ca- and Na-metasomatism are involved. These textures are in addition to those found associated with Na-metasomatism that is observed (a) surrounding carbonatite-alkaline silicate complexes where distinct sodic ferromagnesian silicate minerals (aegerine, arfedsonite, and riebeckite) are formed and (b) where albite replacements of microfractured, relatively more-calcic plagioclase in sheared rocks occur. These additional textures include those formed during (a) Na-metasomatism of mesoperthites, (b) Na- and Ca-metasomatism of mesoperthites; of interiors of microfractured orthoclase phenocrysts; of exteriors of primary K-feldspar; along grain boundaries between two K-feldspar crystals, and (c) Ca-metasomatism of borders of primary more-sodic plagioclase; and that resulting from reaction rims between Ca-bearing pyroxenes and adjacent plagioclase.

Textures formed in mesoperthites can be observed in the Lyon Mountain granite gneiss in New York where both primary albite-twinned plagioclase and mesoperthite with coarse plagioclase lamellae occur. Na-metasomatism is easily demonstrated where secondary plagioclase replaces the K-feldspar portion of mesoperthite (Figure 40). During this process remnants of coarse plagioclase lamellae remain in the secondary plagioclase. However, because the introduced metasomatic fluids contain mostly Na, the secondary plagioclase in such places is relatively sodic, and the exchange of Na for K does not produce any left-over silica to form quartz vermicules.

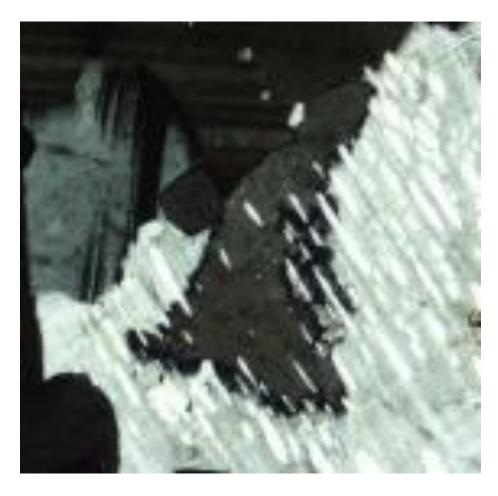


Figure 40. Replacement of K-feldspar (gray; right and bottom sides) in the mesoperthite by secondary plagioclase (dark gray; center) leave plagioclase lamellae (cream) of the perthite projecting into the secondary plagioclase or as islands. Albite-twinned primary plagioclase occurs in the upper left quadrant. Source: Collins (1997k, Figure 21). See also Figure 22 in this same article for a similar example.

On the other hand, where Na- and Ca-bearing fluids interact with the mesoperthite, (a) the added Ca requires two Al atoms for every Ca atom, and Si is left-over to form quartz vermicules in myrmekite, (b) the vermicules do not taper toward the K-feldspar and are totally inside the albite-twinned plagioclase (center) of the myrmekite, and (c) the vermicules commonly are nearly uniform in cross-section (Figure 41).

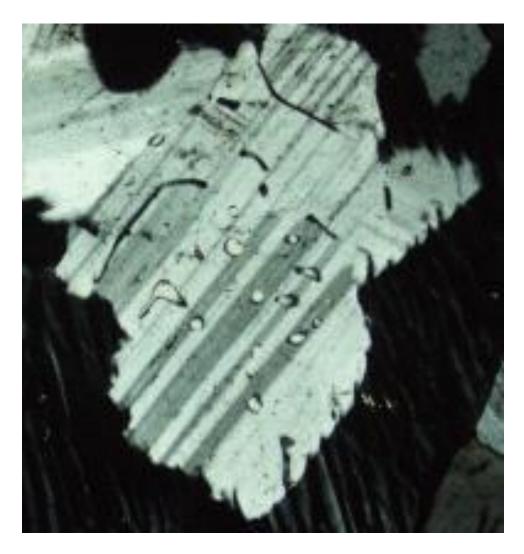


Figure 41. Myrmekite formed by Na- and Ca-metasomatism of K-feldspar in mesoperthite, Some quartz vermicules are seen as cross-sections which have an ovoid shape. Plagioclase of the myrmekite is albite-twinned. Source: Collins, 1997k, Figure 23).

An example of Na- and Ca-metasomatism of interiors of microfractured primary orthoclase phenocrysts occurs near Alastaro, Finland, where megacrystal granite intrudes gabbro. Aggregate mats of myrmekite occur in the microfractured orthoclase crystals, 2 cm long (Figure 42).



Figure 42. Photo of part of a mosaic of magnified images of an Alastaro altered K-feldspar megacryst. The mosaic extends for about 2 m long and 1 m wide. The assembled mosaic images is an aggregate of myrmekite grains filling almost the entire K-feldspar crystal (about 2 cm long in its unmagnified form). Some unreplaced remnant inclusions of quartz and biotite occur scattered among the myrmekite grains. The photo includes about one sixth of the mosaic area. Source: Collins (1997d, Figure 7b). See also Figures 2 and 3 in this same website article for early stage Ca-metasomatism along fractures in the interiors of megacrysts.

On the other hand, there are some kinds of wartlike myrmekite that project into primary K-feldspar along its outer rim instead of as replacements in the interior along microfractures (Figure 43). In such myrmekite the plagioclase has uniform composition, and the quartz vermicules are uniform in size and do not taper toward the K-feldspar. Moreover, the plagioclase of the myrmekite is not gradational to and in optical continuity with adjacent quartz-free plagioclase as occurs during K-metasomatism. An example of such wartlike myrmekite is in a thin section of monzogranite from the Alvand plutonic complex, Hamedan, Iran (Figure 43).

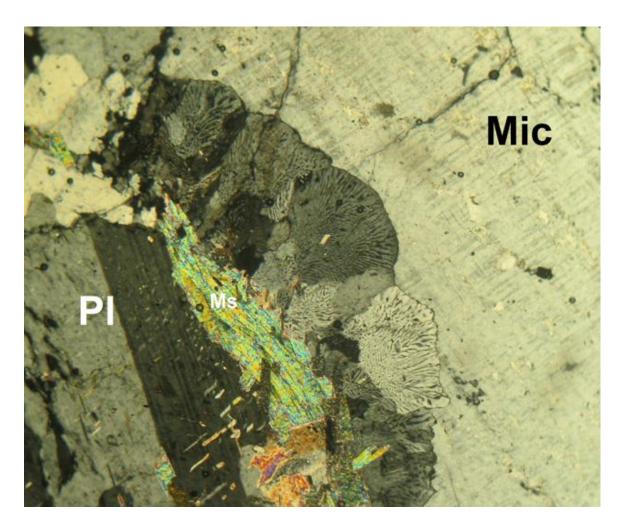


Figure 43. Wartlike myrmekite from Iran. Microcline (Mic; right side). Albite- and Carlsbad-twinned plagioclase (Pl; left side). Muscovite (Ms; green, blue, and red). Biotite (tan). Quartz (cream white; upper left). Image is from monzogranite sample from the Alvand plutonic complex, Hamedan, Iran. Photo contributed by Ali Sepahi.

In a more advanced stage of Ca- and Na-metasomatism of primary K-feldspar in rocks in Iran, an aggregate mat of myrmekite is formed when all the K-feldspar is totally replaced by myrmekite (Figure 44), like that in Figure 42. This total replacement by myrmekite also differs from isolated wartlike myrmekite that is formed by K-metasomatism of primary plagioclase.

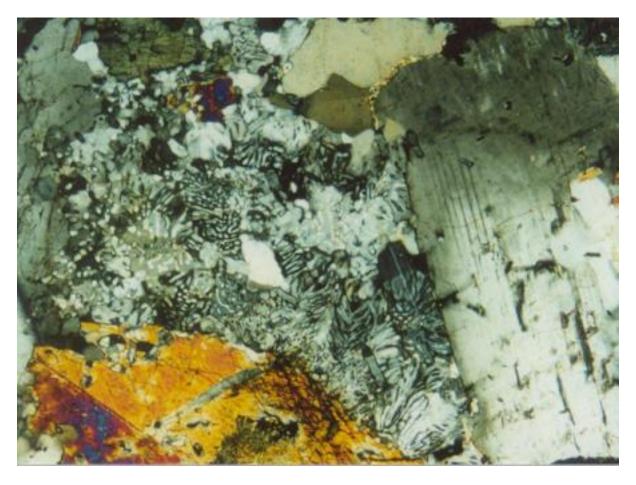


Figure 44. Aggregates of myrmekite (left side) formed around the plagioclase crystals (right side; albite twinned; white and gray) in diorite, which may have resulted from Ca-metasomatism of sodic plagioclase. Quartz (cream; white). Biotite (brown). From the Alvand plutonic complex, Hamadan, Iran. Source: Behnia and Collins (1998, Figure 2).

Another kind of wartlike myrmekite that is common where Ca- and Na-metasomatism of primary K-feldspar occurs is the production of "swapped myrmekite," which occurs in granite in parts of China (Figure 45) and elsewhere. Along a fracture between two primary K-feldspar crystals, introduced fluids carrying Ca and Na ions replace the K-feldspar in positions that alternate along both sides of the fracture to form wartlike myrmekite that projects into the K-feldspars.

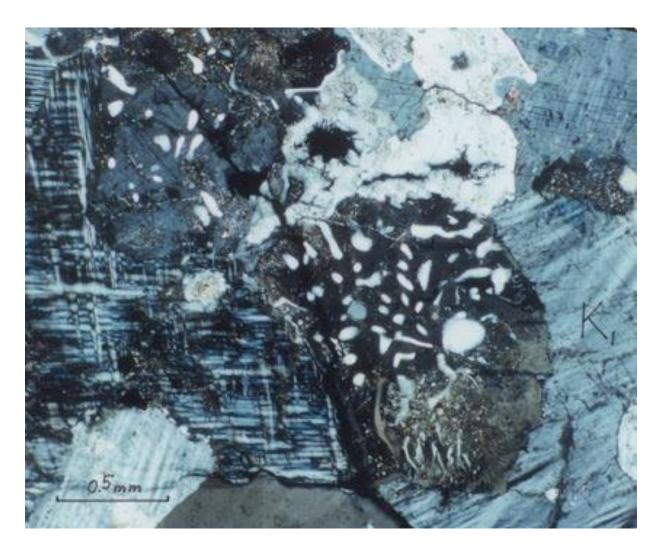


Figure 45. Swapped coarse myrmekite grains occur on the grain boundary between two differently oriented grid-twinned K-feldspar crystals (K₁ and K₂). K-feldspar grain (light gray) in upper right with perfect cleavage (black parallel lines) has nearly invisible, uniformly-distributed, narrow spindles of perthitic lamellae as do all other K-feldspar crystals. Meso-to-fine myrmekite is locally found at the lower corner of the coarse myrmekite (right side of the center of the photo). Bar scale of 0.5 mm length; lower right. Photomicrograph is from an unnamed granite body in Inner Mongolia. Source: Rong (2002, Figure 3a).

Another example of Ca- and Na-metasomatism occurs in the Velay granite in France (Figure 46). In this granite, replacement of K-feldspar by myrmekite is observed only in the enclaves, not in the host granite. This replacement is thought to be driven by the influx of Narich fluids from the host granite in the range of 450-650° C. These Na-rich fluids cause subsequent reequilibration with the Na-poorer feldspars in the enclaves. Here, the Na replaces Ca in plagioclase, and, in turn, the released Ca replaces K-feldspar to form myrmekite. The cathodoluminescent image is provided by Daniel Garcia (Garcia et al., 1996).

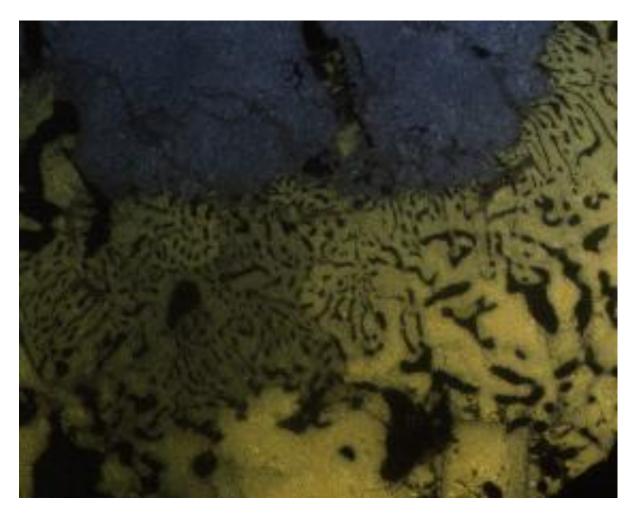


Figure 46. Extensive development of myrmekite replacing a K-feldspar megacryst (blue) in a granodiorite enclave of the Velay granite. Source: Collins (1997d, Figure 10).

Additional examples of Ca- and Na-metasomatism occur where wartlike myrmekite replaces plagioclase in deformed anorthosite masses. In such myrmekite the plagioclase of the myrmekite has a higher Ca content (An content) than in the plagioclase of the adjacent anorthosite mass. No image examples are included here but can be found in the published literature. For example, see De Waard et al., (1977), Dymek and Schiffries (1987), Wager and Brown (1967), and Perchuk et al., (1994).

Finally, Ca-metasomatism can also occur to produce myrmekite as a reaction rim between clinopyroxene and adjacent plagioclase (personal communication with Andrew Putnis) and along K-feldspar veins in granulites (Touret and Nijland, 2012).

VII. DISCUSSION

Yes, we agree that most granitic plutons are primarily magmatic in origin, but a few have been subjected to later K-, Na-, or Ca-metasomatism following their solidification. We also

agree that the old idea of "granitization" promoted in the 1940s and 1950s (Read, 1948) is in error in which almost any rock, including sedimentary rocks, was said to be able to be converted to granite by the addition of K, Al, and Si by solid-state diffusion and replacements. We disagree, however, that because chemical changes found in natural rocks formed by magmatic differentiation (e.g., diorite to granodiorite to granite) are duplicated by experimental work by Tuttle and Bowen (1958) that this duplication is sufficient evidence to prove that all large granitic bodies are formed by magmatic processes. The lack of proof is because chemical studies on granitic rocks formed by metasomatic processes in a replacement sequence of quartz diorite to granodiorite to granite give the same chemical trends as those by magmatic differentiation (Collins 1988). Thus, using chemical analyses of rocks alone is not sufficient to determine the origin of plutonic granitic rocks.

What is required to convert diorite to granodiorite to granite by metasomatic processes is an open system that is created by deformation of solid plutonic igneous rocks at subsolvus temperatures (300-550°C). This open system allows hydrous fluids to introduce K and Si and to subtract some Na, Ca, Fe, Mg, and Al. In these places both plagioclase and K-feldspar are porous and full of tunnels through which fluids can move in and out of the crystals (Putnis et al., 2007). Magmatists rightly say that the conversion of a relatively-mafic plutonic igneous into granite cannot be achieved by solid-state diffusion processes through solid undeformed rocks, but when the solid-state diffusion is on a nano-scale at half the distance between walls of tunnels in altered and deformed feldspar crystals, then whole or parts of whole plutons can be changed into rocks of more granitic composition across distances of kilometers.

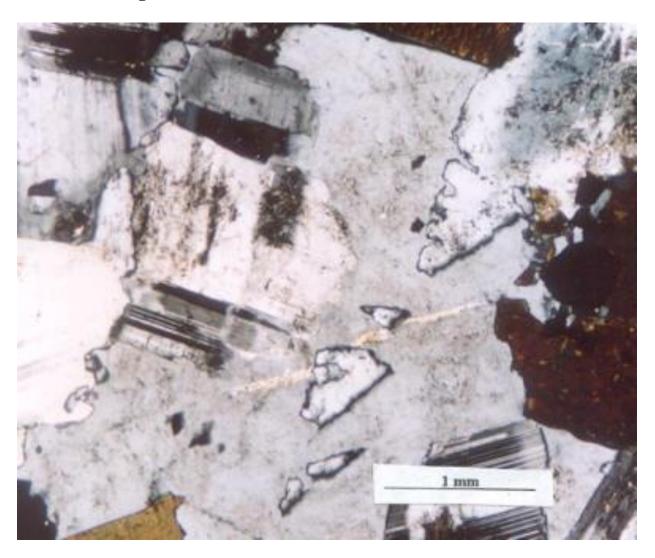
The presence of wartlike myrmekite needs to be used as a clue to possible vast mineralogical and chemical changes in some granite bodies of plutonic size. The large scale K-metasomatism and formation of wartlike myrmekite (a) in the Bonsall biotite-hornblende tonalite that is converted to granite near Temecula, California (Collins, 2002), (b) in the biotite granodiorite in the Papoose Flat pluton (Collins and Collins, 2002b), and (c) in the Gold Peak hornblende diorite in the Twenty Nine Palms quartz monzonite (Collins, 1997f) should be recognized as a guide to looking at other locations where such large scale metasomatism might occur. The art of petrographic studies of thin sections and extensive sampling during careful field work need to be revived.

Other examples of plutonic rocks in which deformation has produced large scale K- and Si-metasomatism and in which wartlike myrmekite is present include the northwestern outer shell of the Main Donegal granite in Ireland where remnants of the Thorr pluton are still present Collins, 1997g). The K-feldspar megacrysts in the outer shell of the Ardara pluton in this same area are also bordered by wartlike myrmekite. Pitcher and Berger (1972) and Pitcher et al. (1987) described these megacrysts as having been formed by K-metasomatism. Barton and Sidle (1994) described K-metasomatism in a mylonite zone associated with a granite porphyry and megacrystal rocks in the Waldoboro granite complex in Maine and in the Benner Hill layer

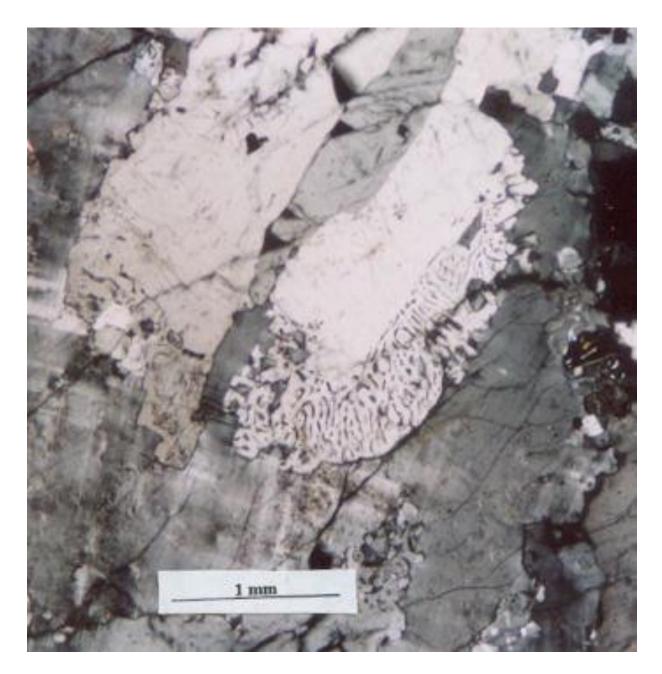
sequence in which wartlike myrmekite occurs with the K-feldspar megacrysts (Collins, 1997e). Loomis (1961, 1983) also described K-metasomatism in deformation zones in granitic rocks in the Fallen Leaf Lake area in California.

APPENDIX: Additional Image Examples

Microfracturing



Remnant islands of plagioclase. K-feldspar (light gray). Islands are optically continuous with a large zoned plagioclase crystal (upper right). Note serrate edges of the plagioclase against the K-feldspar (left side and upper right) where the K-feldspar is replacing the plagioclase. Source: Collins (2003, Figure 8).



Penetration along broken grain-boundary seals. Microcline (gray; grid-twinned; bottom) penetrates plagioclase (white; top) and surrounds tiny remnant islands of plagioclase that are optically continuous with the larger plagioclase grain (white; top). Plagioclase of myrmekite is also in optic continuity. Source: Collins, (2003, Figure 18).

Figure 12 http://www.csun.edu/~vcgeo005/Fig12Nr16Skidoo.jpg (Collins, 1997j).

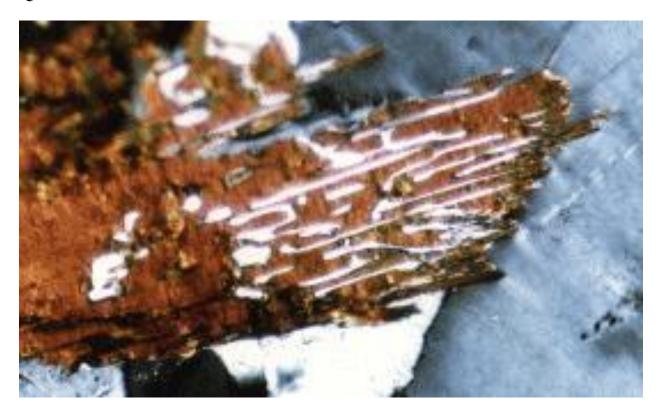
Figure 18 http://www.csun.edu/~vcgeo005/Fig18Nr38Monterey.jpg (Collins, 2001a).

Parallel alignment

Figure 6 http://www.csun.edu/~vcgeo005/Fig6Nr2Myrm.jpg (Collins, 1997b).

Figure 8 http://www.csun.edu/~vcgeo005/Fig8Nr9Twenty.jpg (Collins, 1997f).

Quartz sieve-textures



Quartz sieve-texture in biotite. Biotite (brown) replaced by quartz (white) along cleavage surfaces. Microcline (light gray) may also have replaced portions of the biotite (right side). Source: Behnia and Collins (1998, Figure 25)



Quartz sieve-texture in hornblende. Hornblende crystals (dark brown to black); quartz (center, white). Microcline (gray, grid twinning). Source: Collins (1997c, Figure 5)

Figure 7 http://www.csun.edu/~vcgeo005/Fig7Nr26Controversy.jpg (Collins, 1998a)

Figure 31 http://www.csun.edu/~vcgeo005/Fig31Nr48Fallen.jpg (Collins, 2003).

Wartlike myrmekite

Figure 2 http://www.csun.edu/~vcgeo005/Fig2Nr3Myrm.jpg (Collins, 1997c).

Figure 24 http://www.csun.edu/~vcgeo005/Fig24Nr38Monterey.jpg (Collins, 2001a).

Ghost myrmekite

Figure 10 http://www.csun.edu/~vcgeo005/Fig10Nr2Myrm.jpg (Collins, 1997b).

Figure 16 http://www.csun.edu/~vcgeo005/Fig16Nr33BillW.jpg (Collins, 1998d).

Figure 19 http://www.csun.edu/~vcgeo005/Fig19Nr40Wanup.jpg (Collins, 2001b).

ACKNOWLEDGMENTS

We thank Arthur Sylvester (University of California Santa Barbara) for many valuable suggestions for improving the manuscript during his several days of its examination. We also thank David Liggett (California State University Northridge) for giving the article a careful review for accuracy and clarity of explanations.

REFERENCES CITED (The spacings in these references are uneven and inconsistent, and I have not figured out why the computer has done this so that I can correct it.)

- Anderson, J.L., Davis, G.A., and Frost, E.G., 1979, Field guide to regional Miocene detachment faulting and early Tertiary (?) mylonitization, Whipple-Buckskin-Rawhide Mountains, southeastern California and western Arizona; *in* Abbott, P. L., ed., *Geologic Excursions in the Southern California Area, San Diego, California, San Diego State University*, p. 109-133.
- Barth, AP. and Ehlig, PL., 1989, Geology of Mesozoic Plutonic Rocks, Central and Western San Gabriel Mountains, Southern California; in Collins, LG. (ed.), Geologic Excursions in the Greater Los Angeles Area: National Association of Geology Teachers, Spring Conference April 21-23, p. 20-37.
- Barton, M., and Sidle, W.C., 1994, Petrological and geochemical evidence for granitoid formation: The Waldoboro pluton complex, Maine. Journal of Petrology, v. 35, p. 1241-1474.
- Behnia, P. and Collins, L.G., 1998, 25. Petrogenesis of the Ghooshchi granite by K- and Simetasomatism of diorites and gabbros, western Azerbaijan, Iran. Myrmekite electronic journal, ISSN 1526-5757, Nr. 25, in http://www.csun.edu/~vcgeo005/Nr25Gooshchi.pdf. (October 2012)
- Brigham, R.H., 1984, K-feldspar genesis and stable isotope relations of the Papoose Flat pluton, Inyo Mountains, California. PhD dissertation, Stanford University, 172 p.
- Bowes, D.R., and Wright, A.E., 1976, Nature and genesis of the appinite suite: Krystalnikum, v. 12, p. 31-46.
- Collins, L.G., 1988, *Hydrothermal Differentiation And Myrmekite A Clue To Many Geologic Puzzles*: Athens, Theophrastus Publications, 382 p.
- Collins, L.G., 1990, Cathodoluminescence microscopy of myrmekite Comment: Geology, v. 18, p. 1163.

- Collins, L.G., 1997a, 1. Origin of myrmekite and metasomatic granite. Myrmekite electronic journal, ISSN 1526-5757, Nr. 1, in http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf. (October 2012)
- Collins, L.G., 1997b, 2. Replacement of primary plagioclase by secondary K-feldspar and myrmekite. Myrmekite electronic journal, ISSN 1526-5757, Nr. 2, in http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf. (October 2012)
- Collins, L.G., 1997c, 3. Microscopic and megascopic relationships for myrmekite-bearing granitic rocks formed by K-metasomatism. Myrmekite electronic journal, ISSN 1526-5757, Nr. 3, in http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf. (October 2012)
- Collins, L.G., 1997d, 4. Myrmekite formed by Ca-metasomatism. Myrmekite electronic journal, ISSN 1526-5757, Nr. 4, in http://www.csun.edu/~vcgeo005/Nr4CaMyrm.pdf. (October 2012)
- Collins, L.G., 1997e, 6. Myrmekite as a clue to metasomatism on a plutonic scale: origin of some peraluminous granites. Myrmekite electronic journal, ISSN 1526-5757, Nr. 6, in http://www.csun.edu/~vcgeo005/Nr6Waldoboro.pdf. (October 2012)
- Collins, L.G., 1997f, 9, Large-scale K- and Si-metasomatism to form the megacrystal quartz monzonite at Twenty Nine Palms, California. Myrmekite electronic journal, ISSN 1526-5757, Nr. 9, in http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf. (October 2012)
- Collins, L.G., 1997g, 10, K- and Si-metasomatism in the Donegal granites of northwest Ireland. Myrmekite electronic journal, ISSN 1526-5757, Nr. 10, in http://www.csun.edu/~vcgeo005/Nr10Donegal.pdf.
- Collins, L.G., 1997g. 11. Myrmekite in garnet-sillimanite-cordierite gneisses and Al-T-Zr trends, Gold Butte, Nevada. Myrmekite electronic journal, ISSN 1526-5757, Nr.11, in http://www.csun.edu/~vcgeo005/Nr11Gold.pdf. (October 2012)
- Collins, L.G., 1997h, 13, Myrmekite in the Rubidoux Mountain leucogranite A replacement pluton. Myrmekite electronic journal, ISSN 1526-5757, Nr. 13, in http://www.csun.edu/~vcgeo005/Nr13Rubidoux.pdf. (October 2012)
- Collins, L.G., 1997i, 14, Myrmekite in muscovite-garnet granites in the Mojave Desert California. Myrmekite electronic journal, ISSN 1526-5757, Nr. 14, in http://www.csun.edu/~vcgeo005/Nr14Mojave.pdf. (October 2012)
- Collins, L.G., 1997j, 16. Sericitization in the Skidoo pluton, California: A possible end-stage of large-scale K-metasomatism. Myrmekite electronic journal, ISSN 1526-5757, Nr. 16, in http://www.csun.edu/~vcgeo005/Nr16Skidoo.pdf. (October 2012)

- Collins, L.G., 1997k, 17. The Mobility of iron, calcium, magnesium, and aluminum during Kand Si-metasomatism. Myrmekite electronic journal, ISSN 1526-5757, Nr. 16, in http://www.csun.edu/~vcgeo005/Nr17Mobility.pdf. (October 2012)
- Collins, L.G., 1997l, 18, Sphene, myrmekite, and titanium immobility and mobility; implications for large-scale K- and Na-metasomatism and the origin of magnetite concentrations. Myrmekite electronic journal, ISSN 1526-5757, Nr. 18, in http://www.csun.edu/~vcgeo005/Nr18LyonMtn.pdf. (October 2012)
- Collins, L.G., 1997m, 23. A close scrutiny of the "Newer Granites" of the Caledonian Orogen in Scotland, Myrmekite electronic journal, ISSN 1526-5757, Nr. 23, in http://www.csun.edu/~vcgeo005/Nr23Scotland.pdf. (October 2012)
- Collins, L.G., 1997n, 24. Magmatic resorption versus subsolidus metasomatism two different styles of K-feldspar replacement of plagioclase. Myrmekite electronic journal, ISSN 1526-5757, Nr. 24, in http://www.csun.edu/~vcgeo005/Nr24TwoStyles.pdf. (October 2012)
- Collins, L.G., 1998a, 26. The microcline-orthoclase controversy can microcline be primary? Myrmekite electronic journal, ISSN 1526-5757, Nr. 26, in http://www.csun.edu/~vcgeo005/Nr26Controversy.pdf. (October 2012)
- Collins, L.G., 1998b, 27. Metasomatic origin of the Cooma complex in southeastern Australia. Myrmekite electronic journal, ISSN 1526-5757, Nr. 27, in http://www.csun.edu/~vcgeo005/Nr27Cooma.pdf. (October 2012)
- Collins, L.G., 1998c. Primary microcline and myrmekite formed during progressive metamorphism and K-metasomatism of the Popple Hill gneiss, Grenville Lowlands, northwest New York, USA, Myrmekite electronic journal, ISSN 1526-5757, Nr. 28, in http://www.csun.edu/~vcgeo005Nr28Popple.pdf. (October 2012)
- Collins, L.G., 1998d, 33. Origin of the augen granite gneiss in the Bill Williams Mountains, Arizona, USA; A prediction confirmed. Myrmekite electronic journal, ISSN 1526-5757, Nr. 33, in http://www.csun.edu/~vcgeo005/Nr33BillW.pdf. (October 2012)
- Collins, L.G., 1999, 36. Experimental studies demonstrating metasomatic processes and their application to natural granitic environments. Myrmekite electronic journal, ISSN 1526-5757, Nr. 36, in http://www.csun.edu/~vcgeo005/Nr36Experimental.pdf. (October 2012)
- Collins, L.G., 2000, 37. Overlooked experimental evidence for K-replacements of plagioclase and origin of microcline in granite plutons. Myrmekite electronic journal, ISSN 1526-5757, Nr. 37, in http://www.csun.edu/~vcgeo005/Nr37Overlooked.pdf. (October 2012)
- Collins, L.G., 2001a, 38. Modification of a magmatic tonalite to produce a megacrystal granodiorite by K-metasomatism, Monterey peninsula and northern Santa Lucia

- Mountains, California, USA. Myrmekite electronic journal, ISSN 1526-5757, Nr. 38, in http://www.csun.edu/~vcgeo005/Nr38Monterey.pdf. (October 2012)
- Collins, L.G., 2001b, 40, Evolution of a layered diorite-gabbro to become a layered quartz monzonite-granodiorite in the Wanup pluton near Sudbury, Canada. Myrmekite electronic journal, ISSN 1526-5757, Nr. 40, in http://www.csun.edu/~vcgeo005/Nr40Wanup.pdf. (October 2012)
- Collins, L.G., 2002, 43. Myrmekite formation at Temecula, California, revisited: A photomicrographic essay illustrating replacement textures. Myrmekite electronic journal, ISSN 1526-5757, Nr. 43, in http://www.csun.edu/~vcgeo005/Nr43Temecula.pdf. (October 2012)
- Collins, L.G., 2003, 48. Transition from magmatic to K-metasomatic processes in granodiorites and Pyramid Peak granite, Fallen Leaf Lake 15-Minute Quadrangle, California. Myrmekite electronic journal, ISSN 1526-5757, Nr. 48, in http://www.csun.edu/~vcgeo005/Nr48Fallen.pdf. (October 2012)
- Collins, L.G., and Collins, B.J., 2002, 44. K-metasomatism and the origin of Ba- and inclusion-zoned orthoclase megacrysts in the Papoose Flat pluton, Inyo Mountains, California, USA. Myrmekite electronic journal, ISSN 1526-5757, Nr. 44, in http://www.csun.edu/~vcgeo005/Nr44Papoose.pdf. (October 2012)
- Davis, G.A., Anderson, J.L., Frost, E.G., and Shackelford, T.J., 1980, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona: *in* Davis, G. H., Coney, P. J., Crittenden, M., editors, Metamorphic Core Complexes, Geological Society of America Memoir 153, p. 79-129.
- De Waard, D., Hancock, S.A., and Robinson, J.E., 1977, Mineral variation in anorthositic rocks of eastern Paul Island, Nain complex, Labrador. Nederlandse Akademie van Wetenschappen, Afdeeling Natuurkunde, *in* Proceedings, Ser. B, v. 80, no. 4, p. 322-335.
- Dickson, F.W., 1966, Growth of K-feldspar and plagioclases by replacement processes in rocks of the Papoose Flat pluton and in country rocks, Inyo Mountains, California (abstract): Geological Society of America Special Paper 101, p. 53.
- Dymek, R.F., and Schiffries, C.M., 1987, Calcic myrmekite: possible evidence for the involvement of water during the evolution of andesine anorthosite from St-Urbain, Quebec. Canadian Mineralogist, v. 25, p. 291-319.
- Engvik, A.K., Putnis, A., Fitz Gerald, J.D. and Austrheim, H., 2008, Albitisation of granitic rocks: The mechanism of replacement of oligoclase by albite. Canadian Mineralogist, v. 46, p. 1401-1415.
- Garcia, D., Pascal, M-L., and Roux, J., 1996, Hydrothermal replacement of feldspars in igneous enclaves of the Velay granite and the genesis of myrmekite: European Journal of Mineralogy, v. 8, p. 703-711.

- Hopson, R.F., and Ramseyer, K., 1990a, Cathodoluminescence microscopy of myrmekite: Geology, v. 18, p. 336-339.
- Hopson, R.F., and Ramseyer, K., 1990b, Cathodoluminescence microscopy of myrmekite Reply: Geology, v. 18, p. 1163-1164.
- Hyndman, D.W., *Petrology of igneous and metamorphic rocks*: New York, McGraw-Hill, 533 pp.
- Liu, J., Hay, R.I., Deino, A., and Kyser, T.K., 2003, Age and origin of authigenic K-feldspar in uppermost Precambrian rocks in the North American Midcontinent: Geological Society of American Bulletin, v. 115, p. 422-433.
- Loomis, A.A., 1961, Petrology of the Fallen Leaf Lake area, California: Ph.D. thesis, Stanford University.
- Loomis, A.A., 1983, Geology of the Fallen Leaf Lake 15-minute Quadrangle, El Dorado County, California Division of Mines and Geology Map Sheet 32, scale 1:62,500, 24 p.
- Morad, S., El-Ghahi, M.A.K., Caja, M.A., Sirat, M., Al-Ramadan, K., and Mansurbeg, H., 2010, Hydrothermal alteration of plagioclase in granitic rocks from Proterozoic basement of SE Sweden, Geological Journal, v. 45, p. 105-116.
- Pearson, J.M. and Taylor, W.R., 1996, Mineralogy and geochemistry of fenitized alkaline ultrabasic sills of the Gifford Creek complex, Gascoyne Province, Western Australia, The Canadian Mineralogist, v. 34, p. 201-219.
- Perchuk, L.L., Gerya, T.V., and Korsman, K., 1994, A model for charnockitization of gneissic complexes: Petrology, v. 2, p. 395-423.
- Pitcher, W.S., and Berger, A.R., 1972, *The Geology Of Donegal: A Study Of Granite Emplacement And Unroofing*: Wiley Interscience, New York, 435 p.
- Pitcher, W.S., Hutton, D.H.W., Atherton, M.P., and Stephens, E., 1987, Guide to the granites of Donegal; from the symposium on the 'Origin of Granite,' Edinburgh, September 14-16, 1987.
- Pluemper, O., 2009, The complex history of granitic rocks; multiple feldspar replacement reactions under subsolidus conditions. Journal of Petrology, v. 50, p. 967-987.
- Podruski, J. A., 1979, Petrology of the upper plate crystalline complex in the eastern Whipple Mountains, San Bernardino County, California: unpublished master of science thesis, University of Southern California, Los Angeles, 193 p.
- Putnis, A., Hinrichs, R., Putnis, C. V., Golla-Schindler, U., and Collins L. G., 2007, Hematite in porous red-clouded feldspars: evidence of large-scale crustal fluid-rock interaction. Lithos, v. 95, p. 10-18.
- Read, H.H., 1948, Granites and granites; in Gilluly, J., (ed.), Origin Of Granite: Geological Society of America Memoir 28, p. 1-19.
- Rong, J, 2002, 45 Myrmekite formed by Na- and Ca-metasomatism of K-feldspar, Myrmekite electronic journal, ISSN 1526-5757, Nr. 45, in http://www.csun.edu/~vcgeo005/Nr45Rong1.pdf. (October 2012)
- Schmid, S.M., et al, 1996, The Bergell pluton (Southern Switzerland, Northern Italy): overview accompanying a geological-tectonic map of the intrusion and surrounding country rocks: Schweizerische Mineralogische und Petrographische Mitteilungen, v. 76, p. 329-355.

- Takagi, T., Naito, K., Collins, L.G., and Iizumi, S., 2007, Plagioclase-quartz rocks of metasomatic origin at the expense of granitic rocks of the Komaki District, southwestern Japan, Canadian Mineralogist, v. 45, pp. 559-580.
- Touret, J.L.R., and Nijland, T.G., 2012, Chapter 11. Prograde, Peak and Retrograde Metamorphic Fluids and Associated Metasomatism in Upper Amphibolite to Granulite Facies Transition Zones; in Harlov, D.E., and Austrheim, H., (eds.), Metasomatism and the Chemical Transformation of Rock, The Role of Fluids in Terrestrial and Extraterrestrial Processes. Springer, New York, p. 415-469.
- Tuttle, O.F., and Bowen, N.L., 1958, Origin of granite in the light of experimental studies in the system NaAlSi₃O₈-KAlSi₃O₈-SiO₂-H₂O, *Geological Society of America Memoirs*, nr. 74, 153 p.
- Vernon, R.H., 1991, Questions about myrmekite in deformed rocks: Journal of Structural Geology, v. 13, p. 979-985.
- Vernon, R.H., and Paterson, S.R., 2002, Igneous origin of K-feldspar megacrysts in deformed granite of the Papoose Flat pluton, California, USA: ISSN 1436-2511, Electronic Geosciences, DOI 10.1007/s10069-002-005-3.
- Wager, L.R., and Brown, G.M., 1967, Layered Igneous Rocks. San Francisco, Freeman and Company, 588 p.
- Weigand, P.W., Barth, A.P., and Ehlig, P.L., 1989, Field trip guide to a portion of the western San Gabriel Mountains, Los Angeles County, California, in Collins, L.G. (ed.), Geologic Excursions in the Greater Los Angeles Area: National Association of Geology Teachers, p. 38-44.
- Wenk, H.R., 1982, A geologic history of the Bergell granite and related rocks; *in* Transformists' Petrology, Drescher-Kaden, F. K., and Augustithis, S. S., eds.: Theophrastus Publications, Athens, p. 113-148.
- Winter, J.D., 2002, *Introduction to Igneous and Metamorphic Petrology*, Prentiss-Hill, New Jersey, 697 p.