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43. Myrmekite formation at Temecula, California, revisited: A photomicrographic essay illustrating replacement textures

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Abstract

A sequence of sixteen photomicrographs of thin sections of unaltered quartz diorite through a zone of deformation to myrmekite-bearing granite near Temecula, California, shows the textural and mineralogical changes that occurred in a quartz diorite as (1) K-metasomatism altered the primary plagioclase crystals to form microcline, myrmekite, quartz-bleb clusters, and recrystallized sodic plagioclase and as (2) Si-metasomatism converted microfractured biotite and hornblende into quartz. Cathodoluminescence, electron microprobe, and scanning electron studies confirm the chemical changes that occurred in the altered and recrystallized minerals. These photomicrographs and others (a) provide clues to the origin of metasomatic granitic in other terranes, (b) show that massive granite lacking gneissic fabric or cataclasis can be formed by K-metasomatism, (c) indicate that sharp contacts between mafic and felsic igneous rocks are not always caused by injection of magma into fractured rock, (d) reveal that complete cataclasis of all normally zoned plagioclase crystals in a mafic rock followed by K-metasomatism results in metasomatic granite lacking both normally zoned plagioclase and K-feldspar megacrysts, and (e) suggest that selective deformation of a few normally zoned plagioclase crystals in a primary rock can result in K-feldspar megacrysts coexisting with normally zoned plagioclase in granodiorite or quartz monzonite.

Introduction

This article is intended to be a supplement to articles http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf and http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf and to provide additional illustrations that show how myrmekite formed in the site near Temecula, California (Collins, 1988ab; Hunt et al., 1992). These illustrations expand the evidence to show how myrmekite can be used as a clue to metasomatic transformations on a plutonic scale in other localities. The description of the field location and outcrops in the Temecula site are given in Collins (1988b). Fig. 1, Fig. 2, and Fig. 3 from this publication show the general locations of the samples from which thin sections and photomicrographs were obtained.

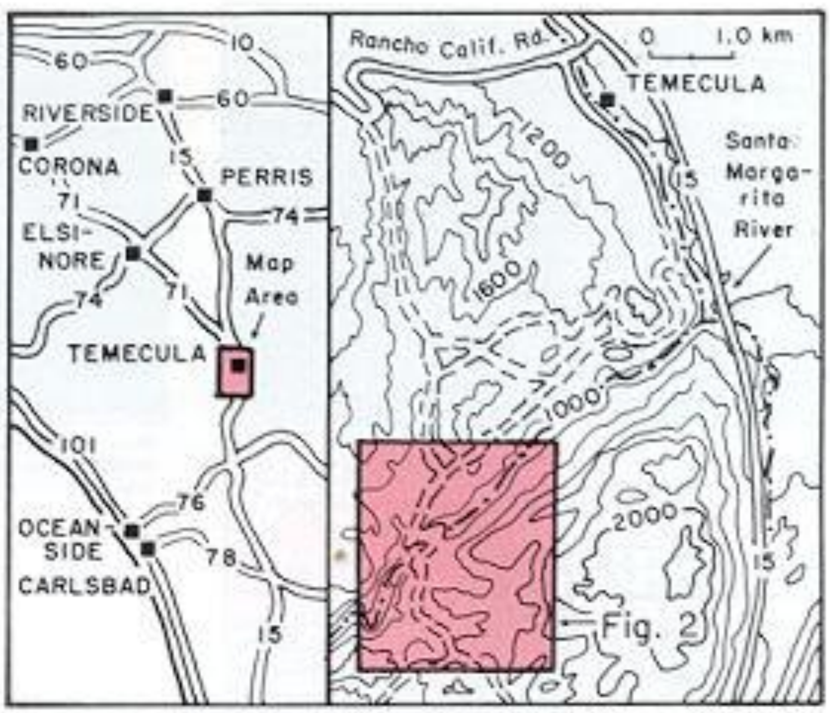


Fig. 1. Location maps for myrmekite-bearing granite extending from the Woodson Mountain granodiorite into Bonsall tonalite near Temecula, California, and locations of outcrops in Fig. 2 and Fig. 3; from Collins (1988b).

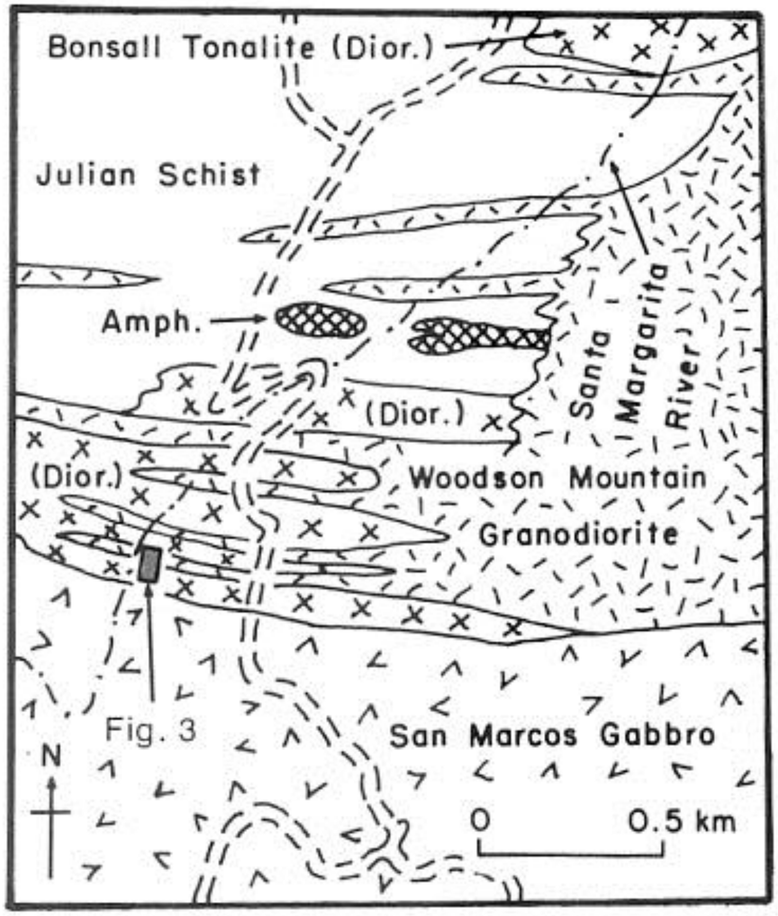


Fig. 2. Simplified geologic map of rocks in the Temecula area; from Collins (1988b). Fig. 3 location at left side; arrow pointing to small rectangle.

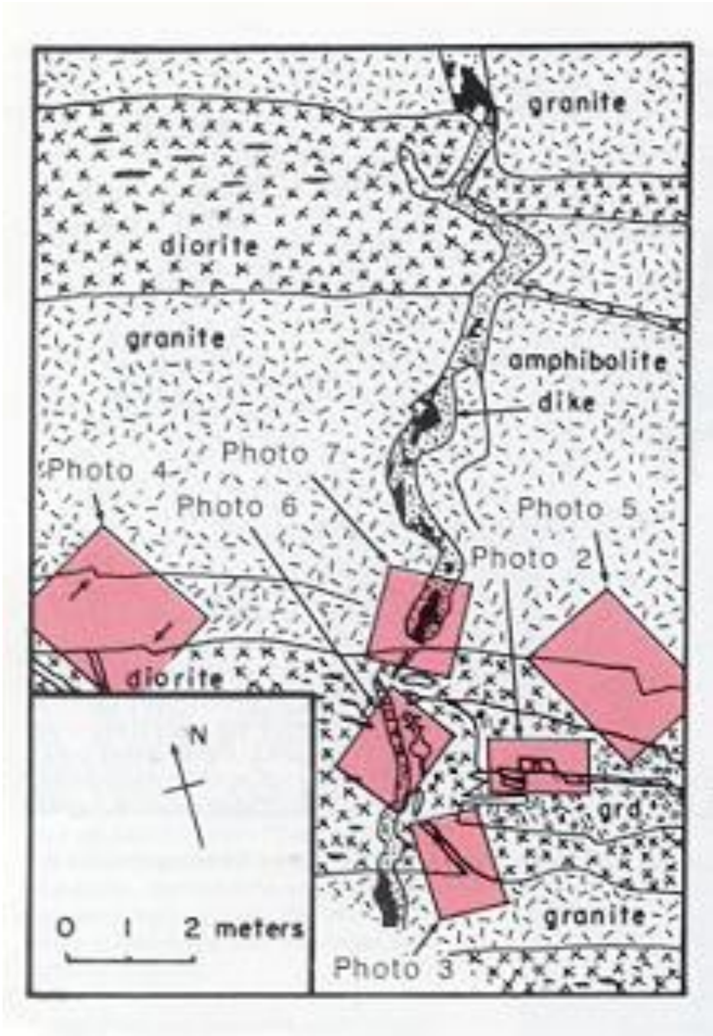


Fig. 3. Schematic outcrop map (not to scale), showing field relationships of different rock types: granite, diorite (Bonsall tonalite, quartz diorite), granodiorite (grd), and amphibolite dike. Elongate black blebs are xenoliths of amphibolite. Pink outlined areas are photo locations in Collins (1988b), but only photo number 7 is shown in this article (Fig. 7).

Geologic setting and generalized petrography

Southwest of Temecula the Bonsall tonalite and the San Marcos gabbro intrude the Julian schist, and then the Woodson Mountain granodiorite intrudes all three of these rock types (Fig. 1, Fig. 2, and Fig. 2). The Bonsall tonalite is labeled diorite on Fig. 3, but hereafter it is called quartz diorite because locally in the area of study it contains quartz. Granitic dikes, extending from the Woodson Mountain granodiorite and penetrating this quartz diorite (Fig. 3), are exposed in stream polished outcrops along the Santa Margarita River. The granitic dikes contain about 55-60% microcline, 30-35% quartz, 1-3% biotite, 5-10% plagioclase An_{12-15}, and up to 1% myrmekite (Fig. 4. Where the quartz diorite is unaltered (west of photo 6, Fig. 3), it consists of 5-15% biotite, 5-15% hornblende, 60-75% plagioclase, and 5-10% quartz. The plagioclase is normally zoned (cores An_{39}; rims An_{20} and albite twinned (Fig. 5). On the basis of electron-microprobe studies, this plagioclase lacks any K in the cores or rims except in parts per million or less. Hornblende and biotite lack quartz in their cores (Fig. 5) and have no apparent alteration. The quartz diorite and the granite dikes (Fig. 3) are cut by an amphibolite dike (a former andesite porphyry; Fig. 6), and the quartz diorite also contains xenoliths of older amphibolite. Compositions of both amphibolites are nearly the same but slightly more mafic than the quartz diorite (Fig. 5). Barely-visible narrow remnants of quartz diorite (3-6 cm wide) border the amphibolite dike on both sides where the amphibolite dike extends through the granite, and narrow fingers of the amphibolite dike extend into remnant quartz diorite **but not into the granite** (Fig. 7).

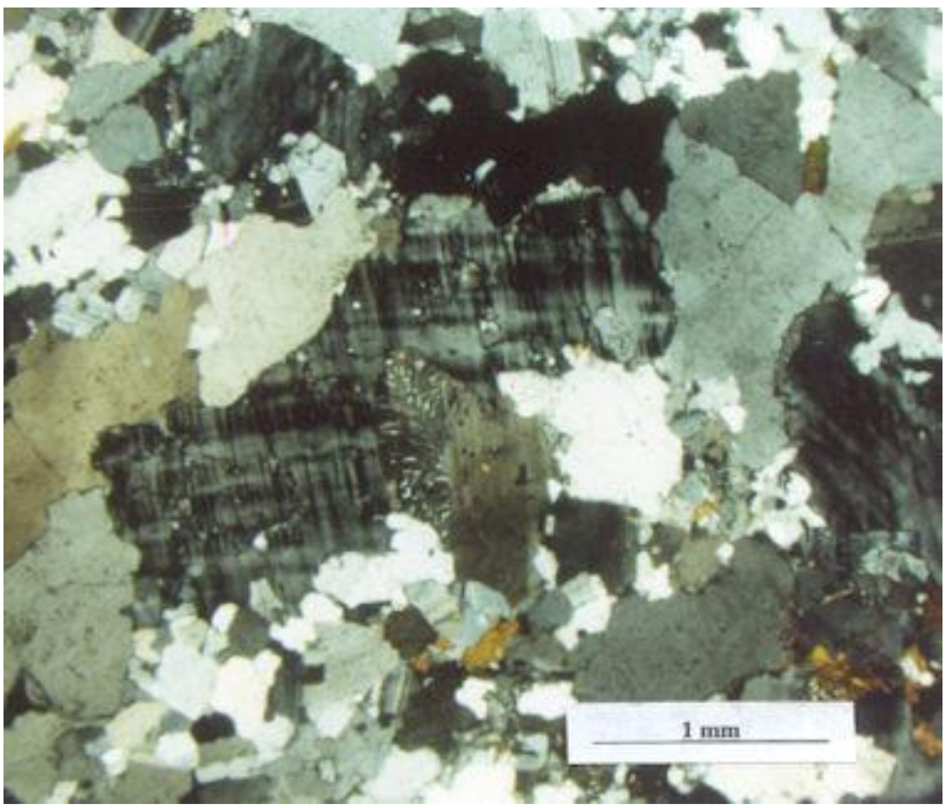


Fig. 4. Photomicrograph of granite containing microcline (grid-twinned; gray), plagioclase (albite-twinned; tan, gray, white), myrmekite (attached to plagioclase and projecting into microcline), quartz (white, gray, cream, tan), and biotite (brown). Texture is hypidiomorphic and has the appearance of being crystallized

from magma. Most microcline grains (not shown in photo) lack myrmekite borders. From granite dike about 3 meters northwest of photo 7 in Fig. 3.

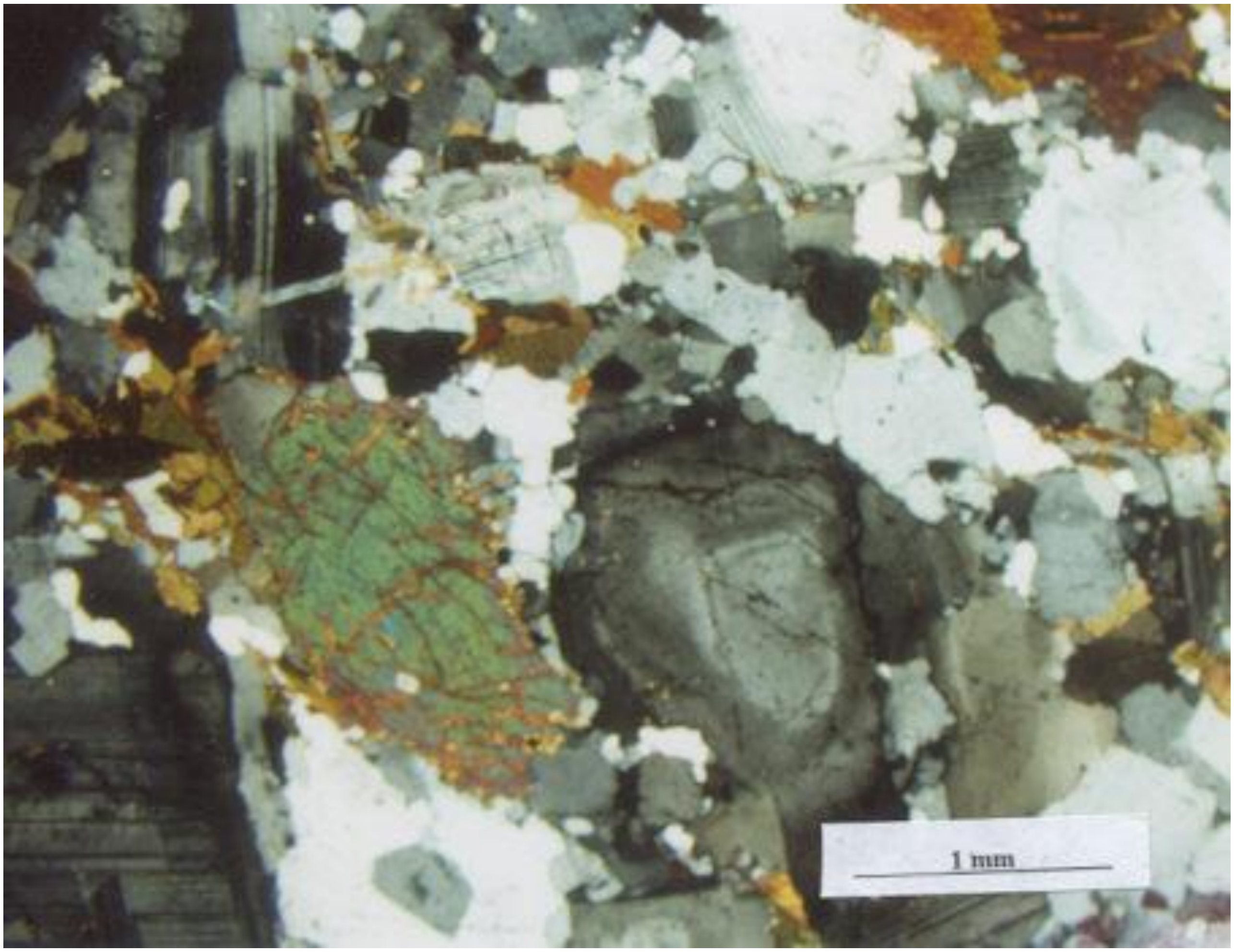


Fig 5. Photomicrograph of quartz diorite (Bonsall tonalite) with unaltered hornblende (green); biotite (brown); zoned plagioclase (gray and dark gray; cores An_{39}; rims An_{20}), quartz (white); albite twinned plagioclase (black, white, and light gray); quartz (mottled gray). Sample collected from relatively unaltered rock west of Photo 6 in Fig. 3.

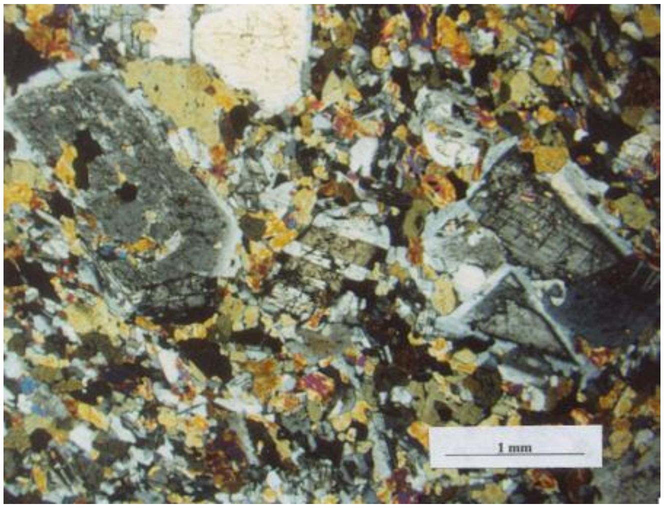


Fig. 6. Photomicrograph of amphibolite dike rock (andesite porphyry), extending north-south through the Bonsall tonalite and Woodson Mountain granite (Fig. 3). The dike has nearly the same composition as the Bonsall tonalite (quartz diorite) but is finer grained. Biotite and hornblende (brown); zoned plagioclase phenocrysts (gray, cream, and white).

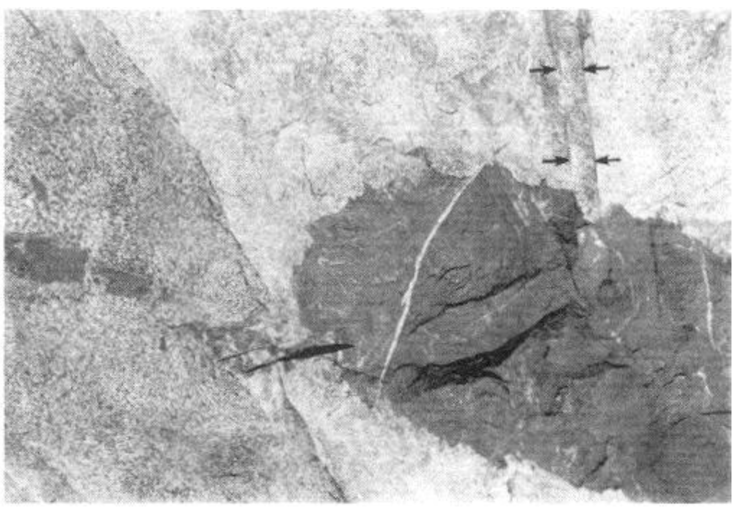


Fig. 7. Quartz diorite encloses a dark amphibolite dike on left and at one time also enclosed a thick part of the dike on the right. A thin remnant of the quartz diorite encloses the amphibolite on both sides, and fingers of the amphibolite extend into the quartz diorite but not into the granite. A thin granite vein extends through the amphibolite, and myrmekite-bearing granite also extends between the thin and thick parts of the amphibolite dike parallel to the quartz diorite-granite contact. Arrows point to two diamond-saw cuts where samples were broken out and where all transition stages between the quartz diorite and granite can be observed in thin sections.

The amphibolite dike has the first appearance of being younger than the granite dikes because the amphibolite dike cuts through the granite (Fig. 3). Closer examination, however, shows that the amphibolite must be older because the granite extends through the amphibolite (photo 7 in Fig. 3; Fig. 7). Therefore, the geologic relationships shown in the outcrop are enigmatic. Which is older -- the amphibolite dike or the granite dike? Moreover, if the granite dike is younger than the amphibolite dike and is formed by magma extending from the Woodson Mountain granodiorite (Fig. 3), a second puzzling aspect is how can a hot, viscous, granitic liquid penetrate the quartz diorite to form the granite dike without disrupting, breaking, or displacing the amphibolite dike?

The textural problem that myrmekite poses for determining its origin

Because the magmatic origin of the granite dikes is problematic, a metasomatic origin is a possibility. In previous studies Collins (1988a) and Hunt et al. (1992) suggested that myrmekite is a clue to K-metasomatic transformations. The microcline in the granite dikes near Temecula, however, looks primary, as if the microcline were former orthoclase of magmatic origin. Moreover, the wartlike myrmekite (Fig. 4), projecting into the microcline, has the appearance of either having been formed **(a)** by exsolution from the microcline or **(b)** by Ca- and Na-replacement of the microcline (Collins, 1997a, 1997c; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf; http://www.csun.edu/~vcgeo005/Nr4CaMyrm.pdf). If the hypidiomorphic texture and mineralogy in the myrmekite-bearing granite (Fig. 4) are compared with the magmatic texture and mineralogy in the biotite-hornblende quartz diorite (Fig. 5), no logical reason seems to exist that would suggest a metasomatic origin of the granite. Nevertheless, close scrutiny of the textures and mineralogy of the quartz diorite and granite provides reasons to support the field evidence of such an origin (Collins, 1988b).

The evidence for metasomatism

Although west of the amphibolite dike (west of photo 6, in Fig. 3), the quartz diorite is unaltered, east of the amphibolite dike (west and north of photo 2, in Fig. 3), it is microfractured, and its plagioclase, hornblende, and biotite show early stages of alteration. The normally zoned plagioclase crystals develop mottled extinction under cross-polarized light (Fig. 8) and have lost some of their albite twinning.

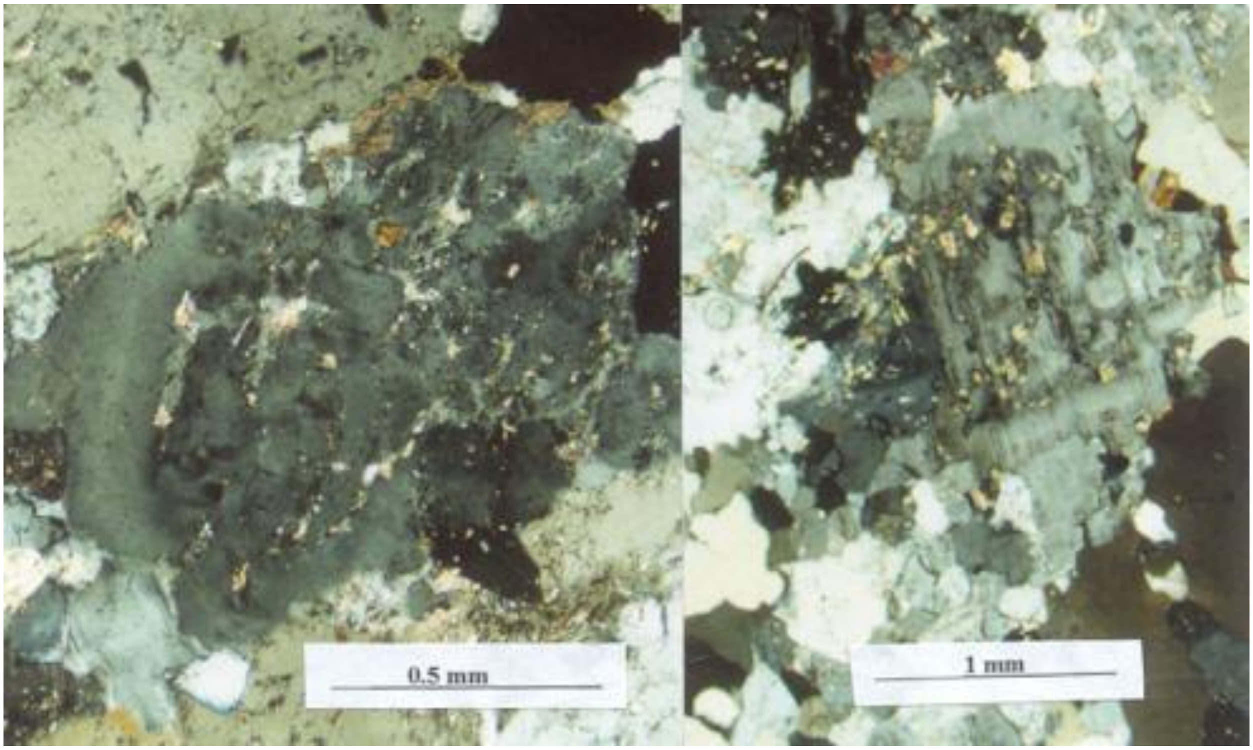


Fig. 8. Left side. Normally zoned plagioclase (light gray with outer sodic rim) in which the core (darker gray, mottled) is microfractured and in the process of losing Ca. **Right side**. Mottled extinction in zoned plagioclase which has been microfractured and in the process of losing Ca from cores of the crystal. Quartz (brownish, tan, cream, white). Microfractures in the plagioclase are not visible under cross-polarized light but are visible in cathodoluminescence images; see Fig. 1 and Fig. 2 in Collins 1997b; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf).

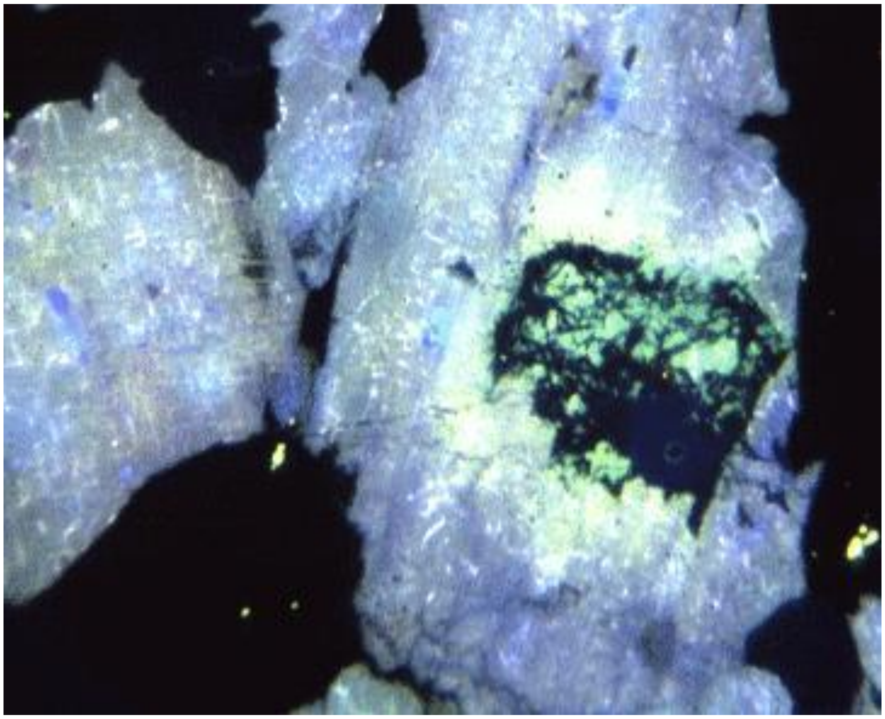


Fig. 1 from Nr2Myrm.pdf. This photo shows a cathodoluminescent image of a normally zoned plagioclase crystal where the host diorite is only slightly deformed. Relatively calcic cores luminesce with pale yellow or yellow-green colors. Toward the rim where it is more sodic, the color becomes beige, then purplish. Not seen in cross-polarized light but apparent under cathodoluminescence is the fact that the plagioclase crystal is slightly fractured. Electron-microprobe studies show that along the fractures calcium has been lost, producing veins of more-sodic residual plagioclase (gray purple) that extends through the crystal (bottom of central crystal and extending into the crystal at top). Locally, tiny islands of K-feldspar (light or bright blue) occur in the center of the veins. Electron microprobe studies show that cores in an unaltered zoned plagioclase grain are $An_{37\text{-}39}$ and rims $An_{17\text{-}20}$. All Si in the analyses fits into the plagioclase crystal structure.

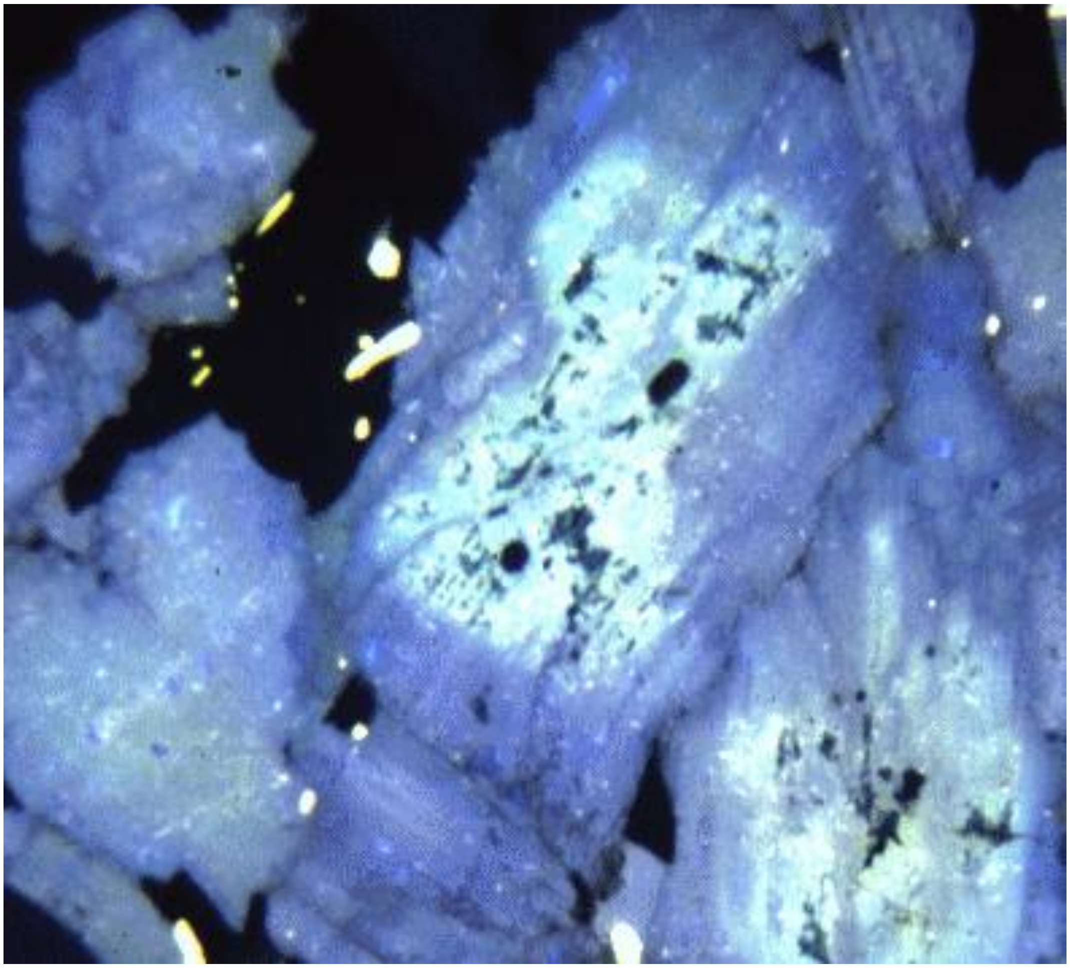


Fig. 2 from Nr2Myrm.pdf. This photo shows a cathodoluminescent image of textures in deformed diorite in transition towards the myrmekite-bearing granite. Two plagioclase crystals show remnant zoning. Cores are now less calcic than in Fig. 1 (greenish-yellow color is now gone). Under cross-polarized light the crystal has mottled extinction, lacks strong zoning, shows no apparent fractures, and exhibits no K-feldspar islands. Under cathodoluminescence, however, fractures are visible, cutting the calcic cores, and along these fractures calcium has been removed (dark veins). Locally, K-feldspar islands (blue) occur where loss of calcium is most advanced. For the plagioclase crystals with uniform beige color, electron-microprobe studies show that both cores and rims have compositions of An_{17-20}. In these crystals electron-microprobe studies also show that Ca has been lost because some Si is in excess of what would normally fit into a balanced feldspar structure relative to the residual Na, Ca, and Al. Note that crystal in upper left has a relatively calcic rim (beige) and more sodic core (purplish) and is in transition to what occurs in Fig. 3.

Cathodoluminescence and electron microprobe studies of the mottled crystals show that the mottling results **from loss of Ca along microfractures**. The subtraction of Ca destroys the zonation and albite twinning and leaves residual Na in the altered lattice (Fig. 1 and Fig. 2 in Collins 1997b; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf; see above). Locally, in nano-sized cracks that penetrate to the cores of the microfractured plagioclase crystals, **tiny islands of K-feldspar are found**. These K-feldspar islands and the microfracturing (cracks) that allowed the removal of Ca and apparent penetration by K-replacement fluids are **invisible under cross-polarized light** (Fig. 8).

In the same places that broken plagioclase crystals are modified east of the amphibolite dike (Fig. 3), some hornblende and biotite crystals develop a quartz sieve texture where the interiors of microfractured crystals are replaced by quartz (Fig. 9 and Fig. 10). Quartz would not be expected to be in the cores of hornblende that would have crystallized at much higher temperatures than quartz. **Therefore, the occurrence of quartz in hornblende cores must represent Si-replacements**.

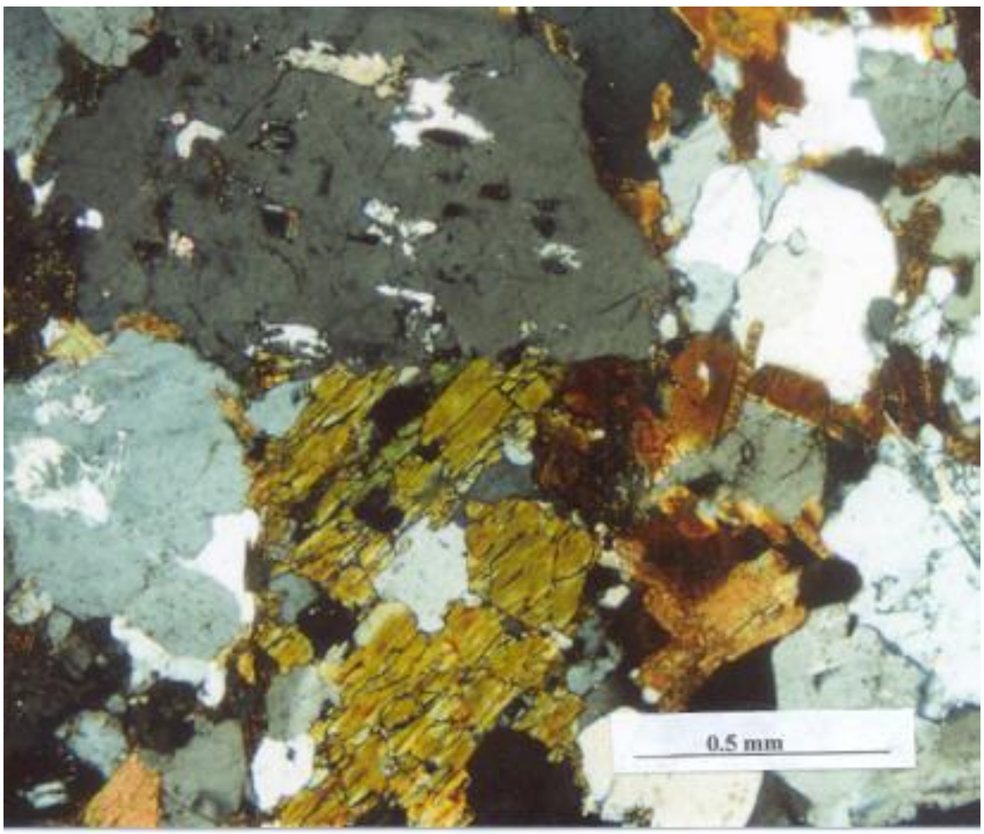


Fig. 9. Hornblende (khaki brown; bottom center) replaced by quartz in interior (white, gray, dark gray). Biotite (brown); quartz (white); plagioclase (shades of gray).

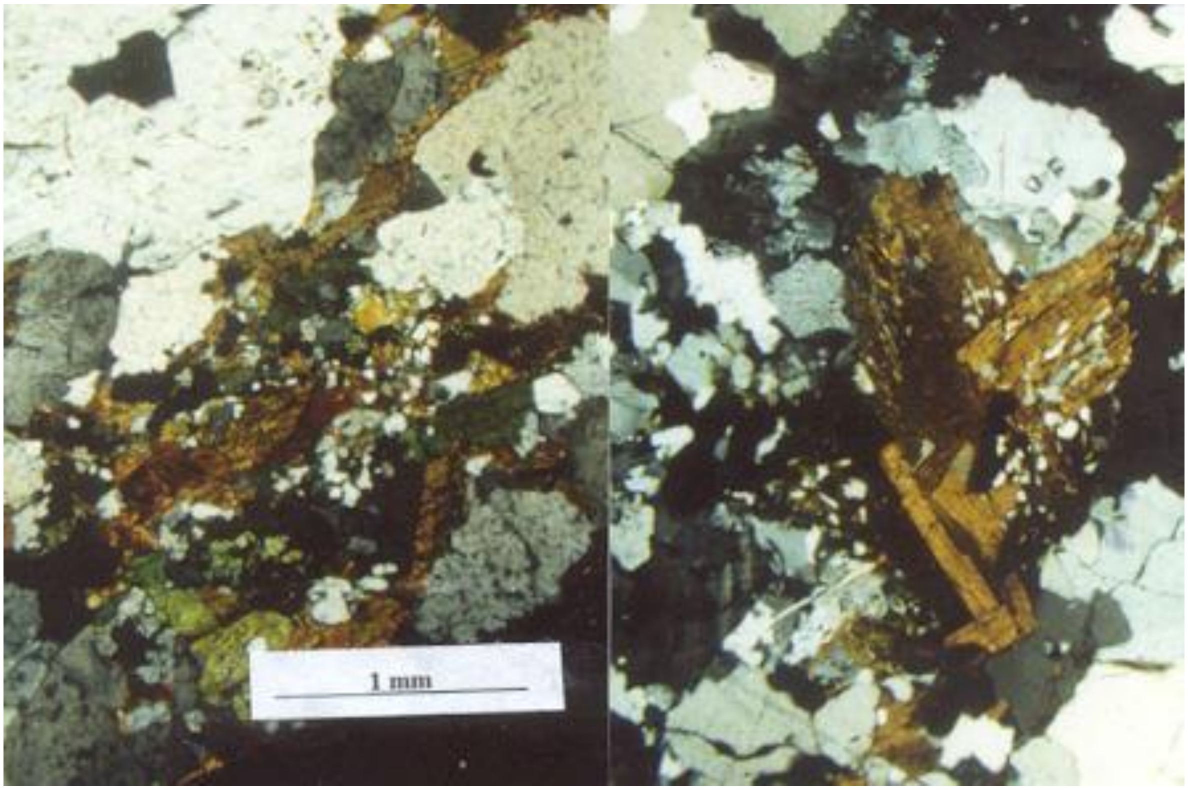


Fig. 10. Left side. Hornblende (brown and olive green) replaced in the interior by tiny grains of quartz (white). Plagioclase (white, cream, gray). **Right side**. Biotite (brown) replaced in interior by tiny quartz grains.

In a few places, interiors of microfractured plagioclase are replaced by visible microcline (Fig. 11), but here also the microfractures that allowed the removal of Ca and Na and introduction of K cannot be observed in cross-polarized light but only in cathodoluminescence images. If these islands of K-feldspar were formed by magmatic processes to produce anti-perthite, then almost all plagioclase crystals should show this K-feldspar-plagioclase intergrowth, and that is not the case.

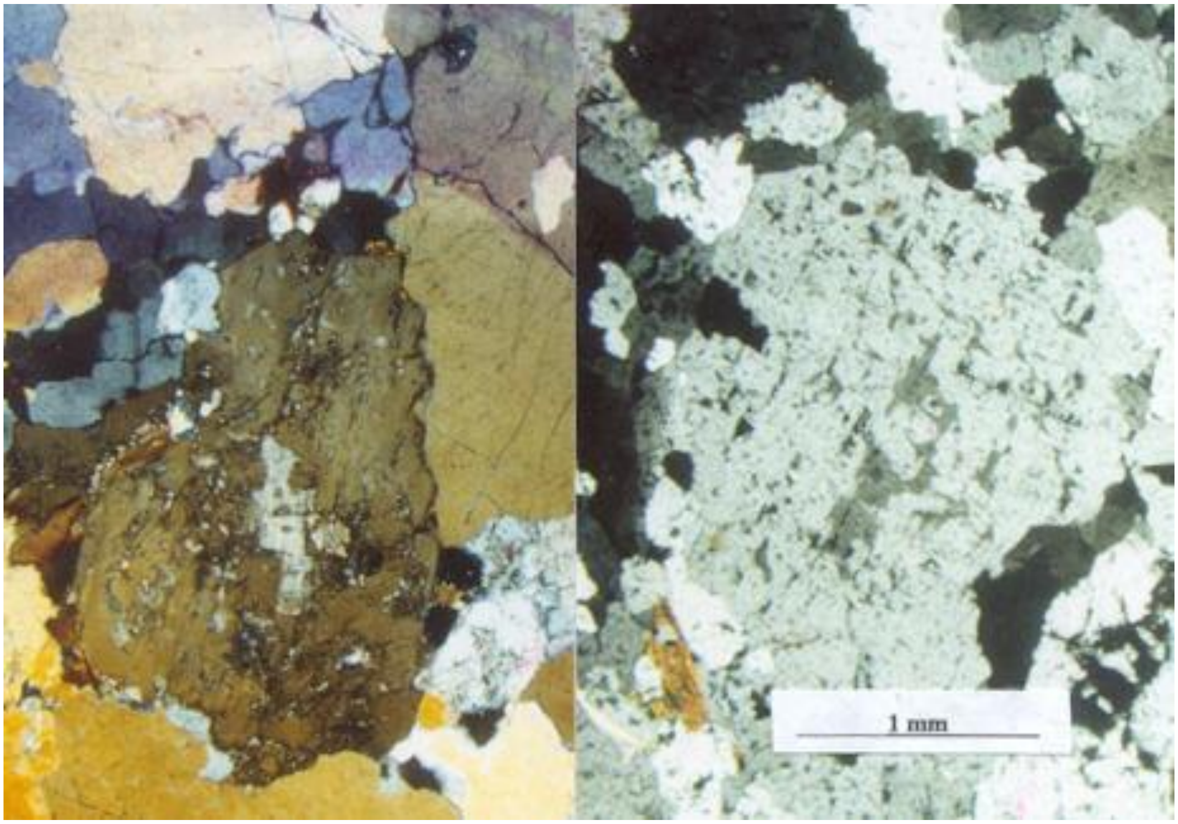


Fig. 11. Left side. Plagioclase crystal (center; tan) replaced in its core by microcline (gray; grid-twinned). Albite twinning of the grid-twinning in the microcline is parallel to the albite twinning of the plagioclase. Quartz adjacent to the plagioclase (orange, yellow, cream gray, and white). **Right side**. Plagioclase (light gray) replaced in the interior by irregular islands of microcline (dark gray). Quartz (white, gray, black). Biotite (brown). The plagioclase grain (whitish gray) has lost its normal zoning and albite twinning. Most nearby plagioclase grains lack these microcline islands.

Mineralogical and textural changes in a 16 cm transition zone

On the west side of the amphibolite dike where it cuts across the granite dike (photo 7, Fig. 3), samples of the narrow border of remnant quartz diorite obtained between the diamond-saw cuts (Fig. 7), contain some hornblende (Fig. 9) and zoned plagioclase (Fig. 8) similar to that in Fig. 5. Microfractured parts of this quartz diorite show early stages in which the normally zone plagioclase crystals begin to lose their albite twinning and zoning. Under cross-polarized light, they exhibit mottled extinction (Fig. 12, left side). Electron microprobe studies show that rims of these mottled crystals are An_{18-20}, and cores are reduced from An_{39} to An_{25-30} (Collins, 1988a). This bordering quartz diorite is first in a sequence of textural and mineralogical changes that occur westward across an interval of 16 cm to the granite (between the saw cuts; Fig. 7). The changes are not uniform but irregular from place to place, depending upon the local degree of microfracturing and cataclasis.

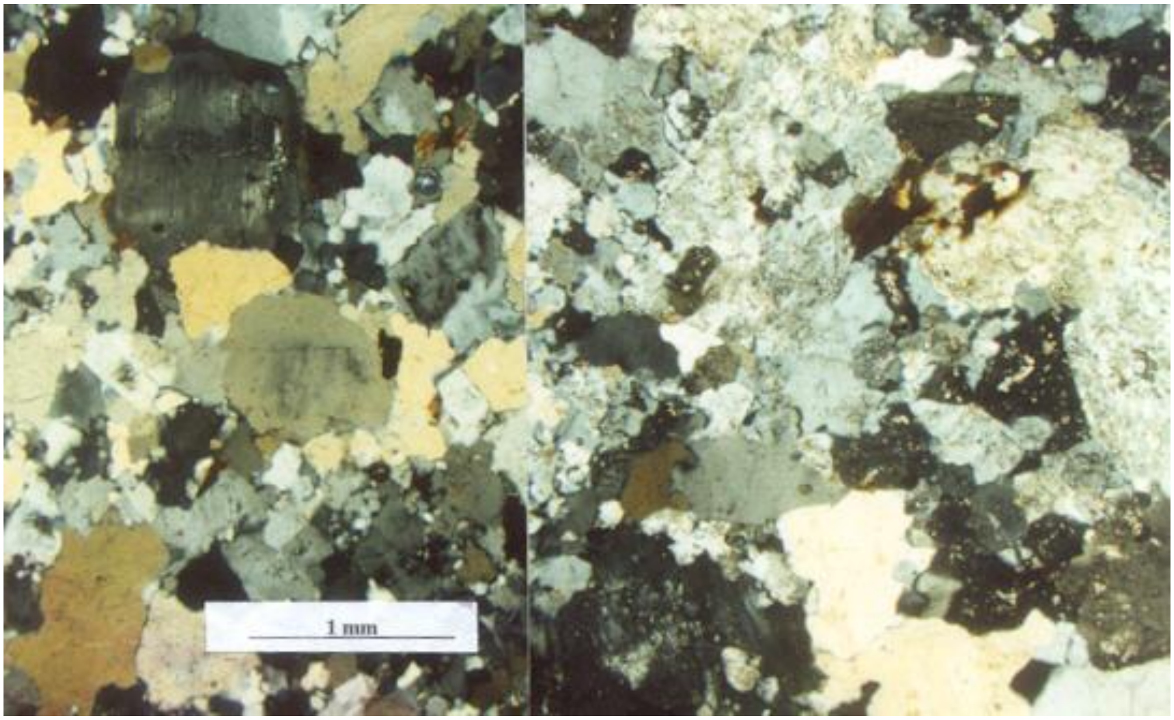


Fig. 12. Left side. Plagioclase grains (cream, white, gray), some of which show mottled extinction under cross-polarized light. The dark gray plagioclase (top left) has remnant albite twinning. Several plagioclase crystals have been altered internally and have lost their albite twinning and normal zoning. 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 invisible islands of K-feldspar. See Fig. 3 in Collins (1997b; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf). Biotite (brown); quartz (white).

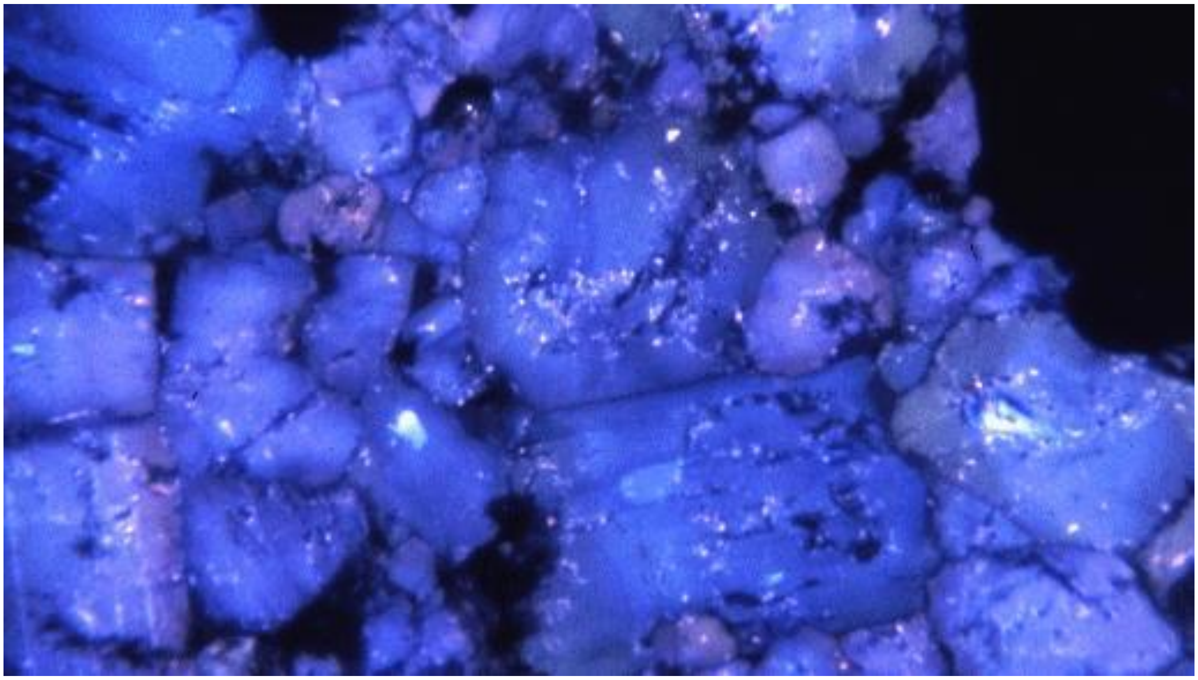


Fig. 3 in Nr2Myrm.pdf. Plagioclase crystals in this cathodoluminescent image are still closer to the myrmekite-bearing granite in strongly altered diorite that lacks hornblende (replaced by quartz). Abundant K-feldspar has not yet been introduced. Here, many plagioclase crystals have reversed zoning with sodic cores (pink) and relatively-calcic rims (beige grading to dark blue in center of crystals). Under cross-polarized light, the crystals are speckled but clear and lack any albite twinning. One crystal has a tiny island of K-feldspar (light blue, center of photo). Electron microprobe studies show that pink grains have rims An_{17-20} and cores An1-5 while beige-grading-to-purple grains have cores and rims of An_{17-20}. In cores of some pink grains with sodic cores, silica is in excess of what would fit into a plagioclase feldspar structure, but no quartz is visible under cross polarized light. Also in some cores, probe analyses show that K_2O locally ranges from 1 to 50%, but no microcline is visible in cross-polarized light but may be seen in cathodoluminescence (not shown).

Next in this sequence, (a) hornblende is no longer present and presumably replaced totally by quartz, (b) biotite is reduced in volume and presumably partly replaced by quartz, (c) quartz increases in volume proportional to probable losses of hornblende and biotite, and (d) the mottled plagioclase crystals gradually but completely lose their albite twinning and normal zoning (Fig. 12, right side). In these places cores and rims of some modified plagioclase crystals have about the same composition, An_{18-20}; others have reverse zoning with cores An_{15} and rims An_{18-20}. Electron microprobe studies show that these altered plagioclase crystals contain local concentrations of K (up to 50% K-feldspar), but there is no optical indication of either K-feldspar or microfractures in these altered plagioclase crystals under cross-polarized light (Fig. 12, right side). It is apparent from the textures and alterations that the volumes of the plagioclase crystals remain constant, but Ca and some Al in the plagioclase interiors are being emptied as K is introduced locally in some places.

Still farther west toward the granite, many large plagioclase crystals are broken into an aggregate of smaller crystals (Fig. 13, right side). All these plagioclase crystals (large and small) are strongly altered internally as indicated by cathodoluminescence and electron microprobe studies. The large plagioclase crystals (not shown in Fig. 13) and the small plagioclase crystals in the aggregates (Fig. 13, right side) all have reversed zoning with rims of An_{17-18} and cores ranging as low as An_5. Residual Na, remaining after Ca and some Al were subtracted, makes the cores albitic in composition (Fig. 3 in Collins, 1997b; http://www.csun.edu/~vcgeo005/Nr2.pdf; see above).

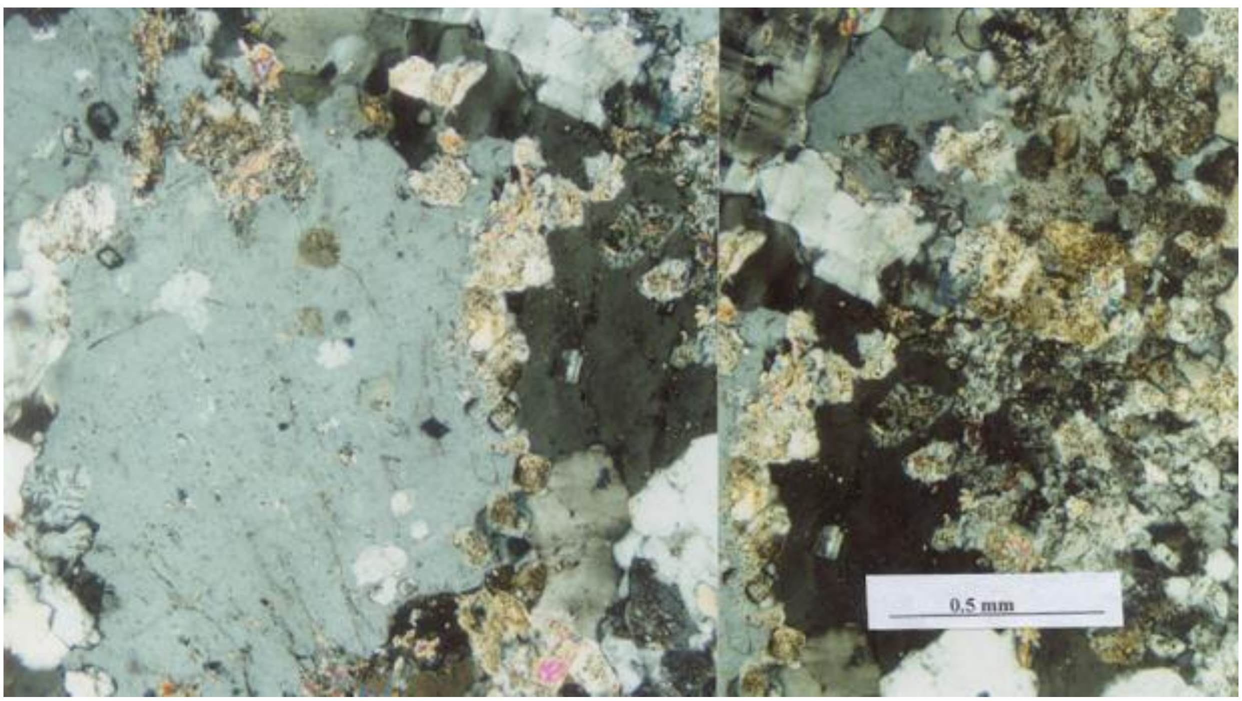


Fig. 13. Left side. Microcline (light gray; large grain in left half) surrounded by granules of plagioclase with speckled appearance. **Right side**. This image is from the same thin section and adjacent to the image on the **left**, but the image is diagonally offset downward to the right to show a different optic orientation. Microcline (black) in the right image is the same as microcline (dark gray) in the left image. Note that plagioclase grains in the right image have been broken into

an aggregate of speckled grains. In the upper part of the dark gray and black microcline grain is an **isolated grain that is in the process of recrystallizing to become myrmekite with quartz vermicules**. In the far lower left side of the light gray microcline (**left side**) are two myrmekite grains (white, projecting into the microcline) that are farther along in their recrystallization and have lost their speckled appearance. The quartz vermicules (dark gray) are very narrow and not well developed. Speckled grains have reversed zoning with cores as low as An_5 and rims An_{17-18}. See Fig. 3 in Collins (1997b; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf ; see above).

In thin section these altered grains have a speckled appearance (Fig. 12 and Fig. 13) because of later low-temperature weathering (alteration) of the rocks. Scanning electron images of these speckled grains at magnifications of 1600x and 8000x show that these grains are full of nano-sized holes, and that K and Ba have replaced the plagioclase along the rims of the holes. (Fig. 4a and Fig. 4b in Collins, 1997b; http://~www.csun.edu/~vcgeo005/Nr2Myrm.pdf).

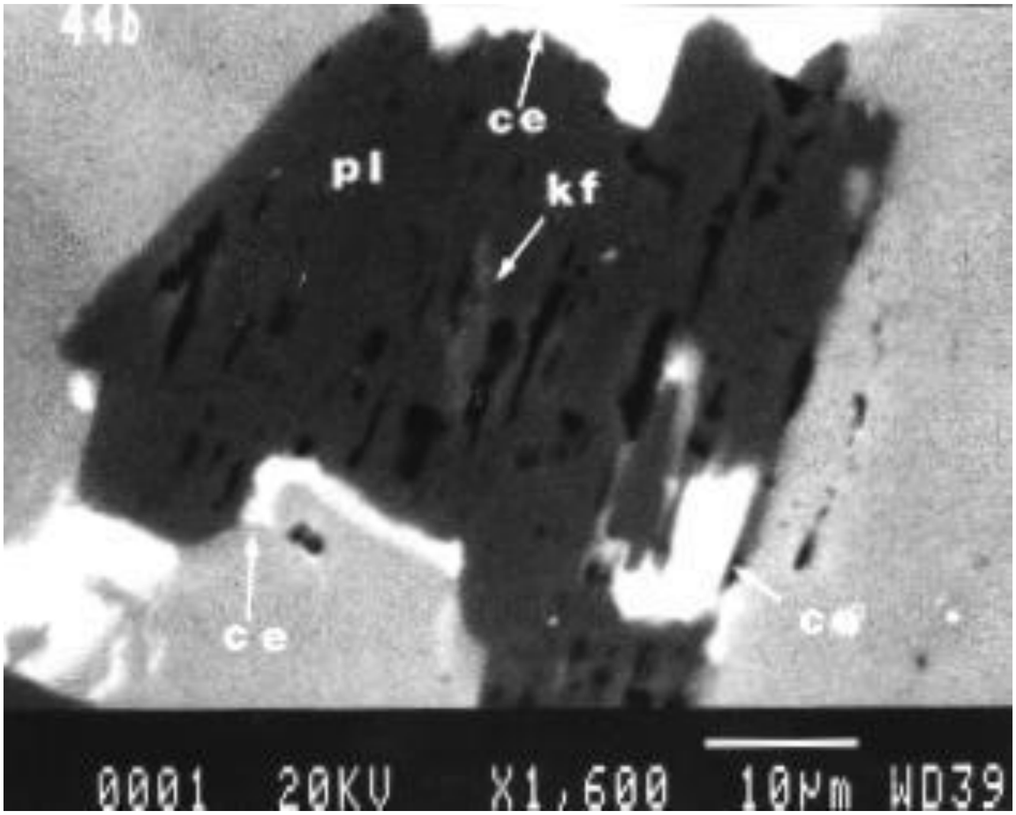


Fig. 4a in Nr2Myrm.pdf. This scanning-electron photomicrograph is an image in the center of a soda-rich core of a plagioclase crystal in Fig. 3, but now magnified 1,600x. The enlarged image shows that the plagioclase (pl, dark gray) is full of holes (black) with angular boundaries parallel to the plagioclase crystal lattice and that many holes are bordered by concentrations of K (lighter gray, incipient K-feldspar, kf). Locally, Ba is concentrated in celsian (ce, white, both images), and in some places the celsian occurs on hole walls adjacent to the K concentrations. The identification of element concentrations is confirmed by microprobe studies

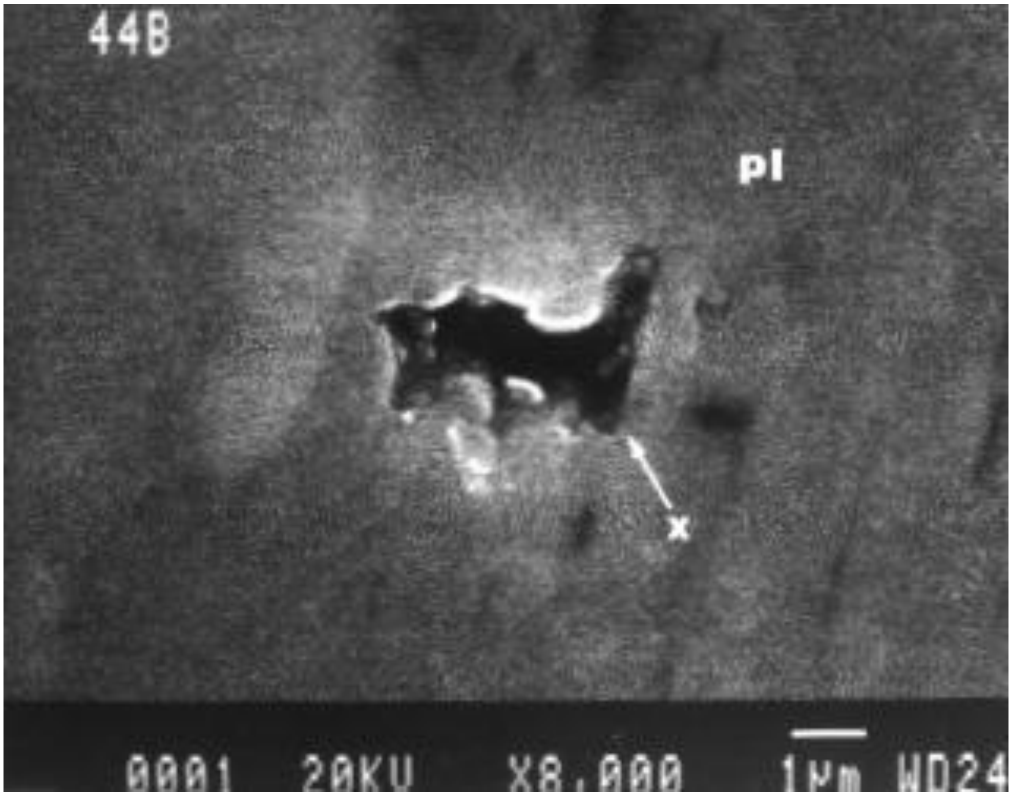


Fig. 4b in Nr2Myrm.pdf. This scanning-electron photomicrograph is from the same area as in Fig. 4a but now magnified 8,000x. The "x" points to a hole (black) bordered by concentrations of K (light gray). Locally, Ba is concentrated in celsian (ce, white), and in some places the celsian occurs on hole walls adjacent to the K concentrations. Identification of element concentrations is confirmed by microprobe studies.

Nearer to the granite from this stage of mineral modifications, microcline makes its first appearance as large crystals (Fig. 13, left side). On the basis that K is shown to enter the nano-sized holes in the altered plagioclase lattice, the large microcline crystals are interpreted to represent places where many altered plagioclase grains (large and small) were totally replaced by K-bearing fluids. Some altered plagioclase grains, however, did not become replaced and either became inclusions or still remained as aggregates along microcline borders. Some of these inclusions and altered plagioclase crystals bordering the microcline, however, show the **first stages for their recrystallization to become myrmekite**. The first quartz vermicules in the altered plagioclase grains (early myrmekite) initially have fuzzy poorly-defined borders (Fig. 13) or are represented by narrow veins with little quartz in them (Fig. 13; lower left of **left** side).

The origin of the quartz vermicules in the myrmekite is interpreted to result from recrystallization of the altered (speckled) plagioclase grains that lost both Ca and some Al from their cores. That is, the altered plagioclase lattice has an imbalance in the amounts of residual Ca, Na, Al, and Si that would normally all combine to produce only plagioclase feldspar. During recrystallization, too much Si remains in the altered lattice to utilize all of the residual Na, Ca, and Al to form only plagioclase. The excess Si migrates to localized places to form quartz vermicules as the remaining altered lattice recrystallizes as plagioclase, which encloses the vermicules. The fuzzy and narrow boundaries of the initial quartz vermicules (Fig. 13) show the early stages of the recrystallization of the altered (speckled) plagioclase grains that are converting to myrmekite.

The narrowness of the tiny quartz vermicules in the final recrystallized myrmekite reflects the fact that the primary plagioclase crystals had little Ca and Al in them initially (averaging An_{30}) in comparison to more calcic primary plagioclase species in other terranes with greater amounts of Ca and Al and higher An-contents. Therefore, at Temecula, where lesser amounts of Ca and Al are lost from the altered plagioclase lattice, nut much excess Si remains to produce quartz vermicules in myrmekite (Collins, 1988a; Hunt et al., 1992). For examples, compare quartz vermicules in myrmekite in Fig. 19 with:

(a) intermediate-sized quartz vermicules in Fig. 4 in Collins (1997a; http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf) where the primary plagioclase was An_{40-50},

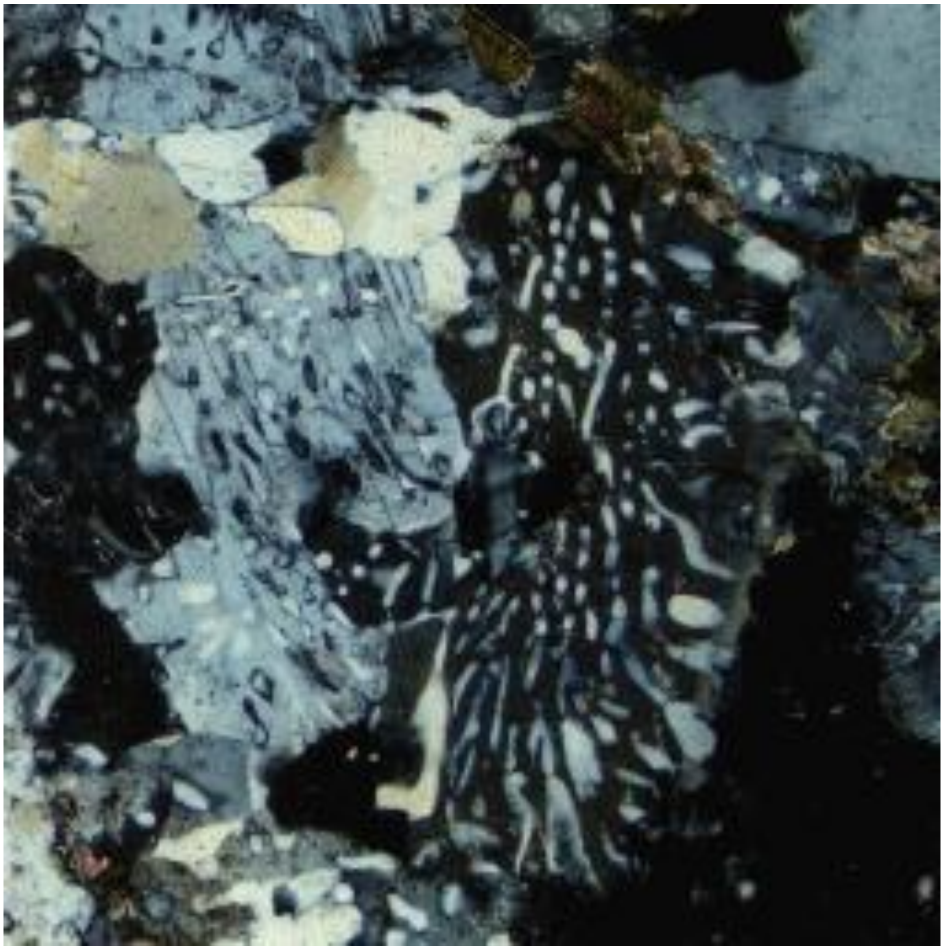


Fig. 4 in Nr1Myrm.pdf. This photomicrograph is from granite in the Cargo Muchacho Mountains in southeastern California.

(b) very wide vermicules in Fig. 16 and Fig. 17 in Collins (2001b; http://www.csun.edu/~vcgeo005/~vcgeo005/Nr40Wanup.pdf where the primary plagioclase was about An_{60-70},

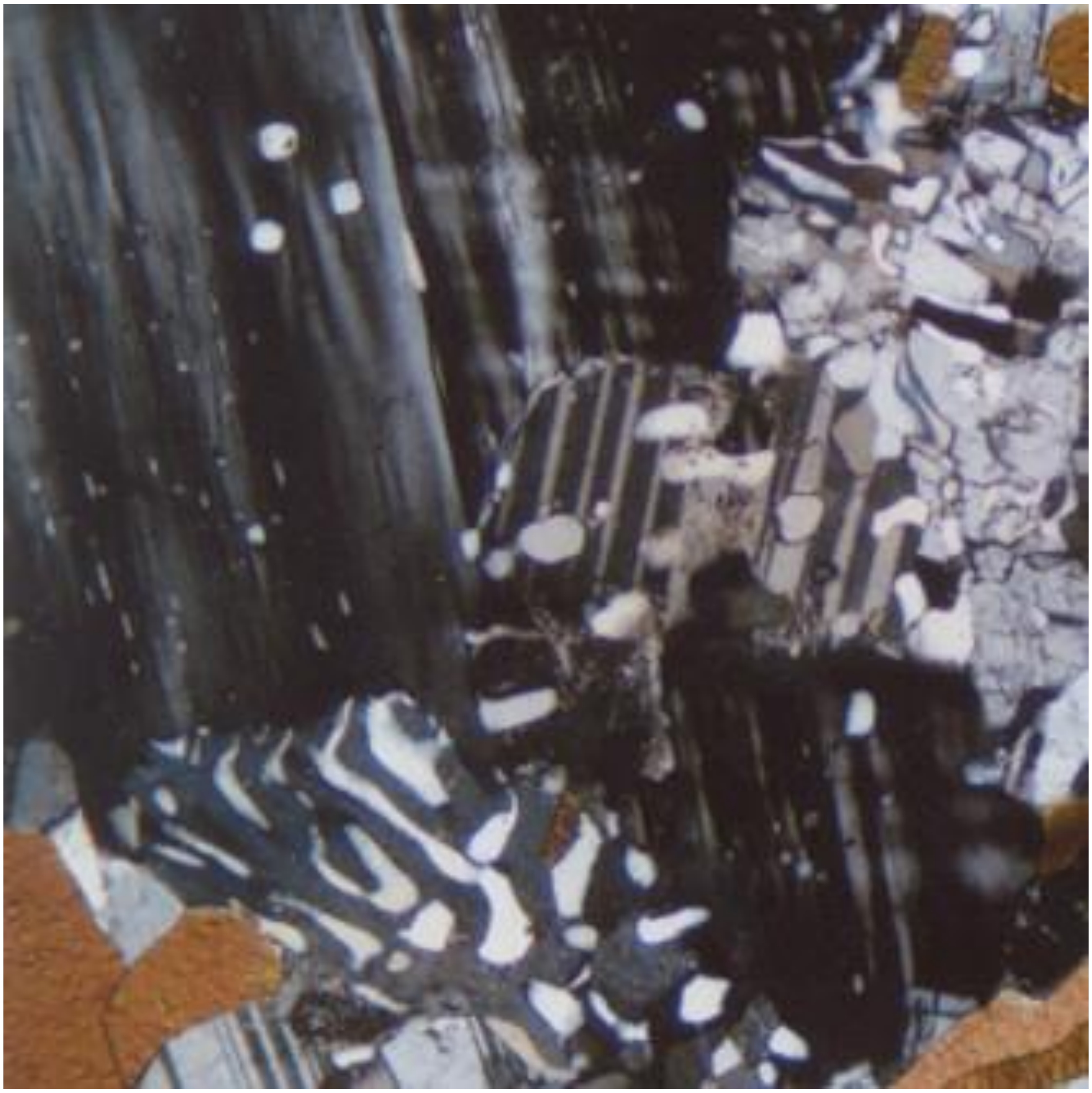
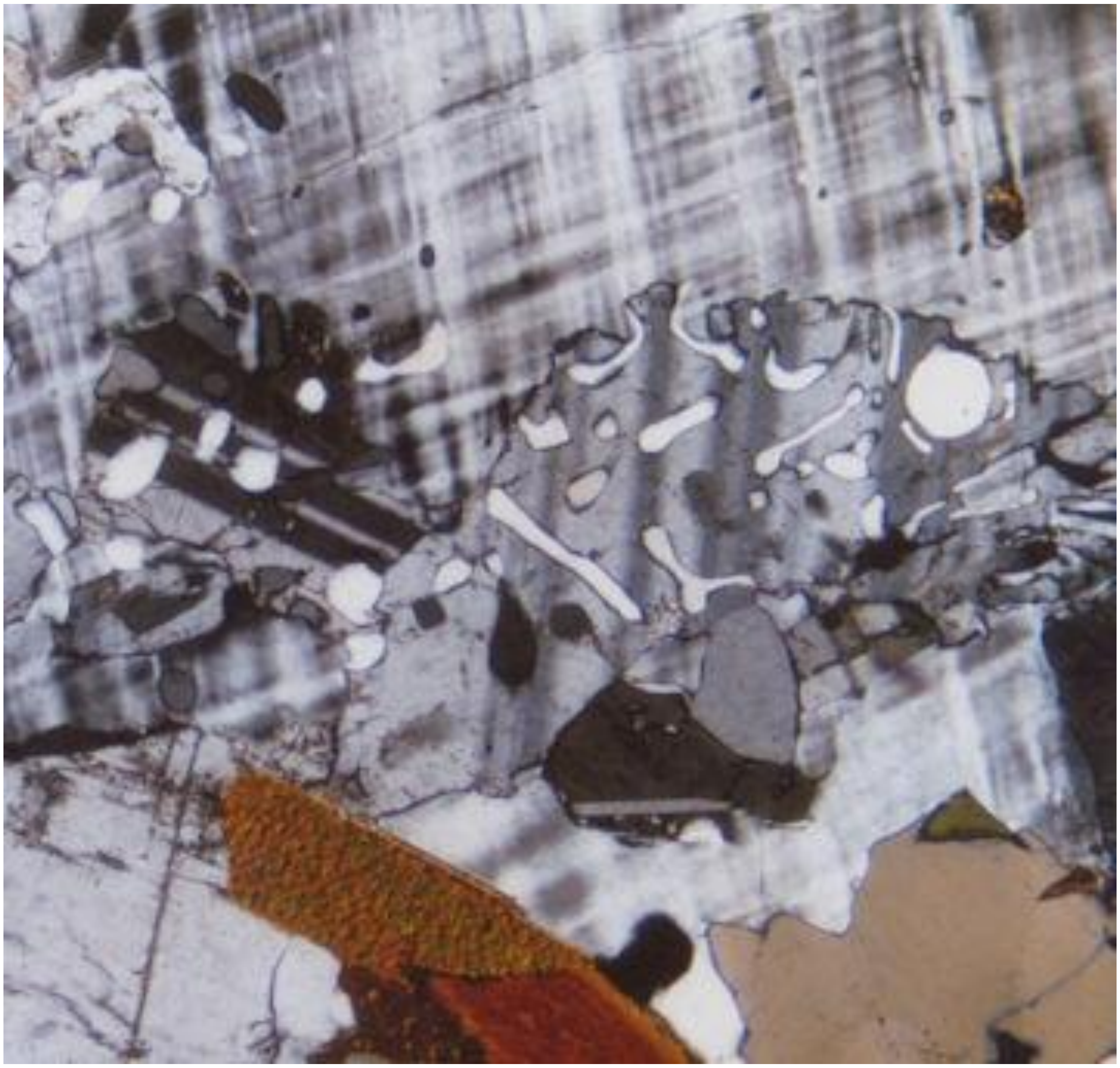


Fig. 16 in Nr40Wanup.pdf. Myrmekite from a megacrystal granitic layer in the Wanup pluton on the south side of Route 69. Microcline (black, grid pattern) contains large and small quartz blebs of ghost myrmekite. Biotite (brown); plagioclase (albite-twinned; gray and white); quartz (white).



Nr17 in Nr40 Wanup.pdf. Myrmekite from a megacrystal granitic layer in the Wanup pluton on the south side of Route 69. Microcline (black, grid pattern) contains large and small quartz blebs of ghost myrmekite. Biotite (brown); plagioclase (albite-twinned; gray and white); quartz (white).

And **(c)** very tiny, narrower vermicules in Fig. 2 in Collins (1997a; http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf) where the primary plagioclase was about An_{20}.

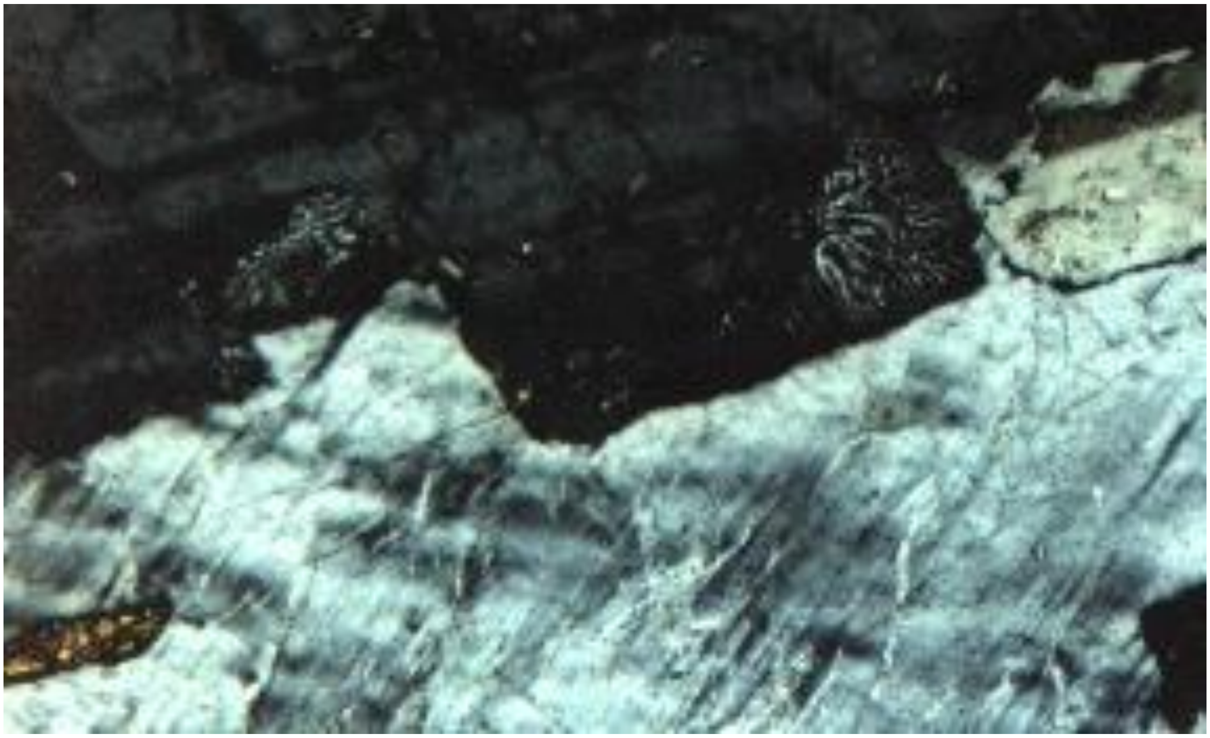


Fig. 2 in Nr1Myrm.pdf. This photomicrograph shows myrmekite (upper right quadrant) in the S-type Cottonwood Creek granite pluton in Australia.

At any rate, the transitional stages between the speckled altered plagioclase grains free of quartz vermicules and the same-sized grains with quartz vermicules in myrmekite make it clear that the tiny myrmekite granules bordering microcline **did <u>not</u> result from (1) primary crystallization from magma, (2) exsolution from primary orthoclase, or (3) Ca- and Na-metasomatism of former primary K-feldspar (orthoclase or microcline), but <u>originated by recrystallization of altered primary plagioclase grains</u>**; see also Collins (1988a; Hunt et al., 1992).

Still farther west toward the granite, two types of quartz-bleb clusters appear in the microcline and represents different degrees to which some of the altered plagioclase grains (Fig. 13, right side) were modified prior to incomplete replacement by the microcline. One type consists of tiny quartz blebs instead of tapering quartz vermicules in residual plagioclase (left third and middle third, Fig. 14 and Fig. 15). The enclosing plagioclase fades into the microcline without a distinct border against the microcline. The other type consists of clusters of quartz blebs in the microcline without any evidence of being enclosed by plagioclase (left third and right third, Fig. 14).

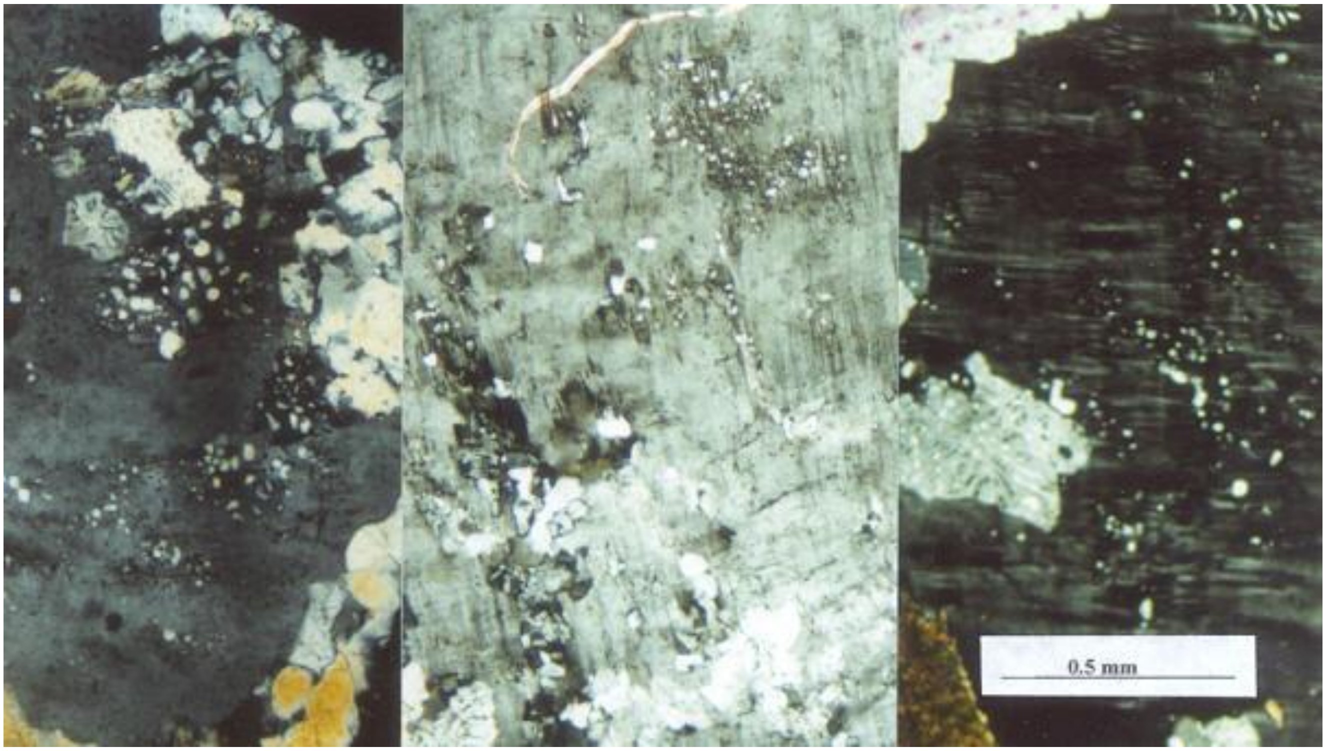


Fig. 14. Left third. Microcline (dark gray) surrounding (a) myrmekite, (b) quartz-bleb clusters in plagioclase in which the boundary between the plagioclase and the microcline is not well defined, and (c) quartz-bleb clusters in the microcline. Quartz (cream, yellow). **Middle third**. Grid-twinned microcline (light gray) with quartz-bleb clusters in plagioclase with fuzzy borders against the microcline (upper half, near cotton tissue thread). **Right third**. Microcline (black) with a myrmekite projection (left side) in which the tiny quartz vermicules are not yet well developed by recrystallization. Quartz-bleb clusters with tiny quartz blebs (white) occur in the microcline.

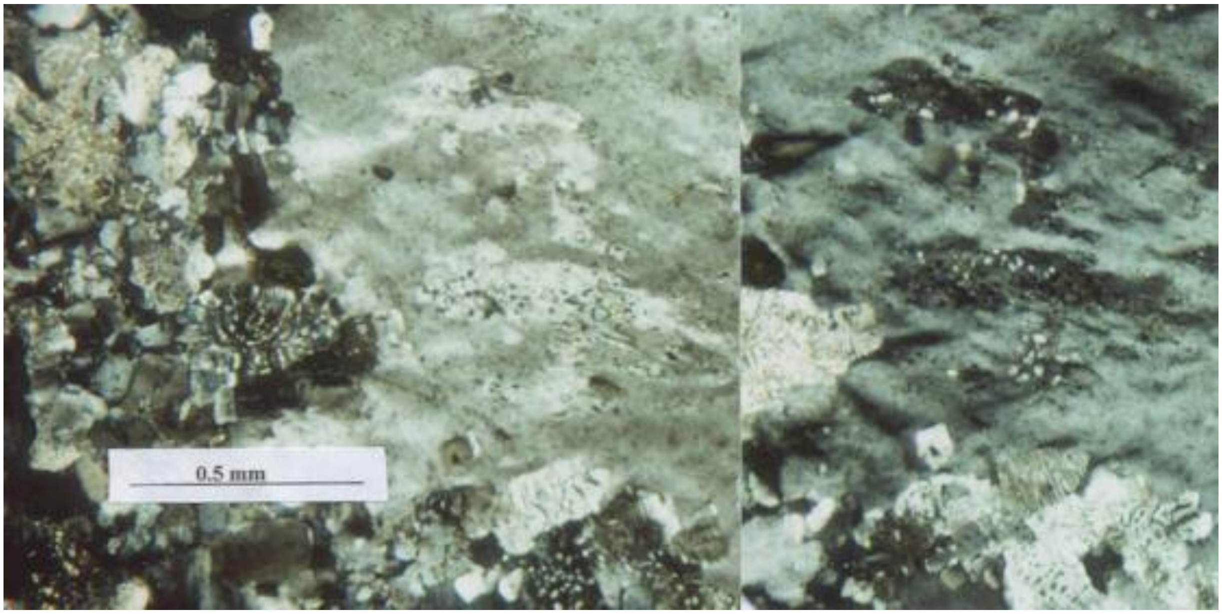


Fig. 15. Left side. Myrmekite with tiny quartz vermicules (white; left side) borders microcline (light gray; right half). All myrmekite granules now have lost the speckled appearance that is seen in Fig. 12 and have well-defined quartz vermicules that do not have hazy borders. **Right side**. The image here is the same as seen in the right part of the **left side** but in a different optic orientation. Quartz-bleb clusters in the **left image** consist of plagioclase (white) that has poorly defined borders against the microcline and the enclosed quartz blebs are black and gray spots. Quartz-bleb clusters in the **right image** consist of plagioclase (black) that encloses tiny quartz blebs (white and black spots).

In the first type, the imbalance of Na, Ca, Al, and Si probably includes some K mixed into the lattice, as indicated by the scanning electron images of K in rims of holes in an altered plagioclase lattice (Fig. 4a and Fig. 4b in Collins, 1997b; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf; see above). The lattice in these places, however, still has excess Si to form quartz blebs when the remainder of the lattice recrystallized as a mixed Na-K plagioclase feldspar. K in the mixed Na-K plagioclase feldspar allows this feldspar (hosting the quartz blebs) to fade into the microcline as the K-content in the altered lattice gradually increases to the amounts in the adjacent microcline.

In the second type, the residual altered plagioclase lattice has lost, not only Ca and Na where the K has been introduced, but also more Al than is required to make microcline in the same volume. If insufficient residual Al remains in the altered silicate lattice, introduced K cannot incorporate all of the silica in this lattice to form only microcline, and, therefore, some is left over to form clusters of isolated quartz blebs.

These two types of quartz-bleb clusters were initially called "**ghost myrmekite**" (Collins, 1988a), because the textures looked as if microcline had incompletely replaced former myrmekite, leaving it as a ghost, but that is not the case. The "ghost" replacement possibility is implied in some rocks, particularly when quartz vermicules seem to continue from the margin of the myrmekite into the microcline as strings of quartz blebs. Nevertheless, myrmekite and these two types of quartz-bleb clusters have their own but related origins, and the latter two are not "ghosts of myrmekite." What forms is a function of the degree to which Al, Ca, and Na have been removed from the altered plagioclase lattice and the degree to which K entered this altered lattice prior to recrystallization, as described above.

Where the two types of quartz-bleb clusters are found, the coexisting myrmekite inclusions in the microcline and aggregates of myrmekite on microcline borders have completely recrystallized (Fig. 15), and they no longer have the speckled appearance that is observed in Fig. 12 and Fig. 13). The excess Si has completed its diffusion from the altered lattice, where Na, Ca, Al, and Si were imbalanced, to form distinct quartz vermicules, and these vermicules are slightly thicker than in the first stages and no longer have fuzzy borders (Fig. 13).

The final mineralogical and textural changes that produce the myrmekite-bearing granite

Finally, in the last stages of the gradual conversion of the altered quartz diorite to is granite (across the 16 cm of the transition), the large altered plagioclase crystals (like that in Fig. 12, right side) have recrystallized to form **unzoned** plagioclase An_{12-15} **that develops albite twinning again** (Fig. 16). As the recrystallized plagioclase is formed, the volume of coexisting microcline increases to greater than 50 percent. Some of these microcline crystals have aggregate myrmekite on their borders (Fig. 16 and Fig. 17) and/or interior quartz-bleb clusters (Fig. 18), but most are relatively clean, devoid of inclusions or myrmekite borders. Generally, there is less than 1 vol. % myrmekite, but included in this volume is an additional type of myrmekite, called **wartlike myrmekite**. Wartlike myrmekite is distinguished from aggregate myrmekite in that wartlike myrmekite consists of a single quartz-plagioclase intergrowth-grain that is attached to non-quartz-bearing plagioclase while projecting into microcline as "warts" or cauliflower-like structures. Aggregate myrmekite is composed of many isolated grains are unattached to non-quartz-bearing plagioclase. To explain the origin of wartlike myrmekite requires understanding how the unzoned plagioclase An_{12-15} is formed.

Fig. 16. Microcline (black; above scale) bordered by myrmekite granules and adjacent to albite-twinned plagioclase (dark gray; left of center). Brightly colored lozenge-shaped grains are contaminants in the glue holding the cover slip.

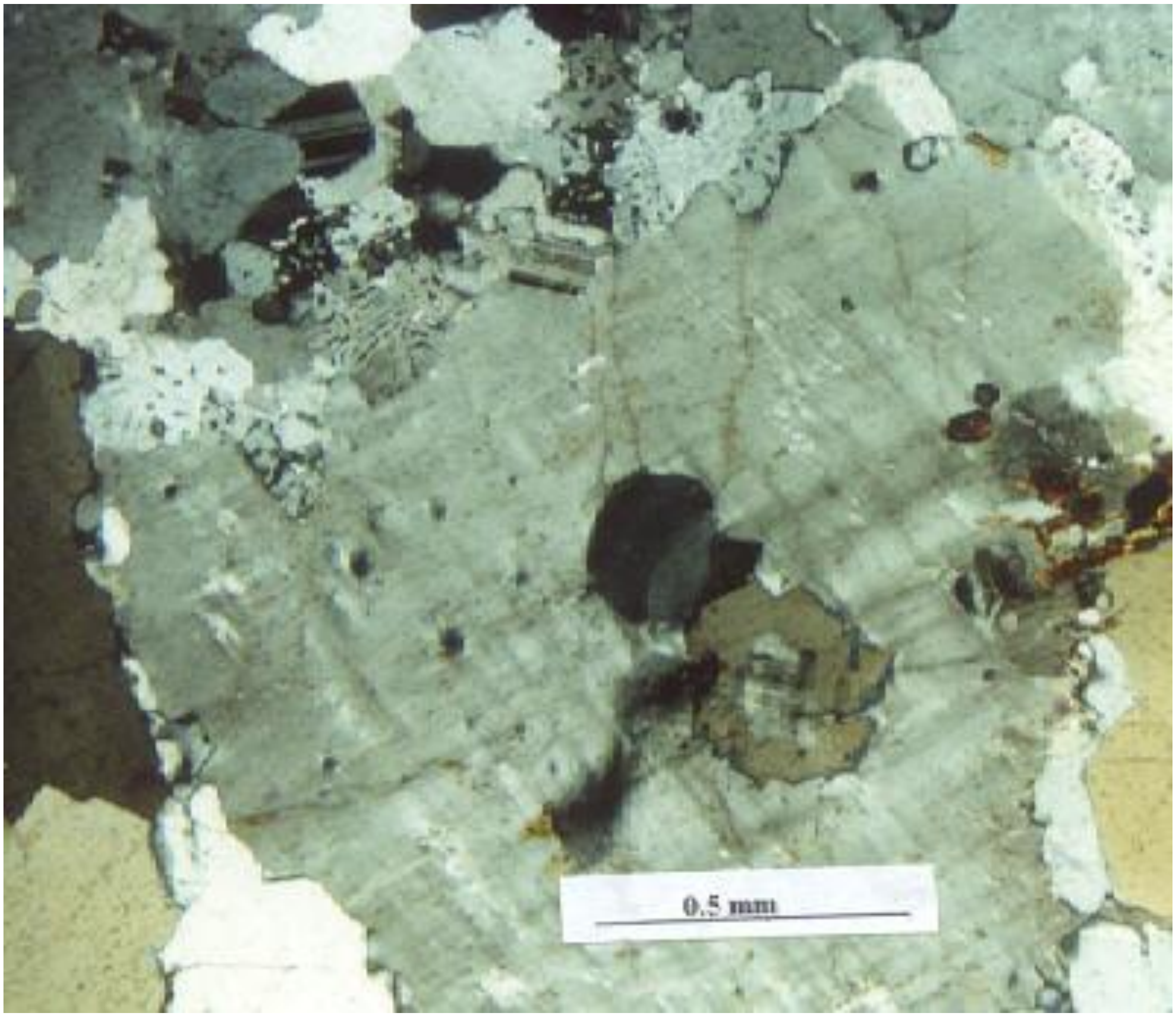


Fig. 17. Microcline (light gray; grid-twinned) bordered by myrmekite granules (top left). A plagioclase grains (above scale) enclosed in the microcline is scalloped along its borders. Inside this plagioclase inclusion is microcline (grid-twinned) that has replaced the core of the plagioclase crystal and in which the grid-twinning has a different orientation from that in the grid-twinning in the outer larger microcline crystal. Quartz (white, cream). Albite twinned plagioclase An_{12-15} (black, light gray; upper left).

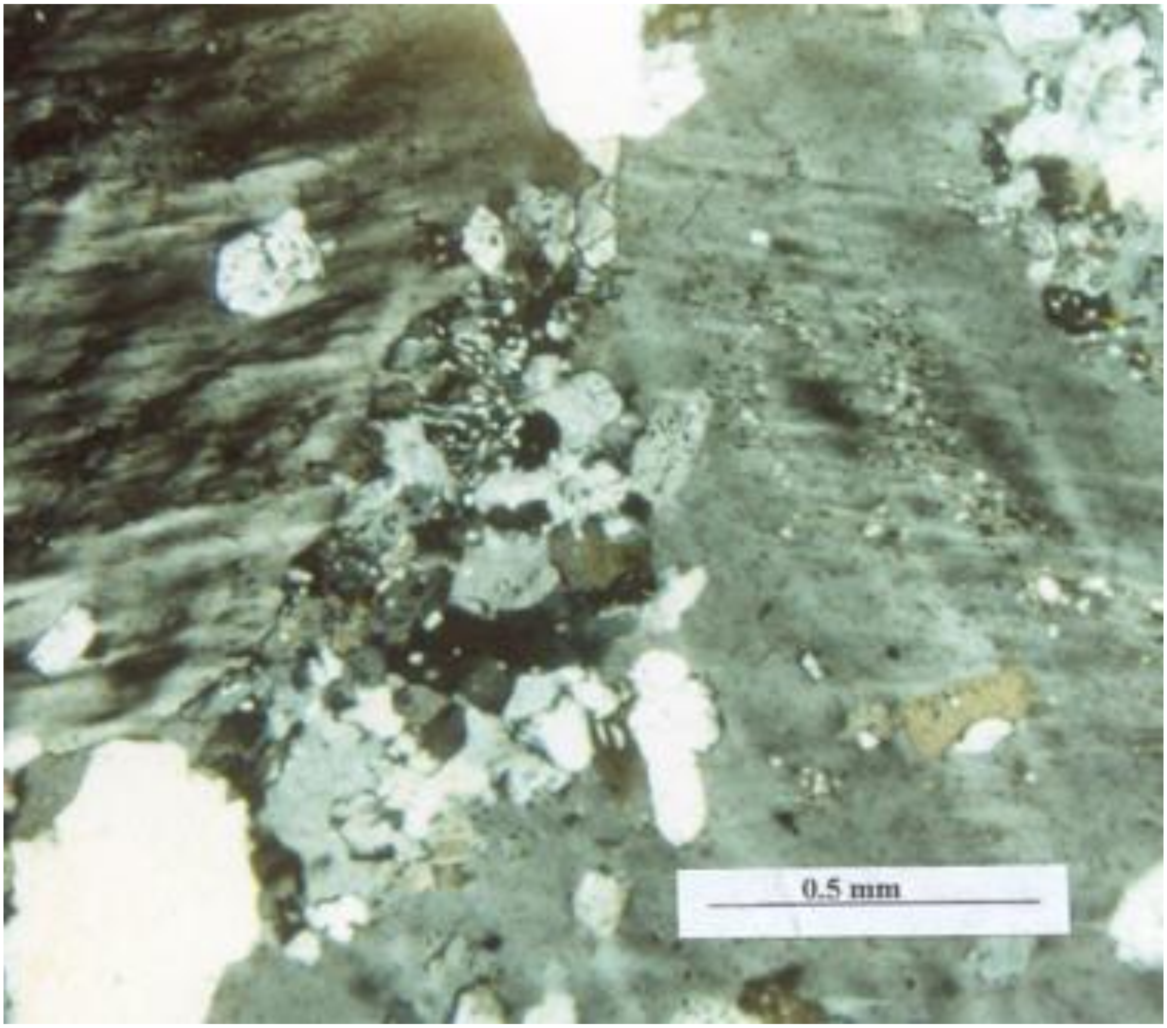


Fig. 18. Two microcline crystals (light gray and dark gray; grid-twinned) bordered by an aggregate of myrmekite (center). Microcline crystal on right side has tiny quartz-bleb clusters in plagioclase that fades into the microcline. Quartz (white, large grains).

The recrystallized plagioclase An_{12-15} in both large and small crystals in the granite results because **not all (speckled) plagioclase crystals are replaced by microcline or converted to myrmekite or quartz-bleb clusters**. Where microcline replaces some altered plagioclase lattices, some Na that is displaced by the K moves into other adjacent altered plagioclase lattices to recrystallize them as a more sodic unzoned species. At Temecula, the more-sodic species is An_{12-15}, but in other terranes the An values of the recrystallized plagioclase may be higher or lower. Generally, the An-content of the recrystallized plagioclase is about half the An-content of the original primary plagioclase (Collins, 1988a).

Although most recrystallized sodic plagioclase that is formed by metasomatic processes lacks a myrmekite border against microcline, in a few places where K happens to come into a large altered plagioclase crystal from one side and where displaced Na comes in from the opposite side, disproportionate amounts of Ca and Al relative to residual Na and Si are trapped between the opposing K- and Na-replacement fronts. Consequently, an imbalance in residual Ca, Na, Al, and Si produces an excess of Si that forms quartz vermicules in wartlike myrmekite that **projects into the microcline while being attached to the non-quartz-bearing, recrystallized sodic plagioclase** (Fig. 19).

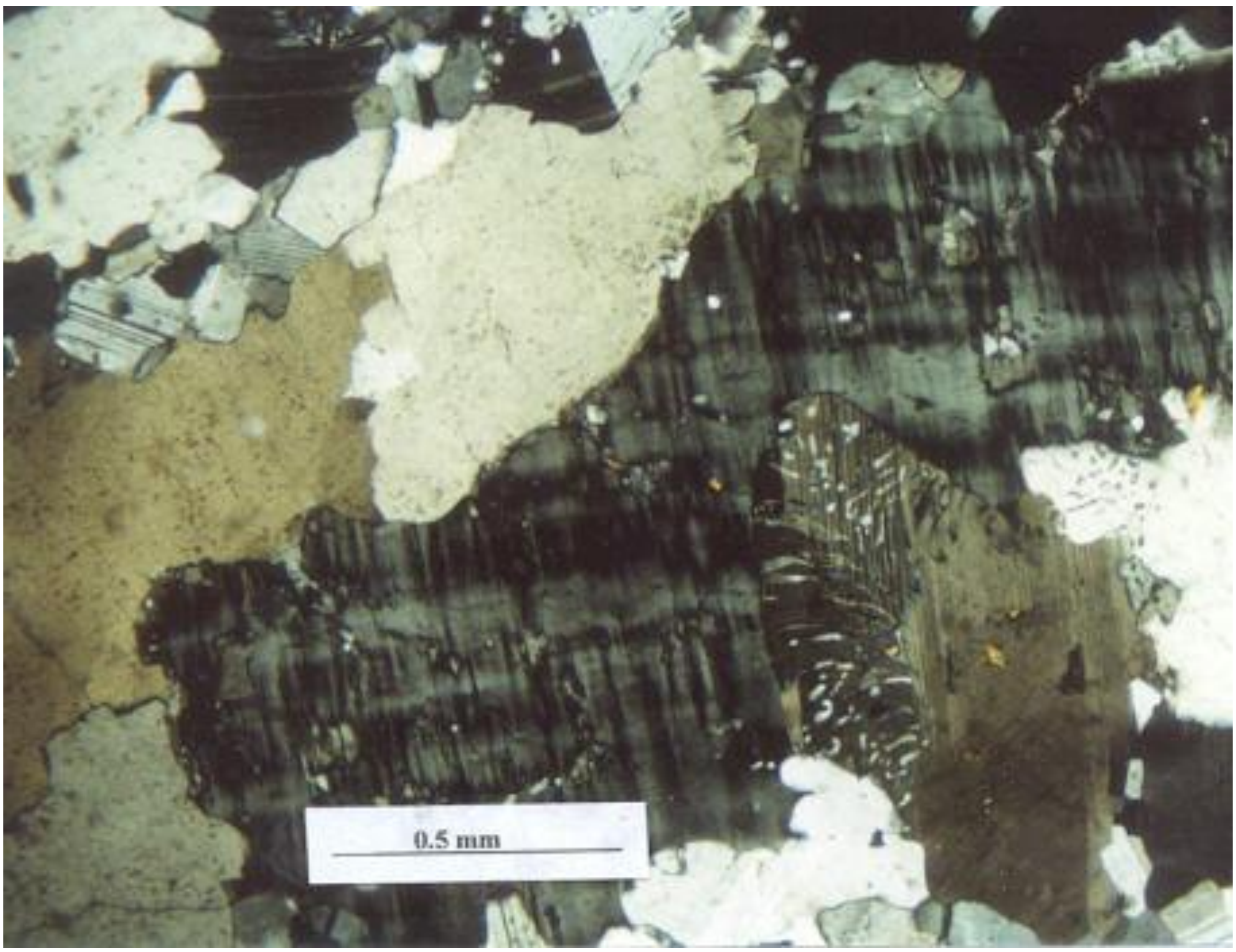


Fig. 19. Microcline (gray; grid-twinned) with myrmekitic plagioclase projecting into margin (an enlarged view of Fig. 4). The albite twinning in the myrmekite with tiny quartz vermicules (white) is continuous with albite twinning in the non-quartz-bearing plagioclase outside the microcline. The albite twinning of the grid-twinning in the microcline is parallel to the albite twinning of the myrmekite and the non-quartz-bearing plagioclase. Many plagioclase grains that lacked twinning

and had a speckled appearance have recrystallized as unaltered grains with albite twinning and a composition of An_{12-15}. See small albite-twinned plagioclase grains (upper left corner; white and black).

Note that the albite twinning of the plagioclase in the wartlike myrmekite is optically continuous with the albite twinning in the non-quartz bearing, recrystallized plagioclase crystal outside the microcline (Fig. 19). Moreover, the **albite twinning of the grid twinning of the microcline is also parallel to the albite twinning of the recrystallized plagioclase** (Fig. 19; see also Fig. 11). 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, part of which also became the wartlike myrmekite and the non-quartz-bearing plagioclase (Collins, 2000; http://www.csun.edu/~vcgeo005/Nr37Ooverlooked.pdf).

Because only locally are disproportionate amounts of Ca and Al trapped in altered plagioclase lattices during K-metasomatism, most microcline that replaces the altered, large and small, plagioclase grains lack aggregate and wartlike myrmekite and/or quartz-bleb clusters. The abundant microcline, free of myrmekite and quartz-bleb clusters, occurs because in most places, as K enters an altered plagioclase crystal, outlets for displaced Ca, Na, and Al to escape through broken boundary seals are created against all bordering crystal types so that **only microcline is formed**. On the other hand, if a primary plagioclase crystal is being altered and its crystal boundary on one side is still sealed, for example, against adjacent biotite or quartz crystals, then K, entering the plagioclase from one side, will be unable to displace Ca, Na, and Al out the other side. Residual Ca and Al will remain, disproportionate to the remaining Na and Si, and myrmekite is produced. Myrmekite that is formed against biotite or quartz occurs in some rocks, but it is **not common** because plagioclase seals against biotite and quartz are normally broken. Common places where disproportionate amounts of Ca and Al might be trapped in altered plagioclase include: **(1)** where altered plagioclase grains were surrounded by microcline before the Ca and Al could escape (resulting in **myrmekite and quartz-bleb cluster** inclusions; Fig. 14 and Fig. 15), **(2)** where the Ca and Al were caught between advancing K- and Na-replacement fronts from opposite sides (producing **wartlike myrmekite**; Fig. 19), and **(3)** where the Ca and Al were caught between two advancing K-replacement fronts (forming **swapped myrmekite** or **aggregate myrmekite** between two microcline crystals; Fig. 16, Fig. 17, and Fig. 18). Swapped myrmekite consists of one set of myrmekite grains in the border of a microcline crystal which projects into an adjacent microcline crystal, and these grains alternate with another set of myrmekite grains in the other microcline crystal which projects back into the first microcline crystal.

Still another possibility for myrmekite formation occurs when the primary rock has minimal deformation, just enough to break crystal boundary seals and fracture the margins of zoned plagioclase crystals, but not enough to fracture the cores. In that case, an advancing K-front in hydrous fluids, moving along the broken seals between crystals, may trap disproportionate Ca and Al in the altered marginal lattices of the plagioclase and create **rim myrmekite** (an intergrowth of a narrow band of short quartz vermicules in coexisting sodic plagioclase that borders **zoned** plagioclase). Rim myrmekite generally does not project into coexisting K-feldspar but may do so if the metasomatic K-feldspar crystal has enough volume (e.g., Fig. 19 in Collins, 1997f; http://www.csun.edu/~vcgeo005/Nr19Myth.pdf).

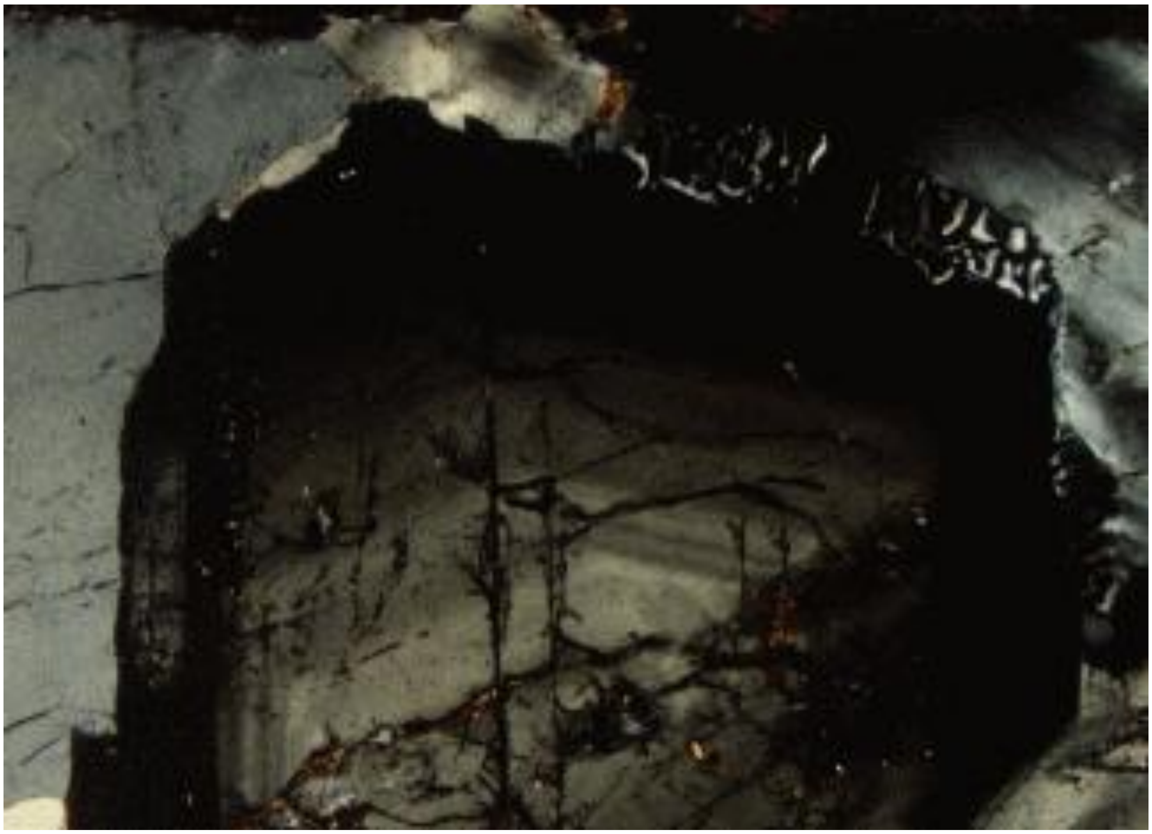


Fig. 19 in Nr19Myth.pdf. Rim myrmekite on zoned plagioclase against interstitial microcline (gray and black).

The total amount of metasomatic K-feldspar that is formed in a rock containing rim myrmekite is generally small (1-10 vol. %); the amount depends on the degree of fracturing. Moreover, in some rocks where K-feldspar is scarce, rim myrmekite may not even have a visible K-feldspar border because all that is necessary to form rim myrmekite is the recrystallization of an altered plagioclase lattice in which the residual Ca, Na, Al, and Si are imbalanced such that excess Si is present to form the quartz vermicules. Furthermore, the associated ferromagnesian silicates may show little to no replacement by quartz. Consequently, the metasomatic alterations in rim myrmekite-bearing rocks are nearly isochemical. **Rim myrmekite is not found in the Temecula site because both cores and rims of former zoned plagioclase crystals were strongly microfractured and/or deformed**.

Significance of low percentages of wartlike myrmekite

On the basis of the general openness of the microfractured system where K-metasomatism has occurred, the small amounts of **wartlike myrmekite** in a granitic rock (generally less than 1.0 vol. %) are **not** an indication of minimal K-replacements. Instead, the presence of wartlike myrmekite, even in small amounts, is a signal of **former extensive microfracturing (with possible cataclasis) and vast amounts of K-replacements that produced abundant microcline, most of which lacks myrmekite along its borders**. This relationship needs to be recognized as well as the realization that an alteration continuum exists between plutons with minimal K- and Si-replacements, where rim myrmekite is formed, and plutons in which extensive K- and Si-replacements have occurred, where abundant microcline and wartlike myrmekite are found.

In the Temecula site, the abundance of microcline (55-60 vol. %) and scarcity of plagioclase (5-10 vol. %) in the granite likely reflects the strong cataclastic granulation of the primary plagioclase (60-75 vol. %) crystals in the former quartz diorite. In most granitic plutons that have been modified by K- and Si-metasomatism, however, about half of the primary plagioclase is replaced by K-feldspar and the other half by recrystallized sodic plagioclase. In the Temecula site, the cataclasis probably involved repeated episodes of deformation that kept the system open so that the microfractured plagioclase crystals were mostly replaced by microcline, and only a little sodic plagioclase remains. The great degree of K-replacement here is similar to that which produced myrmekite-bearing pseudo-aplite dikes consisting mostly of microcline and quartz, which occur in the Cathedral Peak granodiorite (Collins and Collins, 2002; http://www.csun.edu/~vcgeo005/Nr41Cathedral.pdf). Because most plagioclase in the granite dike near Temecula is replaced by microcline, it is not surprising that most primary biotite and hornblende were also replaced by quartz. Further evidence that the granite resulted from replacement of former quartz diorite is the local occurrence of a small undeformed island of the former quartz diorite (4 mm wide; Fig. 20) in the same thin section that Fig. 19 was photographed. This tiny remnant quartz diorite occurs in the midst of the myrmekite-bearing granite, three meters from the remnant quartz diorite that borders the amphibolite dike (Fig. 7).

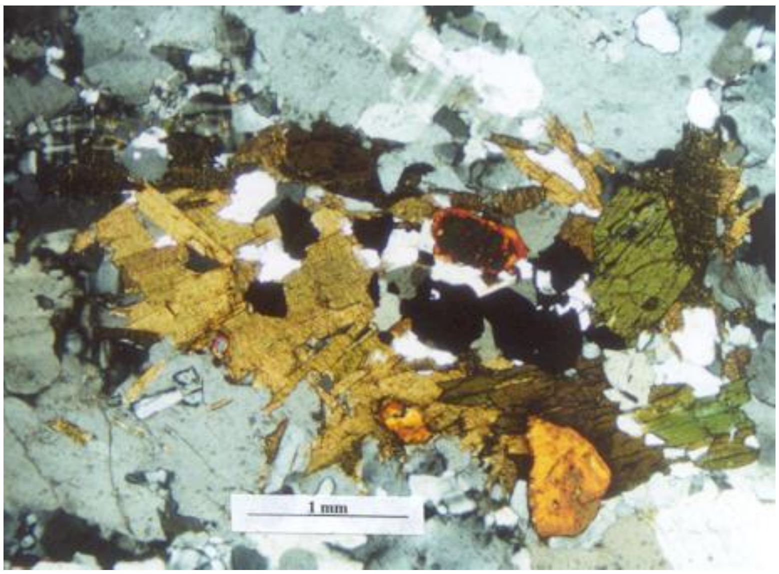


Fig. 20. Undeformed and unreplaced, tiny, island remnant of the original Bonsall tonalite (quartz diorite) in the midst of the granite. Hornblende (olive green, brown); biotite (tan); quartz (white); allanite (orange brown, zoned; three grains); plagioclase (light gray); microcline (dark gray; grid-twinned; outer border of remnant quartz diorite island). Hornblende (green and brown; lower right) partly replaced by quartz (white).

Other significant observations

A significant observation that can be made about the sequence of changes that are observed in Figs. 8-19 is that the final product, the granite, is **massive and exhibits no outward appearance of cataclasis or gneissic foliation that might be expected if the former rock were subjected to intense shearing and granulation**. Most of the quartz lacks undulatory extinction; the microcline and recrystallized plagioclase are not deformed; and the granite has an interlocking hypidiomorphic texture typical of granite crystallized from a magma. It must be recognized that the whole replacement and recrystallization process that produces wartlike myrmekite, not only eliminates or greatly modifies the former precursor minerals, but also destroys the evidence for former strong deformation; see also Sylvester and Christie (1968) for similar evidence of the elimination of strong deformation in quartz by dynamic recrystallization. At Temecula, the only bits of evidence in the granite of the former microfracturing and cataclasis are the **occurrences of myrmekite and quartz-bleb clusters** (e.g., Fig. 18 and Fig. 19). The granulated and microfractured grains are no longer present. Therefore, the absence of deformation in myrmekite-bearing granite is **not** a criterion that can be used to say that K-metasomatism did not take place.

A second significant observation is that although the myrmekite-bearing granite has a gradational contact with remnant quartz diorite adjacent to the amphibolite dike in the 16-cm transition zone (Fig. 7), all other granite contacts against the quartz diorite are knife-edge sharp (photos 3, 4, and 5 in Fig. 3). Such sharp contacts between mafic and felsic igneous rocks are commonly used as a criterion to indicate injection of magma rather than metasomatism. But fluids producing K- and Si-metasomatism did not penetrate the quartz diorite where it was undeformed, and, therefore, replacements of microfractured biotite, hornblende, and plagioclase by quartz, microcline, and sodic plagioclase could occur only to a sharp limit against the quartz diorite that had not been microfractured. **At any rate, these sharp quartz diorite-granite contacts in the Temecula site give false evidence for magmatism**. See: http://www.csun.edu/~vcgeo05/Nr19Myth.pdf; Collins 1997f ; Roddick (1982).

Absence of K-feldspar megacrysts

Another significant observation is the absence of microcline (or orthoclase) megacrysts in the granite dikes at Temecula, even though the K-metasomatism there was quite extensive, producing 55-60 vol. % microcline. Why are myrmekite-bearing microcline megacrysts formed, for example, in the Cathedral Peak granodiorite (Collins and Collins, 2002), the Twentynine Palms quartz monzonite (Collins, 1997d), and the granodiorite near Monterey, California (Collins, 2001a), but not in the granite at Temecula? And, why is there lesser modal microcline in these rocks than in the granite at Temecula? When the textures and mineralogy in these two kinds of metasomatic granitic rocks are compared, the rocks containing microcline megacrysts **still have coexisting normally zoned plagioclase crystals in them**, but that is not the case at Temecula. This difference is a clue for explaining why megacrysts were formed in the above three terranes but not at Temecula.

Microfracturing of plagioclase in the primary rocks in which the microcline megacrysts grew, began selectively in a few scattered zoned plagioclase crystals but not in all. As these microfractured plagioclase crystals were replaced in their interiors by microcline and grew in size, subsequent microfracturing occurred in zoned plagioclase crystals only adjacent to the border of the growing microcline crystal but not beyond the border into the other groundmass zoned plagioclase crystals. Consequently, zoned plagioclase crystals still remained in the rocks because K-bearing fluids could not enter unbroken plagioclase to cause replacements. In these rocks where only a few isolated zoned plagioclase crystals were microfractured, fewer sites for nucleations and K-replacements occurred, and the introduced K was concentrated on these fewer sites to make megacrysts. The lesser amounts of microfracturing in these rocks also limited the opportunities for K-metasomatism, and, therefore, the modal volume of the microcline in these rocks is less than in the granite at Temecula.

In contrast, in the primary quartz diorite at Temecula, the cataclasis was much stronger, and all zoned plagioclase crystals were microfractured to their cores, perhaps nearly at the same time. In that case, where all plagioclase crystals were microfractured, introduced K had multiple, simultaneous places for K-replacements to occur. All these places competed for the K, and none formed microcline that was able to grow large enough to become megacrysts. Furthermore, the greater microfracturing and cataclasis enabled more opportunities for K-replacements and produced greater volumes of microcline.

Conclusions

Knowledge of the sequential changes in Figs. 8-19 that led to the formation of myrmekite-bearing granite should enable the geologist investigating other terranes to recognize K-metasomatism on a plutonic scale in granitic plutons, which heretofore might have been considered to have only a magmatic history. Criteria that can be used to help recognize this possible K-metasomatism include:

(1) microcline in cores of some plagioclase crystals (Fig. 11, left side, and Fig. 17),

(2) isolated irregular islands of microcline in plagioclase (Fig. 11, right side; Fig. 6 in Collins, 1997b; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf,

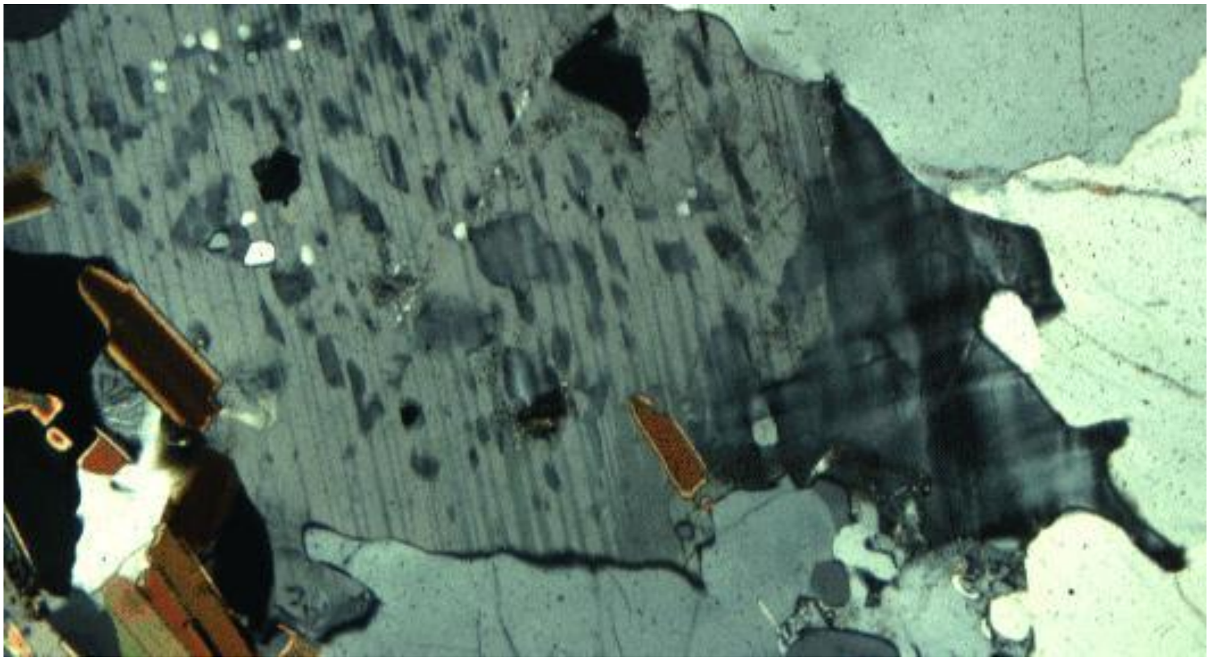


Fig. 6 in Nr2Myrm.pdf. Microcline (dark gray, grid-twinning) in this photomicrograph from myrmekite-bearing granite is in a more advanced stage of replacement of plagioclase. Plagioclase (light tan) in the center and upper left has been completely replaced by K-feldspar (lower right). Note that the albite twinning of the grid-twinning in the microcline is parallel to the albite twinning in the plagioclase.

(3) the parallel alignment of albite twinning in the grid-twinning of the microcline with albite twinning in plagioclase outside the microcline (Fig. 11, left side, and Fig. 19), **(4)** the occurrence of plagioclase inclusions in microcline which are in parallel optical continuity with a plagioclase crystal outside the microcline (e.g., Fig. 9 in Collins, 1997d; http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf).

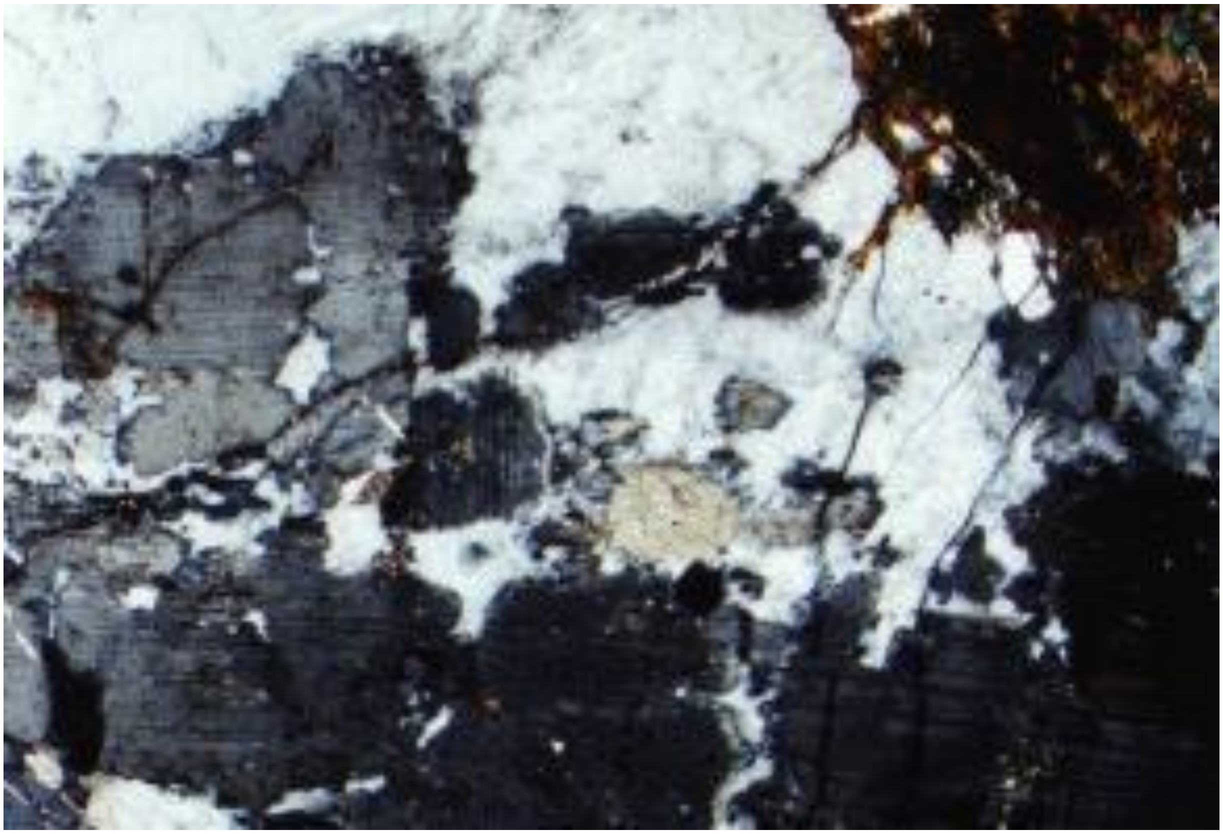


Fig. 9 in Nr9Twenty.pdf. Cataclastically-broken felsic diorite, showing fractured plagioclase crystals (dark gray, light gray; bottom and left) being replaced by microcline (white; center and upper left). Hornblende (brown; upper right) has very minor quartz sieve texture. Unfractured microcline penetrates along fractures (replacing the plagioclase) and surrounds island remnants of plagioclase that are optically continuous with large unreplaced portions of the plagioclase.

And **(5)** the presence of both quartz-bleb clusters and wartlike myrmekite (Fig. 14). See Fig. 5 and Fig. 6 in Collins 1997e (http://www.csun.edu/~vcgeo005/Nr13Rubidoux.pdf and examples of coarse quartz blebs in clusters ("ghost myrmekite").

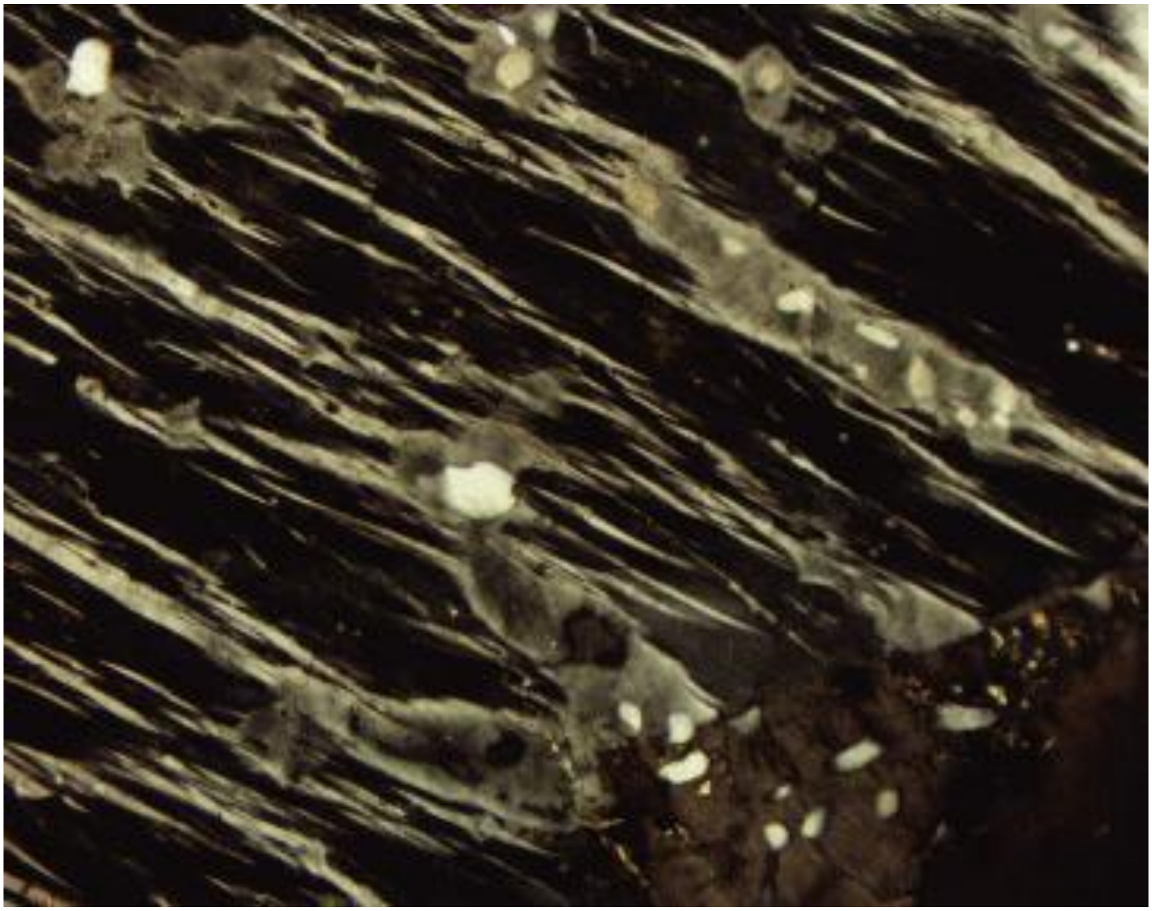


Fig. 5 in Nr13Rubidoux. Isolated vein myrmekite (ghost myrmekite). Albite (gray) occurs as spindles, veins, and enclosing quartz blebs in ghost myrmekite. Wartlike myrmekite occurs in lower right corner (brown; white quartz vermicules).

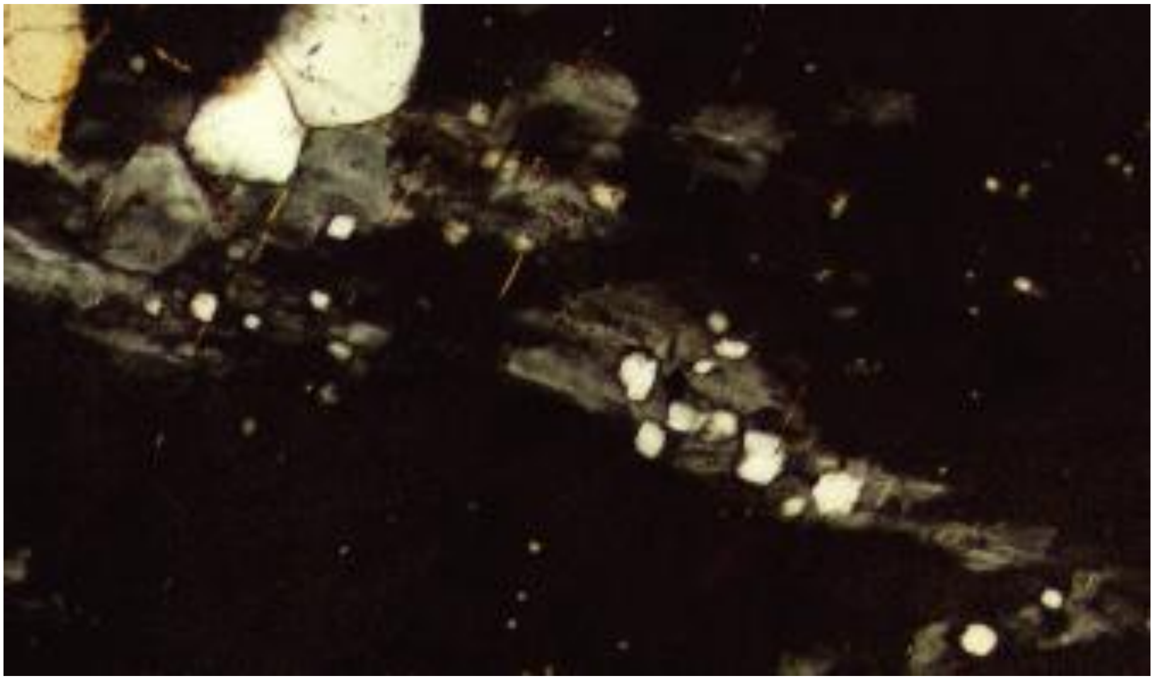


Fig. 6 in Nr13Rubidoux. Isolated island myrmekite (ghost myrmekite). Albite (gray), K-feldspar (black), quartz blebs (white), and quartz crystal inclusions (white and cream).

And Fig. 18 and Fig. 19 in Collins (2001b; http://www.csun.edu/~vcgeo005/Nr40Wanup.pdf) for examples of myrmekite with very coarse quartz vermicules that are transitional to coarse quartz-bleb clusters.

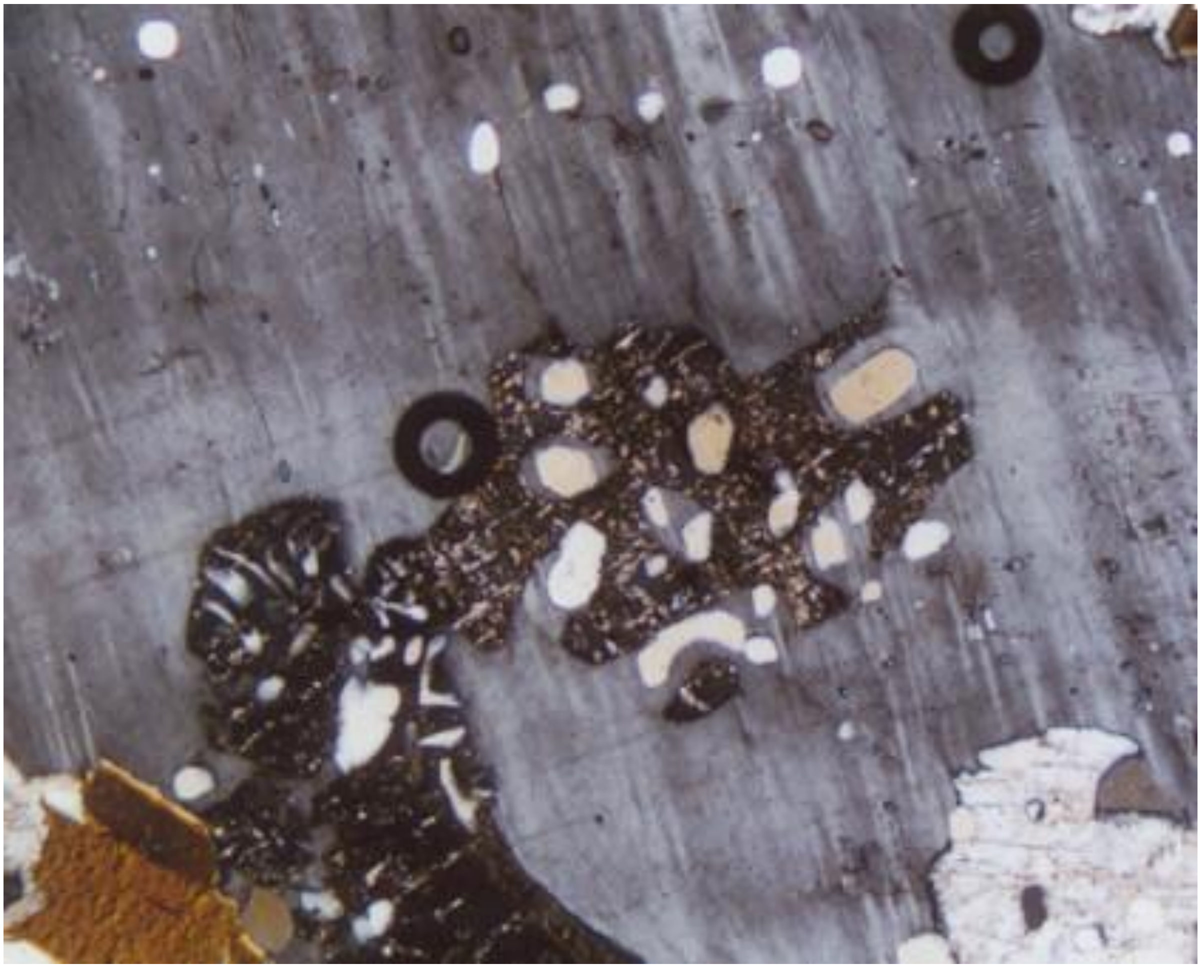


Fig. 18 in Nr40Wanup.pdf. Myrmekite with coarse quartz vermicules (white and cream), enclosed in microcline (grid pattern, light gray). Plagioclase of myrmekite is speckled brown (sericite alteration). Microcline penetrates the plagioclase along fractures and encloses some of the coarse quartz vermicules. Similar-sized or smaller islands of quartz occur in the microcline (top) as ghost myrmekite.

Fig. 19 in Nr40Wanup.pdf. Myrmekite with coarse quartz vermicules in megacrystal granitic rock near base of Wanup pluton, south of Route 69. Microcline (black) with scattered quartz blebs (white); some quartz blebs are the same size as those in the myrmekite, and others are tiny in ghost myrmekite. Plagioclase (albite-twinned; light and dark gray); quartz (mottled gray).

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