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45. Myrmekite formed by Na- and Ca-metasomatism of K-feldspar

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Abstract

Myrmekite, an intergrowth of plagioclase and quartz vermicules, often occurs in felsic-to-intermediate, calc-alkalic plutonic and gneissic rocks. Several hypotheses for myrmekite genesis are briefly reviewed and discussed. The proportional relationship between the volume of quartz vermicules and the An value of plagioclase is consistent with the hypothesis or replacement, solid state exsolution, and recrystallization of primary plagioclase. (1) Perthitic albite and K-feldspar relicts in myrmekite and (2) swapped myrmekite between two differently oriented K-feldspar crystals obviously indicate that myrmekite is formed by nibble replacement of K-feldspar by myrmekitic plagioclase because of modification by Ca-bearing sodic emanation or fluid. Myrmekite of different morphology and spatial distribution are of the same metasomatic origin. The myrmekite that was produced during deformation should be later than that formed prior to deformation.

Characteristics of myrmekite

Myrmekite was first described by Michel-Lévy (1874) and named by Sederholm (1897) as an intergrowth of plagioclase and quartz vermicules. Myrmekite is commonly observed in felsic-to-intermediate calc-alkalic granitic rocks (but not in alkalic-tending plutonic rocks) and in granitic gneisses of similar composition.

On the basis of the geologic environment, Phillips (1974) classified myrmekite in the following ways:

1. rim myrmekite, occurring at the contact of plagioclase with another differently oriented K-feldspar;
2. intergranular myrmekite, situated at the boundary between two differently oriented K-feldspars;
3. wartlike myrmekite, located on the border of a K-feldspar megacryst, with the curve convex toward the K-feldspar;
4. enclosed myrmekite, in K-feldspar; and
5. double myrmekite lobes with trails of muscovite flakes.

Generally, myrmekite occurs at the grain boundary between one K-feldspar and another feldspar (either plagioclase or K-feldspar) with different orientation. Myrmekite is commonly 0.1-0.5 mm wide but may be 1 mm wide in coarse-grained granite, especially in granite pegmatite. Modal volumes are generally about 1-3% but may range up to 10%.

The quartz in myrmekite is vermicular (tapered, curved, and/or sinuous) and rodlike with round to oval sections. The elongated direction of the quartz vermicules is always toward the myrmekite border, and different quartz vermicules may have one or several crystallographic orientations. The thickness of vermicular quartz varies from fine (<0.005 mm) to coarse (>0.015 mm); thus, myrmekite may be classified as fine myrmekite, meso-myrmekite, and coarse myrmekite. Correspondingly, the plagioclase of myrmekite varies from sodic to more calcic. Coarse myrmekite in some places is bordered by meso-to-fine myrmekite. The volume of quartz in the vermicules is directly proportional to the An content of the plagioclase in the myrmekite. Measurements of the volume of quartz in vermicules versus An values of plagioclase in the myrmekite generally coincide with a theoretical curve for balanced chemical equations (Fig. 1; Ashworth, 1972; Phillips and Ransom, 1968). See Appendix for the method of calculating the theoretical volume percent of quartz vermicules in myrmekite.

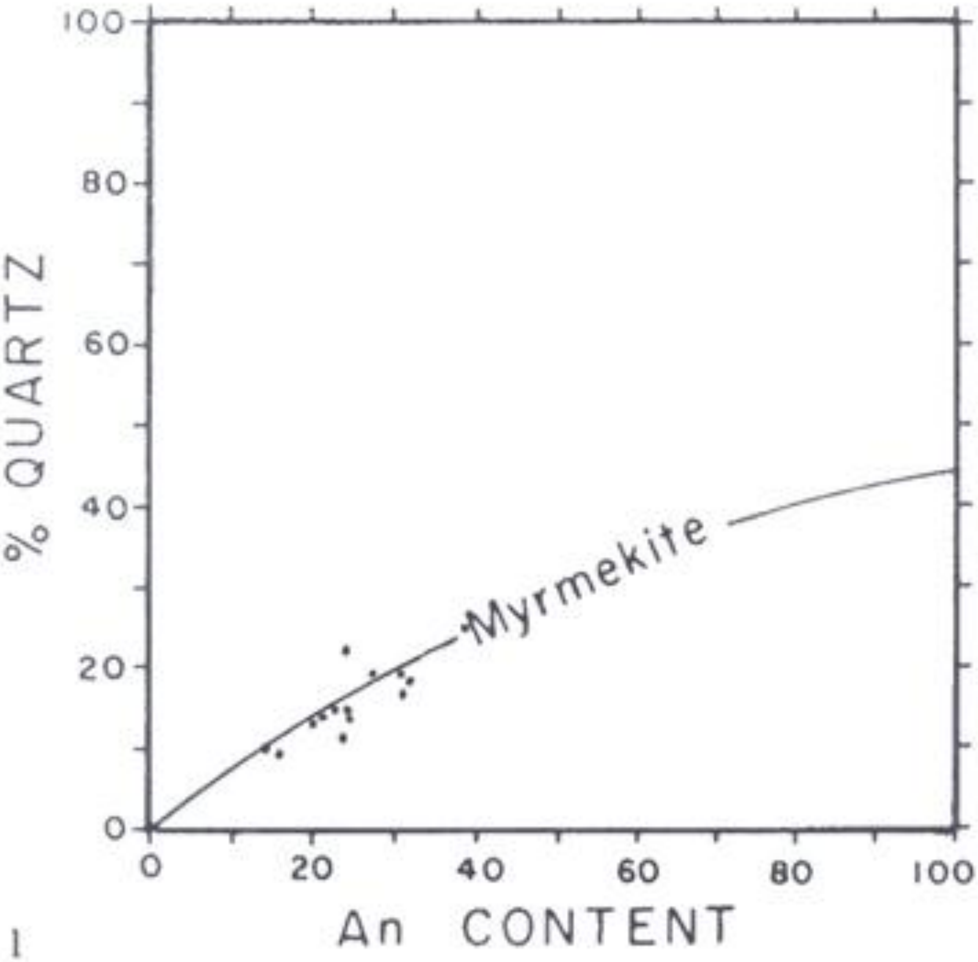

Fig. 1

Fig. 1. Measurements of volumes of vermicular quartz (black dots) coincide generally with the theoretical volume percent of vermicular quartz versus An content of plagioclase of myrmekite (curved line). The figure is after Ashworth (1972) and Phillips and Ransom (1968).

The thickness of a quartz vermicule gradually increases as the An content of the adjacent plagioclase in the myrmekite increases. In general, the finer and greater numbers of quartz vermicules, the smaller is the volume of quartz in the vermicules and the lower the An content of plagioclase in the myrmekite. At the other extreme, the coarser and fewer numbers of quartz vermicules, the greater is the volume of quartz in the vermicules and the higher the An content of the plagioclase in the myrmekite. In rocks containing K-feldspar, the An content of plagioclase in myrmekite is always less than that of the primary plagioclase (zoned or unzoned) in the same granitic rock and increases with the increase of An content of the primary plagioclase in the granitoid rocks. The editor (Collins) notes that exceptions occur where K-feldspar is absent as in some anorthosites where more calcic plagioclase in myrmekite replaces more sodic plagioclase (e.g., Dymek and Schiffries, 1987; De Waard et al., 1977) or in some gneisses where albite is replaced by more calcic plagioclase during prograde metamorphism (Ashworth, 1986).

Hypotheses for the origin of myrmekite

There are at least seven hypotheses for the origin of myrmekite.

1. Simultaneous crystallization or direct crystallization (Sugi, 1930).
2. Quartz recrystallization. Quartz vermicules were recrystallized and then enclosed in the blastic plagioclase (Shelley, 1964).
3. Replacement of preexisting plagioclase by K-feldspar (Drescher-Kaden, 1948), on the basis that some vermicular quartz can be contained in K-feldspar.
4. Replacement of preexisting K-feldspar by sodic plagioclase (Becke, 1908). Because the SiO_2 content needed for the formation of the anorthite end member is less than that contained in K-feldspar and albite, the surplus SiO_2 then was precipitated as vermicular quartz as Na^{+1} and Ca^{+2} replaced K in the K-feldspar:

   $$2KAlSi_3O_8 + 2Na^{+1} = 2NaAlSi_3O_8 + 2K^{+1}$$

   $$2KAlSi_3O_8 + Ca^{+2} = CaAl_2Si_2O_8 + 4SiO_2 + 2K^{+1}$$

5. Exsolution or unmixing during a decrease in temperature of ($NaAlSi_3O_8$) and the so-called *Schwantke molecule* [$CaAl_2Si_6O_{16}$ or $Ca(AlSi_3O_8)_2$], which are both contained in a former high-temperature K-feldspar (Schwantke, 1909; Spencer, 1945). The inner diffusion to the border of the K-feldspar of ($NaAlSi_3O_8$) and of the Schwantke molecule results in the formation of myrmekite in which the Schwantke molecule recrystallizes to form $CaAl_2Si_2O_8 + 4SiO_2$. The $4SiO_2$ become the quartz in the myrmekite, which forms against another feldspar.
6. Recrystallization of plagioclase (Collins, 1988, p. 6-50), which was altered by hydrothermal solutions after cataclastic deformation. The loss of Ca and Al and the retention of Na of the plagioclase are accompanied by an increase in excess silica, which results in quartz

vermicules forming in myrmekite. The An content of plagioclase of myrmekite is about half of the An content of the primary plagioclase.

7. Complex hypothesis (Ashworth, 1973; Phillips, 1974, 1980). Myrmekite can be formed by both exsolution and replacement. The exsolution origin is suitable for undeformed high level intrusion, forming rim myrmekite, grain boundary myrmekite and enclosed myrmekite, while the replacement origin is fit for deformed metamorphic rocks, forming wartlike myrmekite (especially when the K-feldspar is quite small and the myrmekite is very large). The exsolution model is also suitable for double myrmekite lobes with trails of muscovite flakes. Phillips (1980) even came to a conclusion that it is unnecessary to use one hypothesis to explain the origin of various kinds of myrmekite.

Discussion

Some hypotheses are now abandoned because the evidence to support arguments for them seems unreasonable; for example, hypotheses (1) and (2). The evidence for hypothesis (3) is that some vermicular quartz in K-feldspar may be relicts of replaced myrmekite, occurring as "*ghost myrmekite*." In these places the plagioclase of the myrmekite appears to have been replaced by K-feldspar or the myrmekite must have been formed earlier than the K-feldspar.

The correlation of the volume of the vermicular quartz with the An content of the plagioclase in the myrmekite is obviously not accidental. Consistent with this correlation are hypotheses (4) where K-feldspar is replaced by plagioclase, (5) in which the Schwantke molecule is exsolved, and (6) the recrystallization of plagioclase.

The exsolution hypothesis (5) is an attractive hypothesis because no penetration of fluid material from outside is needed. That fits the desire of those who do not believe (therefore do not consider) that dense and hard granitic rocks could have been penetrated by Ca- and Na-bearing fluid from an outside source.

Phillips (1964) and Hubbard (1967) believe that Ca with lesser ionic radius diffused away from the alkali-feldspar framework at the beginning of exsolution, forming myrmekite on the border. After Ca was exhausted (after a period of time), the albite with lesser Ca was exsolved. Therefore, an albite rim was formed on the border of the myrmekite, and albite lamellae were produced in the alkali-feldspar. However, the presence of the Schwantke molecule has not yet been proved. In addition, large myrmekite may occasionally be enclosed in a small K-feldspar crystal, making it impossible for the myrmekite to have formed by exsolution from the adjacent smaller volume of K-feldspar.

In regard to hypothesis (6) Collins and Collins (2002) emphasized that "*the origin of the quartz vermicules is interpreted to result from recrystallization of the altered (speckled) plagioclase grains that lack both Ca and Al from their cores during hydrothermal K-metasomatic process after the rocks were deformed*." In the light of K-metasomatism, either microcline or myrmekite may be produced, depending upon the following conditions which they described: "*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 the 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*." "*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 K-replacement of altered plagioclase to form myrmekite does not fit the metasomatic relationships that are found in the granites of China. The lack of fit occurs because (a) it is uncertain that the myrmekite-bearing rocks in China must have undergone strong deformation, recrystallization, and alteration to reduce the An content of the primary plagioclase before myrmekitization; (b) the An content of the plagioclase in the myrmekite is not necessarily equal (or nearly equal) to half the An content of the primary plagioclase, but just lower than the An content of the primary plagioclase; (c) myrmekite consistently occurs at the contact of K-feldspar with another feldspar (whether K-feldspar or plagioclase) with different orientation; and (d) myrmekite may not be formed, when plagioclase was altered to become albite after undergoing sericitization and saussuritization; on the contrary, myrmekite occurs when plagioclase is zoned and basically unaltered. Therefore, the metasomatic origin for the myrmekite in the rocks examined in this article **is likely different from the K-replacement origin of myrmekite that occurs in other terranes**.

The Na- and Ca-metasomatic model for the origin of myrmekite in granites in China

On the basis of considering the following three facts for the granitic rocks examined in this article: **(1)** the preexistence of K-feldspar is one of the main prerequisites to the appearance of myrmekite; **(2)** the volume of vermicular quartz is consistently proportional to the An content of plagioclase in the myrmekite (Fig. 1), and **(3)** remnants of albite lamellae in perthitic K-feldspar extend with unchanged crystallographic orientation in adjacent myrmekite containing sodic plagioclase when both perthitic lamellae and myrmekite with sodic plagioclase were intensively developed (Fig. 2a, Fig. 2b, and Fig. 2c), it is reasonable to suggest that myrmekite is formed by Na (with less Ca) replacement of K-feldspar (i.e., K-feldspar is replaced by sodic plagioclase, as proposed by Becke, 1908).

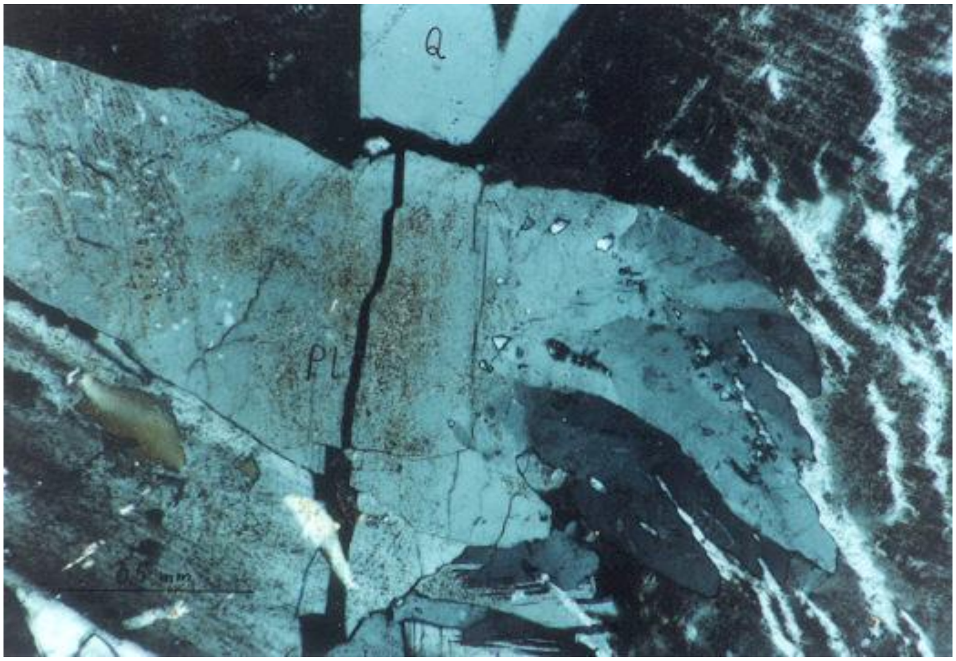

Fig. 2a. Normal interference colors are shown under cross-polarized light. Upper right corner and right side show perthitic K-feldspar with grid twinning. On the right side remnants of albitic lamellae (white) with unchanged crystallographic orientation extend into myrmekitic plagioclase (light gray; center of photo). The primary plagioclase crystal (center of photo) lacks quartz vermicules, whereas the two replacing plagioclase (myrmekite) with the same orientation as the primary plagioclase occur at its left side (having vermicular quartz) and right side (having tiny vermicular quartz, which is more clearly seen in Fig. 2c). The crystallographic orientation of the right replacing plagioclase was somewhat distorted as it grew forward. There is no clear boundary between the primary plagioclase (An$_{7-8}$; without vermicular quartz, in center part) and the myrmekitic portions (An$_{4-6}$) at opposite ends. Photomicrographs are from an inner facies of the Naqin granite, Taishan County, Guangdong Province.

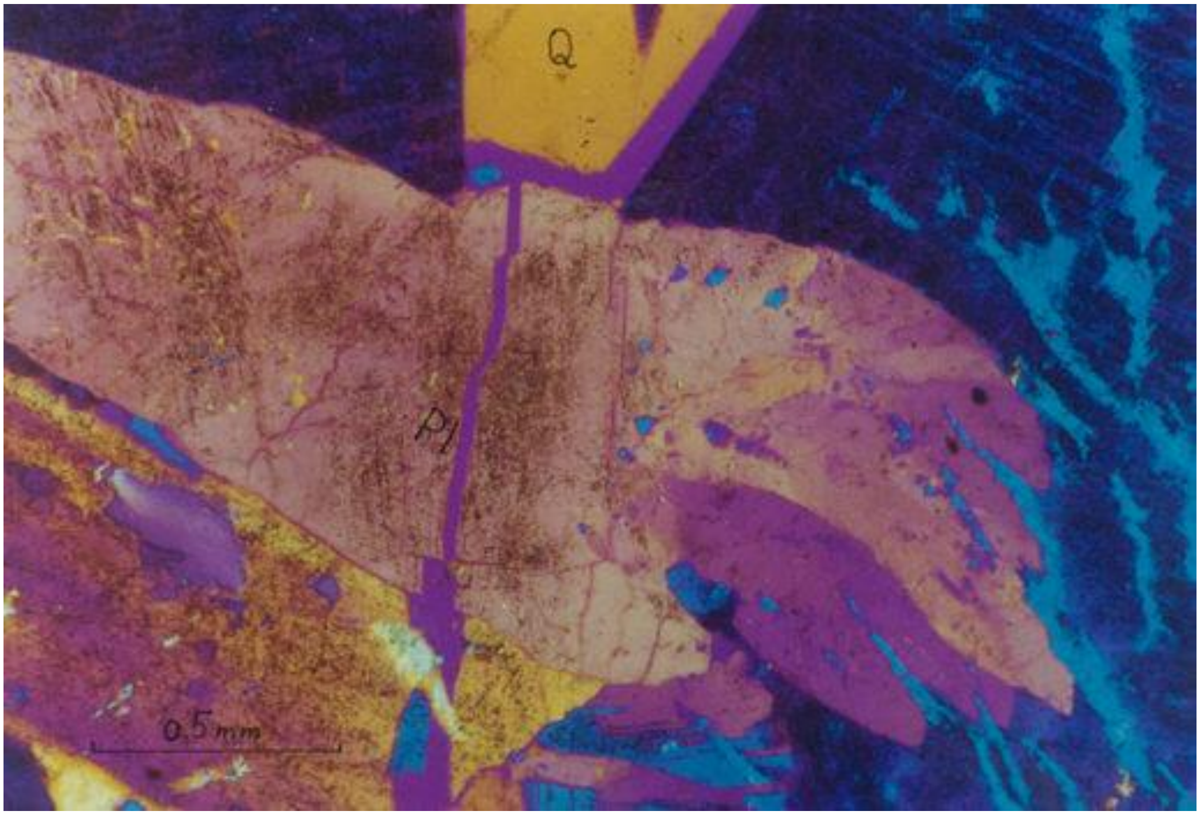

Fig. 2b. Same as Fig. 2a, but colors that are seen occur after a quartz plate (first order red) has been inserted. Remnants of albitic lamellae are now blue and the myrmekitic plagioclase is now tan to pink (center of photo). Tiny quartz vermicules are now white to light yellow.

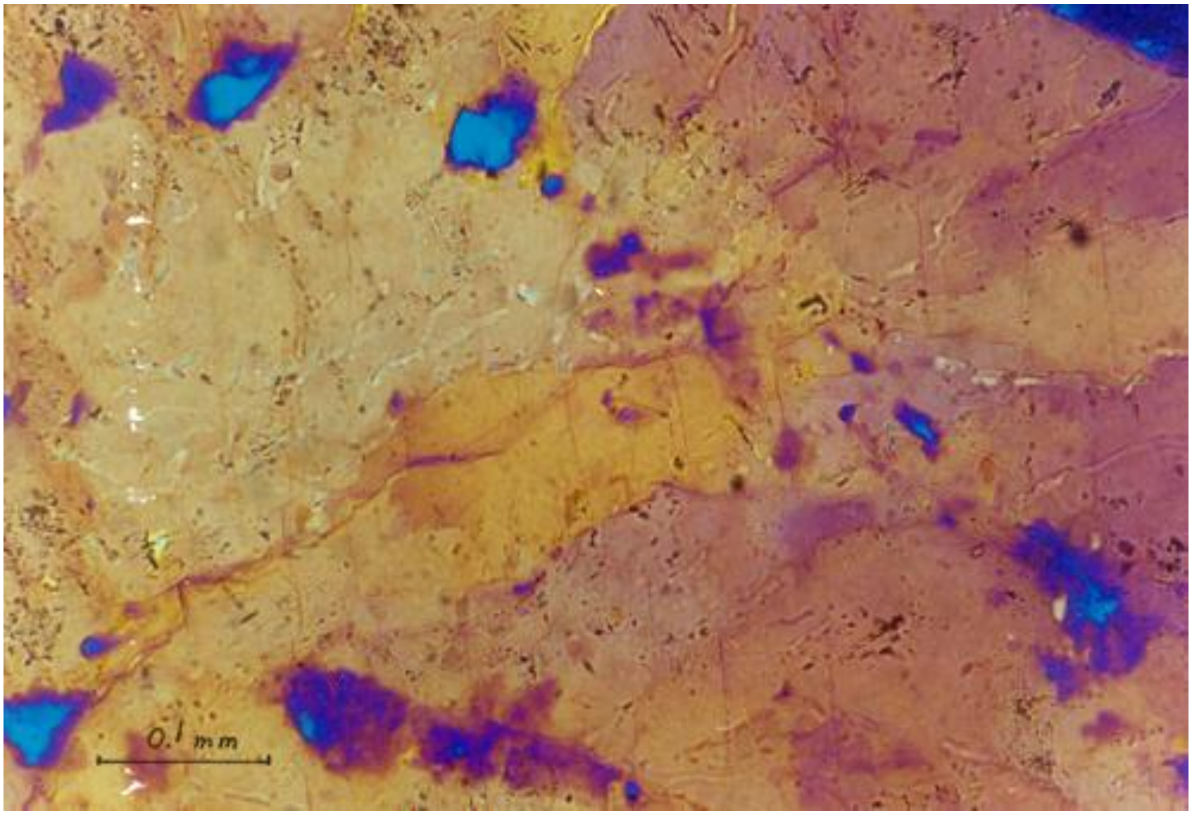

Fig. 2c. Enlarged view of the upper right center portion of Fig. 2b.

The Na bearing gas or fluid (plus less Ca), that was needed for the formation of myrmekite in an undeformed granitic body soon after its emplacement, was probably introduced from the underlying dehydrated magma chamber. Under high pressure the above-mentioned gas or fluid might penetrate and migrate along crystal borders in the solidified rock.

In regions where temperatures of the introduced fluids were relatively high, the borders of K-feldspar crystals contacting the Na- and Ca-bearing fluid would become unstable, and sodic plagioclase (with some Ca) would become the stable phase (Orville, 1963). Because of changed conditions, displaced K would migrate in the fluids to regions of lower temperature and pressure.

Where two K-feldspar crystals are adjacent to each other with different lattice orientations (these two K-feldspar crystals must be differently oriented, otherwise the grain boundary of similar minerals with the same crystallographic orientation would be too tight and not be penetrated by gas or fluid), the Na bearing gas or fluid (with some Ca) might gradually corrode (nibble at) the K-feldspar on either side of the crystal boundaries (Rong, 1982). The K would be carried away in the fluids while the Al and Si remained, and the introduced Na and less Ca would combine with this Al and Si to form a new, more stable plagioclase. The excess SiO_2 from the corroded K-feldspar would be incorporated in the growing plagioclase, forming myrmekitic quartz. The plagioclase of the myrmekite would take the same crystallographic orientation of the feldspar (plagioclase or K-feldspar) on which the plagioclase of the myrmekite nucleated and grew. The crystallographic orientation of the further growing plagioclase of the myrmekite may be somewhat distorted (Fig. 2a and Fig. 2b), as it occurred in solid-state crystal growth, especially for the fine myrmekite with more sodic plagioclase. Because quartz, hornblende, biotite, and primary plagioclase are comparatively stable during the Na (plus Ca) replacement, they may remain unchanged. Therefore, the An content of the plagioclase in the myrmekite will **not necessarily be half the An content in the coexisting primary plagioclase**.

Support for this kind of Na- and Ca-replacement is found in Figs. 2abc and 3abcd. When both perthitic lamellae and fine myrmekite are developed, relicts of perthitic lamellae with unchanged orientation from that in a former perthite commonly occur in the myrmekite (Fig. 2a, Fig. 2b, and Fig. 2c), indicating that the perthitic lamellae were formed earlier and that the K-feldspar of the perthite was replaced by the myrmekitic plagioclase. In these places the plagioclase (including perthitic lamellae) was more stable than K-feldspar during the Na- and Ca-metasomatism. Generally, however, remnants of perthitic lamellae (sodic plagioclase) would hardly be preserved in coarse myrmekite when contacting perthitic lamellae. The ability of Na metasomatism accompanied by more Ca would be stronger than that of Na metasomatism accompanied by less Ca. Nevertheless, the remnant patch (or patches) of K-feldspar can still rarely be found in a swapped coarse myrmekite grain, and such patches are in optical parallel continuity with the lattice of the larger perthitic K-feldspar crystal outside the myrmekite (Fig. 3a, Fig. 3b, Fig. 3c, and Fig. 3d). The presence of these patches and swapped myrmekite (occasionally one row of myrmekite) between two differently oriented K-feldspar crystals (Fig. 3e) **provide strong evidence that Na- and Ca-metasomatism of K-feldspar have occurred**.

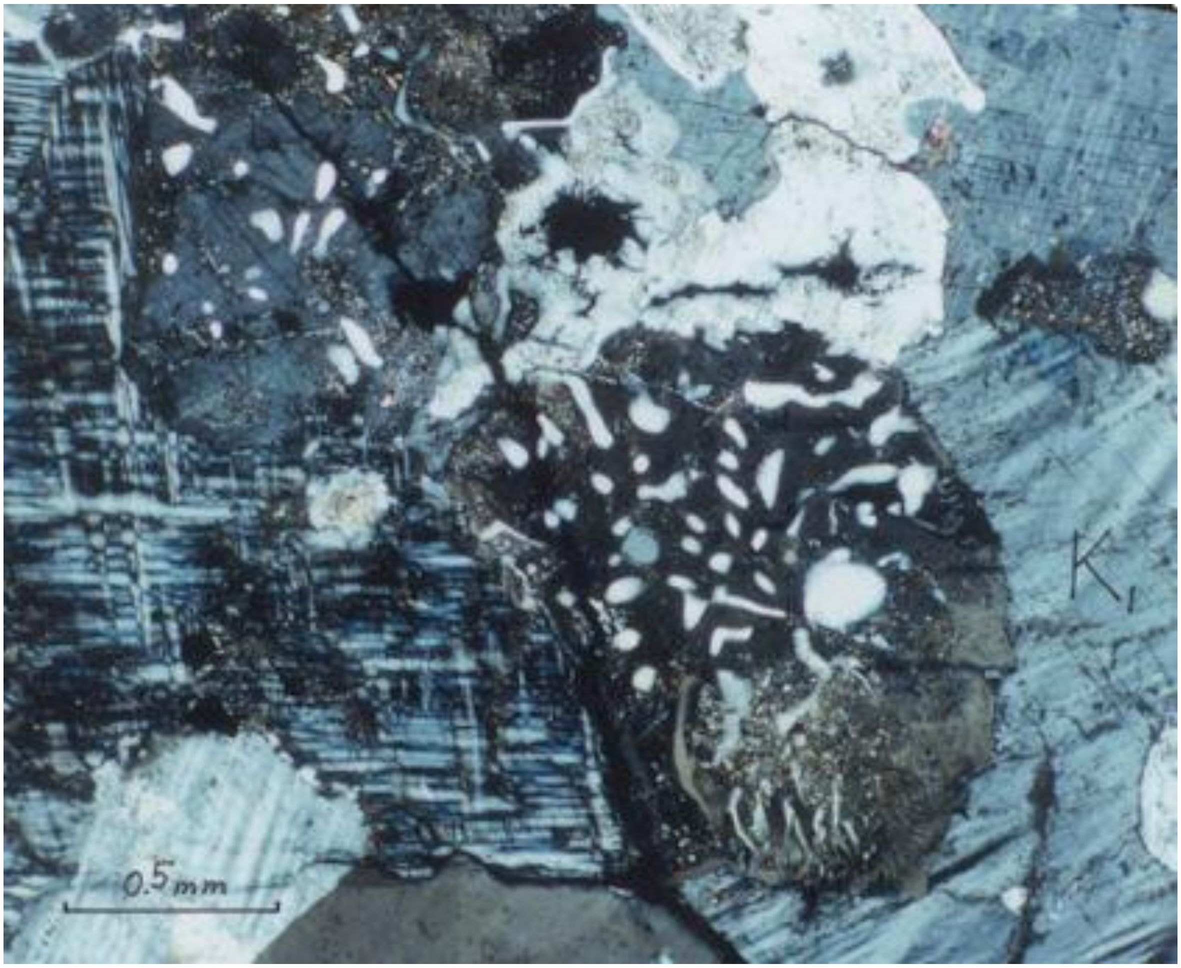

Fig. 3a. Swapped coarse myrmekite grains occur on the grain boundary between two differently oriented grid-twinned K-feldspar crystals (K_1 and K_2). K-feldspar grain (light gray) in upper right with perfect cleavage (black parallel lines) has nearly invisible, uniformly-distributed, narrow spindles 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 a granite body in Inner Mongolia.

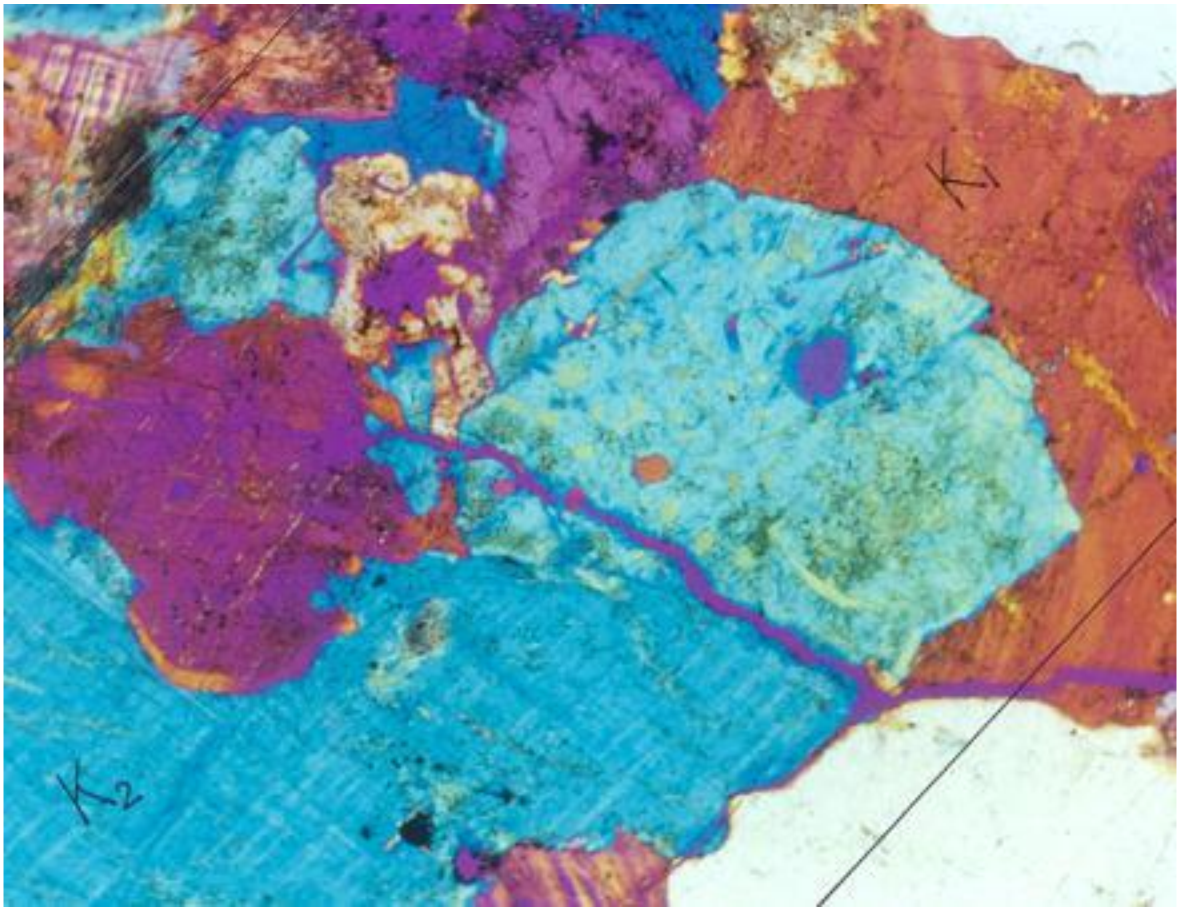

Fig. 3b. Same as Fig. 3a but with a quartz plate (first order red) inserted. A small, rounded, tanish-orange patch of K-feldspar occurs in the myrmekite in the center of the photo to the right of the crack (first order red) in the thin section. This tanish-orange matches the tanish-orange of the K-feldspar K_1 along the right edge of the photo. Because this rounded grain is in parallel optic orientation with K_1, it is interpreted to be a preserved K-feldspar remnant of K_1 in the myrmekite. This same orange patch can also be seen in Fig. 3c and Fig. 3d. Bar scale of 0.5 mm length; lower right.

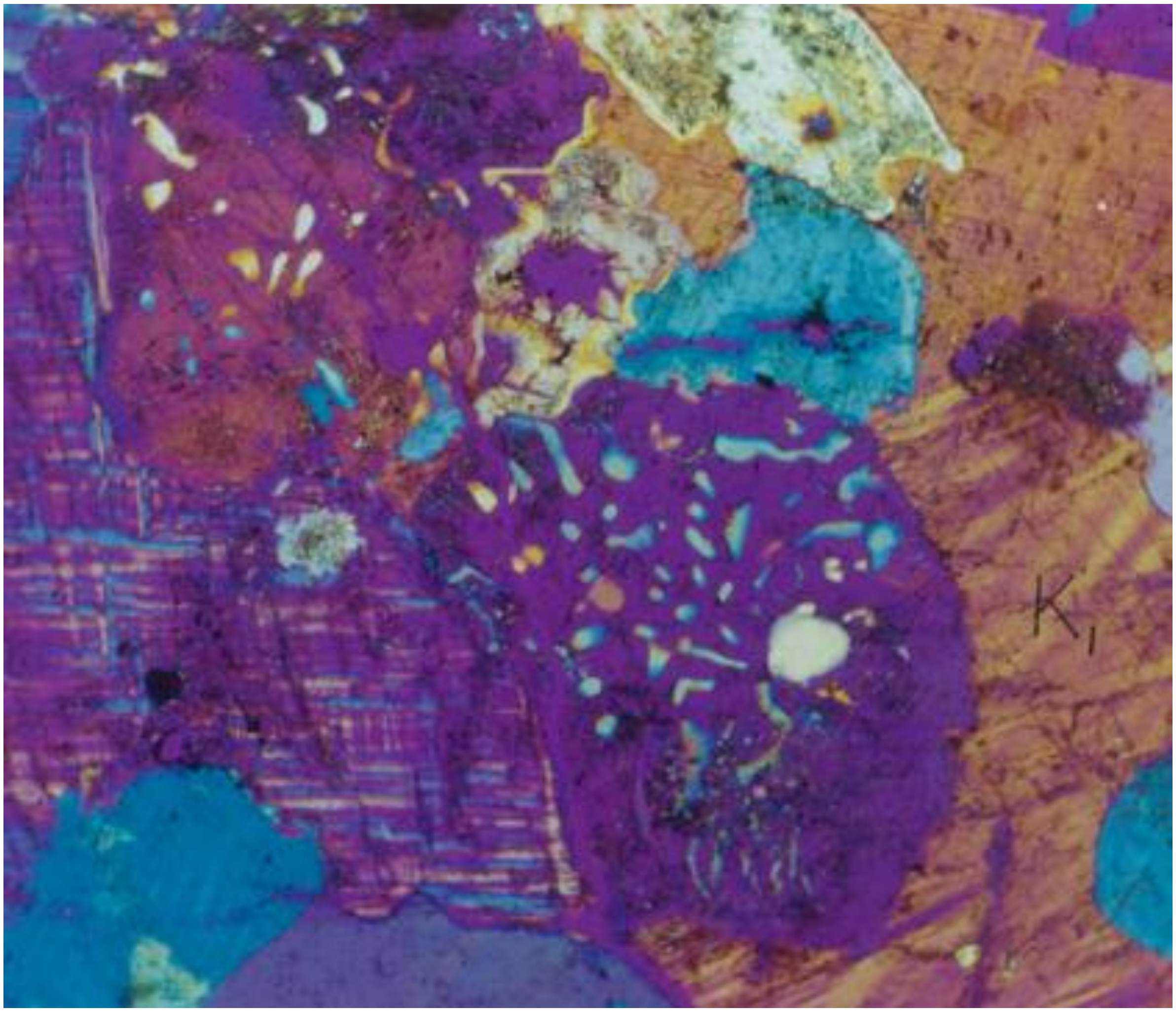

Fig. 3c. Same as Fig. 3a and Fig. 3b, but rotated slightly.

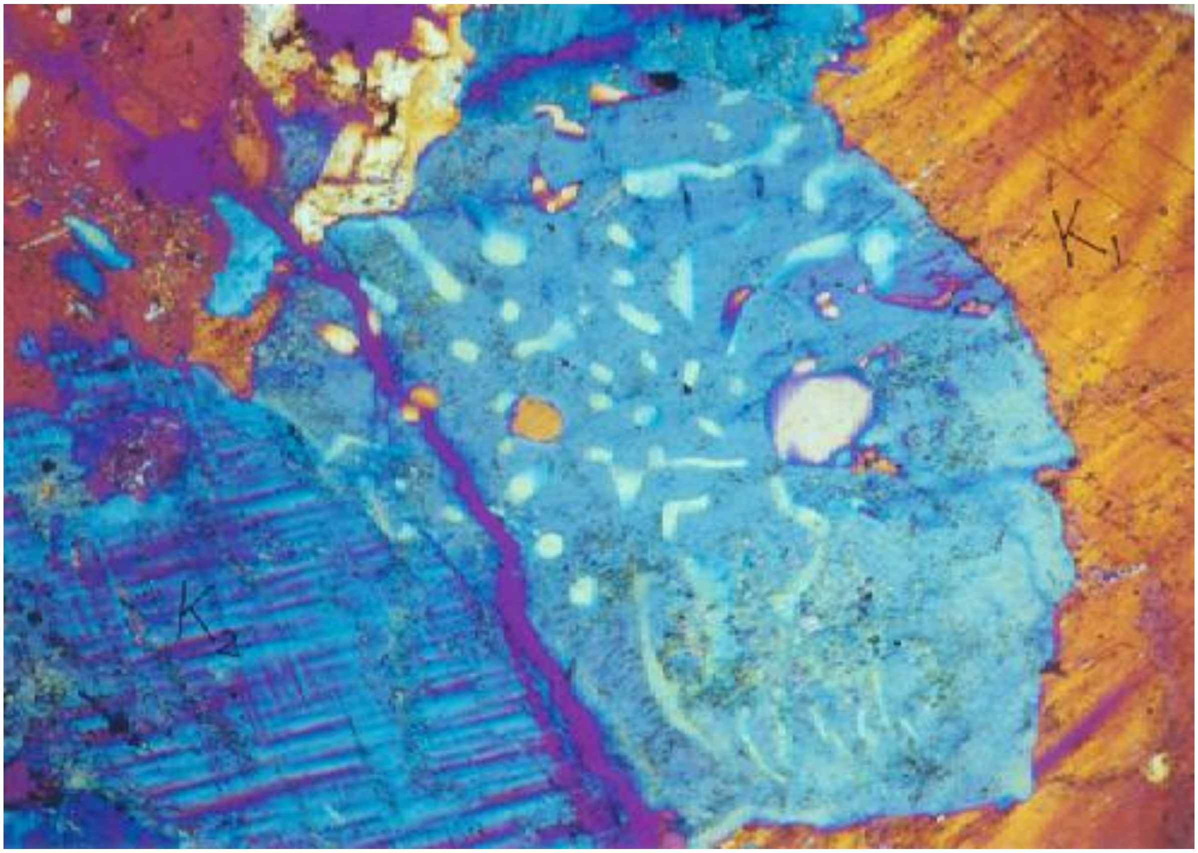

Fig. 3d. Same as Fig. 3c but rotated counter-clockwise slightly.

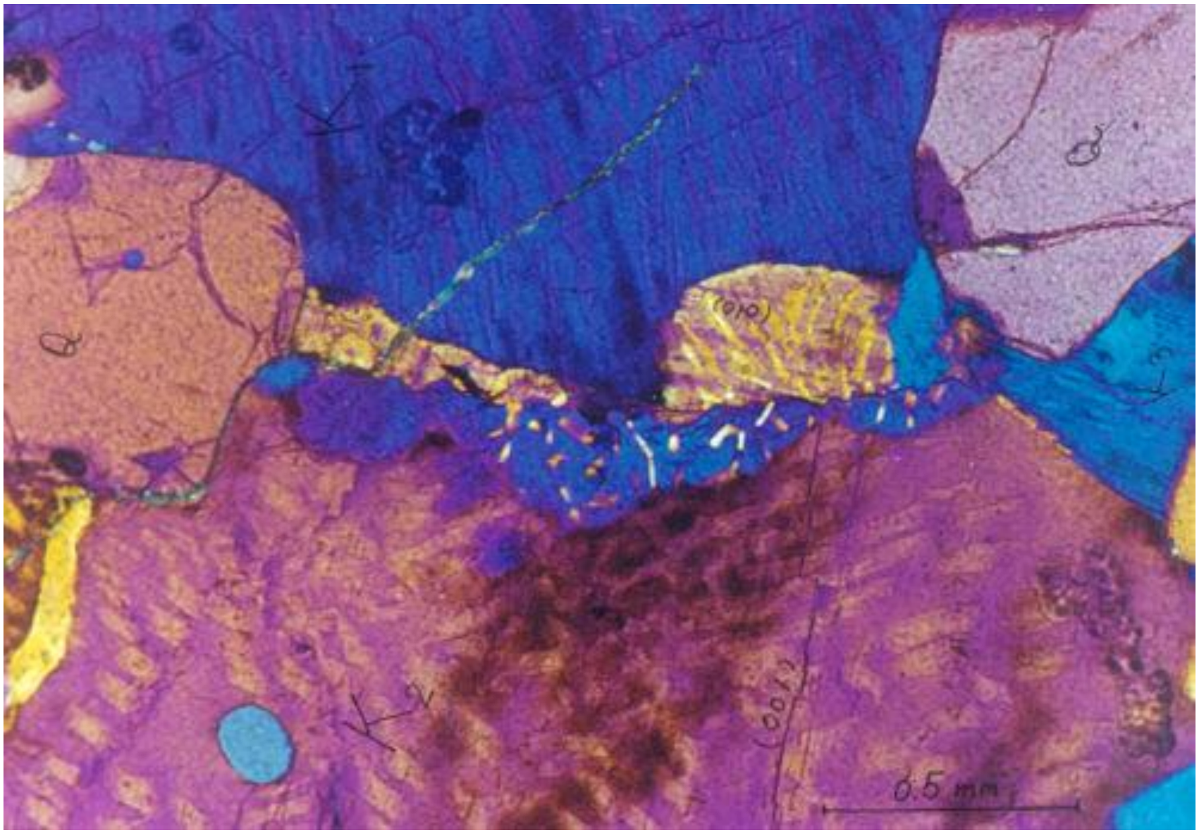

Fig. 3e. Swapped myrmekite grains (double row, center) occur on the boundary between two differently oriented perthitic K-feldspar crystals, (K_1, blue purple, top and K_2, violet with orange lamellae, bottom). Notice that the albite-twinning plane (010) of the top row plagioclase of myrmekie (containing yellow quartz vermicules) is nearly perpendicular to the cleavage (001) of the K-feldspar K_2 (bottom, on other side of the lower row of myrmekite grains), indicating the same orientation that K_2 and the upper myrmekite have. Bar scale of 0.5 mm length; lower right. Location of sample is unknown.

When the size of myrmekite is greater than 0.3-0.6 mm, i.e., 10-20 times the thickness of a thin section, the mineral on which the myrmekite grew may not be seen in one thin section (Fig. 4 and Fig. 5). The unseen feldspar might also have been K-feldspar, which was nibbly replaced by the myrmekite. Because the replacing fluids likely have nearly a constant composition of dissolved Na^{+1} and Ca^{+2} ions at a given temperature and pressure, the resulting plagioclase in the myrmekite has a nearly constant An content, and the resulting quartz vermicules have nearly a constant thickness (Fig. 4 and Fig. 5).

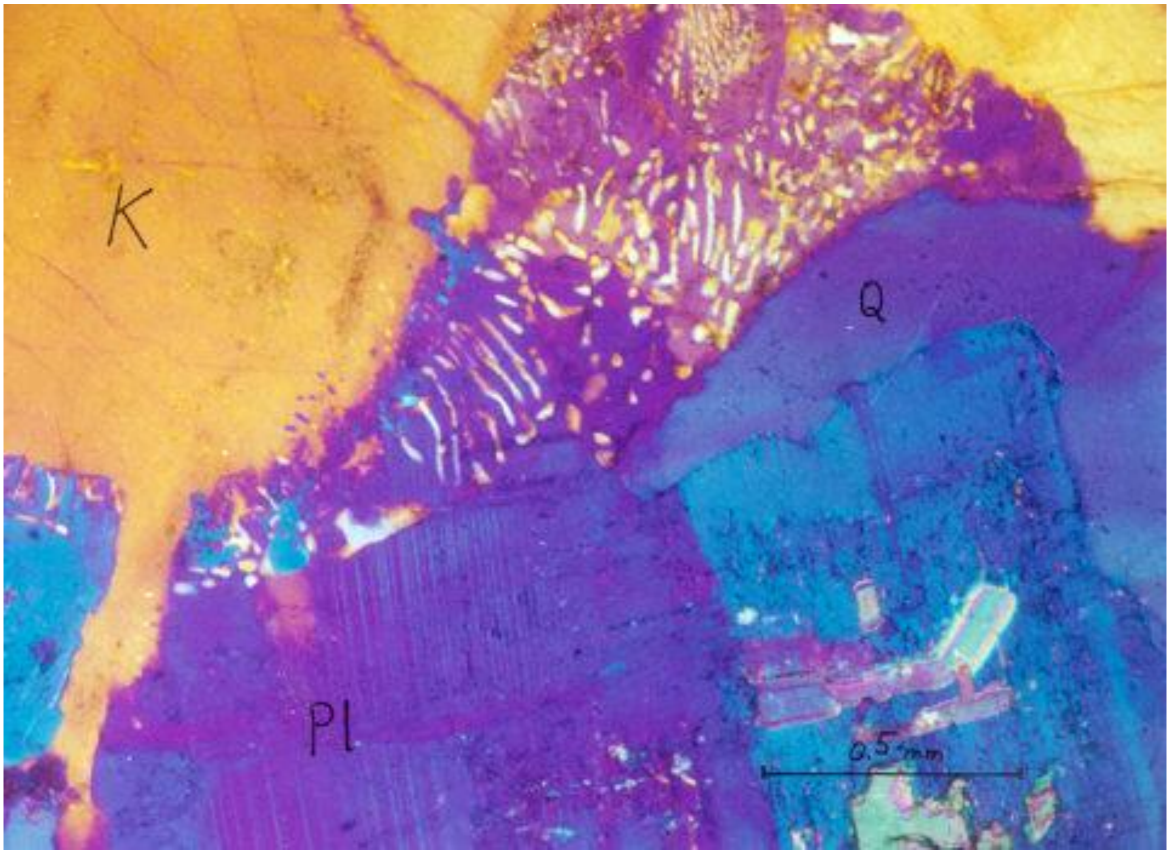

Fig. 4. The plagioclase of the myrmekite (top, center) has taken the same or nearly the same crystallographic orientation as the primary, albite-twinned, euhedral plagioclase (bottom; blue and purple) and has nibbly replaced K-feldspar (yellow). Some vermicular quartz (tiny purple ovals) occurs in the K-feldspar adjacent to the myrmekite, which may be named "ghost myrmekite." Bar scale of 0.5 mm length; lower right. Photomicrograph is from Guanshigou pegmatoid granite, South Shaanxi Province.

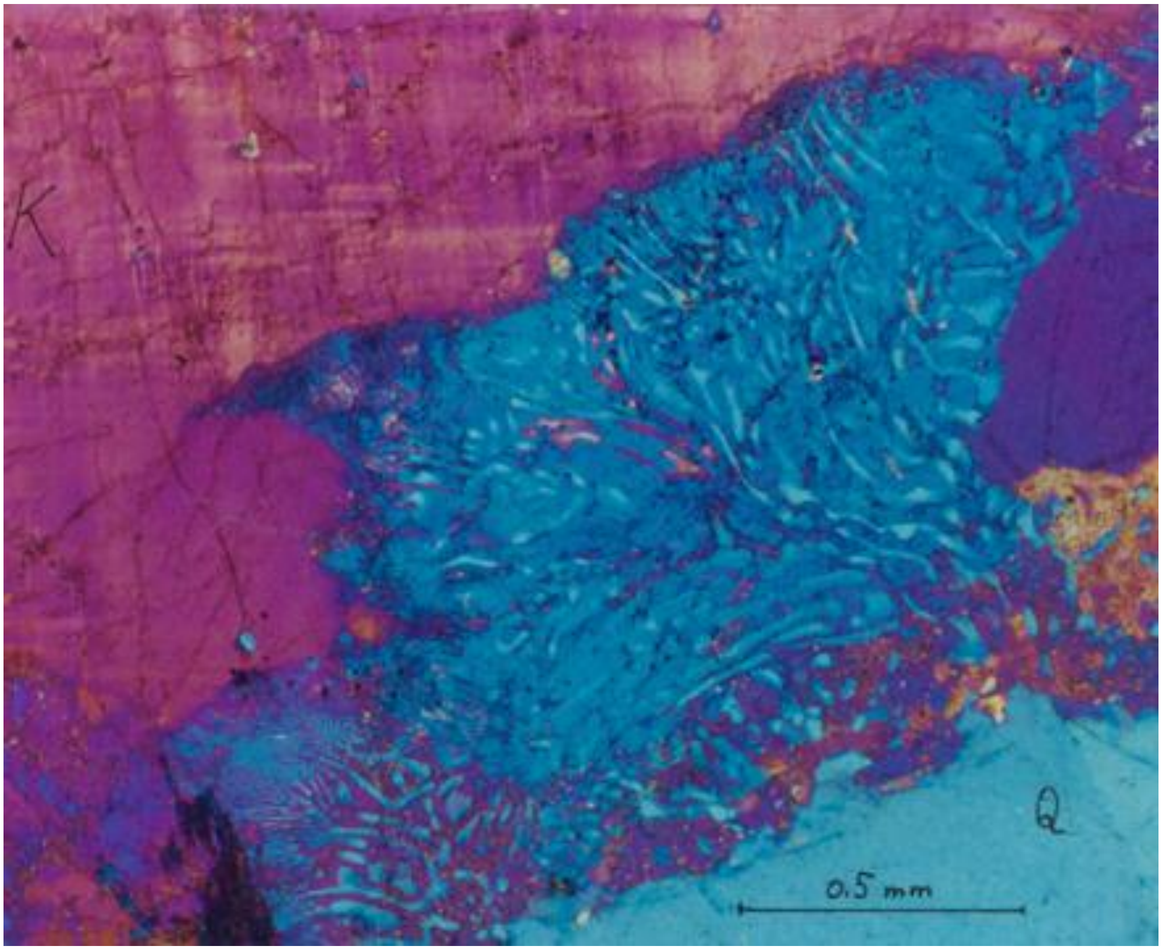

Fig. 5. Grid-twinned K-feldspar (upper left), myrmekite (dark blue) with quartz vermicules (light blue), and quartz (clear blue, lower right). Because myrmekite is relatively large (with a width greater than 1.5 mm), the mineral (likely K-feldspar) on which the myrmekite grew naturally may not appear together with the myrmekite in one thin section which is only 0.03 mm thick Bar scale of 0.5 mm length; lower right. Photomicrograph is from Guangshigou pegmatoid granite, South Shaanxi Province.

When the granitoid bodies, especially gneissic rocks, were intensely deformed, the Na and Ca bearing gas or fluid, needed to form myrmekite in these rocks might also be produced from metamorphic processes or other geological events. The amount of Ca participating in a Na metasomatic process, in any case, would surely determine the An content of the plagioclase in myrmekite that is formed and the volume and thickness of the vermicular quartz.

After clarifying the way in which myrmekite is created in undeformed rock, the origin of myrmekite in deformed rock might be explained more reasonably.

Aggregates of myrmekite may be distributed along the border of a K-feldspar megacryst (Fig. 6) or at one corner.

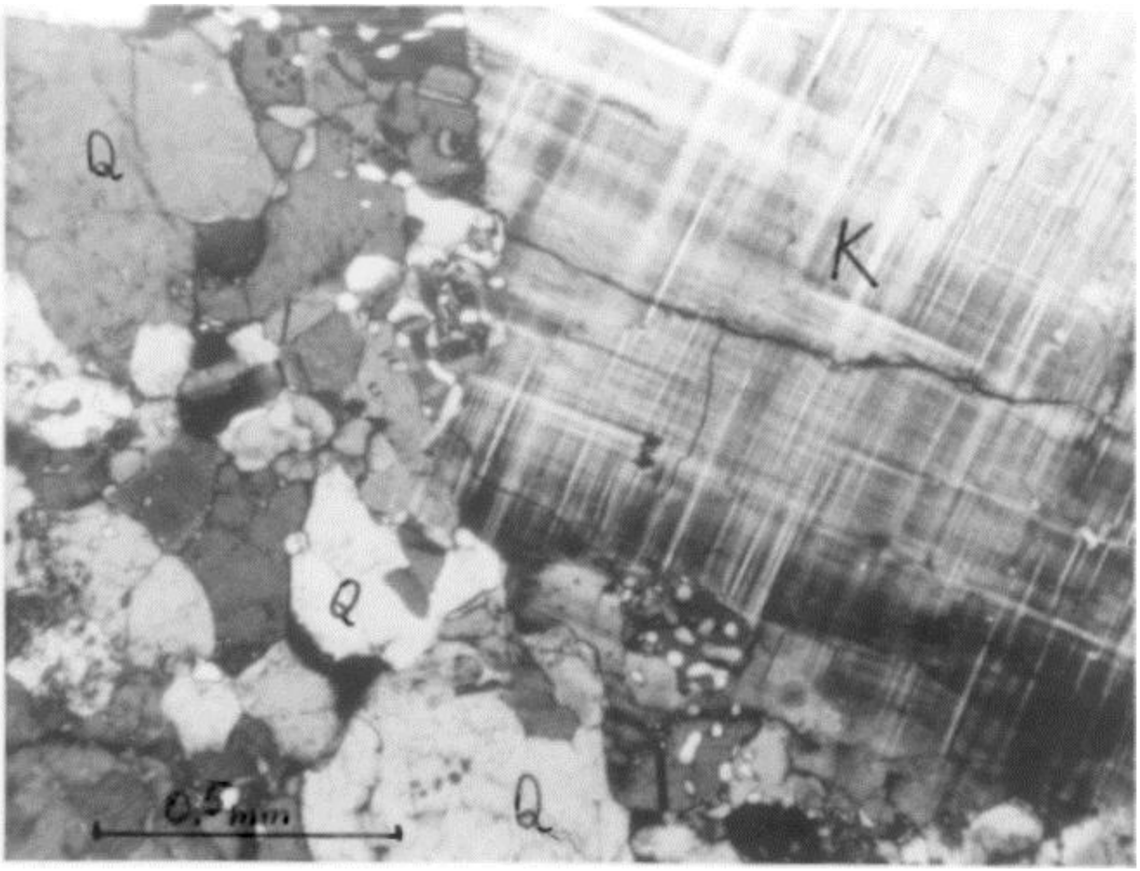

Fig. 6. Myrmekite aggregates distributed along the border of a K-feldspar megacryst (grid twinned; right side). Bar scale of 0.5 mm length; lower left. Photomicrograph is from Guangshigou pegmatoid granite, South Shaanxi Province.

Outside the megacryst, grains of quartz might have existed upon which no myrmekite would have grown. If the rock, however, was subjected to intense deformation before Na- and Ca-metasomatism so that the quartz and some microcline grains were cataclastically broken, the tiny fractured grains of K-feldspar would serve as crystal nuclei for myrmekite replacement. Such myrmekite could then grow toward and into an adjacent unbroken K-feldspar megacryst. In this way the myrmekitic borders of coexisting megacrysts would occur adjacent to bands of cataclastically granulated quartz with trails of muscovite flakes, and the chain of myrmekite grains along the megacryst borders would occur in double lobes although separated from each other (Fig. 7).

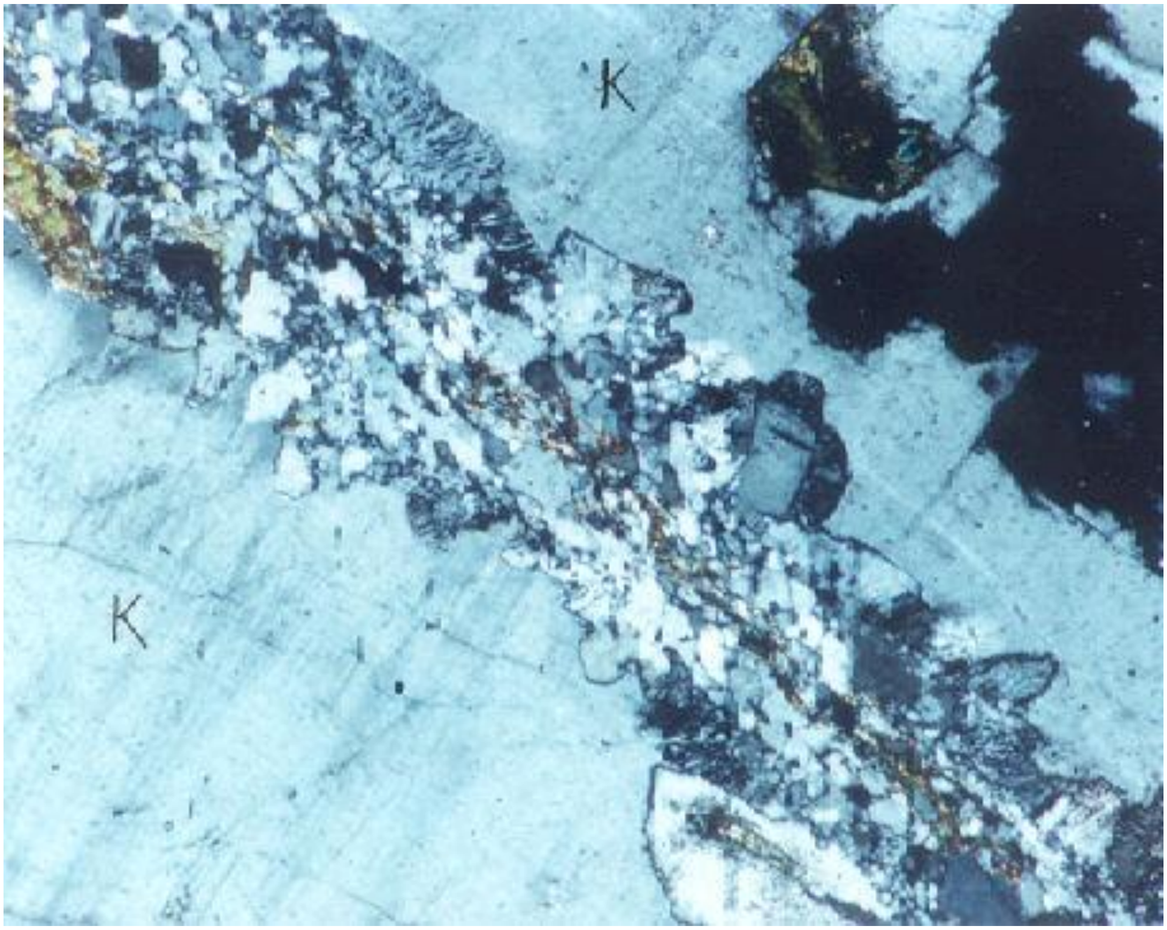

Fig. 7. Myrmekite granules with tiny quartz vermicules (black) on borders of two grid twinned K-feldspar crystals (light gray; lower left and upper right). Together these myrmekite granules constitute double lobes. The myrmekitic borders are separated by trails of muscovite flakes mixed with granulated quartz. Image is same scale as Fig. 5. Photomicrograph is from Nanguan granite, North Hebei Province.

Na- and Ca-metasomatism in other terranes

Support for the Na- and Ca-metasomatic origin of myrmekite in the granites in China is provided indirectly by studies and evidence found in other terranes. Simpson and Wintsch (1989) proposed such a Na- and Ca-metasomatic origin for double myrmekite lobes with tiny quartz vermicules bordering K-feldspar in a mylonite in California. Collins (1997b), however, also studied this same mylonite and suggested that the fine myrmekite grains were formed by K-metasomatism of deformed altered plagioclase grains. Vernon (1999) agreed with Simpson and Wintsch's model and used it to explain the origin of swapped myrmekite in metapelites near the Cooma granodiorite in Australia, but Collins (1998) also suggested that this swapped myrmekite formed by K-metasomatism. In Australia, however, unlike the swapped myrmekite in China (Figs. 2, 3, and 4), insufficient evidence exists to support either metasomatic model fully. Voll (1960) suggested that albite lamellae are exsolved first in K-feldspar and that later exsolution caused swapped myrmekitic rims to form between two adjacent K-feldspar crystals. Nevertheless, in spite of the differences in opinion among these investigators about the origin of swapped myrmekite in other terranes, the evidence in Figs. 2, 3, and 4 strongly support a Na- and Ca-metasomatic origin for the myrmekite in the granites occurring in China.

More importantly, however, Collins (1996a, 1997c) has also found places where primary perthitic K-feldspar has undergone Na- and Ca-metasomatism to produce myrmekite in which unreplaced albite lamellae stick out like teeth of a comb into the replacement plagioclase of the myrmekite, similar to that seen in Fig. 2a and Fig. 2b (see Collins, 1997a, Fig. 1a and Fig. 1b; http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf and Collins, 1997c).XX

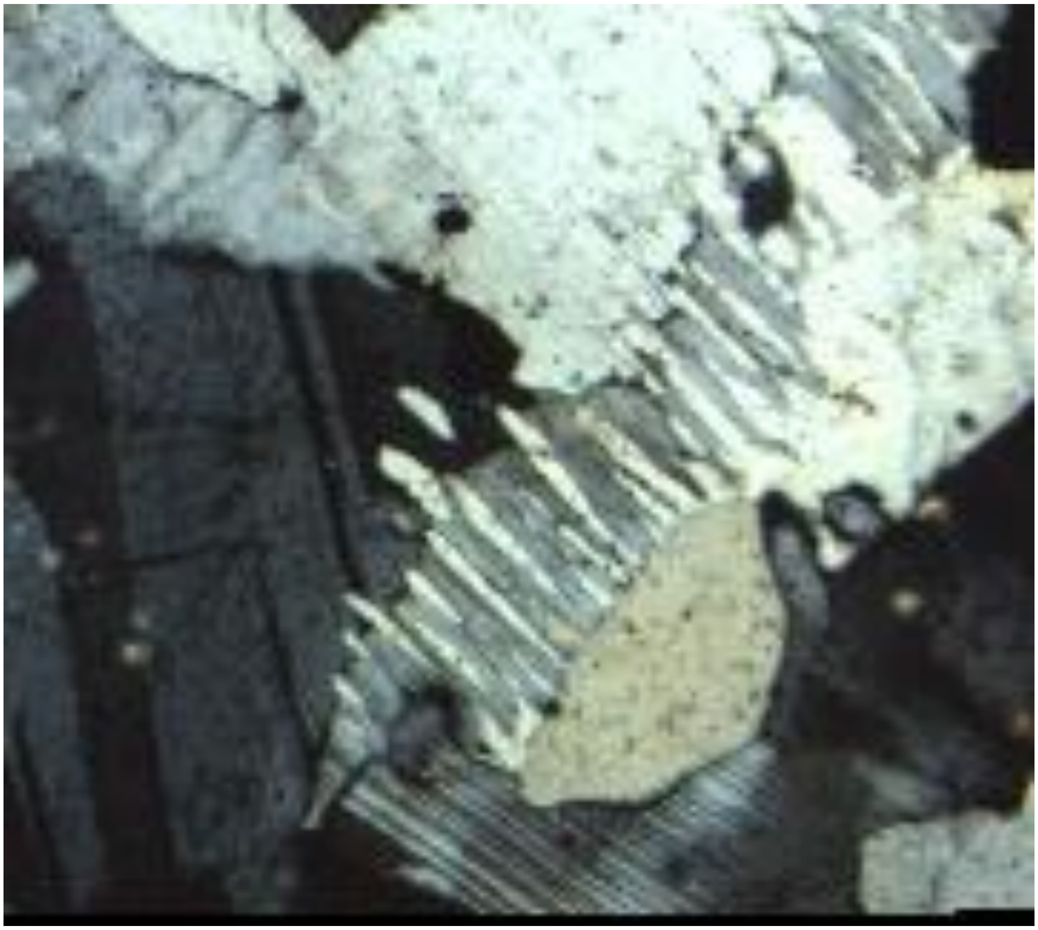

Fig. 1a of Nr1Myrm.pdf.

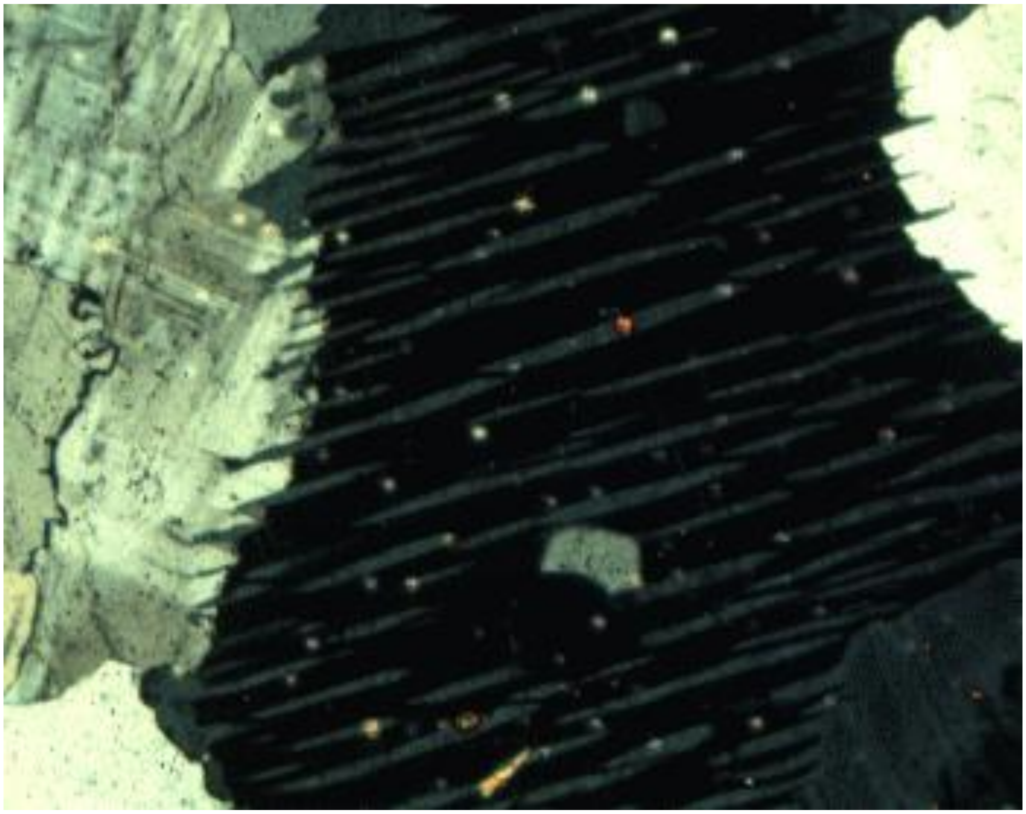

Fig. 1b of Nr1Myrm.pdf. These photomicrographs show magmatic granite that contains coarse mesoperthite and clinopyroxene in a granulite facies. Where the granite is slightly-deformed, secondary albite-twinned plagioclase An_{20} has replaced the K-feldspar of the perthite leaving plagioclase lamellae sticking out like teeth of a comb into the secondary plagioclase. Note remnant plagioclase lamellae (cream-yellow) in secondary plagioclase (upper left) and remnant plagioclase lamellae (black) projecting into secondary plagioclase (light gray, lower right). Primary, unreplaced microcline enclosing the lamellae is either light gray or very dark gray.

One such place occurs in a Precambrian granite gneiss in New York covering more than 400,000 square kilometers. Furthermore, fractured primary K-feldspar megacrysts in Finland (Collins, 1997a) have been replaced by Na- and Ca-bearing fluids to produce myrmekite similar to that seen in Fig. 3e, Fig. 4, and Fig. 5. In both New York and Finland, it is common for the quartz vermicules to have nearly constant thickness (similar to that in Fig. 2, Fig. 5, and Fig. 7) or to occur in the interior of the myrmekite as seen in Fig. 2b and Fig. 2c.

Origin of ghost myrmekite

Vermicular quartz may occasionally appear isolated in K-feldspar near myrmekite, and this relationship can be named **ghost myrmekite** (Fig. 4). Here, some quartz vermicules occur in the K-feldspar outside the myrmekite, as a possible extension of the quartz vermicules of myrmekite. This relationship might serve as tenable evidence indicating that the K-feldspar replaced the plagioclase of former myrmekite, and, therefore, the whole K-feldspar must be metasomatic. This phenomenon, however, can be explained by the so-called *reversed K-metasomatism*, which took place after the formation of myrmekite ceased. The newly formed K-feldspar (being of nibble replacement pattern, too) grew by crystallizing on the preexisting K-feldspar behind, taking its crystallographic orientation, while nibbling at the myrmekite in front. In this way, a small part of the plagioclase of the myrmekite was replaced, leaving quartz vermicules (hard to be replaced) as remnants. Thus, the reversed K-metasomatism results in the formation of ghost myrmekite. Therefore, in fact, only a limited part of the K-feldspar, i.e., the K-feldspar in ghost myrmekite, was formed exactly by K-feldspathization (secondary K-feldspar). As the secondary K-feldspar grows on the lattice of the primary K-feldspar and takes the same crystallographic orientation as the primary K-feldspar, there is no obvious boundary between them, resulting in a false impression of the whole K-feldspar being metasomatic in origin. For the same reason, the K-feldspar megacryst as a whole may not necessarily be formed by metasomatism, when plagioclase somewhere is nibbly replaced by K-feldspar, provided that the replacing K-feldspar is attached to a small part of the whole K-feldspar megacryst. Hopson and Ramseyer (1990) also found oval quartz inclusions in K-feldspar adjacent to myrmekite in the Rubidoux Mountain leucogranite in California and also suggested a complex origin for this relationship but attributed their formation to magmatic processes.

Additional observations and discussion

Although myrmekite can be produced in granitic rocks, no myrmekite would be created in trondhjemite or quartz diorite though extremely deformed, as long as these rocks lack K-feldspar. The presence of "isolated" myrmekite in rocks having no K-feldspar can reasonably be deduced that all the preexisting (with lesser content of) K-feldspar crystals in rocks have fully been replaced by the "isolated" myrmekite.

No myrmekite would occur in volcanic or hypergenetic rocks bearing K-feldspar, perhaps because the surrounding pressure was too low and/or the cooling rate was too rapid for hydrothermal fluids to enter a grain boundary to react with K-feldspar.

A certain rock may be subjected to more than one action; for example, (1) different types of deformation (generally ductile at first, then brittle later) and (2) different types of metasomatism, including K-metasomatism and Na-metasomatism.

The author believes that the rim, the intergranular, and the enclosed kinds of myrmekite in intrusive rocks are formed after emplacement when the rocks remain undeformed, whereas the double myrmekite lobes with trails of muscovite flakes, the myrmekite aggregates at the border of K-feldspar megacrysts, outside which are crushed quartz grains, and other myrmekite in gneissic plutonic rocks are formed after cataclastic deformation. Myrmekite with different morphology and occurrence, in fact, are possibly formed by a uniform mechanism, i.e., Na- and Ca-metasomatism of K-feldspar. The presence of coarse-, meso-, and fine-myrmekite in a certain rock is a reflection of multiple processes of Ca-bearing sodic metasomatism and the general decreasing amounts of Ca involved in the metasomatism with the passage of time. These processes are likely controlled by temperature (Orville, 1963). Generally, the coarse myrmekite occurs in the inner and middle parts while the meso-to-fine myrmekite is found in or near the rim. But the distribution of quartz vermicules in myrmekite from coarse to fine may sometimes be irregular as shown in the right myrmekite in Fig. 3a, Fig. 3b, Fig. 3c, and Fig. 3d. The different styles of quartz vermicule growth in the myrmekite in granites in China can be explained because during Na- and Ca-metasomatism of primary K-feldspar, the An content in the plagioclase of the myrmekite and coarseness of the quartz vermicules are controlled by the temperature of the fluids. At higher temperatures, more Ca in the fluids will replace the K-feldspar and create coarse quartz vermicules and plagioclase of higher An value. At lower temperatures, but higher than temperatures at which K-feldspar is stable, more Na and less Ca in the fluids will replace the K-feldspar and create finer quartz vermicules and plagioclase of lower An value.

Conclusions

The Na- and Ca-metasomatic replacements of primary K-feldspar to produce myrmekite in granites of China and in other terranes are characterized by the following features.

1. The myrmekite is always associated with K-feldspar.
2. Remnants of perthitic lamellae of a former perthite may be preserved in the myrmekite with sodic plagioclase. The remnants of perthitic lamellae do **not** change their crystallographic orientations.

3. All K-feldspar, either phenocryst or ground mass in a thin section, is mainly primary, and has nearly the same kind and distribution of perthitic lamellae, although across the granite body, variations may occur in the K-feldspar appearance.
4. Swapped myrmekite, consisting of a double row of grains, commonly occurs on the boundary between two differently oriented adjacent K-feldspar crystals.
5. Modal quartz in the vermicules is proportional to the An content of the adjacent plagioclase in the myrmekite.
6. An content of the plagioclase in the myrmekite need not be half the An content of the primary plagioclase, but only some value less than the An content of the primary plagioclase.

The Na- and Ca-metasomatism to produce myrmekite in the granites of China has broad implications about the P-T environment in which this process occurred.

The formation of myrmekite, especially swapped myrmekite, results not from exsolution from alkali feldspar (Ramberg, 1962) but from nibble replacement for K-feldspar by Na (plus Ca) bearing gas or fluid. The nibble replacement pattern of rock-forming minerals occurs not arbitrarily, but regularly (i.e., the replacing mineral grows nibbling at the replaced mineral in front and taking the same orientation as the similar mineral behind), which is completely and strictly distinguished from the lattice replacement pattern (Rong, 1982)*.

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*Lattice replacement occurs later than nibble replacement. Muscovitization and chloritization of biotite, deanorthitization of plagioclase, and complete albitization of K-feldspar are obviously of the lattice replacement pattern. The lattice replacement origin of perthite and antiperthite, however, should be doubtful, regardless of regular or irregular distribution of patches or lamellae, although they are very alike in morphology. The perthite and antiperthite, in any case, must have formed before nibble replacement, i.e., before myrmekitization, since albitic lamellae may remain as relicts in myrmekite.

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Appendix

	Molecular weight	**Specific gravity**	**Molecular volume** (mol. wt./spec. gravity)
K-feldspar	278.28	2.56	108.70
Albite	262.16	2.616	100.21
Anorthite	278.16	2.7614	100.73
Quartz	60.06	2.647	22.69

An = An of Pl of myrmekite
Vpl = 100.21 + (100.73 - 100.21) x An

Theoretical volume % of quartz vermicules in myrmekite is equal to:

4 x An x 22.69/(Vpl + 4 x 22.69) which is equal to:

90.76 x An/(100.21 + 91.28 x An)

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