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## 2. REPLACEMENT OF PRIMARY PLAGIOCLASE BY SECONDARY K-FELDSPAR AND MYRMEKITE

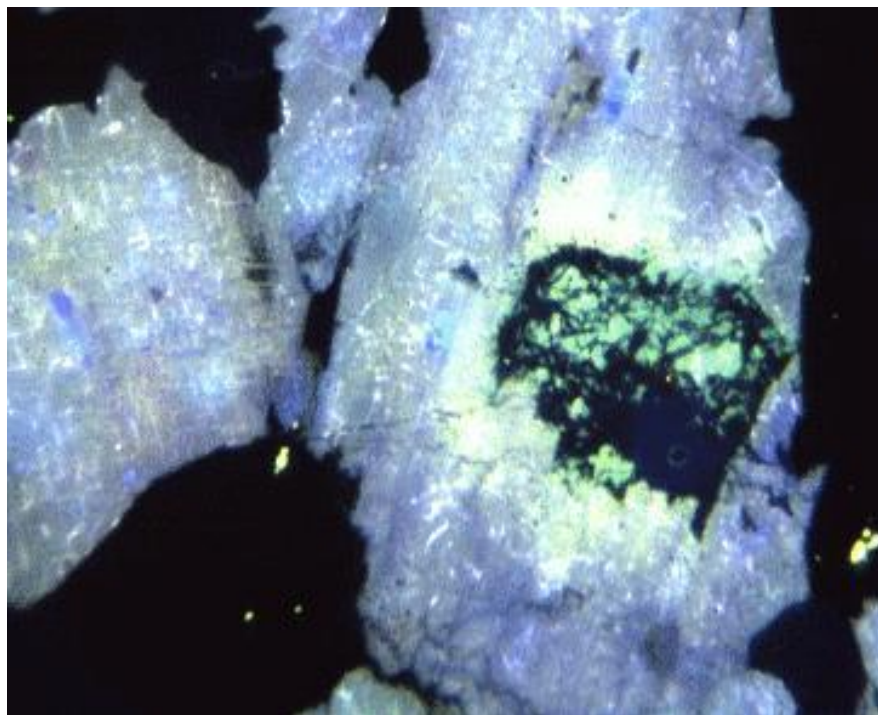
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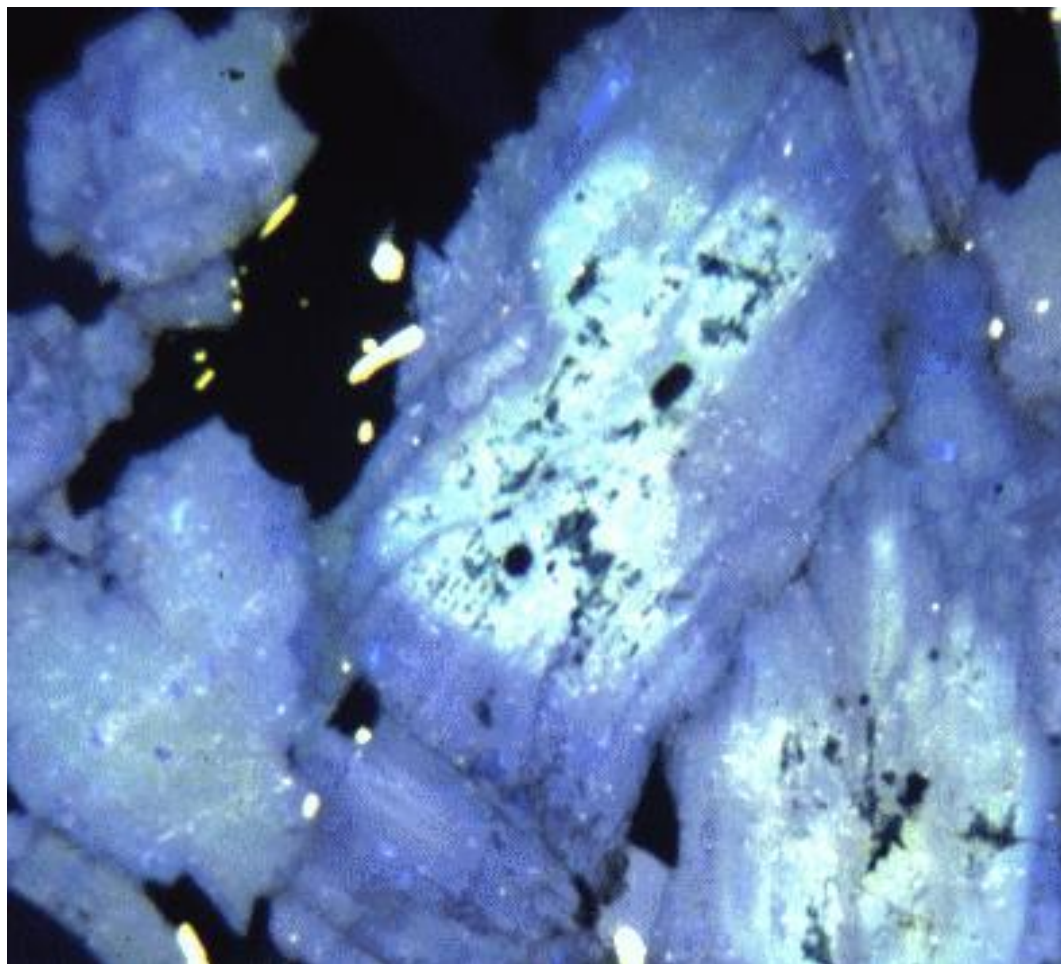
The following illustrations in this presentation show four photomicrographs of cathodoluminescent images, two black-and-white scanning electron microscope images, and six photomicrographs of thin sections in which various stages of replacement of primary plagioclase by secondary microcline and myrmekite occur. Cathodoluminescent images were made by Karl Ramseyer in Switzerland.

**Temecula, California (USA).**



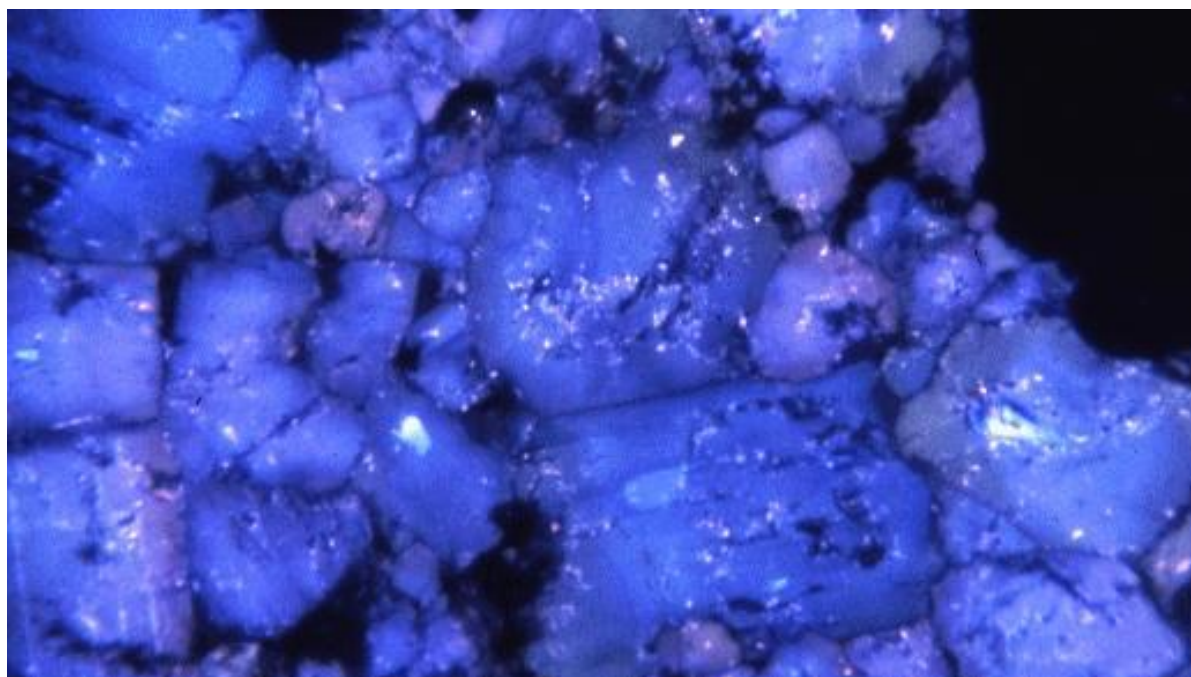
**Fig. 1.** This photo shows a cathodoluminescent image of a normally zoned plagioclase crystal where the host diorite is only slightly deformed. Relatively calcic cores luminesce with pale yellow or yellow-green colors. Toward the rim where it is more sodic, the color becomes beige, then purplish. Not 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  $An_{37-39}$  and rims  $An_{17-20}$ . All Si in the analyses fits into the plagioclase crystal structure.

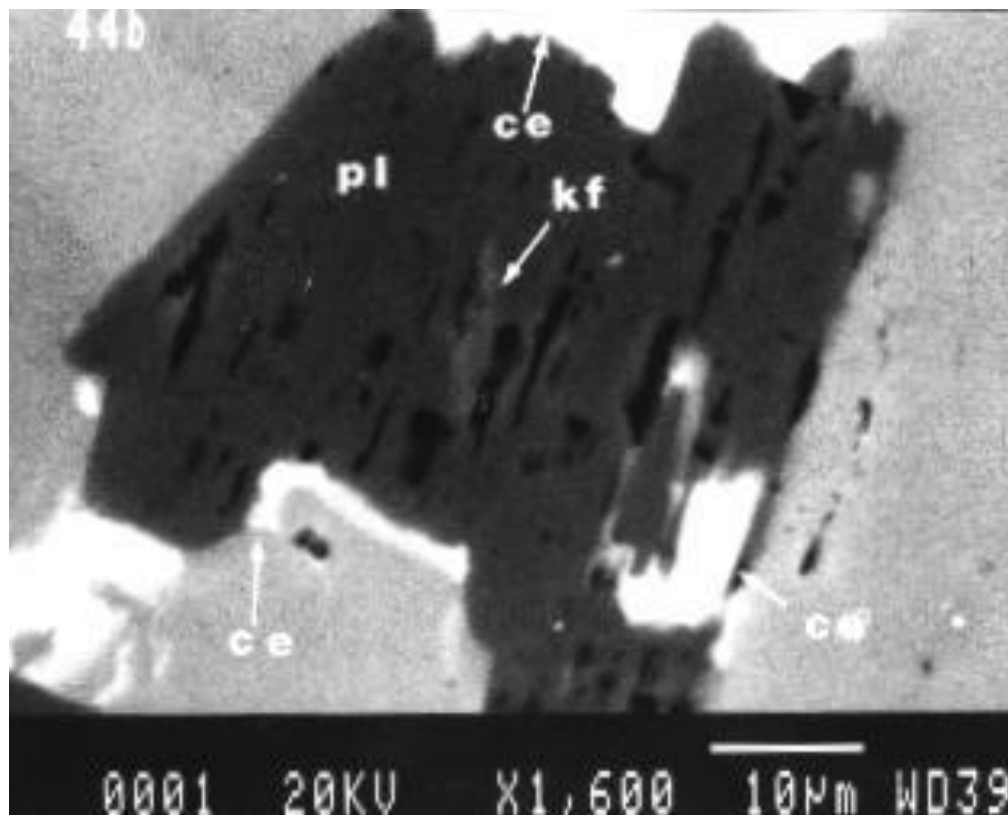


**Fig. 2.** This photo shows a cathodoluminescent image of textures in deformed diorite in transition towards the myrmekite-bearing granite. Two plagioclase crystals show remnant zoning. Cores are now less calcic than in Fig. 1 (greenish-yellow color is now gone). Under cross-polarized light the crystal 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

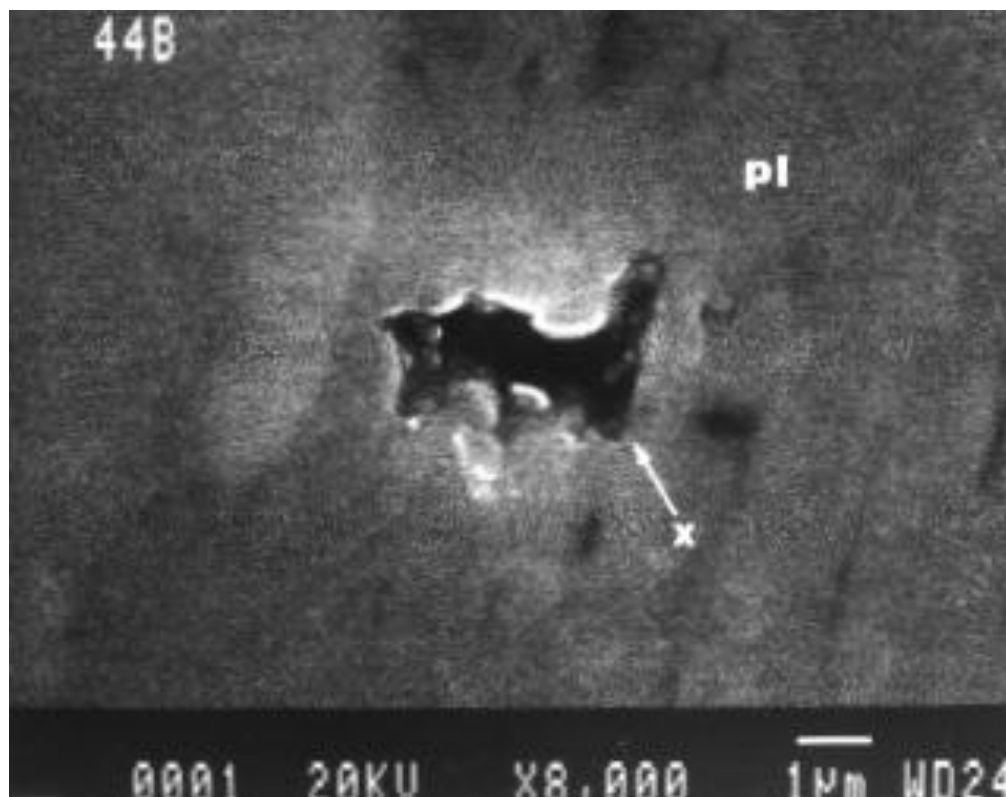
advanced. For the plagioclase crystals with uniform beige color, electron-microprobe studies show that both cores and rims have compositions of  $An_{17-20}$ . In these crystals electron-microprobe studies also show that Ca has been lost because some Si is in excess of what would normally fit into a 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.



**Fig. 3.** 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  $An_{1-5}$  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).

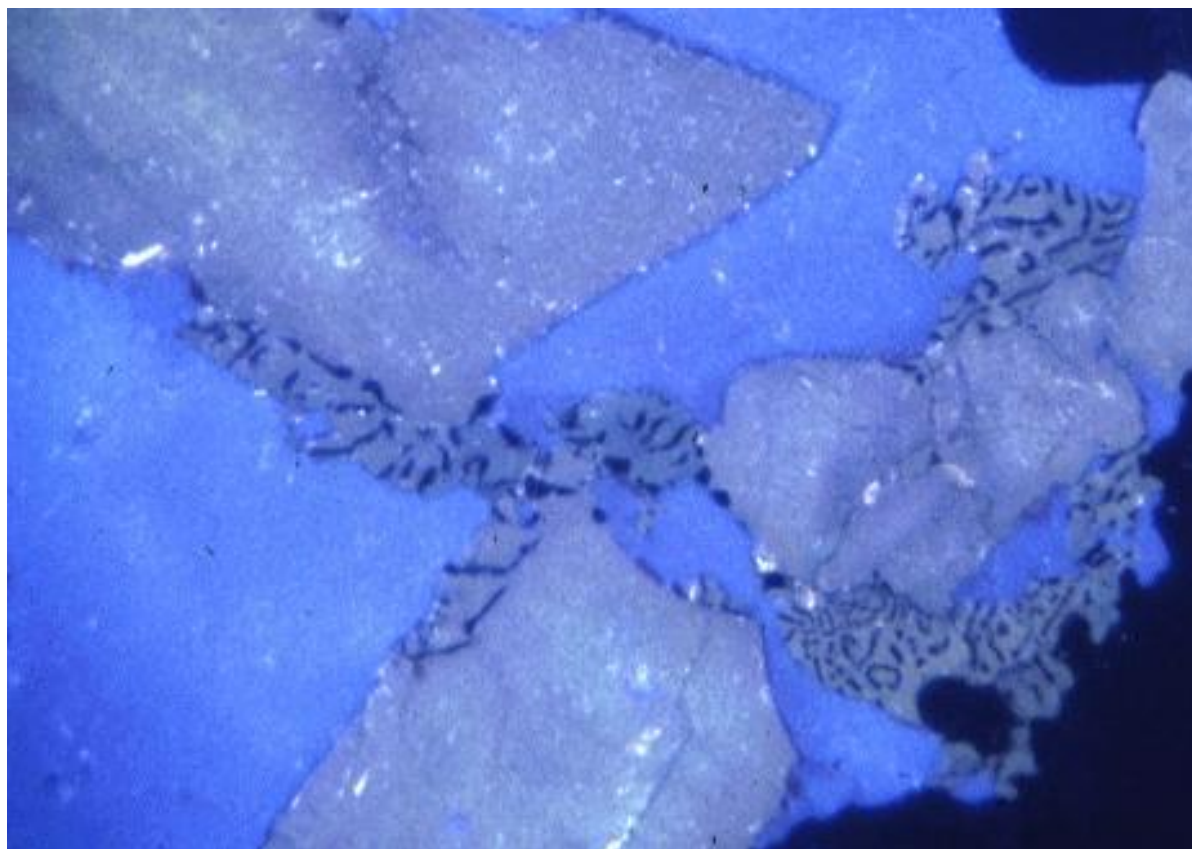


**Fig. 4a.** This scanning-electron photomicrograph is an image in the center of a soda-rich core of a plagioclase crystal in Fig. 3, but now magnified 1,600x. The enlarged image shows that the plagioclase (pl, dark gray) is full of holes (black) with angular boundaries parallel to the plagioclase crystal 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.

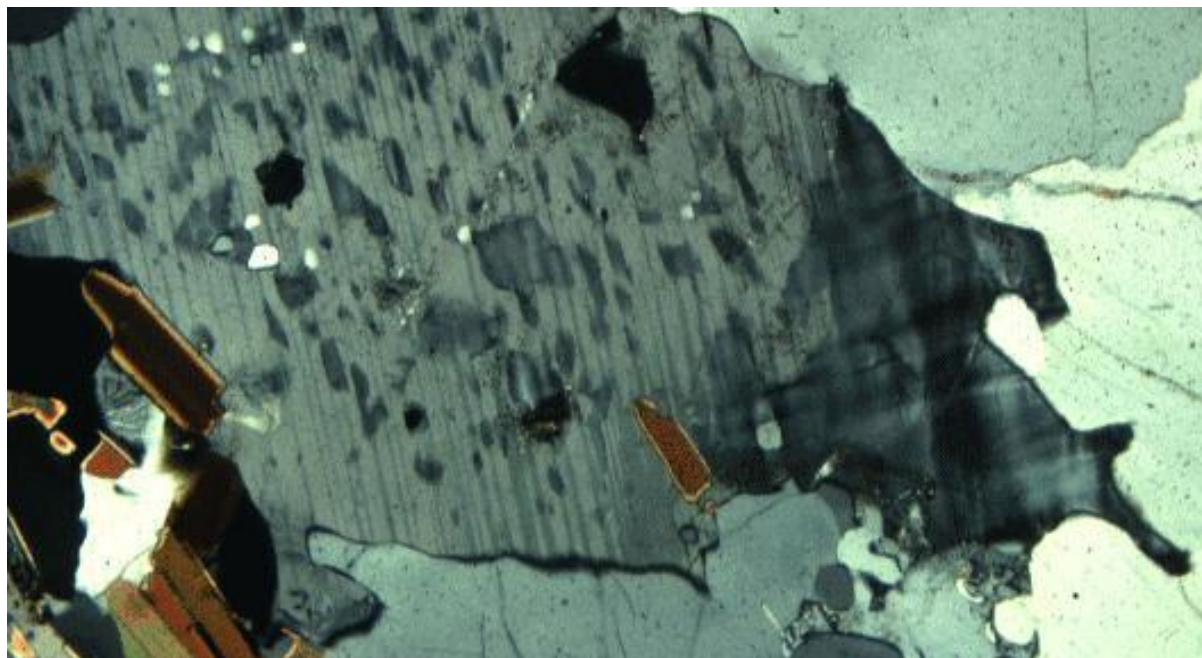


**Fig. 4b.** This scanning-electron photomicrograph is from the same area as in Fig. 4a but now magnified 8,000x. The "x" points to a hole (black) bordered by concentrations of K (light gray). Locally, Ba is concentrated in celsian (ce, white), and in some places the celsian occurs on hole walls adjacent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



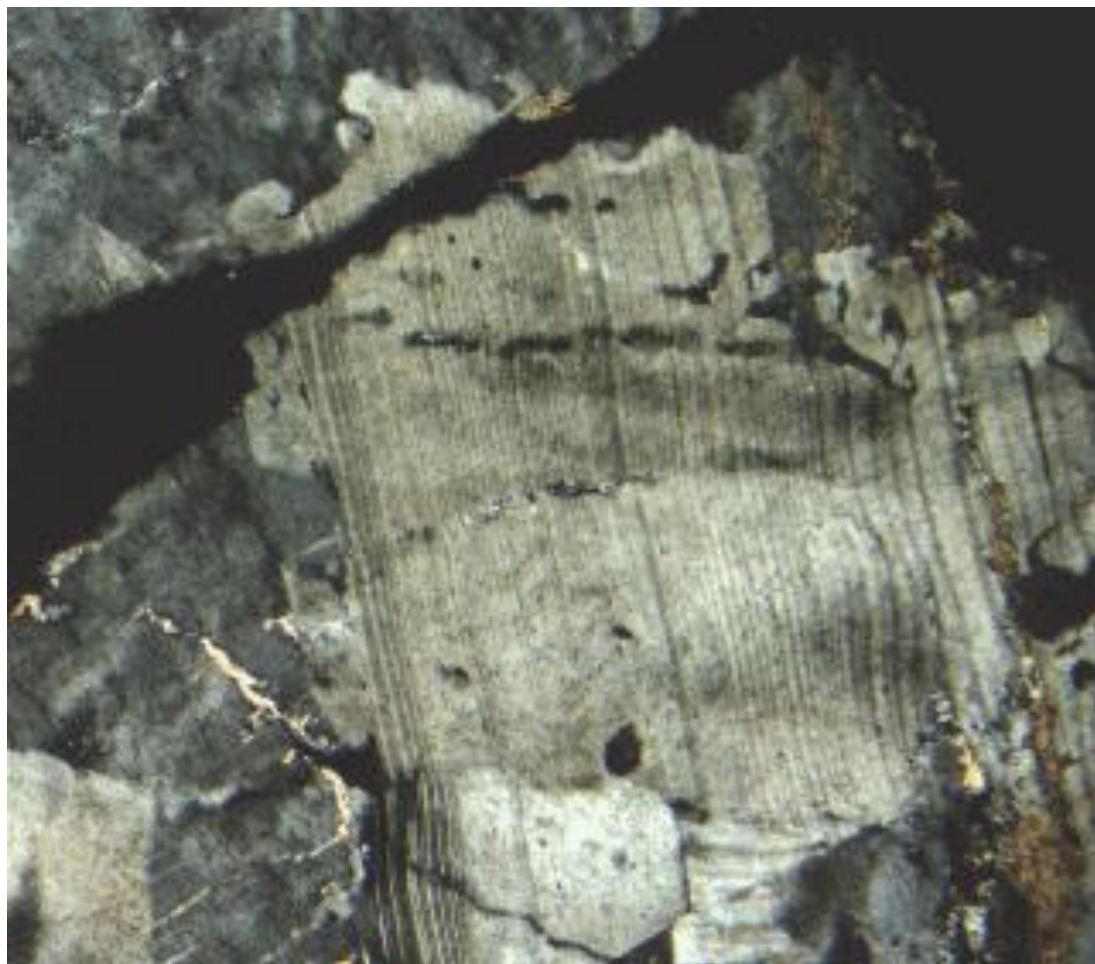


**Fig. 5.** In this cathodoluminescent image myrmekite with quartz vermicules (black) has formed between two K-feldspar crystals (blue) or between K-feldspar and plagioclase (beige). In some places the cores are more sodic (pinkish) than in the more calcic plagioclase of the myrmekite. Large plagioclase crystal (upper left, beige) shows a fracture along which Ca has been removed to make a vein extending into the center of the crystal. The photomicrograph in Fig. 3 of <http://www.csun.edu/~vcgeo005/~vcgeo005/Nr1Myrm.pdf> represents the final stage of replacement in this sequence where all altered plagioclase grains (with sodic cores or with cores and rims having the same An-content) have either been replaced by microcline or by recrystallized, albite-twinned, unzoned, sodic plagioclase An<sub>12-15</sub>. One must be reminded that grains most strongly altered have been replaced by K-feldspar, and those plagioclase crystals less-altered still remain. Unfortunately, replacement processes destroy the evidence.

**Central City, Colorado (USA)**

**Fig. 6.** 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.

## Cape Ann, Massachusetts



**Fig. 7.** In this photomicrograph, microcline (gray, top and left side) has replaced deformed plagioclase (tan, center) in the Cape Ann granite. Albite twins are bent and fractured, and K-feldspar replaces the plagioclase in irregular veins at top right of plagioclase and on left side. The gently-inclined, broad, black area is a fracture (hole) in the thin section. (See Fig. 4a and Fig. 4b in <http://www.csun.edu/~vcgeo005/Nr3.pdf> for photos of drill cores of Cape Ann granite.)





**Fig. 8.** In this photomicrograph, microcline (dark gray, right side, top center, and bottom left) replaces albite-twinned plagioclase (light gray, bottom center) in Cape Ann granite. Myrmekite occurs in top center and lower left side.



**Fig. 9.** In this photomicrograph of Cape Ann granite, microcline is dark gray (bottom, right), and plagioclase is light gray to white and partly altered to clay (tan; left side and top). Microcline penetrates and replaces plagioclase (center, left). Angular parts of plagioclase that project downward into microcline are myrmekitic, containing tiny quartz vermicules. Ghost remnants of incompletely replaced plagioclase continue into the microcline in a light-gray pattern beyond the longer myrmekite projection. Two additional photomicrographs of Cape Ann granite are included as Fig. 5 and Fig. 6: <http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf>.

## Sierra Nevada, California (USA)



**Fig. 10.** In this photomicrograph, the thin section of granite in the Sierra Nevada is turned so that the microcline is at extinction (black) in order to show "*ghost myrmekite*." Albite-twinned plagioclase (tan to light gray and white, upper right side) has an extinction position that is optically parallel to extinction positions of islands of incompletely replaced plagioclase containing tiny quartz blebs (white) which occur scattered to the left of the plagioclase crystal in the microcline and to the far left in the microcline. When the thin section is rotated so the microcline grid-twinning becomes visible, these islands become invisible or nearly so, whereas the large plagioclase crystal is still distinct. The inclined, elongate, rounded grain (left side, center) in microcline is myrmekitic.

## Rubidoux Mountain, Riverside, California (USA)



**Fig. 11.** "*Ghost myrmekite*" also occurs in this photomicrograph of Rubidoux Mountain leucogranite. At the extinction position for microcline (black), clusters of quartz blebs (white) occur in faint traces of remnant plagioclase or as isolated oval islands in the microcline. The maximum sizes of the quartz blebs in the microcline match the maximum diameters of quartz vermicules in myrmekite (left side) where plagioclase is white and quartz vermicules are gray.

### Discussion

The colors in the photomicrographs (Figs. 1-3, 5) are not the fluorescent colors of K, Ca, or Na because these elements do not fluoresce with these colors. The colors represent fluorescence of trace elements associated with the K, Ca, and Na in the feldspars. Electron microprobe or scanning-electron analyses verify that K, Ca, and Na are dominant in the colored areas indicated.

The progressive changes from unaltered normal-zoned plagioclase in the diorite to reverse-zoned plagioclase show the preparation prior to introduction of K in the interior of an altered plagioclase crystal. All plagioclase grains small or large are altered in this fashion in the deformed diorite in this stage. Moreover, at this stage the scanning-electron images (1,600x and 8,000x) indicate that some altered plagioclase crystals are virtual sieves with ample openings for fluids and elements to move in and out. The progression of the alteration shows that primarily Ca is subtracted, but some Al must also move out as Na tends to stay behind.



When K is introduced, the "holes" provide space for the expanded lattice of K-feldspar to grow inside the altered plagioclase crystal which still has a solid, silicate framework. Like a geodesic dome, the framework prevents collapse of the crystal even though adjacent solid grains in the deformed rock are pressing with high pressure on the altered plagioclase crystals.

When a particular altered crystal is replaced by K, then the K displaces most of the Ca and Na (but not all), and much of the Na atoms that are displaced move into other nearby less-altered plagioclase crystals (with holes) to cause them to recrystallize as a more sodic plagioclase. In the rocks at Temecula, some of the original zoned plagioclase crystals with calcic cores  $An_{37-39}$  and sodic rims  $An_{17-20}$  of the diorite are recrystallized as unzoned albite-twinned plagioclase  $An_{12-15}$ ; see Fig. 3 in <http://www.csun.edu/~vcgeo005/Nr1.pdf>.

The myrmekite forms where residual Ca, Na, Al, and Si in the altered plagioclase are in the wrong proportions to recrystallize as plagioclase only. In most places as K comes in, avenues that permit Ca, Na, and Al to escape the plagioclase are available, and consequently, most plagioclase crystals are totally replaced by K-feldspar. But if avenues are not available for the Ca, Na, and Al to escape, then residual proportions of these elements relative to excess Si in the lattice cause the excess Si to recrystallize as either quartz vermicules in myrmekite or as quartz blebs in K-feldspar in ghost myrmekite. In ghost myrmekite most Na and Ca has been displaced by the K, but locally excess Si over Al from the original plagioclase lattice may still remain which cannot fit into the K-feldspar structure.

Myrmekite forms where displaced Ca is trapped between two centers of replacement (K-K or K-Na); e.g., either between two growing K-feldspar crystals or between a growing K-feldspar crystal and a recrystallizing sodic plagioclase crystal. The Ca requires two aluminum atoms in its structure whereas K and Na require only one. So where Ca occurs, excess silica remains to form quartz vermicules or blebs. The plagioclase lacking quartz vermicules is in optical continuity with plagioclase in the myrmekite because plagioclase in both places is recrystallizing from the same former altered crystal.

Because the displacement of Na and Ca by K is never perfect, residual islands remain that can later separate to form albitic perthite lamellae, and thereby, give the appearance that the K-feldspar crystallized from a melt because magmatic K-feldspar crystals are also perthitic. Moreover, in K-feldspar crystals formed by replacement, the albitic perthite lamellae may have a non-uniform distribution.

The preservation of replacement stages at Temecula (Figs. 1-5) is unusual and probably is not observed in most places because the stage showing reversed zoning in the Temecula transition rocks is rare. Undoubtedly, in other rocks, the replacement process normally proceeds rapidly, converting the plagioclase to microcline. In that case, the "reversed zoning" and "holes" are in a nano-environment, moving ahead of the incoming K.

Ghost myrmekite ranges from tiny quartz blebs (barely visible) in microcline where the original plagioclase is relatively sodic, as in granite near Temecula (not shown), in which primary plagioclase averages  $An_{30}$ , but bleb sizes are intermediate in Fig. 10 and Fig. 11 where the primary plagioclase is  $An_{45-60}$ . Ghost myrmekite also occurs in microcline where the primary plagioclase averages  $An_{70-100}$ , but it is no longer a "ghost" because the quartz blebs are so large that generally the K-feldspar-quartz intergrowth would be interpreted to be a graphic texture.

See the following reference for additional photos of myrmekite and ghost myrmekite.

Hopson, R. F., and Ramseyer, K. (1990a) Cathodoluminescence microscopy of myrmekite. *Geology*, v. 18, 336-339.

And see these recent references for discussions of different interpretations.

Collins, L. G. (1990) Cathodoluminescence microscopy of myrmekite: Comment. *Geology*, v. 18, 1163.

Hopson, R. F., and Ramseyer, K. (1990b) Cathodoluminescence microscopy of myrmekite: Reply. *Geology*, v. 18, 1163-1164.

Garcia, D., Pascal, M. L., and Roux, J. (1996) Hydrothermal replacement of feldspars in igneous enclaves of the Velay granite and the genesis of myrmekites. *European Journal of Mineralogy*, v. 8, p. 703-717.

- [Link to article #43 for discussion of the origin of myrmekite at Temecula, California: http://www.csun.edu/~vcgeo005/Nr43Temecula.pdf](http://www.csun.edu/~vcgeo005/Nr43Temecula.pdf).