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24. MAGMATIC RESORPTION VERSUS SUBSOLIDUS METASOMATISM --- TWO DIFFERENT STYLES OF K-FELDSPAR REPLACEMENT OF PLAGIOCLASE

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Introduction

Comparisons of mineral textures in the orthoclase-bearing, copper-porphyry, quartz monzonite Cornelia pluton in Arizona (Wadsworth, 1968) with mineral textures in the microcline-bearing Rocky Hill granodiorite stock in California (Putnam and Alfors, 1969, 1975) reveal two different styles of K-feldspar replacement of plagioclase. The first is by above-solidus magmatic resorption; the second is by subsolidus K-metasomatism. The differences in styles of replacement raise doubts about the common perception among petrologists that *all* K-feldspar replacements of plagioclase in granite plutons are by magmatic resorption (e.g., Hogan, 1993).

The copper porphyry Cornelia pluton, Ajo, Arizona

he granitic rocks in the main mass of the copper porphyry Cornelia pluton occur west and south of Ajo, Arizona (Fig. 1), and were divided by Gilluly (1942, 1946) into an older, outer ring of fine-grained quartz diorite and an inner, medium-grained mass consisting mostly of quartz monzonite. The copper-bearing, porphyritic quartz monzonite that occurs in the eastern part of the pluton, south of Ajo (Fig. 1), is interpreted to be the former top of the magma chamber which was down-faulted eastward relative to the former-lower, western part of the pluton.

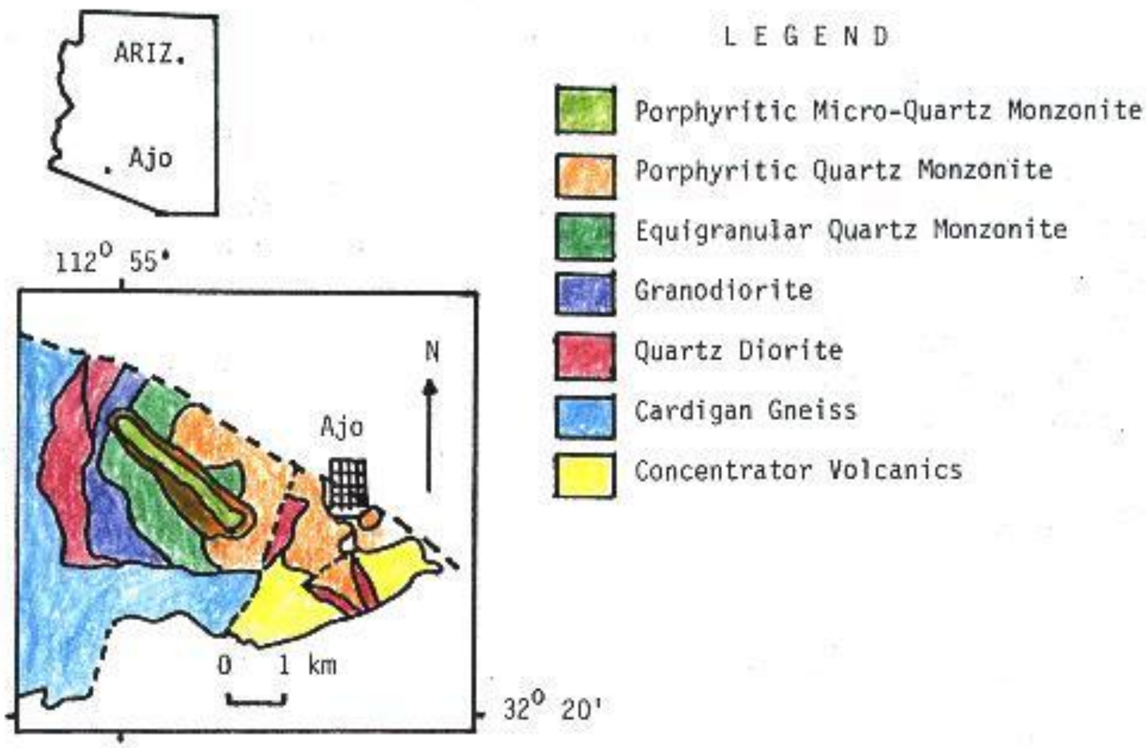

Fig. 1. Location and simplified geologic map of the Cornelia pluton (modified after Wadsworth, 1968, and Gilluly, 1946). Map does not show the same detail of intermixed facies as in Wadsworth (1968).

Wadsworth (1968, 1975) further divided the western part of the pluton into five facies. From oldest to youngest these are quartz diorite, granodiorite, equigranular quartz monzonite, porphyritic quartz monzonite, and porphyritic micro-quartz monzonite (Fig. 1). Wadsworth postulated that these facies evolved during magmatic differentiation as the pluton crystallized inward from the walls, first forming anhydrous phases in the quartz diorite. The granodiorite is intrusive into the quartz diorite, and in late stages, concentrations of volatile components beneath the roof permitted K- and Si-rich aqueous fluids to impregnate, resorb, and replace earlier-formed zoned plagioclase crystals by K-feldspar (orthoclase). Both the orthoclase and plagioclase are also partly replaced by quartz. As a result of these replacements the inner rock's composition is changed from granodiorite to quartz monzonite and then to compositions having more orthoclase than plagioclase, approaching a granite composition in the core of the pluton.

The depletion of K in lower levels and enrichments at higher levels during replacements were also suggested to be accompanied by enrichments in Na (albite) and Si (quartz) in the upper levels, along with disseminated copper sulfides in the mineralized zone. All mineral replacements (resorptions) were postulated to occur at temperatures above the solidus because the K-feldspar is orthoclase rather than microcline. The K-replacements appear to be along planar zones in the pluton (on a large scale, extending NW to SE, as shown in Fig. 1; and on smaller scales throughout the pluton, as in Fig. 2), although there is no evidence of fracturing to produce these planes (Walker, 1969). The zoned plagioclase crystals that are replaced by orthoclase are undeformed and are not fractured (see Figs. 3-7). Later, subsolidus fracturing along fault zones, however, has locally mylonitized all mineral grains. At the lower temperatures at which the faulting took place, any replacements that occurred resulted primarily because of the addition of water, carbon dioxide, or oxygen to produce sericite and calcite in the feldspars and chlorite and iron oxides in the ferromagnesian silicates. Epidote is also a secondary alteration product.

Fig. 2. Connected, non-rotated blocks of dark pinkish-brown porphyritic quartz monzonite, penetrated and replaced by light-gray micro-quartz monzonite. The penetration occurs above and below the blocks along nearly horizontal planes as well as along nearly vertical lobate zones extending into or through the blocks. Picture is of an outcrop in the west wall of the Gibson Arroyo channel in Ajo, Arizona, at the west end of Rocalla Road where this road bends and makes a transition to the north end of the Scenic Loop Road.

Wadsworth (1968) sketched textures of microscopic images which he used to outline the sequence of K-feldspar replacement of the plagioclase (Wadsworth, 1968, 1975). In early stages, orthoclase in the granodiorite coats the borders of the plagioclase crystals. In later stages the orthoclase in quartz monzonite penetrates the exterior of the plagioclase crystals (Fig. 3), enclosing remnant islands of plagioclase which are in parallel optical continuity with the adjacent, larger, unreplaced portions (Fig. 4 and Fig. 5).

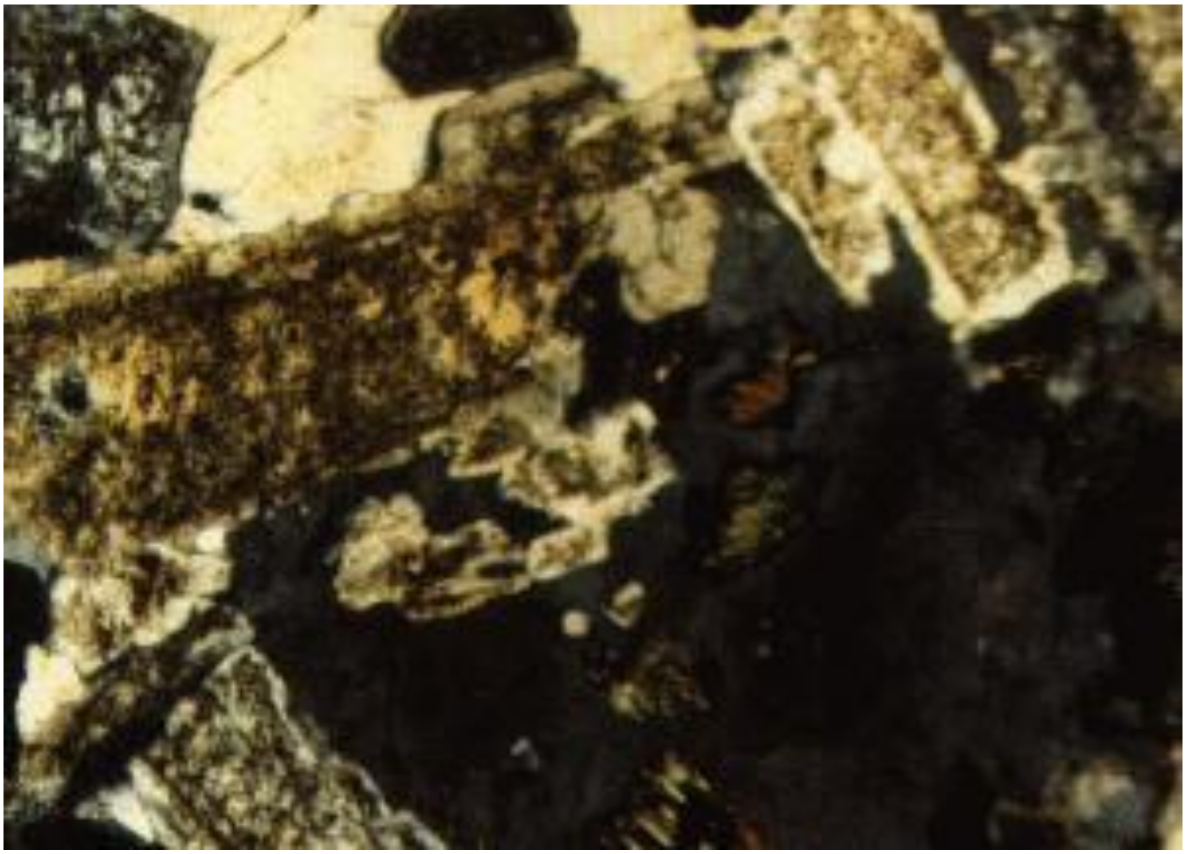

Fig. 3. Orthoclase (dark gray to black; lower right quadrant), penetrating sericitized, albite-twinned, and zoned plagioclase (cream, speckled brown). Quartz (clear, cream; top). Remnant islands of hornblende (right side, green and brown).

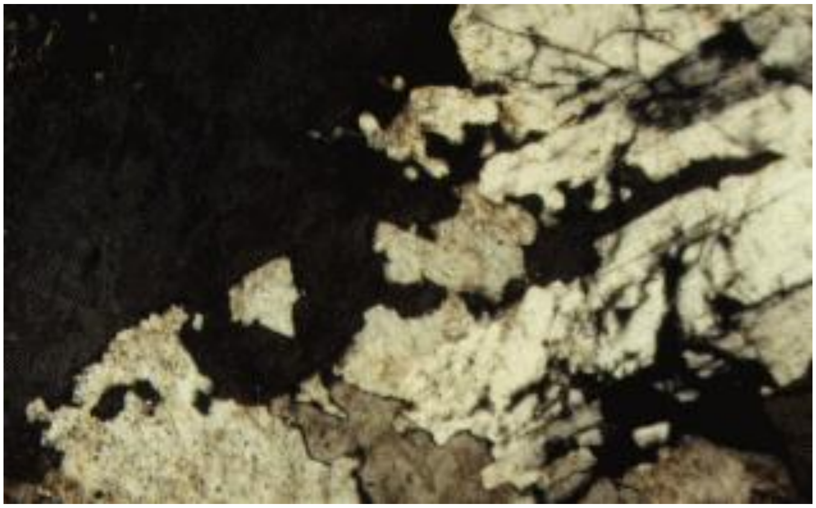

Fig. 4. Remnant islands of plagioclase (cream) in orthoclase (black). Orthoclase penetrates plagioclase along irregular fractures. Islands of plagioclase are optically continuous with adjacent larger plagioclase crystal.

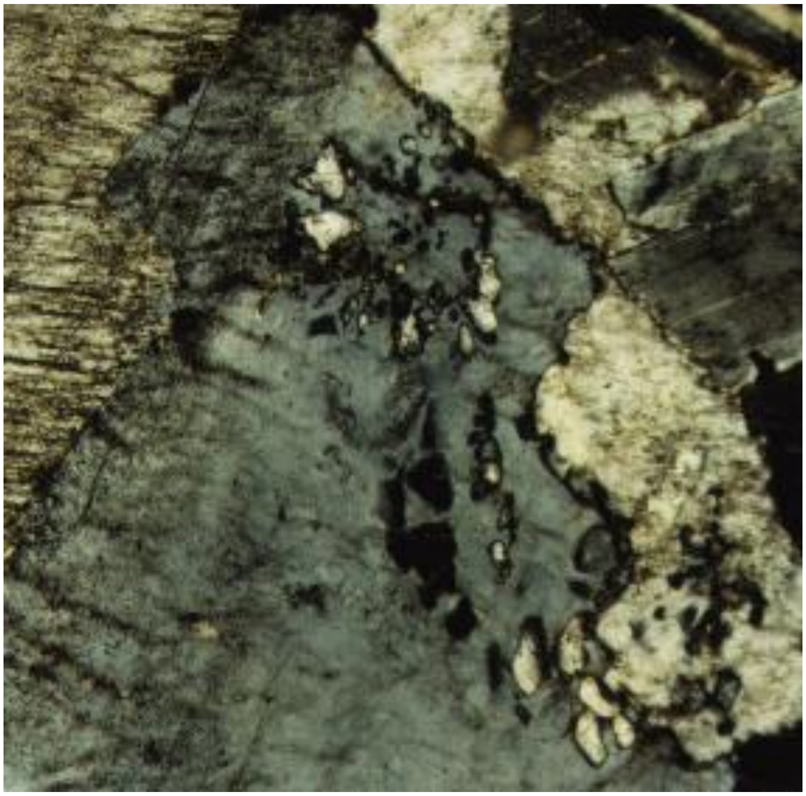

Fig. 5. Remnant islands of plagioclase (cream) in orthoclase (dark gray and black). Islands are optically continuous with adjacent large plagioclase crystal. Orthoclase penetrates and replaces plagioclase along albite twin planes and forms scalloped boundaries.

In final stages only remnants of the plagioclase occur as tiny islands in the orthoclase (Fig. 6). Quartz commonly forms scalloped replacement boundaries with plagioclase (Fig. 7) and may contain highly irregular islands of K-feldspar (Fig. 8).

Fig. 6. Tiny remnant islands of optically continuous plagioclase (light gray) in orthoclase (dark gray).

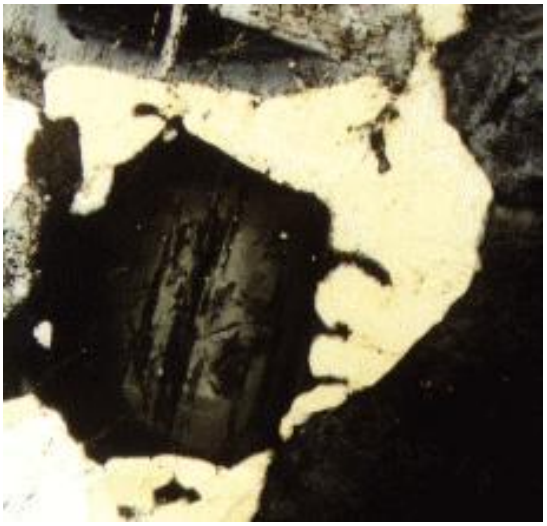

Fig. 7. Quartz (clear, cream) replacing zoned plagioclase (light gray to black) along scalloped boundaries.

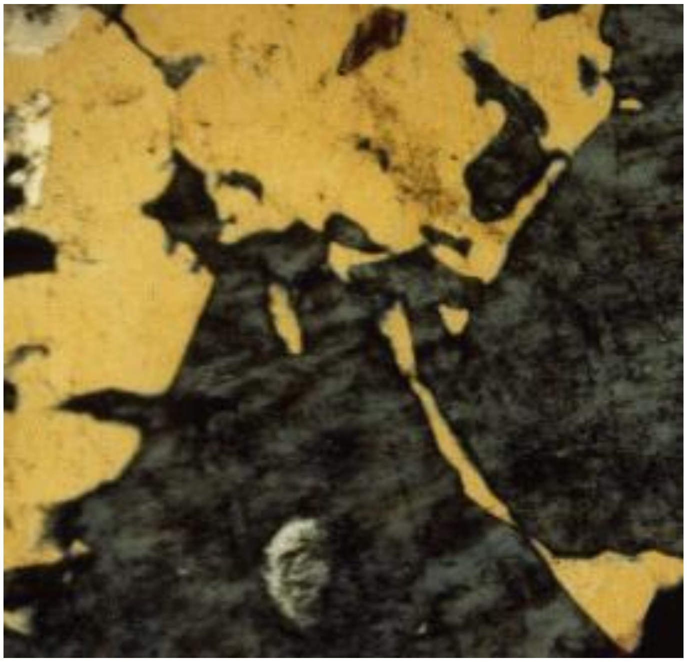

Fig. 8. Irregular islands of orthoclase (dark gray) enclosed in quartz (yellowish cream).

In leucocratic quartz monzonite in the core of the western part of the pluton or associated with the copper ore zone in the eastern part, the K-feldspar occasionally is intergrown with rounded or irregular quartz blebs to form a micrographic textures (Fig. 9).

Fig. 9. Micrographic quartz (white) enclosed in orthoclase (dark gray).

Gilluly (1946) indicated that in and near the copper ore zone the plagioclase is highly albitized and that orthoclase veinlets cut the plagioclase. Locally, both microcline and orthoclase occur in pegmatites near the ore zone, but *microcline is completely absent in the main bulk of the pluton*.

The orthoclase in all facies is slightly perthitic with a uniform distribution of narrow stringers of albite (Fig. 4 and Fig. 10). In quartz diorite and granodiorite the orthoclase coexists with strongly zoned plagioclase that has relatively calcic cores (nearly An_{50}) and rims as sodic as An_{10} (Gilluly, 1946). This same range in An content occurs in the different quartz monzonite facies, but in some places recrystallize plagioclase has lower An contents and a more limited range (An_{35-20}). In pegmatite the plagioclase is albite An_5 (Gilluly, 1946).

Fig. 10. Orthoclase with narrow stringers of albite lamellae.

From an analysis of the granitic rocks in the Cornelia pluton, it is noteworthy that (1) the minerals in the rocks are undeformed, (2) the replacement (resorption) of plagioclase crystals is from the *exterior inward*, (3) *orthoclase is present rather than microcline*, and (4) the *orthoclase may contain micrographic quartz intergrowths but has no myrmekite along its borders*.

Rocky Hill stock, California

Somewhat similar to the orthoclase-bearing, copper-porphyry Cornelia pluton is the Rocky Hill stock in which the K-feldspar is also alleged to have replaced plagioclase by magmatic resorption (Putnam and Alfors, 1969). The Rocky Hill stock is a small granodiorite pluton that is exposed in an area of about 3.9 square kilometers and is located 5 kilometers east of Exeter, California (Fig. 11). It has an outer-rim facies, which is inequigranular and medium-grained, and an inner-core facies, which is finer-grained and subporphyritic. The contact between the two facies is transitional across 30 or more meters. The rocks exhibit steeply-plunging lineation, protoclastic shear, joints, planar grain-fracturing, and late-stage fracturing. The Rocky Hill stock contrasts with the Cornelia pluton in that protoclastic shear is observed in thin section to have *multiple stages of breakage and deformation of plagioclase* and other primary mineral grains *prior* to K-feldspar replacement of the plagioclase (Putnam and Alfors, 1969).

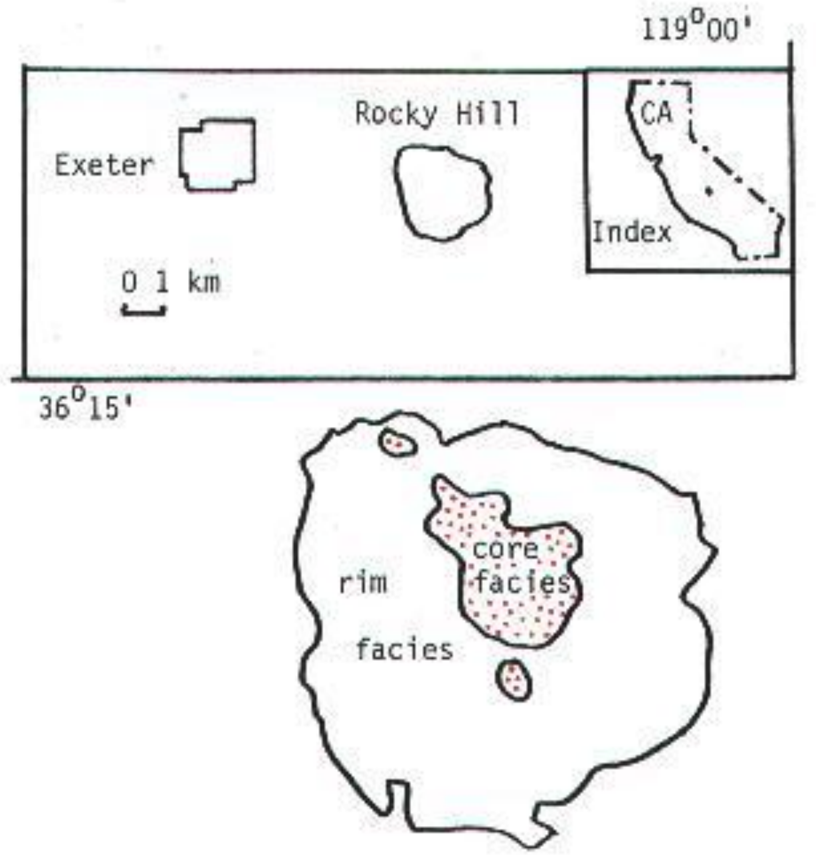

Fig. 11. Location of the Rocky Hill stock and simplified geologic map (modified after Putnam and Alfors, 1969).

The rim facies contains zoned plagioclase (An_{47-11}), quartz, perthitic K-feldspar, biotite, hornblende, rare pyroxene, and accessory magnetite, sphene, apatite, zircon, pyrite, pyrrhotite, ilmenite, and allanite. The core facies contains the same minerals and zoned plagioclase with similar An-contents but is texturally different. In both the core- and rim-facies, deformed and broken mineral grains occur, but generally *the deformation is more severe in the rim facies*. According to Putnam and Alfors (1969), protoclastic deformation began long before crystallization was complete, and permitted early-formed plagioclase to be resorbed and replaced by K-feldspar. The K-feldspar is zoned with Ba-rich cores, and many grains have microcline gridiron twinning. Mild deuteric alteration has converted some biotite to chlorite, and cores of some plagioclase grains contain epidote, sericite, and calcite.

Putnam and Alfors (1969) concluded that "the Rocky Hill stock was emplaced as a primarily vertical intrusion of granodiorite magma which progressively crystallized from the walls inward." These investigators further suggested that the crystallization progressively increased the amount of volatiles in the residual magma until saturation of the melt caused vapor pressure to become equal to the confining pressure of the rock load above. Rupture and consequent loss of the vapor pressure is suggested to cause an isothermal "quench" of the remaining magma to produce the inner-core facies containing a fine-grained matrix and subporphyritic texture.

Textural analysis

In spite of extensive descriptions of chemistry, mineralogy, alterations, textures, and structure, which were very carefully and thoroughly done, Putnam and Alfors (1969) did not mention the occurrence of abundant myrmekite nor that biotite was replaced locally by quartz. These authors described the K-feldspar as being perthitic with the typical gridiron twinning of microcline and probably assumed that the K-feldspar was formerly crystallized from a melt as orthoclase. In that assumption irregular patches of plagioclase enclosed in the K-feldspar were presumably formed by exsolution from orthoclase as the orthoclase inverted to the microcline.

In addition to these observations, there are several contrasting differences in the style of K-replacement and mineral textures in the Rocky Hill stock with that found in the Cornelia pluton in Arizona. In many places the plagioclase crystals are deformed, and in some places interiors of deformed plagioclase crystals show tiny islands of K-feldspar (microcline) that are in early stages of K-replacement of the plagioclase (Fig. 12). In subsequent stages this replacement extends through the plagioclase along former fractures (Fig. 13 and Fig. 14).

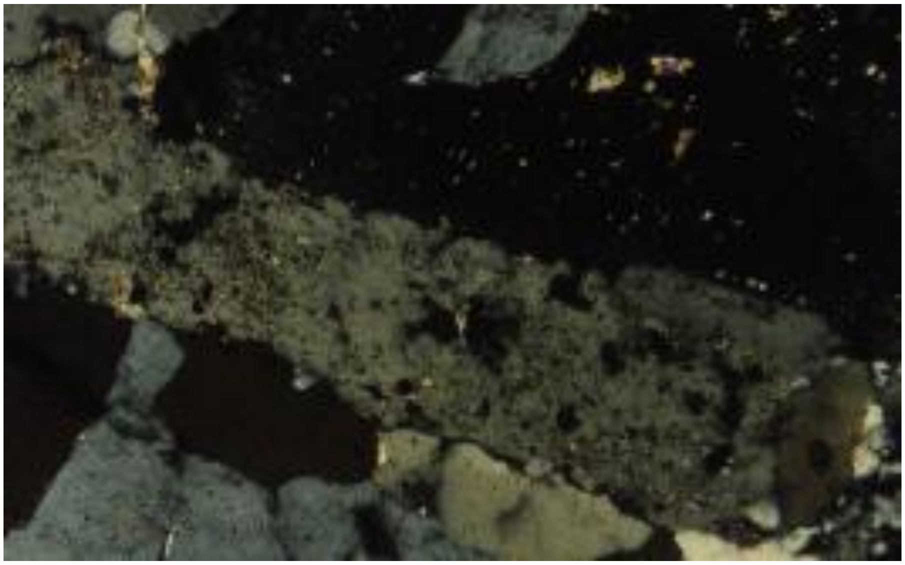

Fig. 12. A Carlsbad-twinned plagioclase crystal (black and light-tan), showing irregular islands of K-feldspar (microcline, black) in the lower half of the twin. Quartz grains (white, gray, cream, tan). Plagioclase is speckled with sericite alteration (bright colors).

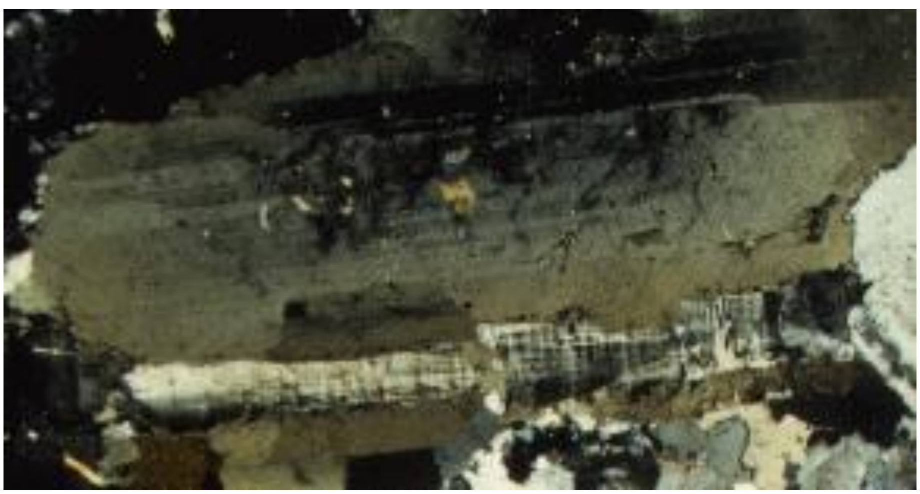

Fig. 13. A normal-zoned, albite-twinned plagioclase grain (black to light tan) is broken parallel to twin planes and replaced by K-feldspar (microcline, lower part). At the right end of the microcline, the plagioclase (dark gray) adjacent to the microcline and abutting against plagioclase (white, light gray) is myrmekite, but the quartz vermicules are too tiny to see. Biotite (brown, lower left side). Core of plagioclase is slightly sericitized.

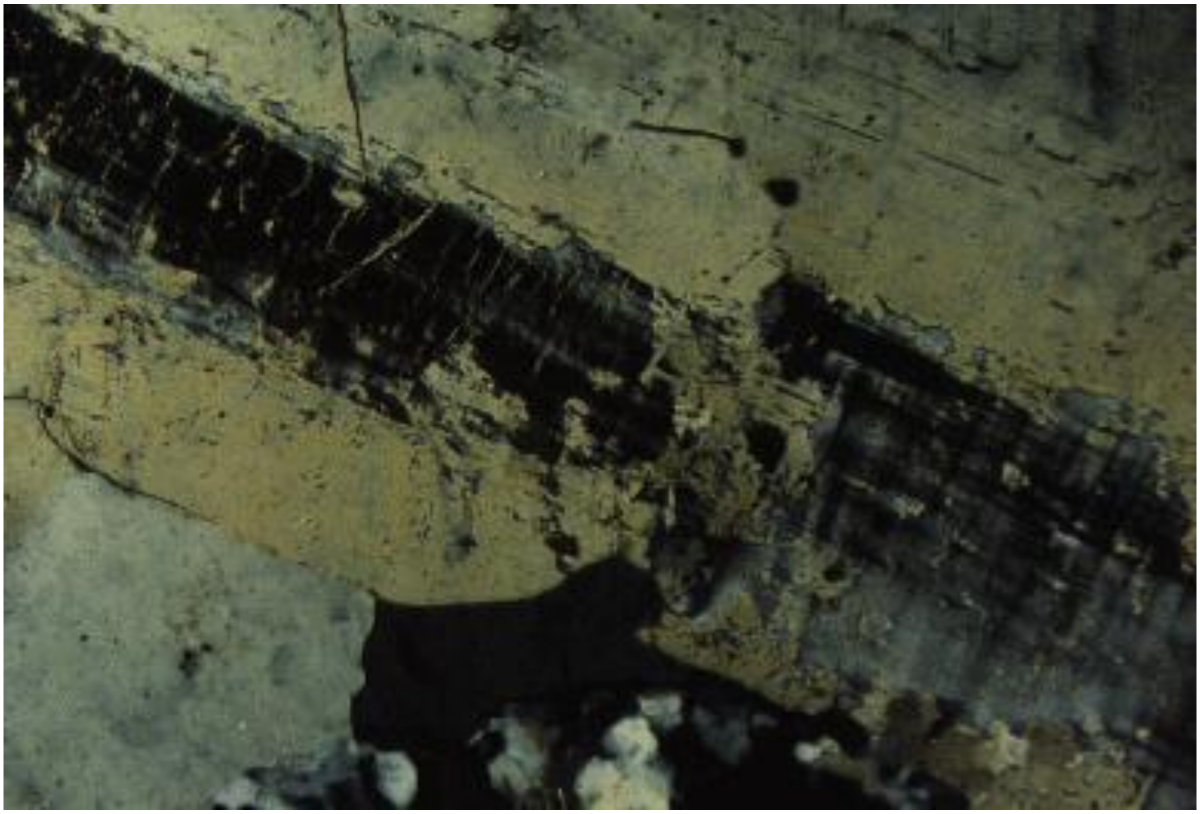

Fig. 14. Enlarged view of portion of Fig. 13, showing details of microcline (gray, black, grid-pattern) replacement of plagioclase (tan). Remnants of the plagioclase exist as island patches or stringers (left of center) in optical parallel continuity with the adjacent larger portions of the plagioclase outside the microcline. Note tiny microcline replacements (light gray) along albite-twin planes in upper left side of the replacement zone. If the whole view were just the microcline, then it likely would be misinterpreted as a primary crystal that contained perthitic patches and stringers of plagioclase that had been formed by exsolution. See perthitic microcline in subsequent illustrations.

Then, in advanced stages the K-feldspar (microcline) more completely replaces the broken plagioclase crystal(s) to leave only remnant islands or perthitic stringers of plagioclase (Fig. 15, Fig. 16, and Fig. 17). Borders of incompletely replaced plagioclase against the microcline are frequently lined by myrmekite (Fig. 12, Fig. 15, Fig. 16, and Fig. 17), and these myrmekite grains are commonly optically continuous with remnant islands of plagioclase in centers of the microcline crystals. Many of these islands have tiny quartz blebs the same size as the diameters of quartz vermicules in the myrmekite.

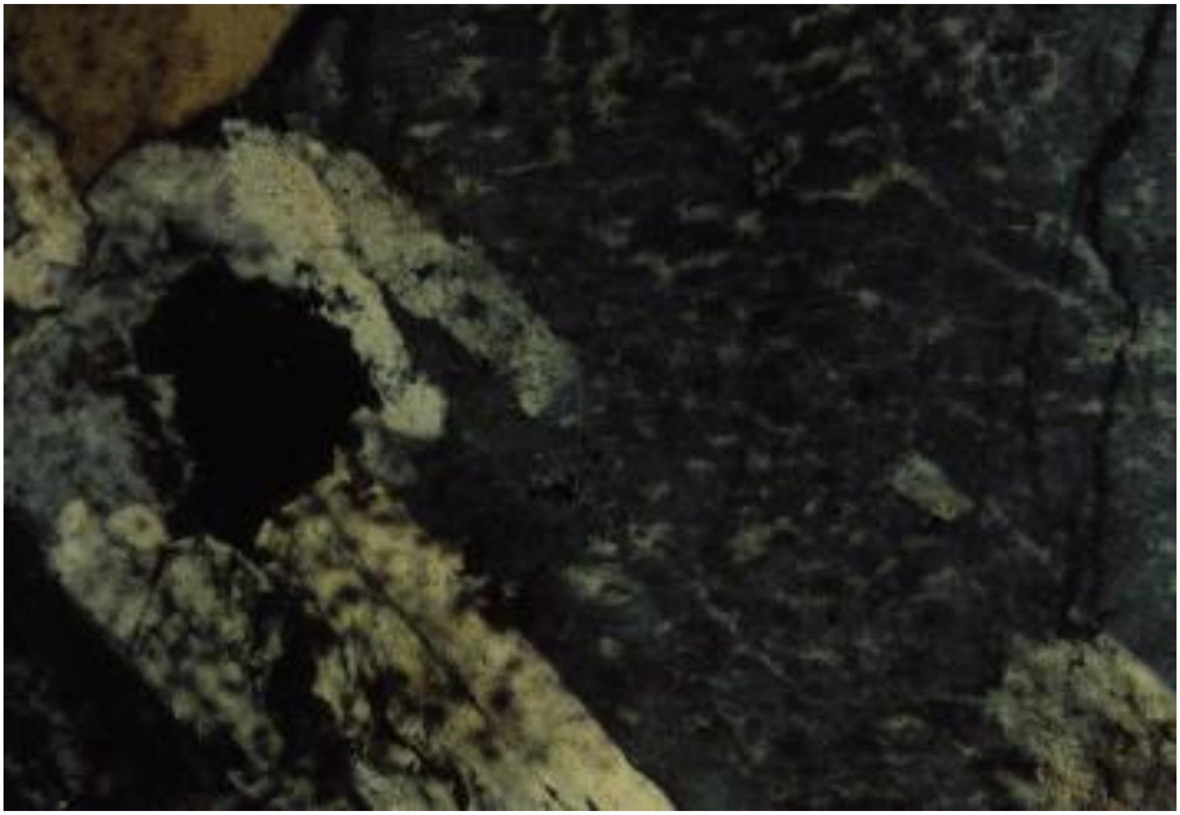

Fig. 15. Albite- and Carlsbad-twinned plagioclase (black and cream, left side), which encloses an island of biotite (dark brown to black; left side). Microcline (right side, gray) contains irregular stringers of plagioclase (tan) and remnant plagioclase islands (right of center and lower right), all of which are in optical parallel continuity with the adjacent plagioclase (left side). The microcline has penetrated and replaced the plagioclase along albite-twin planes (left of center) and is pseudomorphic after a former euhedral plagioclase crystal that once filled this space as is indicated by the continuous extension of the plagioclase border to the microcline border (upper left). The projection of the plagioclase into the microcline (left of center) is myrmekitic.

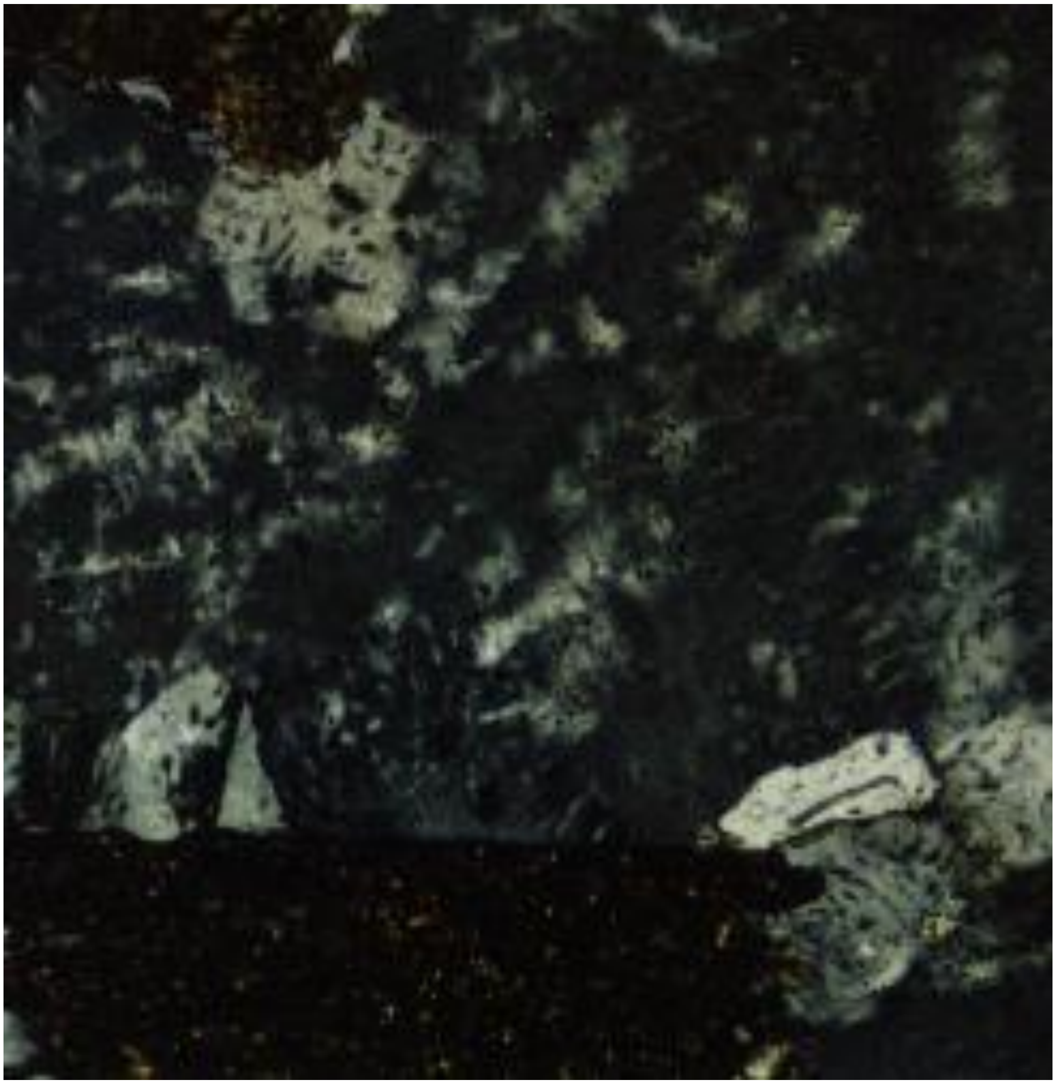

Fig. 16. Microcline (dark gray) bordered by myrmekite grains against biotite (dark brown; bottom right quadrant and upper left). In the microcline are irregular remnant patches of plagioclase (light tan) with tiny quartz ovules (tiny black spots), and the ovules have the same diameter as the quartz vermicules in the myrmekite. The plagioclase patches are all in optical parallel continuity and have an irregular distribution. These relationships are *inconsistent* to their having been formed by exsolution from a high-temperature orthoclase crystal. The volumes of the patches are disproportional to the volumes of adjacent microcline from which they supposedly could have exsolved.

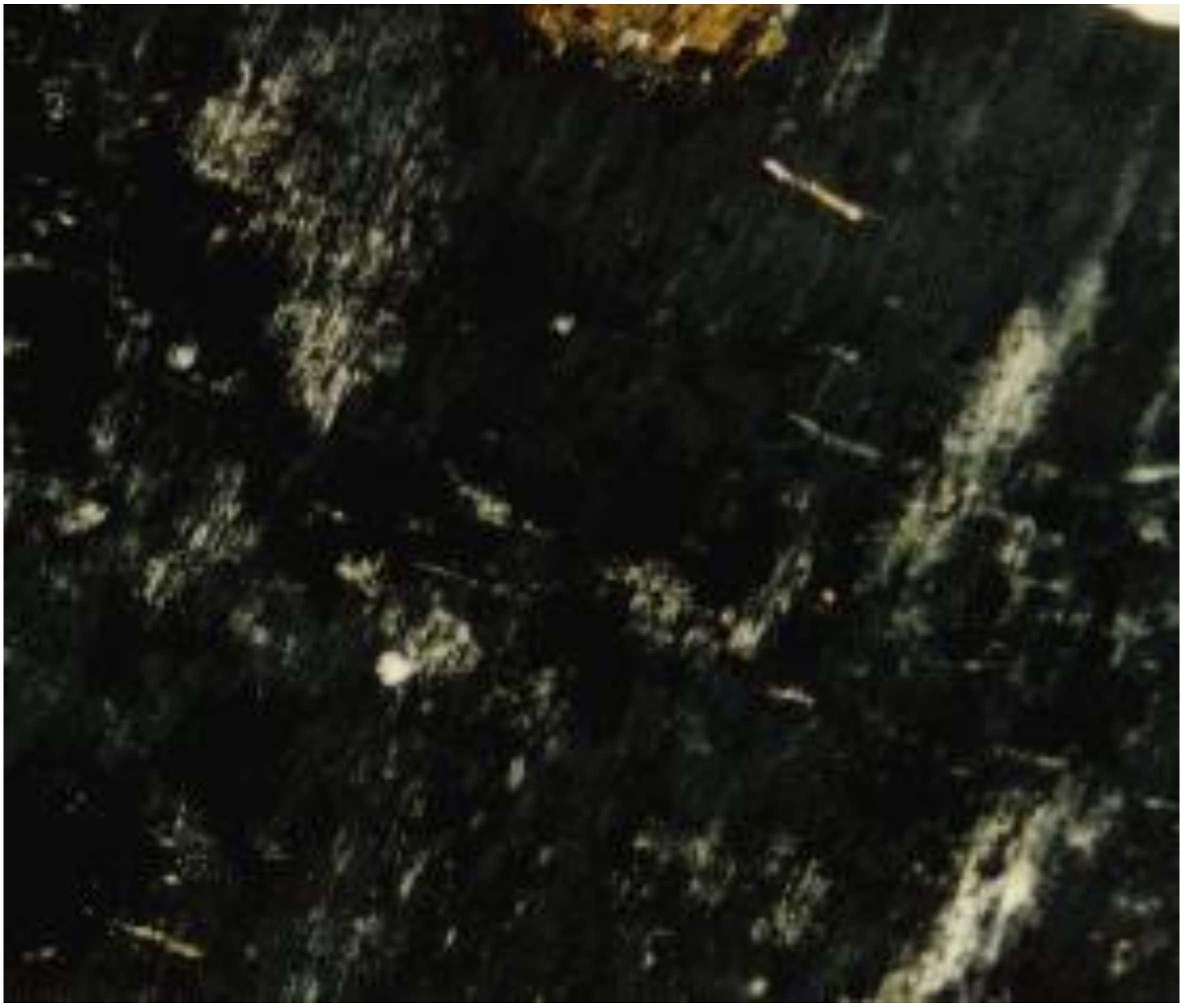

Fig. 17. Microcline (dark gray to black) with relatively large patches of remnant albite-twinned plagioclase containing quartz ovules (white and black; upper left quadrant and center). All patches are in optical parallel continuity and are interpreted to be remnants of a former plagioclase crystal that once filled the space now occupied by the microcline.

In some places the microcline is *pseudomorphic after the former euhedral plagioclase crystal* while retaining islands of plagioclase that are optically continuous with plagioclase crystals outside the microcline (Fig. 15 and Fig. 18). *Remnant patches of plagioclase with quartz blebs in the microcline are too large to have been exsolved from the adjacent volume of K-feldspar even if the K-feldspar were once high-temperature orthoclase* (Fig. 19).

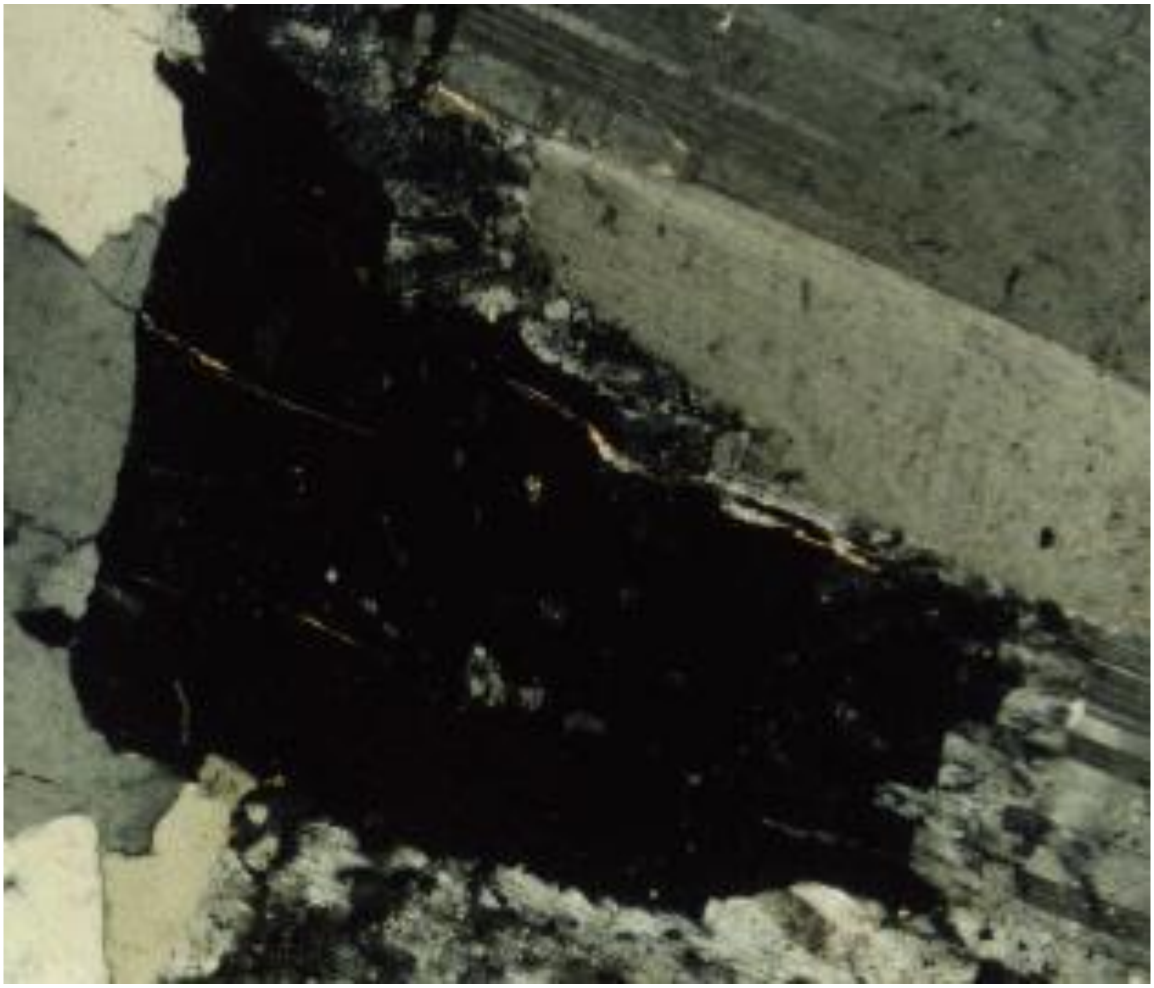

Fig. 18. Microcline (black) contains tiny islands of plagioclase, most of which cannot be seen in the computer image but which are in optical parallel continuity with the albite-twinned plagioclase crystal (light gray and tan) that surrounds the microcline on three sides. The fourth side (left) against quartz (light gray and white) is a straight boundary that is interpreted to be the edge of the former euhedral plagioclase crystal that once filled this space, and, in that case, the microcline is pseudomorphic after the plagioclase. The plagioclase adjacent to the microcline is myrmekitic, but the quartz vermicules are so tiny that they are difficult to see.

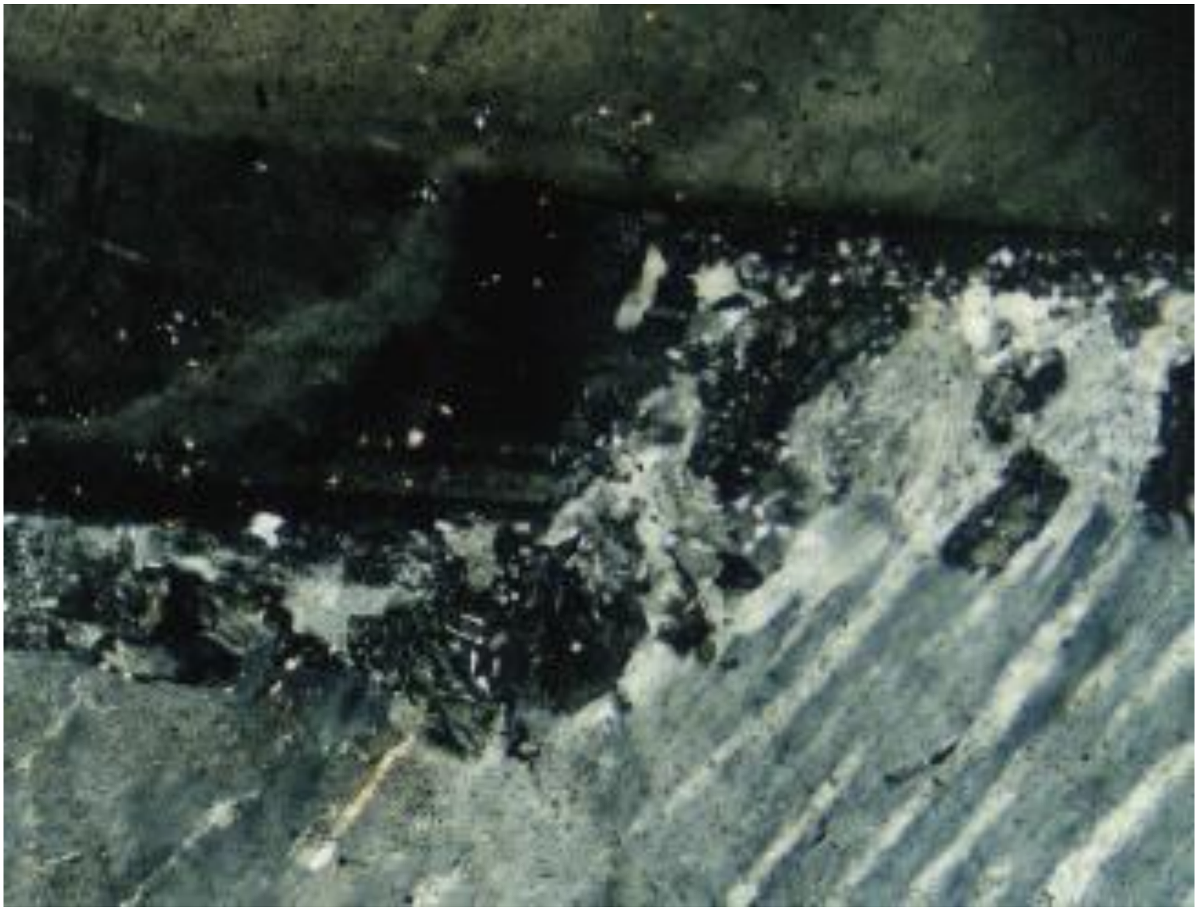

Fig. 19. Albite-twinned, zoned plagioclase (top, black) bordered by myrmekite against microcline (bottom, light gray). Stringers of plagioclase (right side; light tan) in the K-feldspar contain faint quartz ovules and are optically continuous with plagioclase in the adjacent myrmekite.

Moreover, stringers of plagioclase with remnant quartz blebs are optically continuous with myrmekite along the borders (Fig. 20). In other places, islands of non-myrmekitic plagioclase in the microcline are optically continuous with adjacent non-myrmekitic plagioclase (Fig. 21 and Fig. 22).

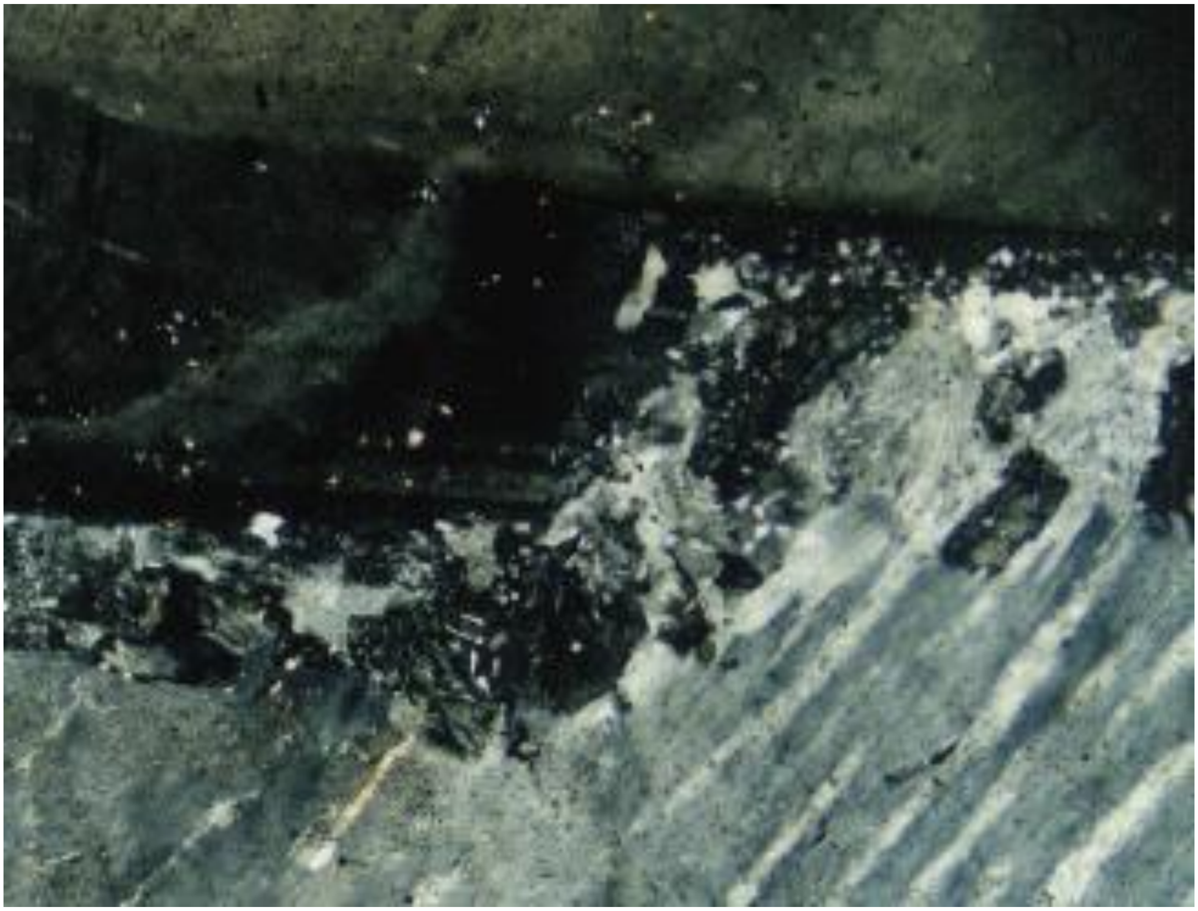

Fig. 20. Albite-twinned, zoned plagioclase (top, black) bordered by myrmekite against microcline (bottom, light gray). Stringers of plagioclase (right side; light tan) in the K-feldspar contain faint quartz ovules and are optically continuous with plagioclase in the adjacent myrmekite.

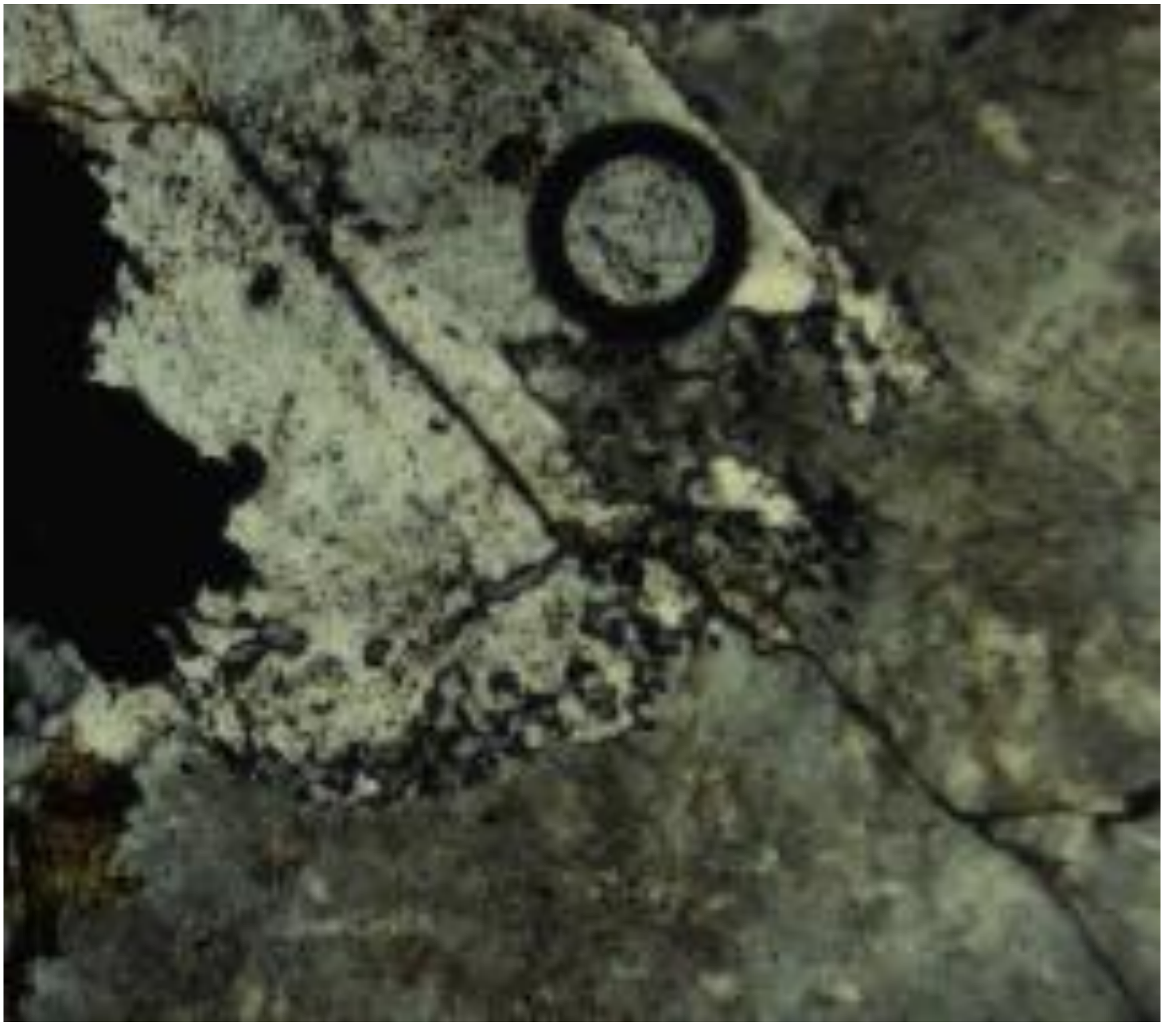

Fig. 21. Albite- and Carlsbad-twinned plagioclase (light gray; top left). Microcline (dark gray; bottom and right side). Microcline penetrates and replaces the plagioclase, leaving tiny island remnants of the plagioclase in optical parallel continuity. Round area with thick black border is a bubble in the thin section glue.

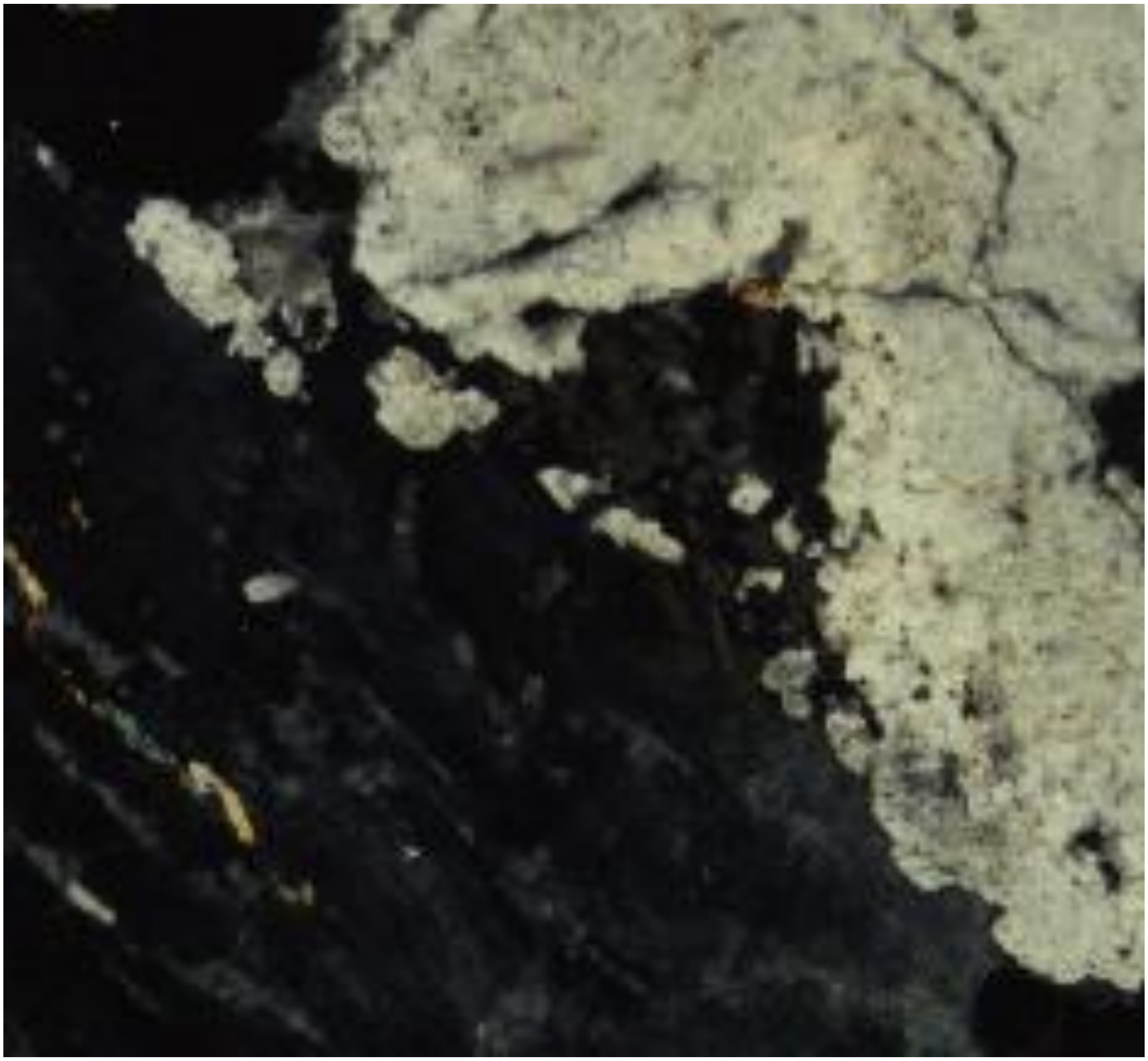

Fig. 22. Plagioclase (white). Microcline (black to dark gray). Microcline penetrates and replaces the plagioclase, leaving tiny island remnants of the plagioclase in optical parallel continuity.

Where microcline is in earliest stages of replacing plagioclase along a fracture, the greater volumes of myrmekite adjacent to the microcline than the volume of the microcline (Fig. 23) makes it *clear that the myrmekite cannot have formed by exsolution from a primary high-temperature orthoclase crystal* but result from alteration and incomplete replacement of the primary plagioclase (Collins, 1988; Hunt et al., 1992). This conclusion also applies to the myrmekite at the end of the microcline linear band in Fig. 13.

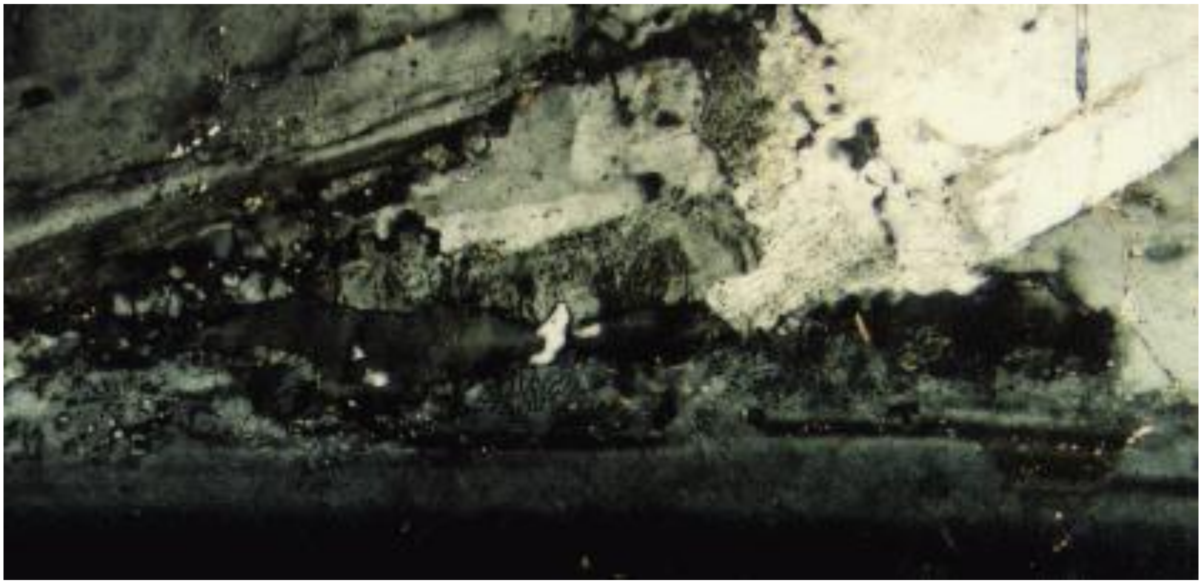

Fig. 23. Tiny sliver of microcline (dark gray to black) extends from left to right (middle of image) and is sandwiched between albite-twinned plagioclase (white, gray, and black) with borders of myrmekite grains with greater thickness than the microcline. Tiny irregular islands of microcline (dark gray) penetrate fractures and replace the plagioclase (white; upper right).

Discussion

In the Rocky Hill stock, the textural relationships and the pseudomorphism of the K-feldspar (microcline) after plagioclase, shown in the photomicrographs (**Figs**. **12 through 18**), support the hypothesis that the K-feldspar formed by *replacement of broken plagioclase crystals* that once completely filled the same space now occupied by the K-feldspar. On that basis, it is unlikely in the Rocky Hill stock that the K-feldspar resorbed early-formed plagioclase floating in a melt, as in the Cornelia pluton, and it is equally unlikely that the plagioclase was somehow deformed and broken in a melt at temperatures above the solidus. The preserved outlines of former euhedral plagioclase crystals give strong support to a replacement model at temperatures below the solidus. Likewise, the resorption of plagioclase in a melt (confined to the volumes of the pseudomorphed crystals) should result in K-feldspar crystals containing much more perthitic plagioclase than is shown. The occurrence of coexisting myrmekite further negates a model for crystallization of the K-feldspar from a melt because melting temperatures *would prevent the formation of plagioclase compositions of variable compositions that are proportional to the thicknesses of the enclosed quartz vermicules in myrmekite*.

Instead, crystallization of quartz-feldspar intergrowths from a melt would produce *micrographic* textures (as in the Cornelia pluton) or *granophyric textures with uniform feldspar compositions enclosing the quartz*, but *not* myrmekite.

Putnam and Alfors (1969) also suggested that quartz is resorbed in the Rocky Hill pluton, but there is nothing in the thin sections resembling the textures (penetrative fingers) that can be seen in some volcanic rocks to support this resorption hypothesis. Instead, quartz can be observed in places to replace biotite to produce a poorly-developed quartz sieve texture.

The hypothesis that the subporphyritic inner facies in the Rocky Hill stock resulted from quenching of the magma seems reasonable, but the core facies contains less K-feldspar (12.6 vol. %) and biotite (6.7 vol. %) and more plagioclase (47.2 vol. %) than in the outer rim-facies (K-feldspar, 15.6%; plagioclase, 44.2 vol. %; biotite, 7.0 vol. %) (Putnam and Alfors, 1969). This relationship for K-feldspar is contrary to a magmatic model because the last stage of crystallization of a quenched granitic magma should be enriched in K-feldspar relative to plagioclase. Therefore, although quenching likely occurred, the original quenched magma probably was relatively plagioclase- and biotite-rich rather than K-feldspar-rich. Later replacement produced the present mineral distributions.

Conclusions

From the studies of the granitic rocks in the copper porphyry Cornelia pluton, it is apparent that K-metasomatism (exterior resorption) of plagioclase to produce orthoclase can occur in magmas on a large scale as part of the differentiation that produced this copper porphyry granitic pluton. The lack of deformation of the plagioclase crystals that is observed in the Cornelia pluton prior to replacement is exactly what would be expected in a melt because shear stresses would not be transmitted through a liquid. Therefore, the insistence by some petrologists that large-scale K-metasomatism cannot produce granitic rocks is mistaken when it can be demonstrated to occur even in magmatic rocks. Then, if K-bearing fluids can move through relatively viscous magmas on a large scale and cause K-replacements of plagioclase by orthoclase, it should be logical to assume that large volumes of K-bearing fluids could also move even more readily at lower temperatures through fractured solids on a plutonic scale and cause K-replacement of plagioclase by perthitic microcline. At any rate, the contrasting styles of replacement of plagioclase (exterior versus interior) in the two plutons show that under magmatic (above-solidus) conditions, orthoclase coexisting with granophyric or graphic textures of quartz and orthoclase are formed, whereas under subsolidus conditions microcline coexisting with myrmekitic intergrowths of plagioclase and vermicular quartz are formed.

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