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41. K-metasomatism of plagioclase to produce microcline megacrysts in the Cathedral Peak granodiorite, Sierra Nevada, California, USA

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Abstract

Higgins (1999) proposed that microcline megacrysts in the Cathedral Peak granodiorite resulted from Ostwald ripening in which textural coarsening of earlier formed small K-feldspar crystals were sacrificed to feed the growth of a select few larger crystals. Textural evidence shows that Ostwald ripening did not occur, but, instead, the megacrysts resulted from K-replacement of broken plagioclase crystals in sites of strong cataclasis, where tiny microcline crystals (1 to 15 mm in mean height) grew to as much as 80 mm. The progressive growth of the microcline encompassed broken remnant fragments of ground mass minerals in concentric shells. The evidence for K-replacement consists of veins of microcline penetrating cores of broken zoned plagioclase, the alignment of one plane of the grid-twinning in the microcline with albite twinning in the plagioclase, the occurrence of myrmekite, and the replacement of biotite by quartz to provide the needed K.

Introduction

Microcline megacrysts, 1 to 10 cm long, are easily observed in the Cathedral Peak granodiorite along the Tioga Road (Route 120) through Yosemite National Park in the eastern Sierra Nevada of California (Fig. 1 and Fig.2; Bateman and Chappell, 1979). These megacrysts are either randomly distributed or occur in concentrations in linear stringers and patches (nests); see Fig. 3 in Higgins (1999). The megacrysts are commonly Carlsbad twinned and exhibit concentric zonation of Ba as well as shell-like arrangements of tiny hornblende, biotite, quartz, and plagioclase inclusions (Kerrick, 1969).

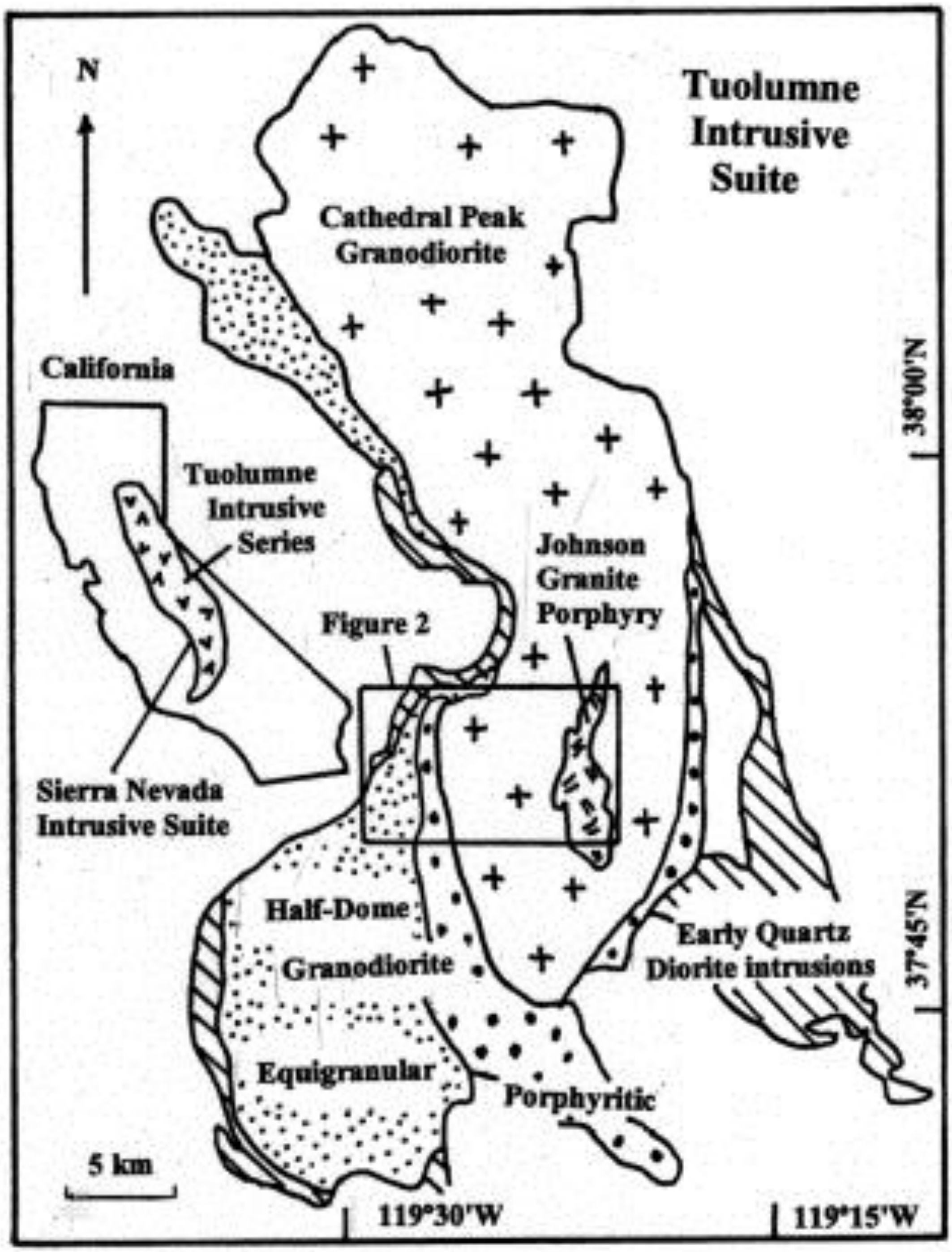

Fig. 1. Geologic map of the Tuolumne Intrusive Suite, Sierra Nevada, California (after Bateman and Chappell, 1979). The outer quartz diorite intrusions were emplaced first, and subsequently the equigranular and porphyritic facies of the Half Dome granodiorite were intruded into the partly solidified interior of the pluton. The north-south linear-aligned Cathedral Peak granodiorite was intruded

next, followed finally by the Johnson granite porphyry. In this sequence, an overall progression from mafic to felsic compositions occurs. Outline area is shown in Figure 2.

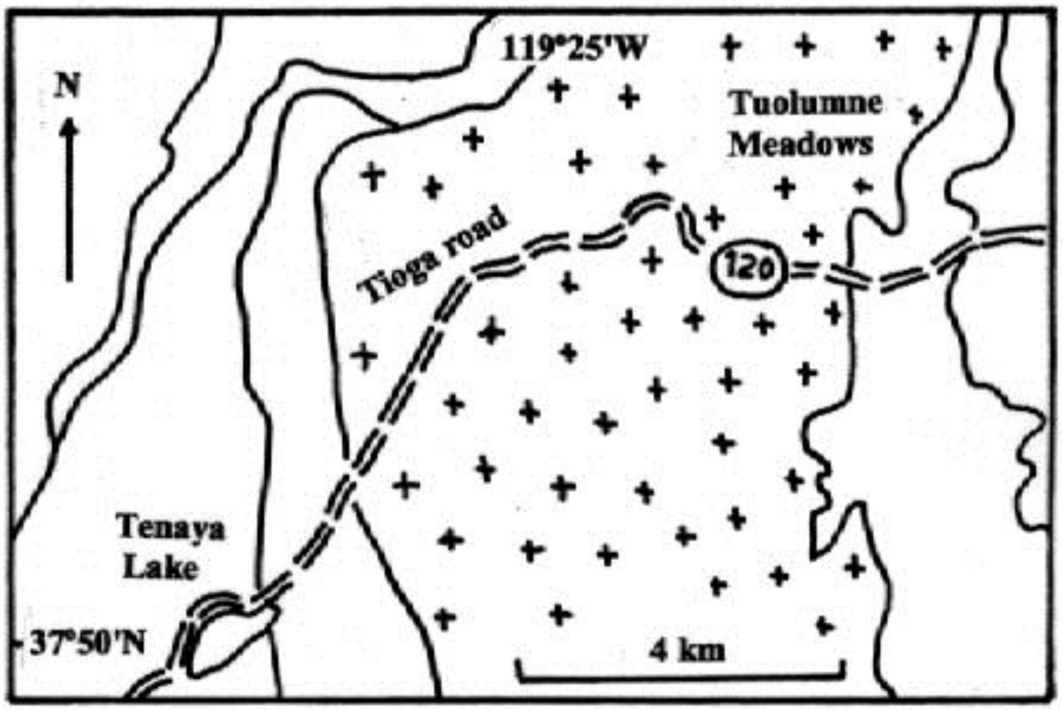

Fig. 2. Geologic map of part of the Tuolumne Intrusive Suite near Tuolumne Meadows, showing where Route 120 crosses the Cathedral Peak granodiorite (+ symbols). Map is modified after Bateman and Chappell (1979). Samples were collected along Route 120 from which photomicrographs of textures in thin sections of the Cathedral Peak granodiorite were obtained (Figs. 3-13).

In this study of the megacrysts Higgins (1999) agrees with Vernon (1986) that the K-feldspar megacrysts in plutonic granitic bodies are magmatic in origin (phenocrysts), but Higgins suggests that the growth of the megacrysts in the Cathedral Peak granodiorite resulted from Ostwald ripening (Voorhees, 1992). That is, smaller K-feldspar crystals are resorbed, and their component elements are transferred to other larger K-feldspar crystals to increase their sizes so that they became the megacrysts. This transfer in the Cathedral Peak granodiorite is alleged to have resulted while the temperature of the granitic mass was held near the eutectic for a long period of time. In this model, small crystals below a critical size have higher surface energies than what occur in larger crystals, and it is this difference in surface energies that supposedly causes the K-feldspar to recrystallize to form different crystal size distributions (CSDs). Higgins (1999) supports this model of Ostwald ripening by using measurements of numbers of microcline grains per unit area and the sizes of the microcline crystals within randomly selected areas. From such measurements CSD values for different populations of microcline crystals within certain size ranges were obtained and plotted to compare the smaller groundmass microcline population densities to the megacryst population densities.

The population densities for **groundmass microcline** crystals, ranging from very tiny crystals to 15 mm in their mean projected-height, plot in a steep linear line while the population densities for **microcline megacrysts**, ranging from 15 to 80 mm in their mean projected-height, plot in a gently-inclined linear line. The difference in slopes of the plotted data suggests to Higgins (1999) that the two kinds of microcline crystals have different origins. He also points out that such differences in CSDs are consistent with other studies in metamorphic rocks (Cashman and Ferry, 1988) and in some plutonic and volcanic rocks (Boudreau, 1987; Cashman and Marsh, 1988; Resmini, 1993; Higgins, 1998). Although he believes that the "*megacrysts grew in a normal igneous fashion from a silicate melt at high temperature and are, indeed, phenocrysts*," he opines that the process involves "*both solution of crystals and transport of material in open systems, which are both features of metasomatic systems*."

In his study Higgins (1999) provides no textural evidence to support the supposed reduction of grain size of the smaller microcline crystals and no mention of cataclastic textures, replacement features, and myrmekite that are found in the Cathedral Peak granodiorite. Therefore, he seems to have based his model entirely on the differences in CSDs in the two different microcline populations and on their similarities to CSD patterns in studies in other terranes. On the basis of the omission of the above important data that have significant implications for the origin of the megacrysts, the following observations are made.

Groundmass microcline

The groundmass microcline in the Cathedral Peak granodiorite is irregular in shape and generally gives the appearance of being interstitial (Fig. 3). Edges of the small microcline grains commonly penetrate as wedges between adjacent quartz and plagioclase grains (Fig. 3). Locally, the microcline is bordered by myrmekite with tiny quartz vermicules (Fig. 3 and Fig. 4).

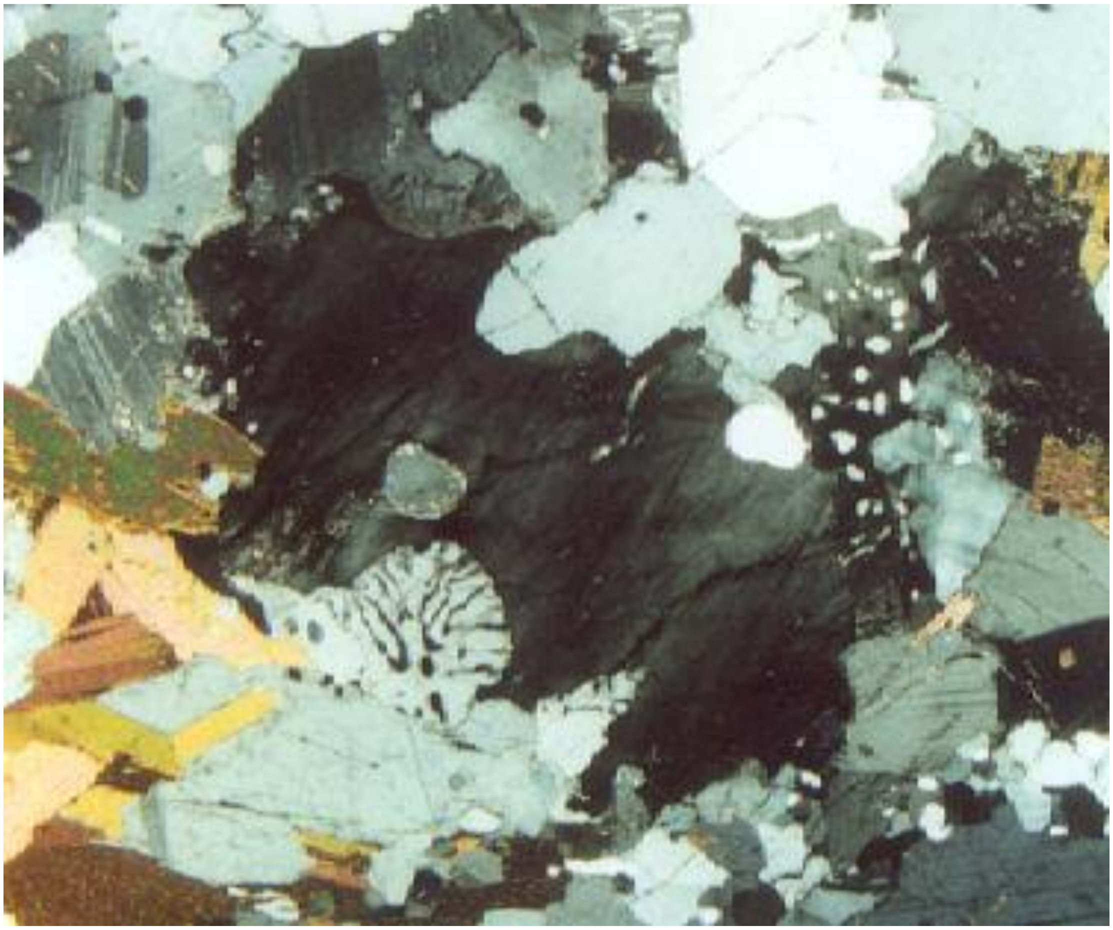

Fig. 3. Interstitial microcline (black; center), surrounded by albite-twinned plagioclase (gray, white), biotite (brown), and myrmekite with tiny quartz vermicules (white, black). Larger quartz (white, gray).

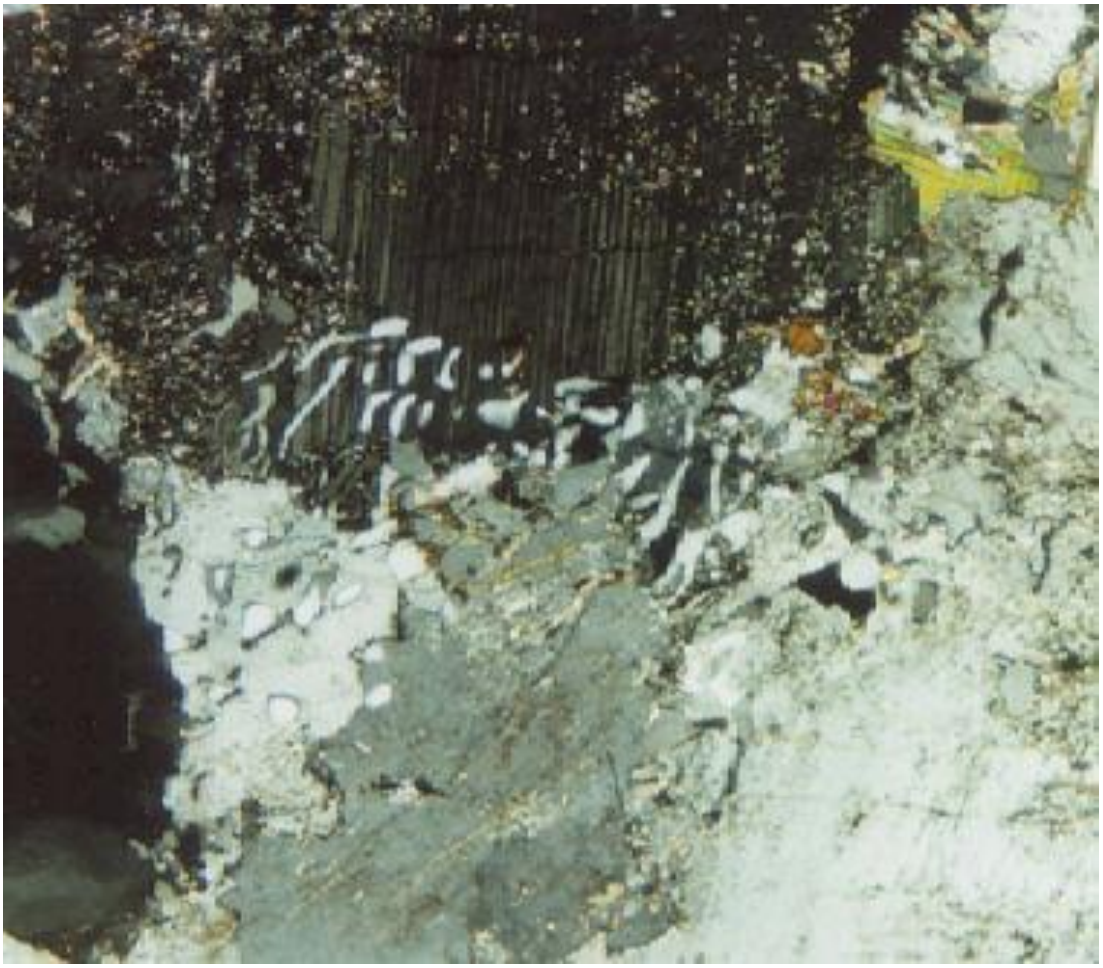

Fig. 4. Myrmekite at end of albite-twinned plagioclase (black; top) and adjacent to microcline (light gray; bottom). Biotite (brown).

Some zoned plagioclase crystals of the groundmass adjacent to the small microcline grains are cataclastically broken and penetrated by veins of K-feldspar that irregularly crosscut the relatively more-calcic cores (Fig. 5). These plagioclase grains in some places are intersected on their borders by microcline that crosscuts the plagioclase zonation, eliminating a part of the outer more-sodic rims (Fig. 5). Untwinned K-feldspar in the cores gradually changes to grid-twinned microcline in which one set of planes of the grid-twinning is parallel to the albite twin planes of the plagioclase (Fig. 5), and in some places the Carlsbad twinning in the microcline is also continuous with the Carlsbad twinning of the adjacent plagioclase.

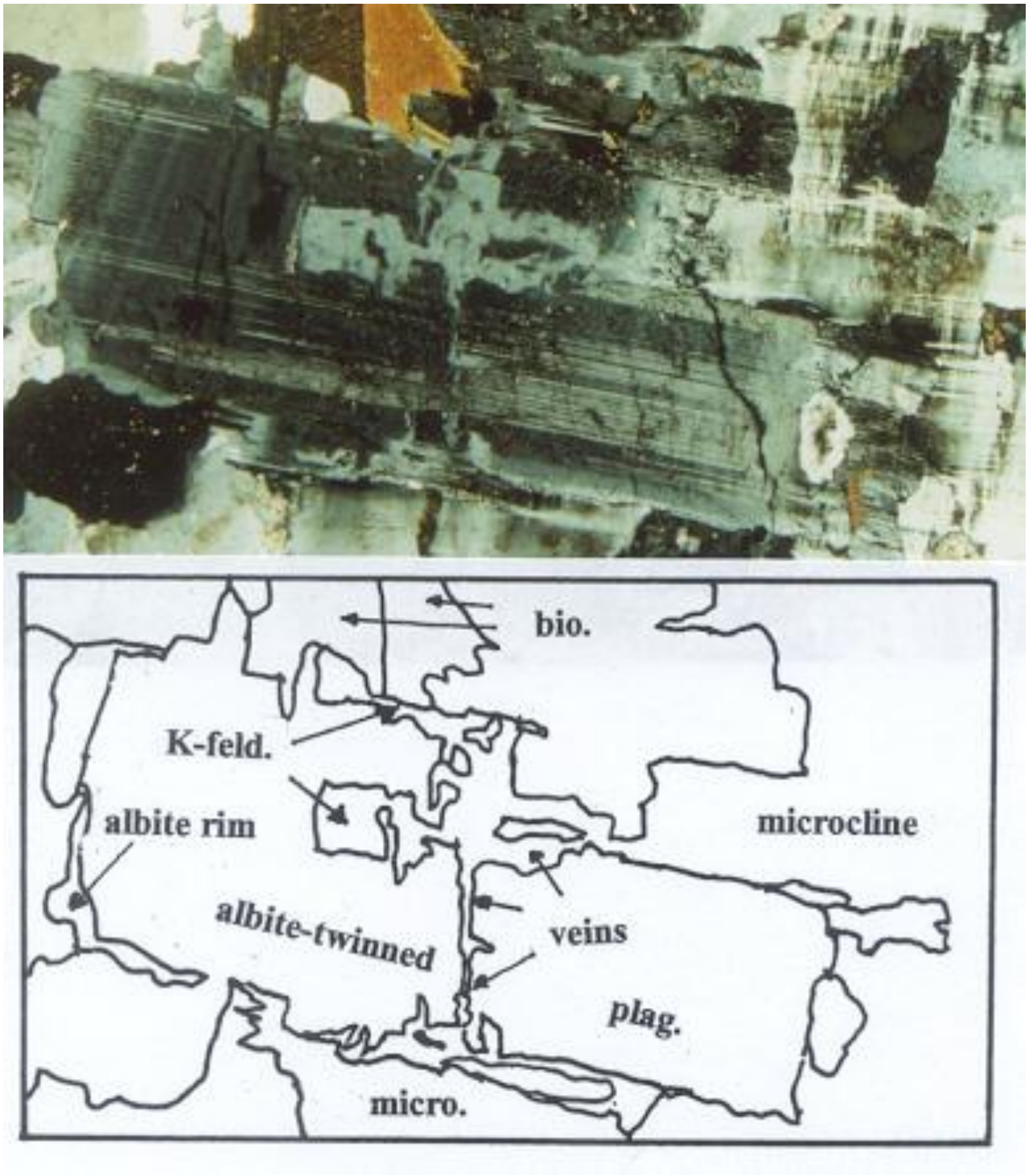

Fig. 5. Veins of K-feldspar (center; light gray) in interior of albite-twinned, zoned plagioclase (black, light gray). Here, the veins crosscut the twinning and extend down to the edge of the plagioclase where veins also crosscut the twinning. From the center to the right, the light gray K-feldspar gradually changes to grid-twinned microcline at the end of the albite-twinned plagioclase crystal. One plane of the grid-twinning in the microcline is parallel to the albite twinning of the plagioclase. At left end of the plagioclase grain is an outer rim of albite, which is replaced by microcline at bottom center of the plagioclase. Biotite (brown); quartz (white, cream, gray).

Microcline megacrysts

In the field, the borders of the microcline megacrysts generally show a rectangular euhedral outline, but in thin sections, borders of the megacrysts do not have straight edges. The microcline of a megacryst extends outward from the approximate euhedral crystal border into the groundmass, penetrating as veins in broken plagioclase crystals or as wedges between unbroken crystals. Moreover, inside the megacryst near its border, remnant fragments of the groundmass plagioclase locally occur in parallel optical continuity with adjacent groundmass plagioclase crystals outside the megacryst (Fig. 6, Fig. 7, and Fig. 8).

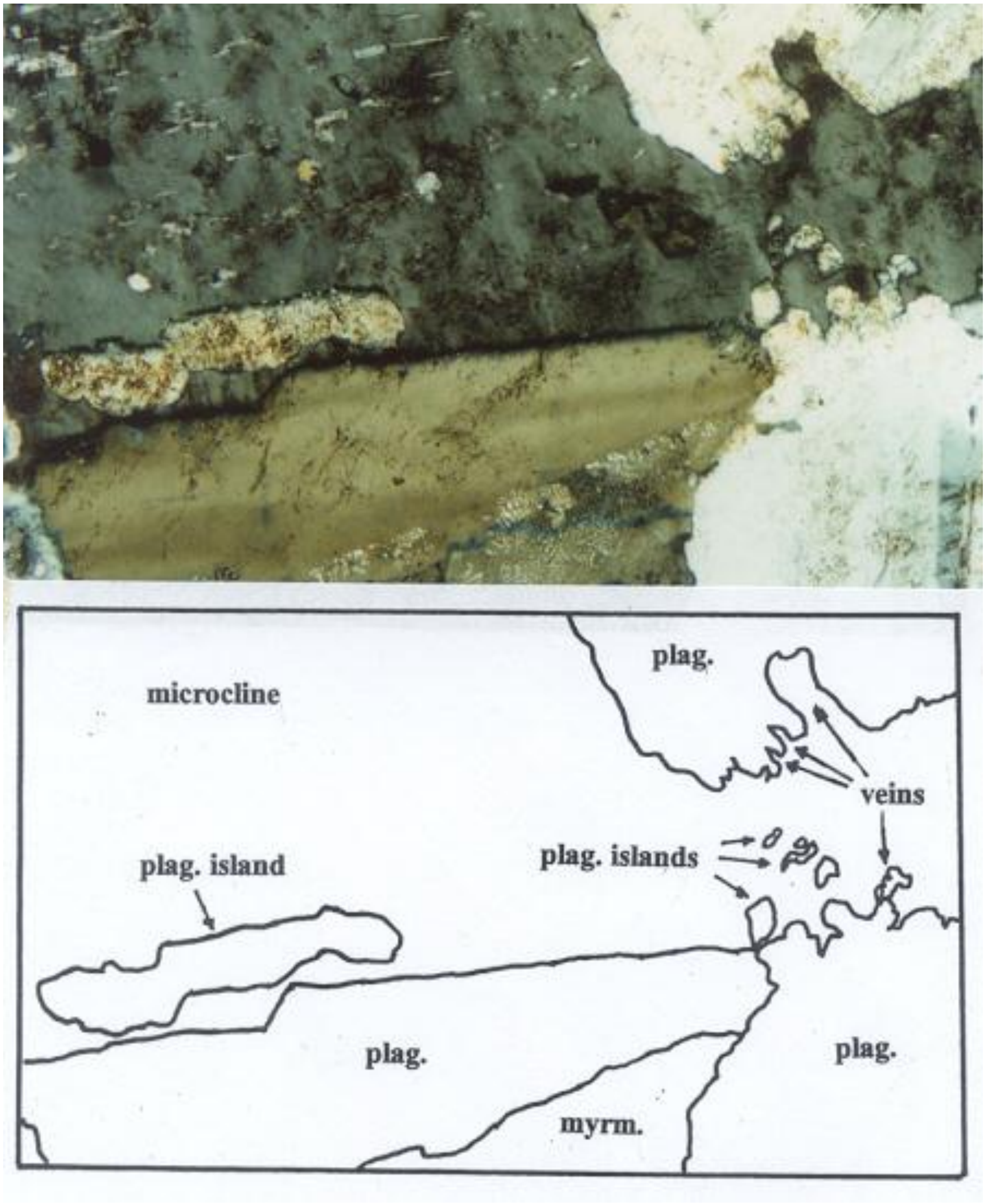

Fig. 6. Border of microcline megacryst (gray), showing veins of microcline penetrating albite-twinned plagioclase (white; upper right). Remnant islands of plagioclase (right side) in parallel optical continuity with adjacent, larger, albite-twinned plagioclase (white; lower right side). Larger, speckled (altered) plagioclase island (center; left side) is in parallel optical continuity with large albite-twinned plagioclase grain (light tan; bottom left). Myrmekite with very tiny quartz vermicules (nearly invisible) forms border of bottom edge of the plagioclase (tan; bottom of photo).

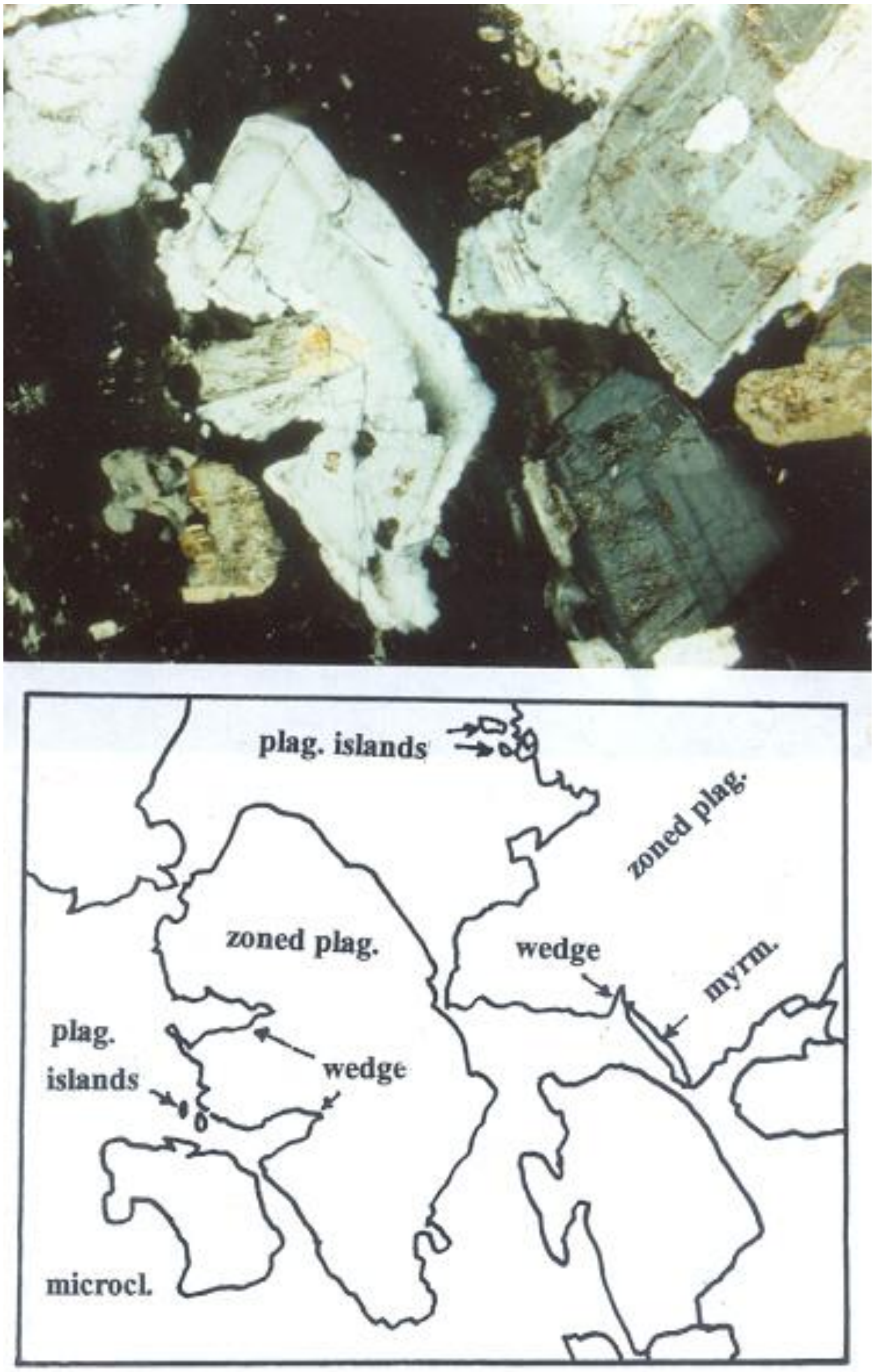

Fig. 7. Partial replacement of zoned plagioclase (white) along border of microcline megacryst (black). Microcline forms wedges and narrow veins that penetrate the plagioclase. Myrmekite with tiny quartz vermicules (nearly invisible) occurs on border of one of the plagioclase crystals. Remnant islands of plagioclase in the microcline occur in parallel optical continuity with an adjacent larger plagioclase grain.

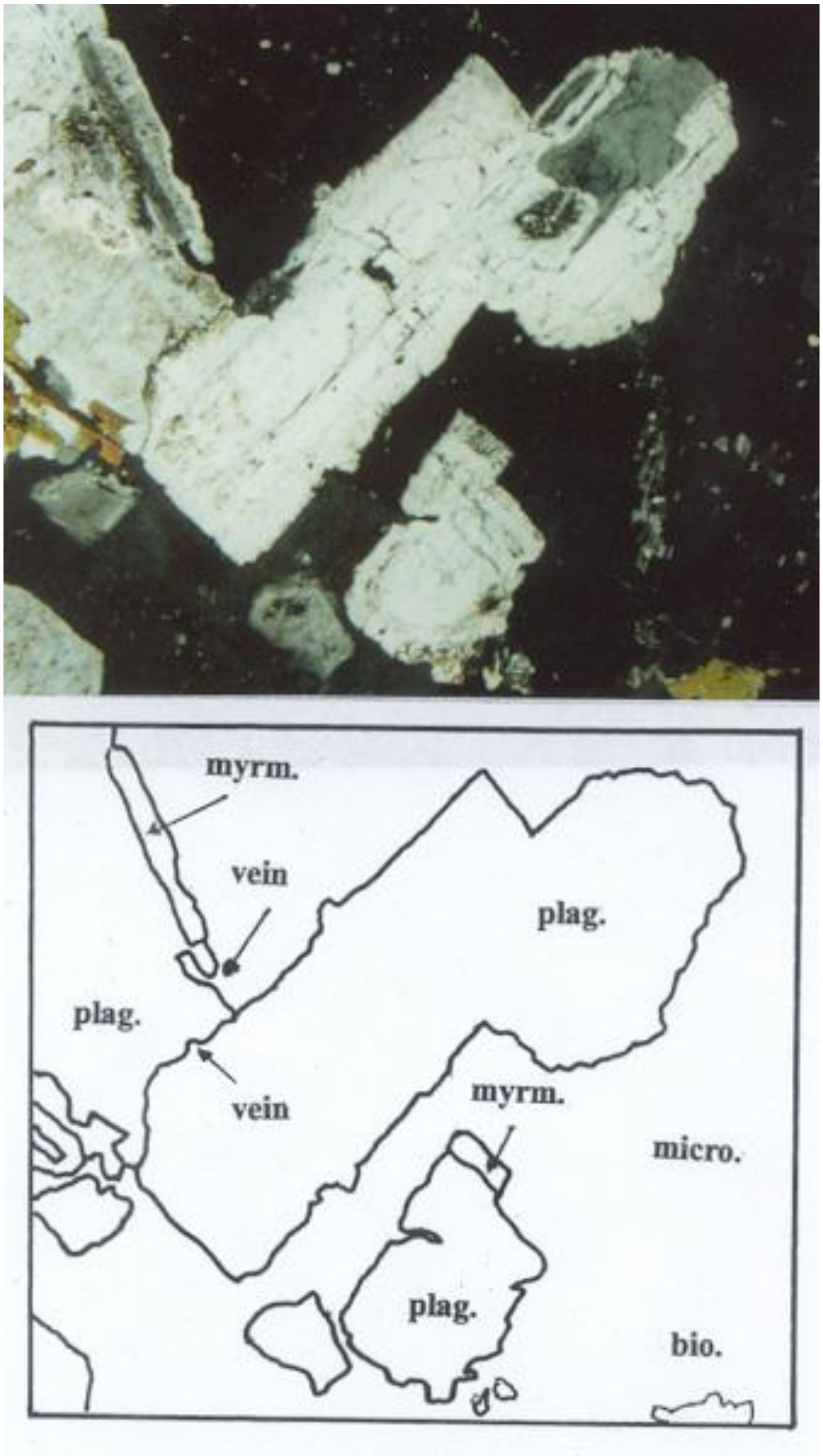

Fig. 8. order of microcline megacrysts (black), enclosing remnant fragments of plagioclase bordered by myrmekite with very tiny (nearly invisible) quartz vermicules. The microcline also penetrates the plagioclase in narrow veins (black; left of center; and in plagioclase inclusions, bottom of photo center). Biotite (brown).

Many tiny biotite, hornblende, plagioclase, and quartz inclusions occur in the microcline megacrysts. Most of these inclusions are **aligned with their lattices parallel** to a possible crystal face of the growing microcline megacryst, but some are disoriented (Fig. 9). Those that are disoriented tend to have scalloped edges, suggesting replacement, and some of the plagioclase inclusions, completely or partly enclosed in the microcline megacrysts, are bordered by myrmekite (Fig. 8, Fig. 9, and Fig. 10) while others are filled with tiny quartz ovals, forming ghost myrmekite (Fig. 11; Collins, 1997). Some of the remnant biotite inclusions in the megacrysts are partly replaced by quartz (Fig. 10 and Fig. 11).

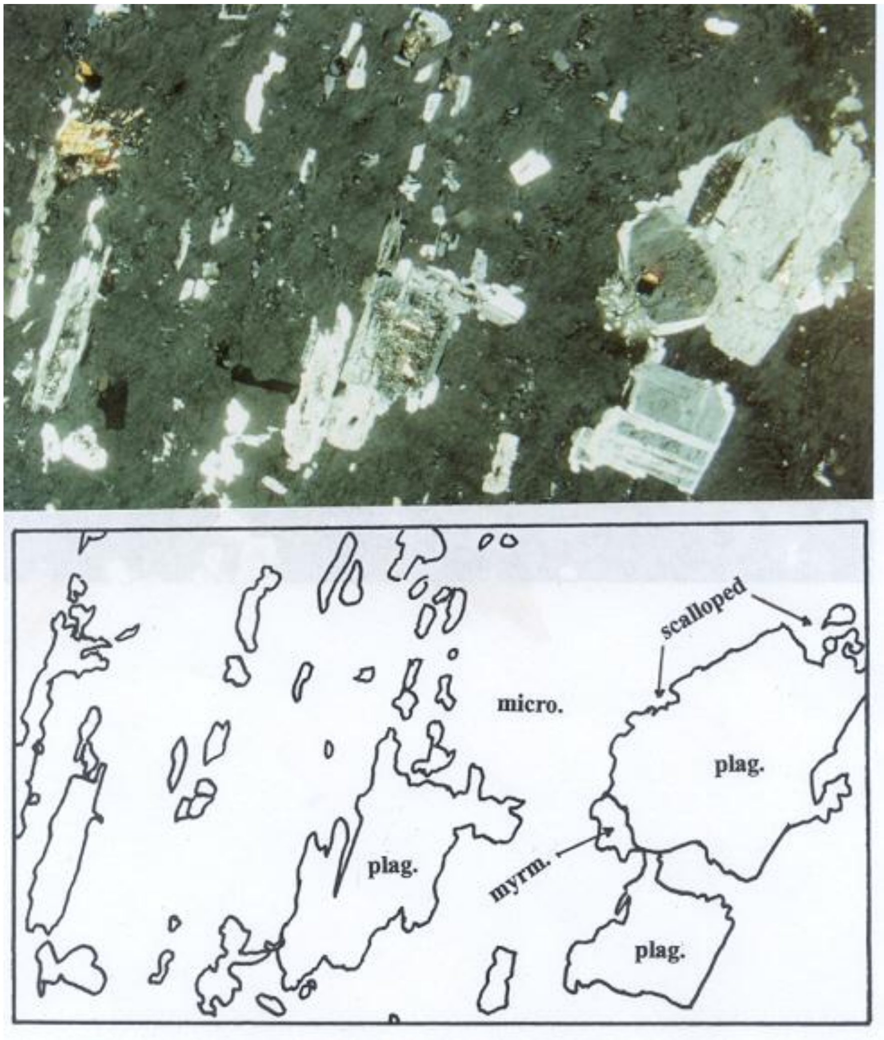

Fig. 9. Oriented remnant fragments of plagioclase (white, light gray) in zoned megacryst of microcline (dark gray). Remnant fragments of plagioclase that are not parallel to a possible crystal face of the microcline tend to have scalloped edges and veins of microcline extending into the plagioclase. Myrmekite forms border (left side) of disoriented plagioclase inclusions on right side of photo.

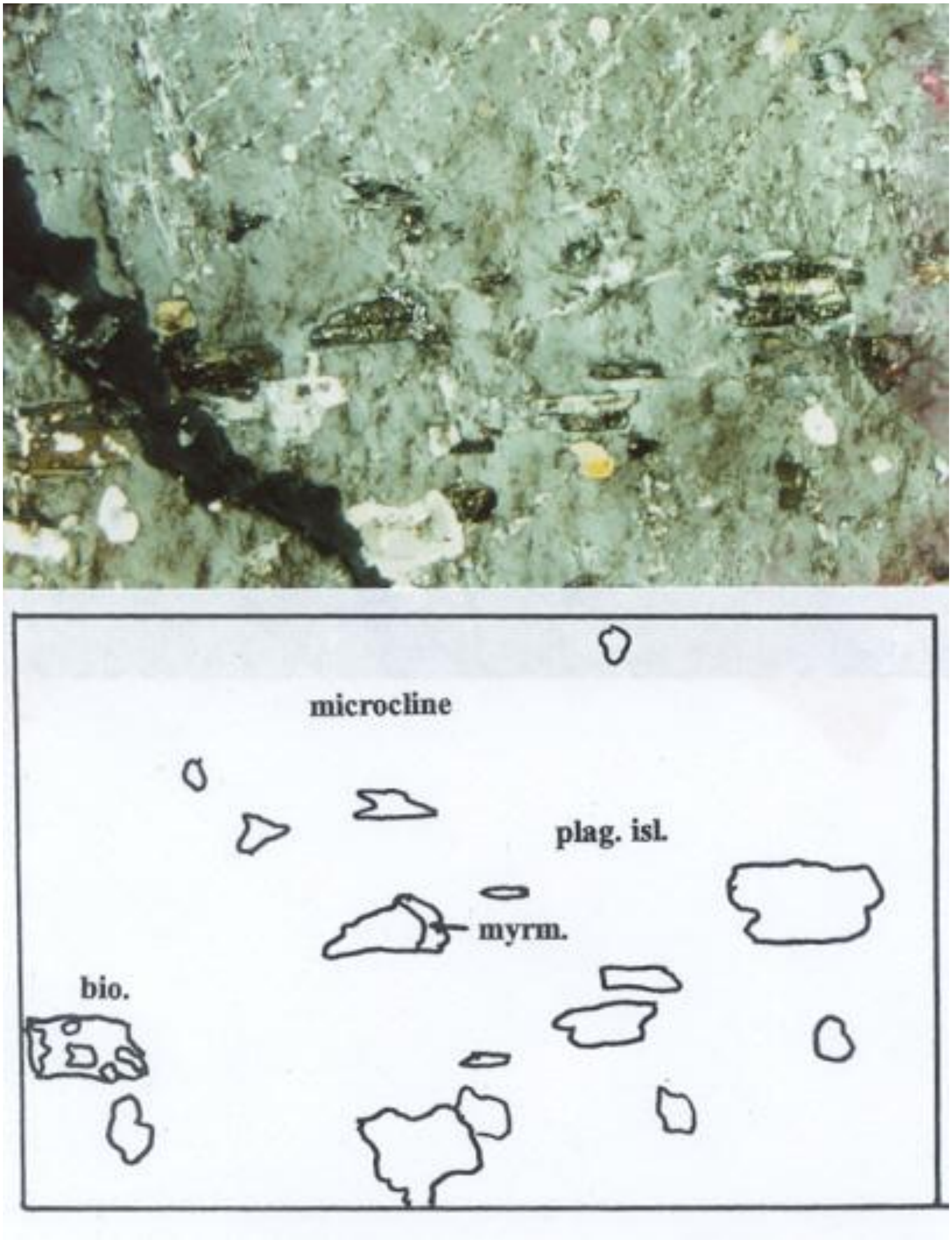

Fig. 10. Portion of perthitic microcline megacryst (light gray) with parallel-aligned, albite-twinned, tiny plagioclase inclusions, some of which are bordered by myrmekite with very tiny quartz vermicules (center). Biotite inclusion (left side) is partly replaced by quartz.

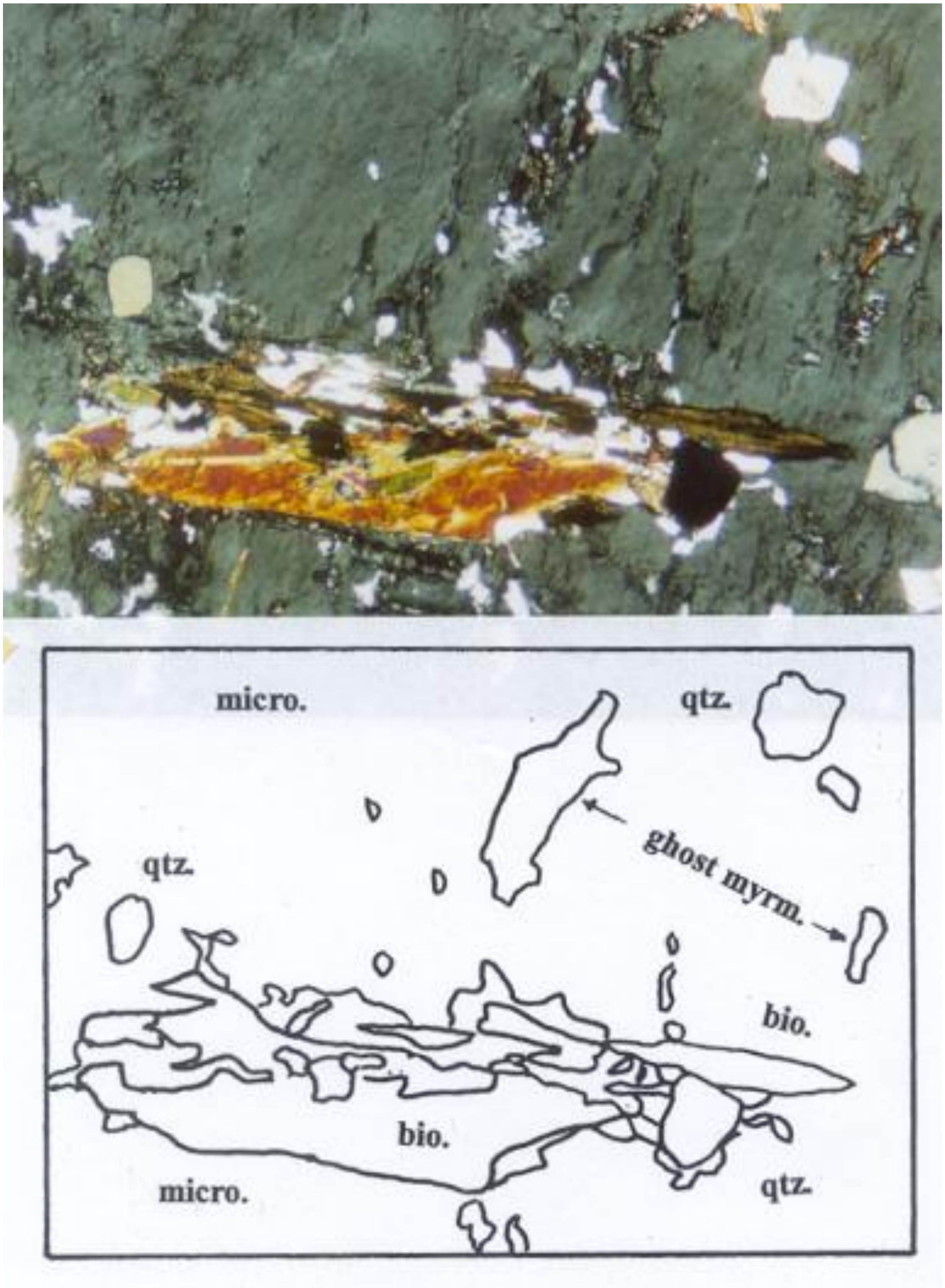

Fig. 11. Remnant inclusions of biotite (brown) in microcline megacryst (gray). Biotite is partly replaced by quartz (white) along borders and in the interior. A few plagioclase remnant grains have tiny quartz ovals in ghost myrmekite (above the biotite).

Cataclastic textures

In some places in the Cathedral Peak granodiorite, cataclastic textures are apparent in thin section. In these places the microcline megacrysts are bordered by smaller granulated groundmass minerals (Fig. 12), and myrmekite is commonly found on the borders of the megacrysts adjacent to the cataclastically broken grains (Fig. 12).

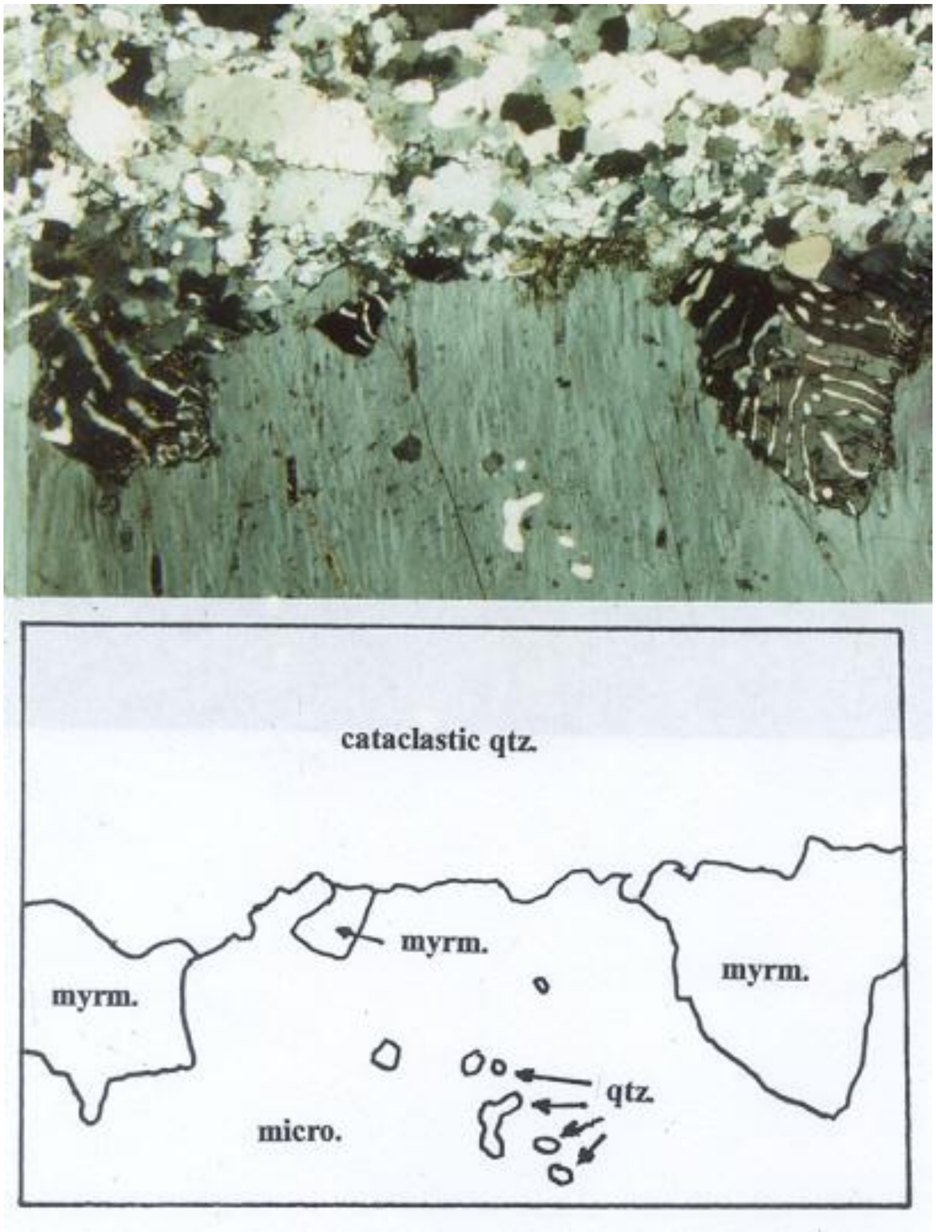

Fig. 12. Myrmekite bordering microcline megacryst (gray) adjacent to zone of cataclastically broken quartz grains (white, gray, cream, black; top). Remnant quartz blebs (white, black) occur in the megacryst.

Where the granodiorite is strongly deformed cataclastically, the rock is quite felsic (a leucogranite) and has a gneissic fabric. In thin sections a few remnant biotite crystals are present among ribbons of tiny crystals of quartz and microcline (Fig. 13). **Plagioclase is generally absent** as well as hornblende although adjacent Cathedral Peak granodiorite may be hornblende-bearing.

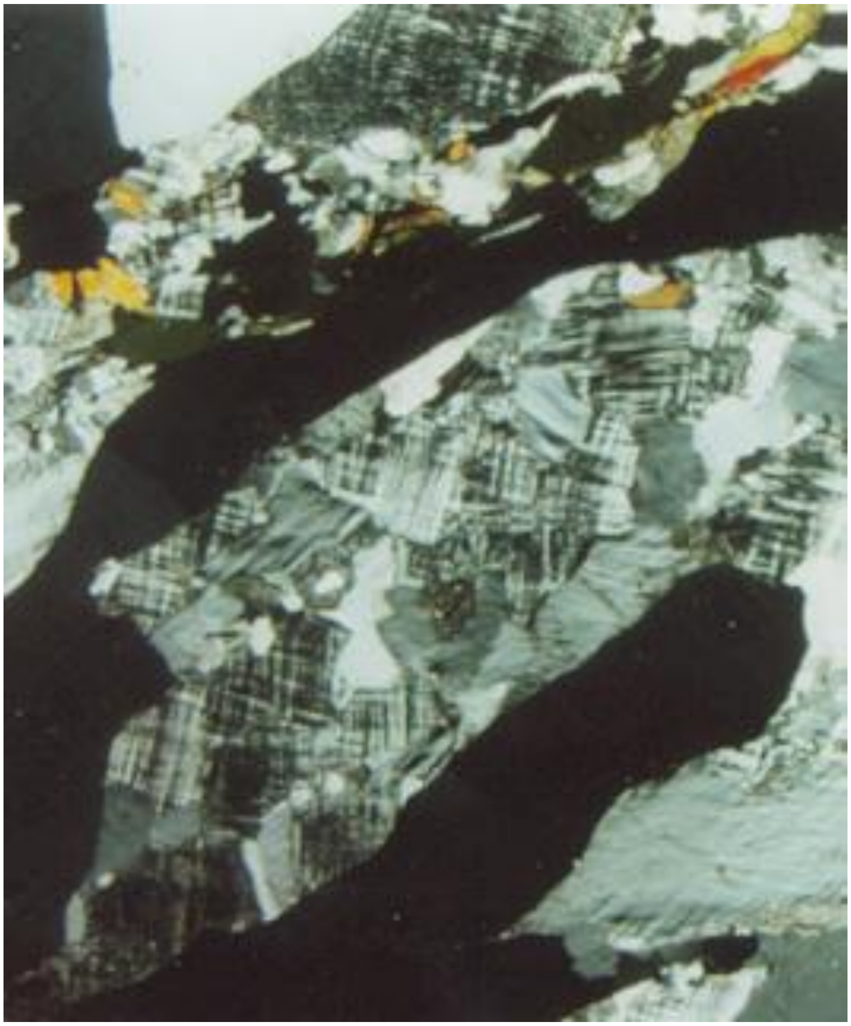

Fig. 13. Ribbons of recrystallized, fine-grained microcline grains (grid-twinned; light gray) with quartz (white, black) and biotite (brown) in a gneissic cataclastic zone in the Cathedral Peak granodiorite. Long black areas are places where small microcline, quartz, and biotite grains have broken out of the thin section.

Problems with the Ostwald ripening model

In the model proposed by Higgins (1999), the microcline megacrysts are formed near the eutectic temperature by "*textural coarsening of earlier formed small K-feldspar crystals during which most original crystals were sacrificed to* *feed the growth of a select few*." If this were true, then at and near the eutectic, most (say 99 percent) of the granitic rock would have been already crystallized, particularly because in his Ostwald ripening model most of the original late-forming K-feldspar crystals were already crystallized that would subsequently be sacrificed. On that basis, **the original rock must have been nearly completely solid (if not entirely solid)**. Therefore, the resorption and disappearance of much interstitial small microcline crystals from nearly completely solidified rock to produce the larger megacrysts would necessarily cause adjacent, coexisting, zoned plagioclase crystals, that impinged on the resorbed interstitial microcline, to readjust their borders to compensate for such large volume losses. No such evidence is visible.

Redistribution of crystals of different volumes occurs in (solid) metamorphic rocks, resulting in coarsening of crystals and **the development of crystal intersections at 120 degrees angles as smaller crystals disappear and their component elements are added to larger crystals** (Cashman and Ferry, 1988). However, no such recrystallization of plagioclase in the nearly completely solidified Cathedral Peak granodiorite occurs to compensate for adjacent volume losses of small microcline crystals; no development of crystal intersection at 120 degree angles exists; and coexisting plagioclase crystals also exhibit no evidence of Ostwald ripening, as would be expected if this model has any merit. Higgins (1999) also noted the absence of any 120 degree angles between the crystals, but still elected to promote the Ostwald ripening model. At any rate, the myrmekite bordering the interstitial small microcline grains (Fig. 3 and Fig. 4) and the penetration of broken plagioclase grains by K-feldspar veins (Fig. 5) provide evidence that the **microcline has replaced the plagioclase** rather than the small microcline crystals being remnants of crystals that were partly resorbed (Collins, 1988; Hunt et al., 1992). Moreover, the megacrysts show evidence that their growth is not simply the addition of transferred component elements in which the K-feldspar **would grow around** preexisting groundmass minerals, but, instead, the megacrysts show that **groundmass minerals**, formerly in the space now occupied by the megacrysts, have **also been subjected to K-metasomatism**. This replacement is illustrated by the disappearance of most of the volumes of groundmass minerals in the space now occupied by the megacrysts, by inclusions that are penetrated by microcline veins (Fig. 6, Fig. 7, and Fig. 8, by the preservation of remnant plagioclase islands in the microcline in parallel optical continuity (Fig. 6), by the enclosure of plagioclase grains with myrmekite borders (Fig. 9 and Fig. 10), and by the presence of ghost myrmekite (Fig. 11). This evidence also includes remnant hornblende and biotite inclusions that have been replaced by quartz (Fig. 10 and Fig. 11). The breakdown and replacement of biotite by quartz would have released the K that subsequently replaced deformed plagioclase crystals to form the microcline.

The parallel alignments of Carlsbad twinning and of one set of planes of the grid-twinning in the microcline crystals with Carlsbad twinning and planes of albite twinning in adjacent plagioclase lattice (Fig. 5) suggest that the lattice structure in the microcline has been inherited from the plagioclase lattice during replacement (Fig. 5; Collins, 1999ab; Orville, 1962, 1963; Wyart and Sabatier, 1956). Such parallel alignments would not be expected in an Ostwald ripening model in which the small interstitial microcline crystals would be formed in late-stage crystallization near the eutectic and should have formed in random orientations independent of the orientations of adjacent plagioclase lattice orientations.

Where the K-replacement of a small plagioclase grain is complete, the resulting microcline grain has the irregular (anhedral) outline of the original plagioclase and appears to be interstitial to adjacent unreplaced plagioclase grains. Thus, in the replacement process the igneous texture of the original rock is preserved. Moreover, after the completion of this stage of initial K-replacement, the small microcline crystals are not interstitial because of late stage crystallization from a magma at a temperature near the eutectic but because selected cataclastically-broken plagioclase crystals were totally or nearly completely replaced by microcline. The evidence for the former cataclasis is largely destroyed by the replacement and recrystallization processes but is indicated by the myrmekite that occurs locally in some places (Collins, 1988, 2001; Hunt et al., 1992).

Implications of cataclasis

Higgins (1999) ignored any cataclasis exhibited in the Cathedral Peak granodiorite, including that around some megacrysts (Fig. 12) and also the fine-grained gneissic zones (Fig. 13). His omission of discussing cataclasis was probably on the assumption that it is a phenomenon that occurred much later than the final crystallization of the magma and, therefore, should have had no bearing on the CSDs between the small groundmass microcline and the megacrysts. However, such cataclasis has a strong bearing on the origin of the features that he wishes to explain. If the fine-grained, gneissic, aplite-appearing, felsic zones (Fig. 13), exhibiting strong cataclasis, were former late-stage aplites crystallized from a granodiorite magma, then such aplites would be expected to have all three minerals: quartz, microcline, and plagioclase, which would have crystallized simultaneously at the eutectic. Instead, **plagioclase is generally absent**. The absence of plagioclase in such cataclastically deformed places and the abundance of microcline again give strong support to the hypothesis that microcline has replaced such plagioclase. Moreover, the abundance of the tiny microcline grains in these gneissic zones lends support to the model that **microcline is not being resorbed** but is being introduced in places where the system is most open to fluid movement. Repeated strong planar deformation in these places would not allow large megacrysts of microcline to be formed and would effectively cause the disappearance of the plagioclase because of the ease by which dissolved Ca and Na ions (replaced by K) would have been carried out of the open system. This displacement of Ca and Na ions (stable in a higher temperature environment) by K (stable in a lower temperature environment), is in agreement with the experimental work of Orville (1962, 1963), and the textural evidence in thin sections of the Cathedral Peak granodiorite shows that it can happen on a plutonic scale.

Regional cause for the cataclasis

The existence of cataclasis is likely associated with the north-south orientations of the Cathedral Peak granodiorite and the Johnson granite porphyry (Fig. 1) because these orientations reflect a north-south zone of deformation that initially opened the system of magma transport. That the original rock was magmatic is evident by the abundance of normally zoned plagioclase crystals with relatively calcic cores and more-sodic rims, indicating crystallization during relatively high rates of magma cooling. Nevertheless, there is no reason why the same forces that deformed the rocks to permit introduction of the magma in a linear body, trending north-south, should cease following solidification of this magma. Subsequent plate tectonic motions would have continued the north-south-aligned deformation at temperatures below the eutectic. These motions would have caused cataclasis and allowed metasomatic fluids to modify former solidified quartz diorite mineral compositions by replacing some of the ferromagnesian silicate minerals with quartz and some of the plagioclase with microcline. In this way the quartz diorite was changed compositionally into quartz monzonite, granodiorite, and granite, depending upon the degree of Si- and K-replacements.

The north-south orientation of the Cathedral Peak granodiorite is also consistent with the generally north-south zone of ductile deformation that extends for several hundred kilometers in the eastern Sierra Nevada (Greene and Schweickert, 1995; Tikoff and Saint-Blanquat, 1997; Saint-Blanquat et al., 1998). Microcline megacrysts are common in many different granitic plutons along this ductile shear zone, and although ductile deformation would occur at temperatures above that which would permit brittle breakage of crystals in these rocks, the deformation need not have ceased when temperatures dropped below conditions for ductile deformation but continued and caused brittle breakage so that fluids could subsequently cause K-metasomatism of broken grains.

On that basis the cataclasis happened and is plausible because of continued plate tectonic motions following the complete solidification of the Cathedral Peak magma, the cataclasis around some microcline megacrysts (Fig. 12) suggests that ongoing deformation continued even after metasomatic modification of the Cathedral Peak rock at temperatures below which K-metasomatism occurs. The inclusions of broken groundmass minerals in concentric shells in the megacrysts are an indication of earlier episodes of cataclasis during plate motions at temperatures in which metasomatism was possible. Therefore, the rock in the Cathedral Peak pluton must have been subjected to repeated periods of deformation, keeping the system open for fluid movement to facilitate the metasomatism. This openness is important because without repeated cataclasis, the metasomatism and recrystallization would close the system to fluid movement.

Origin of oriented inclusions in the zoned megacrysts

The repeated cataclasis also helps to explain the crystal zoning of the tiny inclusions within the megacrysts. As a microcline crystal grew beyond the first plagioclase crystal that it replaced, most of the adjacent fractured groundmass minerals were also replaced by the microcline. Some, however, were not replaced or were only partly replaced, and these became incorporated within the growing megacryst, forming concentric zones of inclusions with each episode of K-replacement. Groundmass minerals with lattice orientations at an angle to the lattice of the growing microcline crystal would most likely have been replaced. It is the broken crystals with parallel orientation that would have been preferentially partly preserved and appear as the concentric zones of tiny inclusions in the megacryst. Each concentric zone represents another sequence of replacement and megacrystal growth and perhaps successive stages of repeated cataclasis of adjacent groundmass minerals. In the final stage, the euhedral megacryst with concentric shells of tiny inclusions would still show evidence of replacement veins and wedges of microcline **extending into adjacent less-fractured groundmass minerals**. Further evidence for the successive stages of replacement are the inclusions of plagioclase fragments with myrmekite borders, representing an earlier episode of localized incomplete K-replacement.

CSD irregularities

In the Cathedral Peak granodiorite, plagioclase crystals are relatively small, ranging from 1 to 15 mm in mean height. Where these plagioclase crystals were cataclastically broken, K-replacement caused many of them to be partly or completely replaced by microcline. Maximum numbers of such microcline replacements have sizes of 1 to 2 mm, and progressively fewer have sizes up to 15 mm (Fig. 6 in Higgins, 1999). Therefore, the CSDs of the microcline crystals in the 1 to 15 mm range plot in a steep linear line, reflecting the original abundance and sizes of the plagioclase crystals. If the mean height of the plagioclase crystals in the Cathedral Peak granodiorite continued its range from 15 to 80 mm, the replacement of plagioclase crystals by microcline in this larger range might then plot as an extension of the steep slope for the crystals plotted for the 1 to 15 mm range. However, this larger range of plagioclase crystals does not exist in the Cathedral Peak pluton. Instead, cataclasis and K-metasomatism allowed the microcline crystals to grow beyond the approximate 15 mm size of the individual plagioclase crystals, and it is this growth of the microcline crystals that produced the size range of 15 to 80 mm. In this process, smaller groundmass crystals were partly replaced and incorporated in the growing megacryst. The numbers of larger microcline crystals were limited to sites where sufficient cataclasis occurs to enable the K-metasomatism. These sites can be scattered and random, occur in nests, or exist in linear stringers (Fig. 3 in Higgins, 1999). But the numbers of microcline megacrysts are necessarily fewer than the numbers of smaller microcline crystals, thereby explaining the gentler slope for the trend of the CSDs of the larger crystals (Fig. 6 in Higgins, 1999). The break in slope of the two linear trends is not from resorption of smaller microcline crystals, as proposed in the Ostwald ripening model, but from successive stages of metasomatism, allowing growth of larger crystals which, in the process, incorporated smaller crystals.

Euhedral shapes of the microcline megacrysts

At mean height dimensions of about 10 mm and larger, the microcline crystals became nearly euhedral (rectangular) because the growing microcline extended beyond an initially replaced, small, anhedral, plagioclase crystal and replaced other adjacent cataclastically broken groundmass minerals. Where these other groundmass minerals were granulated (as seen in Fig. 12), the openness of the system permitted the microcline to expand its lattice and develop crystal control of its outer surface, forming its own euhedral shape.

Ba in the microcline

Kerrick (1969) found that the Ba content in groundmass microcline was 0.25 percent or less, whereas the Ba content in most megacrysts ranged from 1 to 2 percent, although he reported that one megacryst had a rim with low Ba content. Fluctuations in Ba content of the microcline megacrysts can be expected in a metasomatic model because the sources of the Ba are likely from the breakdown of biotite where the Ba ion, because of its similar ionic size to the K ion, might reside and also from K-replaced more-calcic cores of plagioclase crystals, where Ba +2 ions may have substituted for Ca +2 ions. Soluble Ca ions with +2 charges removed from plagioclase would be expected to be transported out of the system because the Ca ion does not readily substitute for the K ion in microcline and would not be stable in recrystallized sodic plagioclase at temperatures below the solidus. On the other hand, subtracted Ba ions with +2 charges would be expected to be re-deposited with K in a growing microcline megacryst because of the similar sizes of the K and Ba ions. In **late stages of deformation** and at cooler temperatures, the fluids causing metasomatism can be expected to carry less Ba because most available Ba would have been removed already from the original biotite and plagioclase crystals. Therefore, at lower temperature, the subsequent deformation of the rock to allow the formation of microcline by additional K-replacement of small broken plagioclase crystals or the overgrowths of microcline on the outer rims of megacrysts can be expected to produce microcline of lesser Ba content.

Hornblende around megacrysts

Higgins (1999) noted that hornblende in the groundmass is slightly enriched near the borders of the large megacrysts. This enrichment would **not be the result of nucleation of hornblende** near the microcline because the hornblende would have formed earlier at higher temperatures and in places unrelated to the late-forming microcline. Instead, hornblende's apparent concentration near the megacryst borders reflects the fact that the site where the megacryst now occurs was a more-mafic volume that was initially enriched in hornblende, biotite, and more-calcic plagioclase. Abundant biotite in these places with its hardness of 3 and planar cleavage would have weakened the rock and facilitated local cataclasis. Because more-calcic plagioclase is less stable than more-sodic plagioclase in a low-temperature environment where brittle deformation occurs, the strong replacement of this calcic plagioclase by K would favor growth of microcline to form the megacrysts. Therefore, the enrichment of hornblende near the megacrysts is **only indirectly related to the microcline** because of the association of the Ca-bearing hornblende with former more-calcic plagioclase now replaced by the microcline.

Myrmekite

The tiny sized quartz vermicules in myrmekite (Fig.3, Fig. 4, and Fig. 12) are expected when incomplete replacement of relatively sodic plagioclase occurs because of the small amounts of silica that remains during this process (Collins, 1988; Hunt et al., 1992). Such relative sodic compositions are present in the zoned plagioclase crystals (albite rims to oligoclase cores) of the Cathedral Peak granodiorite, thus explaining the tiny vermicules.

Microcline versus orthoclase

The fact that the K-feldspar megacrysts are microcline rather than orthoclase is significant and consistent with the model that the microcline originated at subsolidus temperatures. On that basis, the triclinic grid-twinning in the microcline did not necessarily form by inversion from the monoclinic orthoclase lattice as **is common** in other terranes where the primary K-feldspar is orthoclase. Production of microcline from K-replacement of plagioclase has been experimentally demonstrated; see Collins (1999ab; Wyart and Sabatier, 1956).

Conclusion

The replacement textures illustrated in Figures 3 through 13 strongly support a model that the microcline that was formed in both the groundmass and the megacrysts in the Cathedral Peak granodiorite, resulted from K-metasomatism of deformed and broken, primary, zoned plagioclase crystals to form secondary microcline (Collins, 2001). These textures are **inconsistent with the model** that the microcline in the megacrysts was formed by Ostwald ripening in which small crystals of primary magmatic K-feldspar were resorbed (sacrificed) and their component elements transferred to larger primary K-feldspar crystals (Higgins, 1999). The observations of these textures (Figs. 3-13) may have application to the origin of the K-feldspar megacrysts in the Papoose Flat quartz monzonite pluton (Dickson, 1996), but there the megacrysts are orthoclase instead of microcline, and more study is needed.

Certainly, not all K-feldspar megacrysts in granitic plutons result from metasomatic modification of former more-mafic intrusions or form by resorption of smaller crystals. In many places, the megacrysts are entirely magmatic in origin. But the Si- and K-replacements that occurred in the Cathedral Peak granodiorite may be more common in other granitic plutons than many petrologists realize. The zoning from older, outer, more-mafic intrusions progressively to late-stage, inner, more-felsic intrusions, as illustrated in the Tuolumne Intrusive Suite (Fig. 1), likely initially developed by magmatic differentiation in which crystal settling of early-formed, dense, Ca-, Mg-, and Fe-rich crystals produced a residual magma less rich in these elements. This progressive mafic-to-felsic magmatic differentiation-trend, however, may have also been followed and enhanced by K- and Si-metasomatism that removed these elements. This metasomatism would have occurred following late deformation of solidified masses at subsolidus temperatures.

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