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19. CONTRASTING CHARACTERISTICS OF MAGMATIC AND METASOMATIC GRANITES AND THE MYTH THAT GRANITE PLUTONS CAN BE ONLY MAGMATIC

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Introduction

Most geologists believe that plutonic bodies, including granites, have been emplaced as magma, even though the majority of granites contain mineral assemblages that are stable in the temperature range of 400-600º C − well below melting conditions for most granite. Experimental work, testing this hypothesis, has been performed on melts in closed systems, attempting to simulate magmatic conditions. Such experimental studies support the magmatic origin of granites, because that is the sole hypothesis which has been extensively tested. Field observations and thin section studies, however, in many places support metasomatism.

The existence of magmatic granites is not doubted, because natural environments do produce temperatures above eutectic point(s) of granites in many places in the earth's crust. Nevertheless, the evidence that *all granites* are magmatic or that plutonic rocks cannot be altered to granites after emplacement and solidification is based on flimsy logic.

Many geologists accept Na-metasomatism (fennitization) on a large scale where Na-plagioclase (albite), Na-amphiboles, and Na-pyroxenes are produced in plutons, and they will accept K-metasomatism on a small scale (a few centimeters or meters), but only when it is a secondary, minor phenomenon of a magmatic intrusion. If Na-metasomatism can occur in a large-scale, what limits K-metasomatism to a few centimeters? And if K-metasomatism is limited, what then is the basis for the established limit for which it can occur? Should the limit be one meter? If so, what is to prevent metasomatism from occurring in 1.01 meters? And if a higher limit is set, say 100 meters, what is to prevent metasomatism from occurring at distances of 101 meters? If K-metasomatism can occur in a pluton even at one centimeter, given enough time and appropriate conditions, almost any distance across the pluton should be possible. The extent depends upon the degree of deformational movements, crushing, and availability of K, not on some arbitrary number.

The following discussion seeks to provide criteria for distinguishing magmatic granites from metasomatic granites and to show examples of textures that are characteristic of each type. Field relationships as well as mineral-textural fabrics in thin sections are described. These criteria should be useful in determining whether a granite body is magmatic or became granitic by metasomatic processes. On the basis of these criteria, the "granite problem" is examined again, providing answers to the objections raised by experimentalists, geochemists, and petrologists to large-scale creation of granite bodies by metasomatic processes.

Characteristic features of magmatic granites

There are a number of features of mineralogy, texture (fabric), and field relationships that are characteristic of granites crystallized from magma (melts, solutions), which are listed below.

1. *Plagioclase*.

In hot magma, because plagioclase tends to crystallize early with relatively-calcic nuclei in cores and to evolve at lower temperatures to more sodic compositions in rims, the presence of plagioclase with normal zonation is a logical indication of a magmatic origin of a plutonic granitic rock (Fig. 1). The similar presence of normal-zoned plagioclase in volcanic rocks also provides support for the magmatic origin of such plagioclase crystals in plutonic rocks.

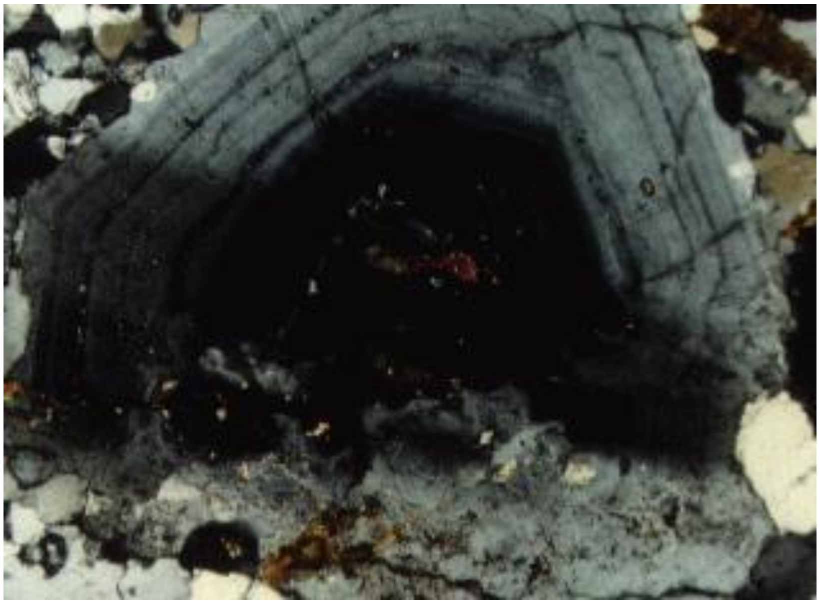

Fig. 1. Plagioclase in a granodiorite showing strong zonation (Vetter pluton, San Gabriel Mountains, California).

2. *Perthite and antiperthite*.

The solid-solution of Na, Ca, and K in high-temperature alkali feldspars (orthoclase and anorthoclase) and the subsequent exsolution of Na and Ca to form perthite in which the plagioclase lamellae are evenly distributed throughout the K-feldspar in diverse patterns but with similar shapes are common characteristics of magmatic granites (Fig. 2 and Fig. 3). In such magmatic rocks both halves of Carlsbad-twinned K-feldspar crystals contain the same kinds of exsolved plagioclase (Fig. 4). Similar relationships apply to antiperthite in which plagioclase is the host and K-feldspar, the exsolved component.

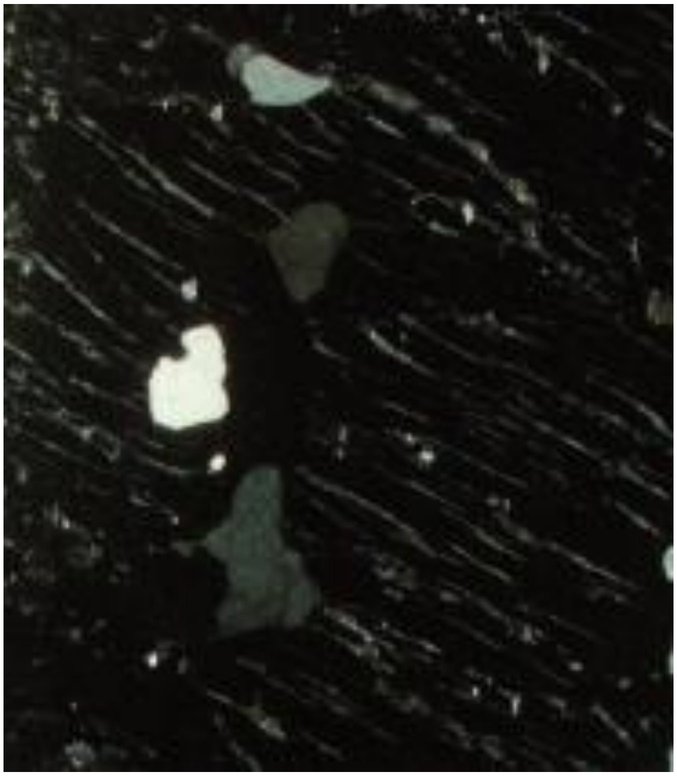

Fig. 2. Perthite. K-feldspar (orthoclase, black) with uniformly distributed plagioclase lamellae (light gray). Inclusions of quartz (cream, white, gray) and plagioclase (light gray). From granite on Mt. Desert Island in Maine, USA.

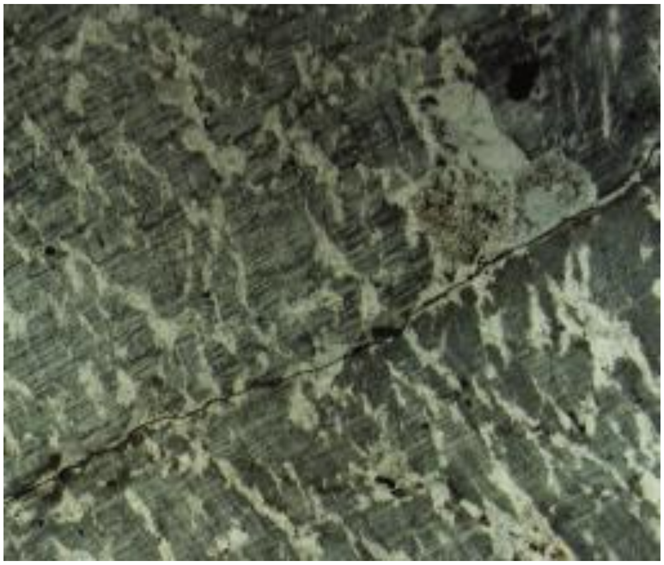

Fig. 3. Perthite. K-feldspar (orthoclase, gray) with uniformly distributed plagioclase lamellae (white). Inclusions of quartz (dark gray) and plagioclase (black and light gray). From granite on Mt. Desert Island in Maine, USA.

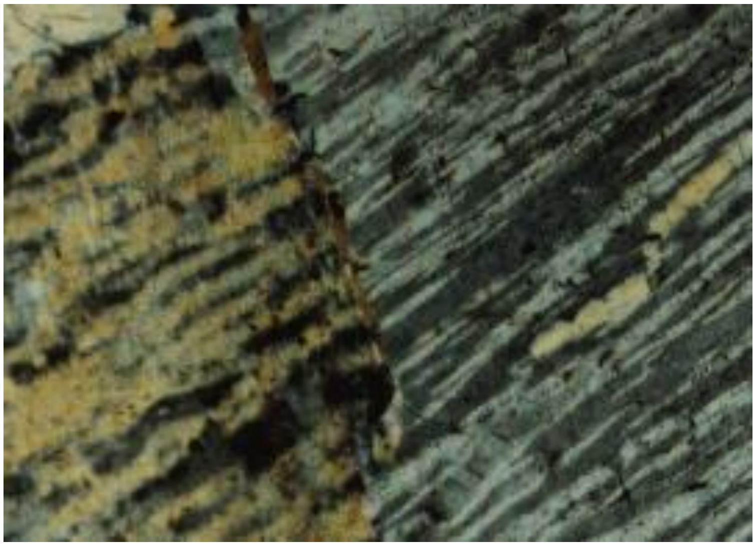

Fig. 4. Perthite. Carlsbad-twinned K-feldspar (orthoclase, light gray and dark gray) with uniformly distributed plagioclase lamellae (cream). From granite in quarry near Wausau, Wisconsin, USA.

3. *Zonation in K-feldspar (orthoclase)*.

At high temperatures in melts, cores of K-feldspar crystals commonly contain more Ca, Ba, and Pb than rims that crystallized at lower temperatures. This creates a chemical zonation that may be visible in thin sections (Fig. 5).

Fig. 5. Zonation in K-feldspar.

4. ***Straight sharp contacts of K-feldspar with other crystals*.**

In magmatic granites, crystal faces of K-feldspar tend to be straight where they contact adjacent crystals and lack any signs of rounded embayments (Fig. 6). Along these straight contacts, adjacent plagioclase crystals generally lack any apparent reaction rims against the K-feldspar. Straightness off crystal faces also applies to inclusions inside the K-feldspar crystals, and such inclusions generally are *not* optically parallel to similar species outside the K-feldspar crystals.

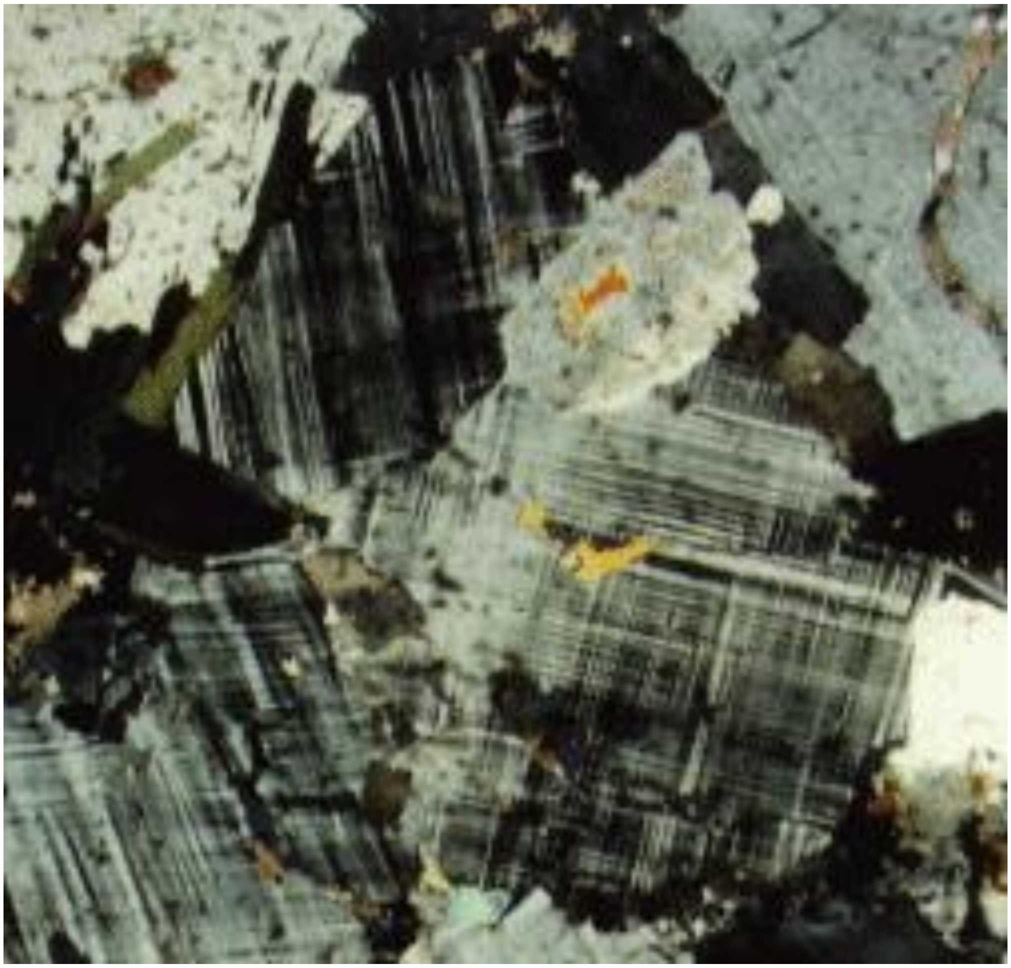

Fig. 6. K-feldspar with angular relationships with ground mass minerals: plagioclase (light gray), quartz (white), biotite (brown, green). No myrmekite occurs in the rock, and the K-feldspar does not embay plagioclase.

5. ***Quartz-K-feldspar and quartz-plagioclase intergrowths*.**

In pegmatites of magmatic origin, runic quartz in *graphic textures* with parallel optic orientation extends through the K-feldspar crystal and may also continue with the same optic orientation in adjacent plagioclase (albite). In granitic rocks containing plagioclase with a strong normal zonation, the K-feldspar interstitial to the plagioclase may have a *micrographic texture* of rounded and irregular shapes (Fig. 7). In dikes where the rock is fine-grained and crystallized relatively quickly, *granophyric textures* of quartz and K-feldspar intergrowths may occur in which the quartz has triangular shapes (Fig. 8). These three kinds of quartz-K-feldspar and quartz-plagioclase intergrowths suggest simultaneous crystallization from a melt and have been produced experimentally.

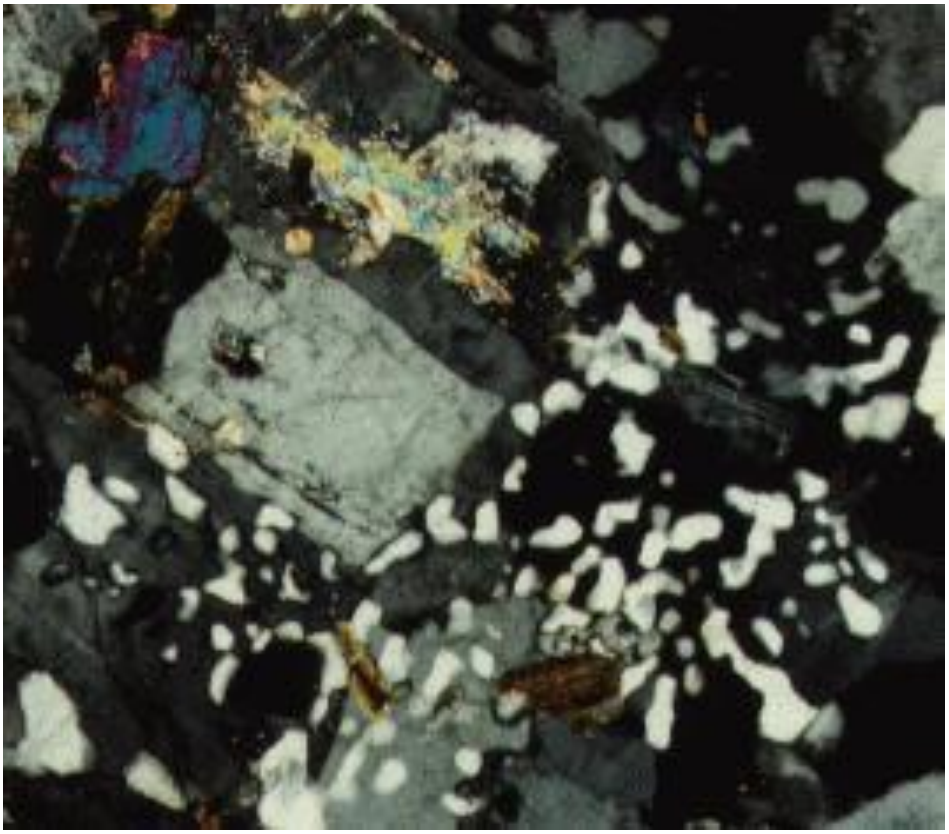

Fig. 7. Micrographic texture with ovoid quartz (white) in K-feldspar (dark gray, black) interstitial to zoned plagioclase (light gray). Epidote (yellow, blue, red); biotite (brown). From McMurray Meadows quartz monzonite, eastern Sierra Nevada, USA.

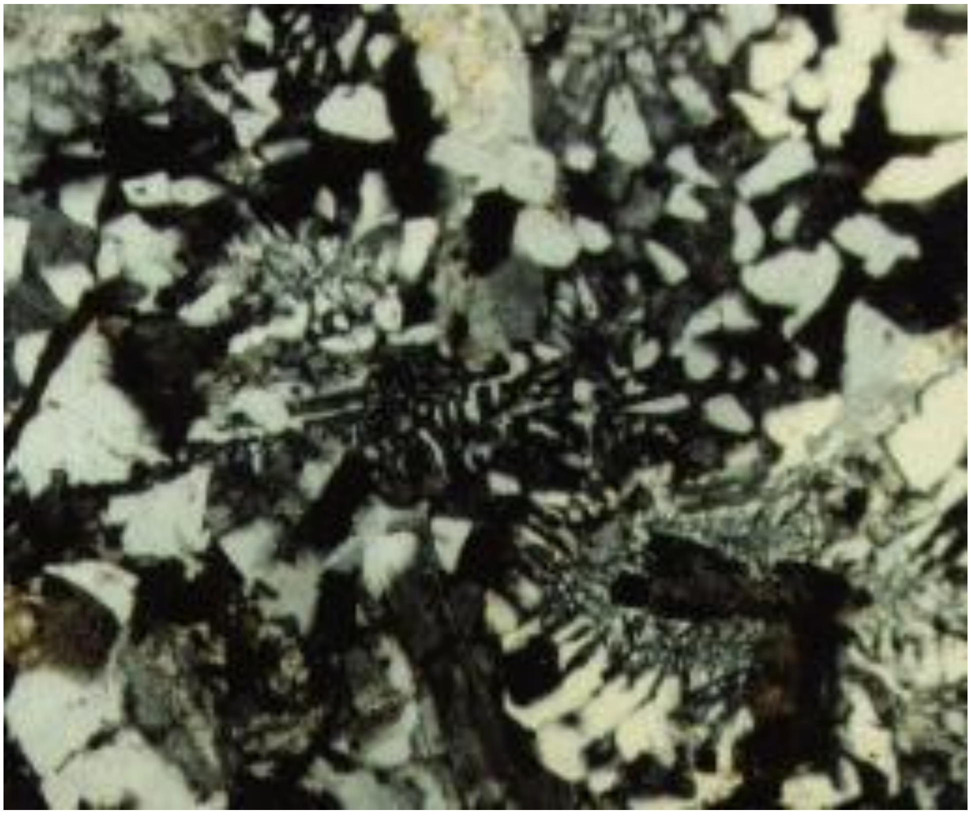

Fig. 8. Granophyric texture with angular quartz inclusions (white) in feldspar (gray and black). Biotite (brown).

Myrmekite (Fig. 9), on the other hand, is a quartz plagioclase intergrowth with vermicular quartz which *has not been produced experimentally*. It is unlike quartz-plagioclase graphic or micrographic textures in which the quartz is runic and the plagioclase has a constant composition. In myrmekite the plagioclase has a variable composition, depending upon the thickness of the adjacent portions of the quartz vermicules. The absence of rim or wartlike myrmekite (Fig. 6) in combination with the straight contacts of K-feldspar against plagioclase and other crystals supports the magmatic origin for a granite, because myrmekite forms by replacement processes; see http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf; http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf; Collins (1988); Hunt et al., (1992).

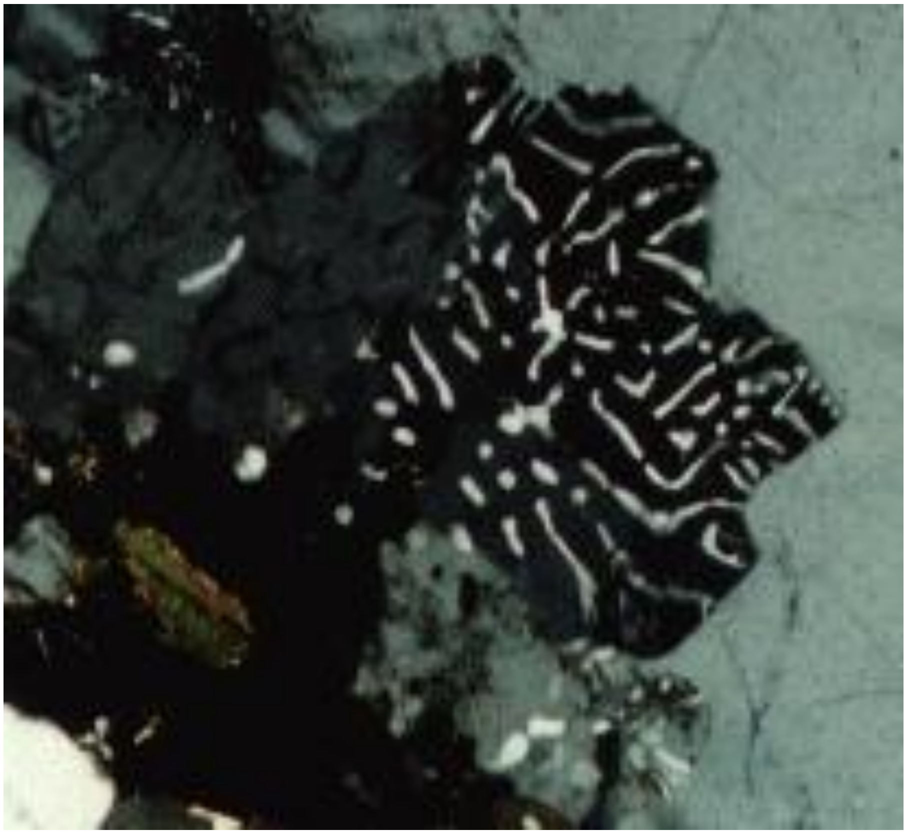

Fig. 9. Wartlike myrmekite with quartz vermicules of intermediate size (center) enclosed in K-feldspar (light gray). Coexisting biotite occurs enclosed in plagioclase (black). From Main Donegal granite in northwest Ireland.

6. *Absence of quartz sieve textures in hornblende and biotite*.

Because quartz is last to crystallized in a granitic melt, it will occur primarily in the ground mass *outside the hornblende and biotite crystals and not in their cores*.

7. *Reaction rims on olivine and pyroxenes*.

In more mafic granitic rocks, such as granodiorites and quartz monzonites, which contain high-temperature minerals (pyroxenes and/or olivine), reaction rims of hornblende and biotite on the pyroxenes would be a common association because of the successive formation of hornblende and biotite at lower temperatures in a crystallizing magma.

8. *Evidence for magma mixing*.

Hybrid rocks of intermediate compositions along contacts and diffusion gradients of elements between two magmas of granitic and mafic composition would support the magmatic origin of the granite. Silicic pipes extending from granite into basaltic layers would also provide additional evidence of the magmatic origin of the granite (e.g., Wiebe, 1996).

9. *Assimilation of enclaves*.

In magmatic granites containing enclaves, mafic components (minerals, elements) are commonly incorporated or assimilated from the enclaves, forming a more-mafic hybrid rock in the granite adjacent to the enclaves. Thus, diffusion of components between the solid enclave and the granite magma would be apparent, and the mafic elements formerly in the enclave are nearby and have not been lost from the system.

10. *Comb layering and gravitational structures*.

Structures which give evidence of crystal settling in a magma, such as comb layering (asymmetric schlieren) in some granites (e.g., Moore and Lockwood, 1973; Trent, 1981) and repeated gradations from mafic to felsic minerals in layered sequences that occur in some gabbros are clear evidence for crystallization from a melt. Line granites composed of alternating layers of garnet, quartz, and feldspar in zoned pegmatites also suggest crystallization and gravitational settling in a hydrous granitic melt (Jahns, 1954; Jahns and Tuttle, 1963).

11. *Presence of evidence for anatexis*.

Where granitic rock is generated because of anatexis (local partial melting), the first components to melt and migrate to relatively low pressure sites are quartz or quartz plus feldspars. This partial melting and migration of elements to form felsic minerals leave behind the ferromagnesian silicate minerals which melt at higher temperatures. In that process, the residue is enriched in mafic components in melanosomes (or restite), and those components that migrate are recrystallized in felsic rocks (leucosomes or granite pods and veins). Such leucosomes or granite pods and veins of melt origin do not contain myrmekite, and their association with melanosomes (or restite) would be clear examples that temperatures above eutectic conditions have been achieved.

12. *Miarolitic cavities and gradation to rhyolite*.

In a few places coarse-grained granite grades upward to fine-grained leucogranites containing miarolitic cavities and then still farther upward, into rhyolite. Such places are rarely found, but occasionally deep erosion provides suitable exposures (e.g., Cater, 1982). Such gradations between plutonic and volcanic equivalents support the hypothesis that granite has a magmatic origin.

Characteristic features of metasomatic granites

The following represent characteristic features of metasomatic granites which are superimposed on former magmatic rocks, modifying the above twelve characteristic features of magmatic granitic rocks. Relationships of metasomatic granites relative to metasedimentary rocks are described in a later discussion.

1. *Plagioclase*.

Metasomatic changes are first observed where the host magmatic rocks are deformed. In early stages of metasomatism, zoned plagioclase crystals begin to exhibit mottled extinction, destroying the distinct zonation (Fig. 10). As the modification continues, the albite- and Carlsbad-twinning in the plagioclase crystals begin to disappear. This occurs because of loss of Ca and Al, which creates holes in the lattice into which K eventually is introduced to convert some of the plagioclase to K-feldspar (see item 4 below). Not all plagioclase crystals are replaced by K-feldspar, however, because residual Na displaced by K eventually replaces other altered plagioclase crystals. As a result, some of the original plagioclase crystals are recrystallized with albite-twinning reappearing, but the plagioclase crystals now lack zoning and have a uniform, more-sodic composition than initially present in the original magmatic rock. See http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf.

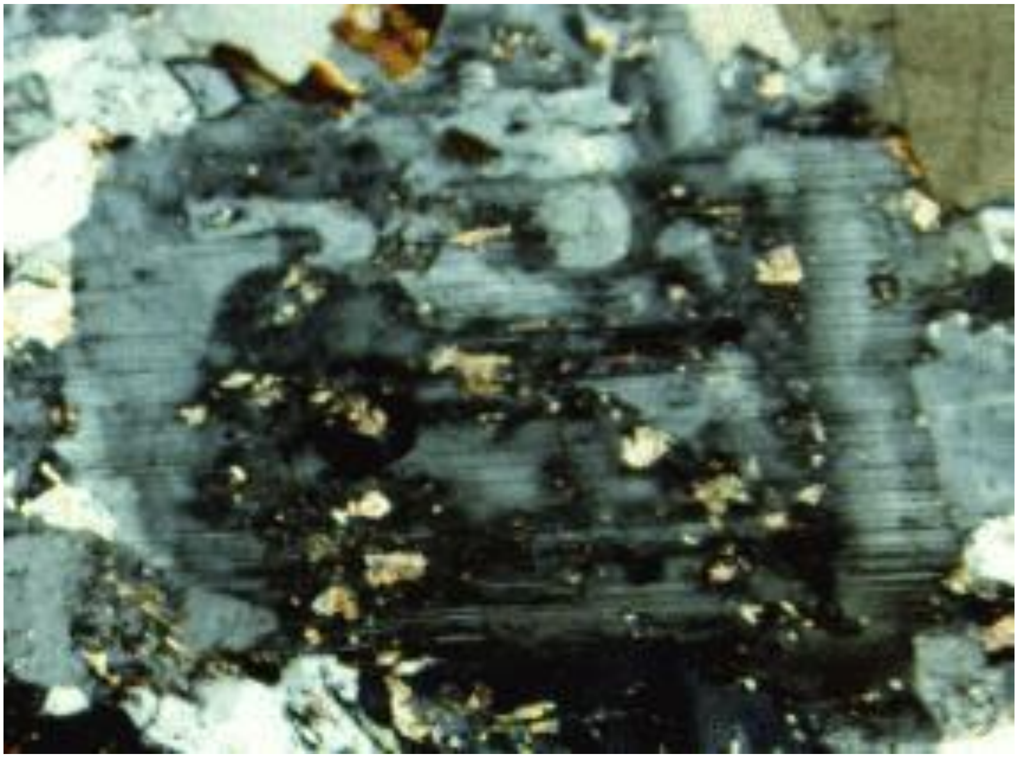

Fig. 10. Plagioclase with mottled extinction and faint albite twinning. From Bonsall tonalite near Temecula, California, USA.

2. *Perthite and antiperthite*.

In metasomatic granites, the K-feldspar may be perthitic and the plagioclase antiperthitic, but the distributions plagioclase lamellae in perthite and K-feldspar lamellae in antiperthite commonly are irregular. For example, in antiperthite, one half of a Carlsbad-twinned plagioclase crystal may lack K-feldspar lamellae or contain different amount of K-feldspar from that in the other half (Fig. 11 and Fig. 12). These relationships reflect the fact that some parts of original plagioclase crystals are deformed and replaced partly by K-feldspar while other parts are not deformed or replaced or are deformed and replaced to a lesser extent. Similar relationships would occur for perthite.

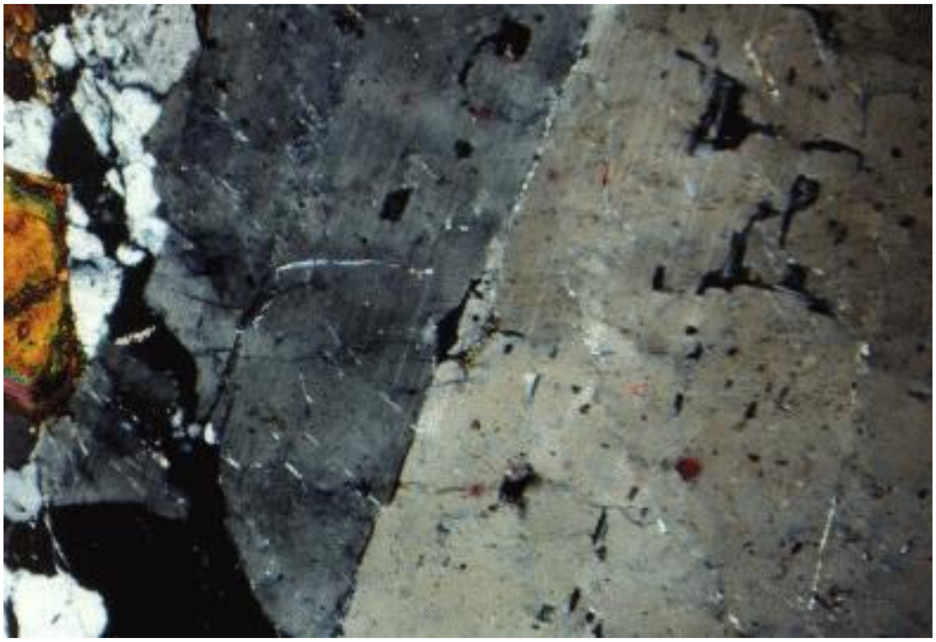

Fig. 11. Antiperthite. Carlsbad-twinned plagioclase (light gray and tan; albite-twinned) with unequal distribution of irregular islands of K-feldspar (black, gray). From Gold Park diorite near Twentynine Palms, California, USA.

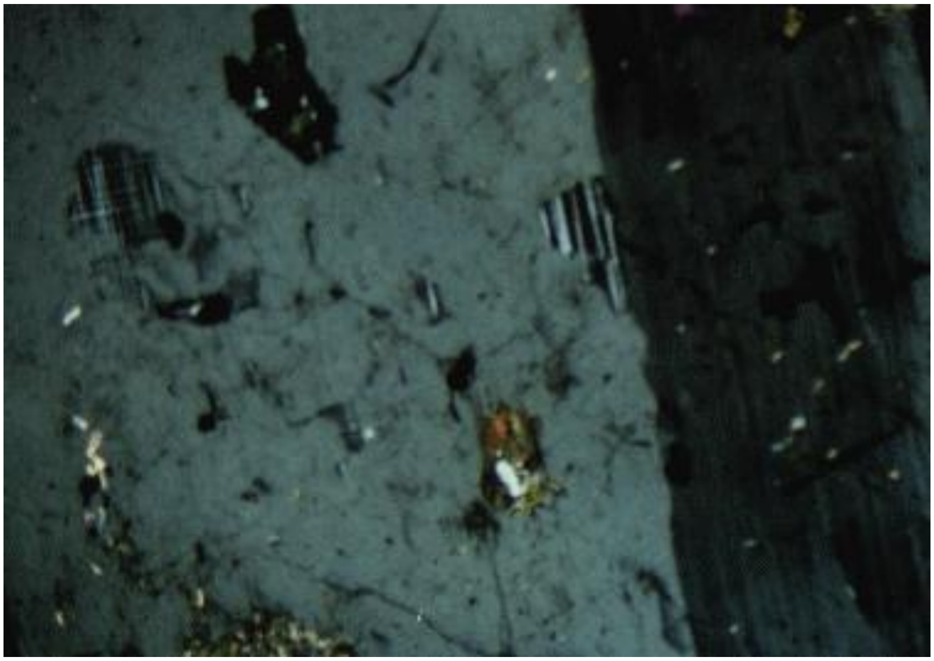

Fig. 12. Antiperthite. Carlsbad-twinned plagioclase (light gray and albite-twinned, dark gray) with unequal distribution of irregular islands of K-feldspar (black, gray, and white, cross-hatch pattern). Biotite (brown). From border facies of Ardara pluton in northwest Ireland.

3. *Lack of chemical zonation of K-feldspar*.

Because K-feldspar formed by replacement of plagioclase occurs nearly at constant temperature, there should be no tendency to produce a chemical zonation from core to rim. Moreover, the irregular escape of Ca, Ba, and Pb in a zoned plagioclase crystal prior to K-replacement of the plagioclase would destroy any zonation that could have been present in the plagioclase. Instead of a diffuse, gradational zoning of Ba in a magmatic K-feldspar, the released Ba in the metasomatic K-feldspar tends to concentrate in scattered islands of celsian (Fig. 13a and Fig. 13b).

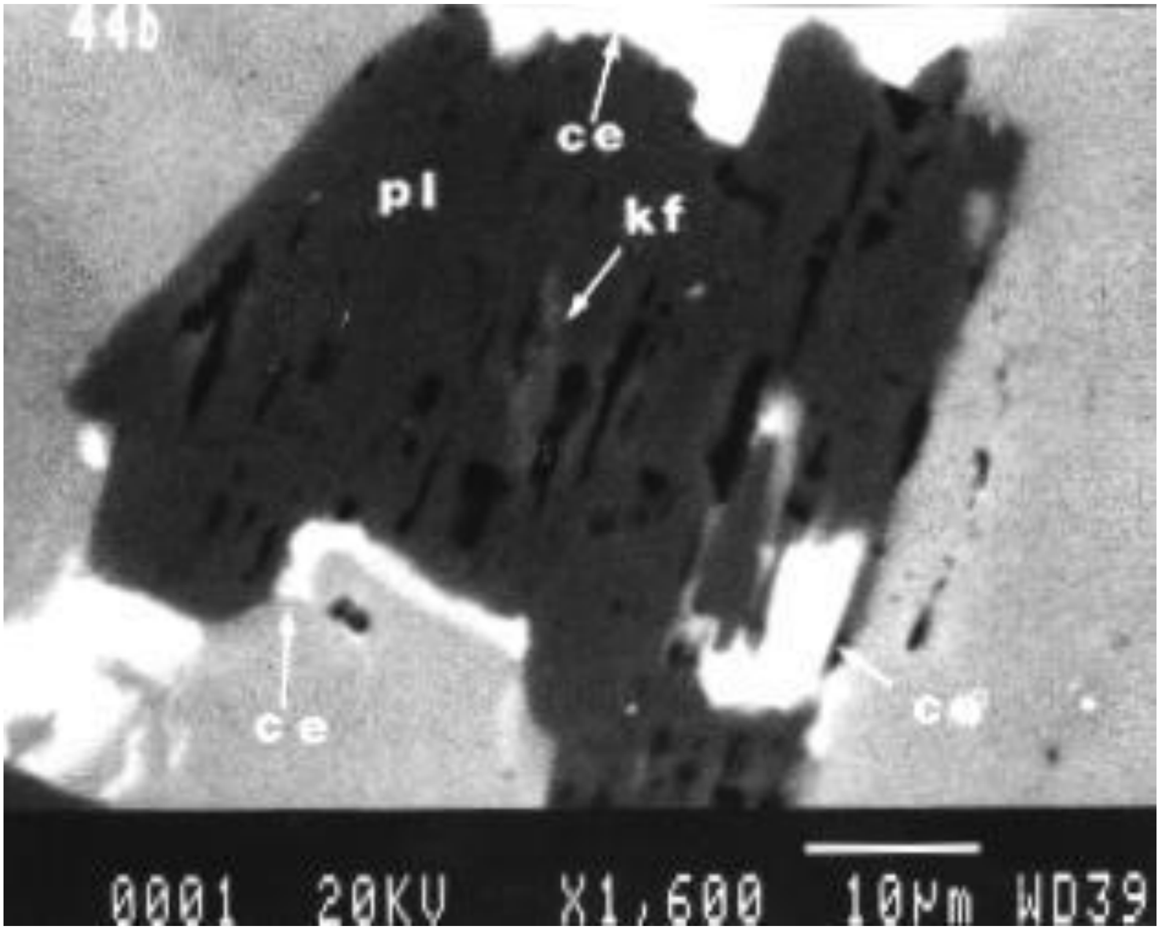

Fig. 13a. A scanning-electron photomicrograph that shows celsian islands (ce, white) in altered plagioclase partly replaced by K-feldspar (magnification: 1600x). The plagioclase (pl, dark gray) is full of holes (black) with angular boundaries parallel to the plagioclase crystal lattice, and many holes are bordered by concentrations of K (lighter gray, incipient K-feldspar, kf). In some places the celsian occurs on hole walls adjacent to the K concentrations.

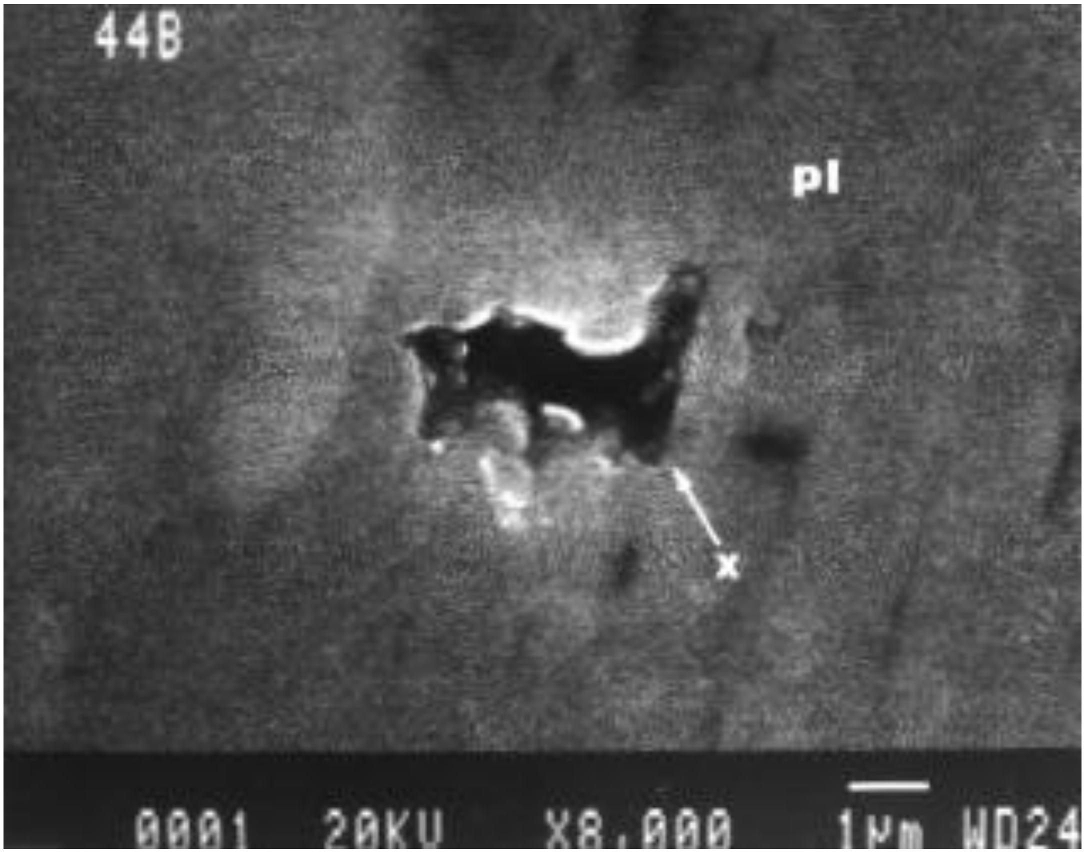

Fig. 13b. A scanning-electron photomicrograph that shows celsian islands (white) in altered plagioclase partly replaced by K-feldspar (magnification: 8,000x). Image is from same area as in Fig. 13a. The holes are bordered by concentrations of K (lighter gray, incipient K-feldspar, kf). In some places the celsian occurs on hole walls adjacent to the K concentrations.

4. *Irregular, embayed contacts of K-feldspar*.

Initially, K-metasomatism of plagioclase to form K-feldspar is commonly in the interior of the plagioclase and then outward toward the rims. In later stages, however, the K-feldspar may grow beyond boundaries of the original plagioclase crystal. In any case, contacts with other ground mass minerals or in the interior of the plagioclase tend to be irregular and embayed rather than straight (Fig. 14 and Fig. 15).

Fig. 14. Embayment of albite-twinned plagioclase (cream) by K-feldspar (gray to black). Plagioclase also occurs as remnant islands in microcline, and the islands are in parallel optic-continuity with large plagioclase crystal outside the K-feldspar. The microcline penetrates the plagioclase along fractures. Minor muscovite (blue) occurs in the plagioclase. (From granitic rocks in Mojave Desert, California, USA.

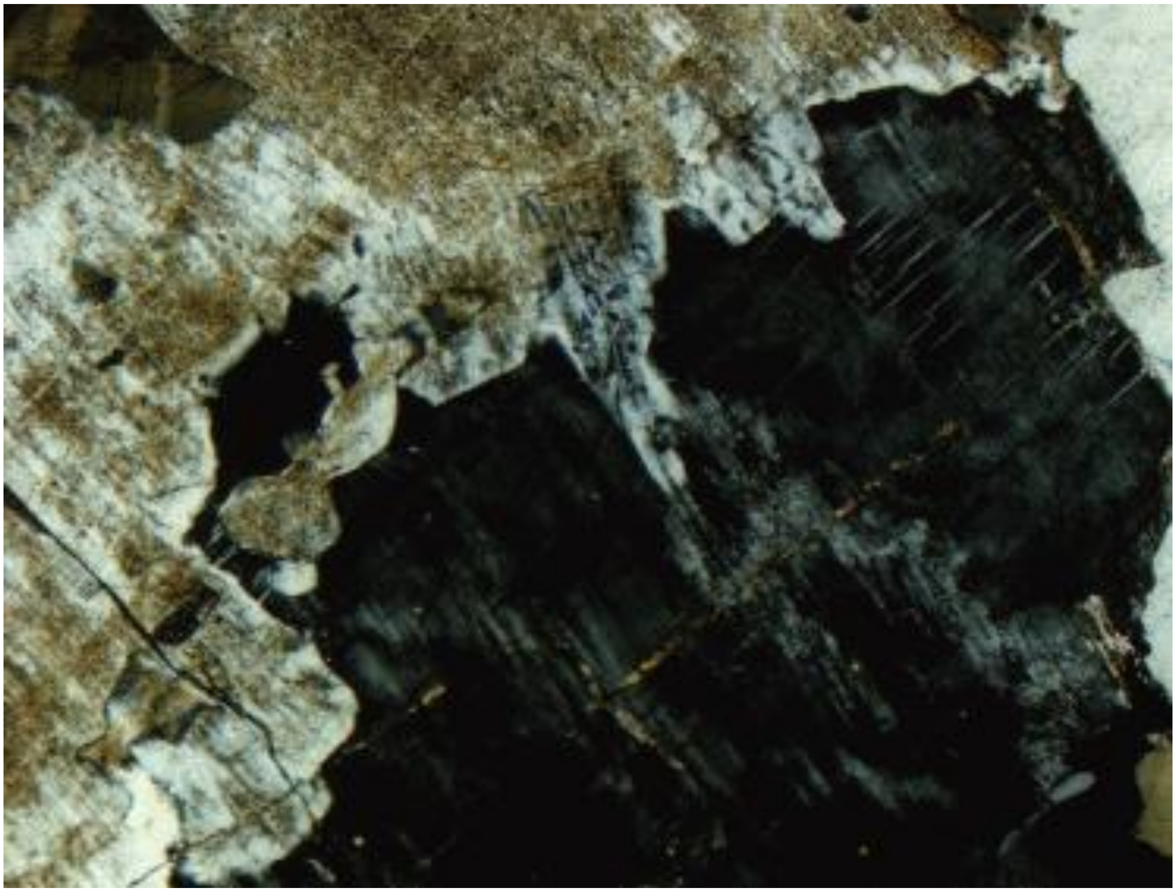

Fig. 15. Microcline (dark gray to black, bottom right) penetrates and replaces plagioclase (top center and left side, light gray to white; partly altered to clay, tan). Angular parts of plagioclase that project into microcline are myrmekitic (center), containing tiny quartz black vermicules. Ghost remnants of incompletely replaced plagioclase continue into the microcline in a light-gray pattern beyond the longer myrmekite projection. From Cape Ann granite in Massachusetts, USA.

Where K-metasomatism penetrates a plagioclase crystal from many different directions, island remnants of unreplaced plagioclase may remain as tiny inclusions, and these inclusions are optically parallel to larger plagioclase grains outside the K-feldspar (Fig. 16).

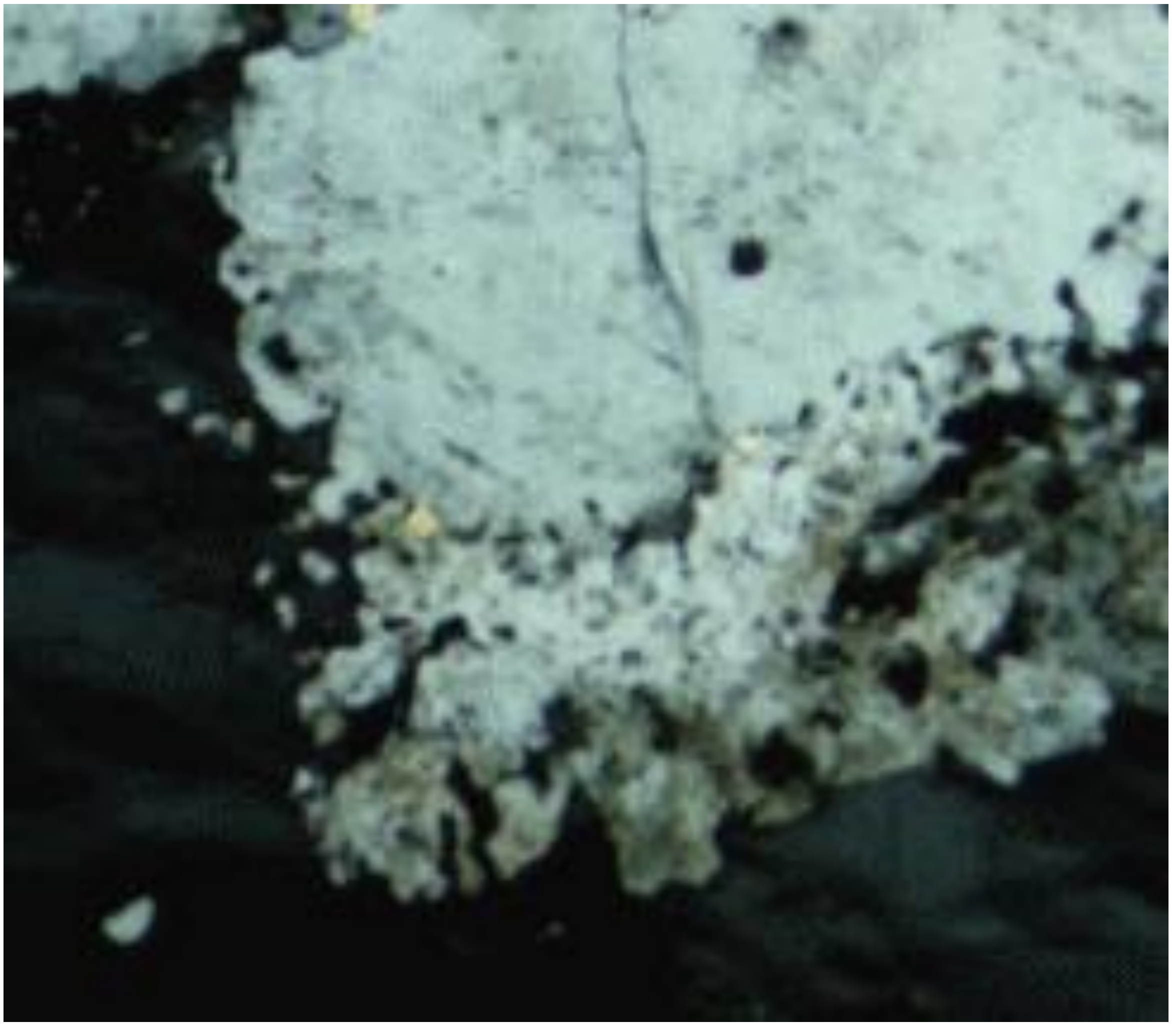

Fig. 16. Plagioclase inclusions (light gray) in K-feldspar (dark gray and black), which are optically parallel to adjacent plagioclase outside the K-feldspar. K-feldspar penetrates the plagioclase along irregular fractures. From Thorr granite on eastern side of the Main Donegal granite, northwestern Ireland.

Although replacements of deformed plagioclase crystals are from the interior outward, because the cores of deformed, zoned plagioclase crystals are more calcic and less stable at low temperatures than the more sodic rims, the interior replacements may occur in deformed, outer, wide rims of a zoned plagioclase crystal without replacing the core, if the core is undeformed. Examples occur in the Palms quartz monzonite near Twentynine Palms, California, where remnant, unreplaced, zoned plagioclase crystals occur (Fig. 17) that are associated with other places where the rims are replaced by K-feldspar and myrmekite while the cores remain unreplaced (Fig. 18). Similar broad-rim replacements of zoned plagioclase in Bonsall tonalite occur to produce K-feldspar in the Rubidoux Mountain leucogranite; see http://www.csun.edu/~vcgeo005/Nr14Mojave.pdf.

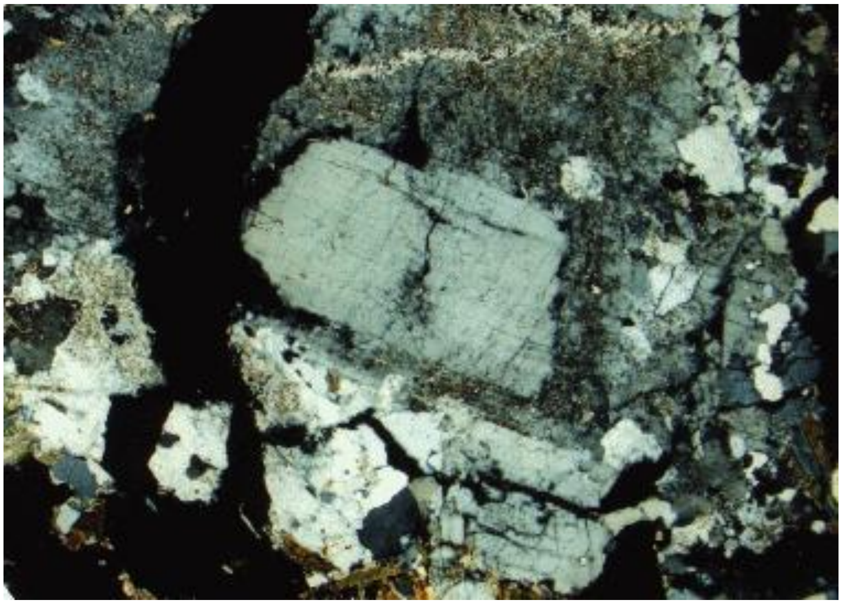

Fig. 17. Zoned plagioclase crystal with an unaltered, relatively calcic core, and fractured and weathered, more sodic, broad rim. In the Palms quartz monzonite near Twentynine Palms, California, USA (From Rogers collection, sample number 17134).

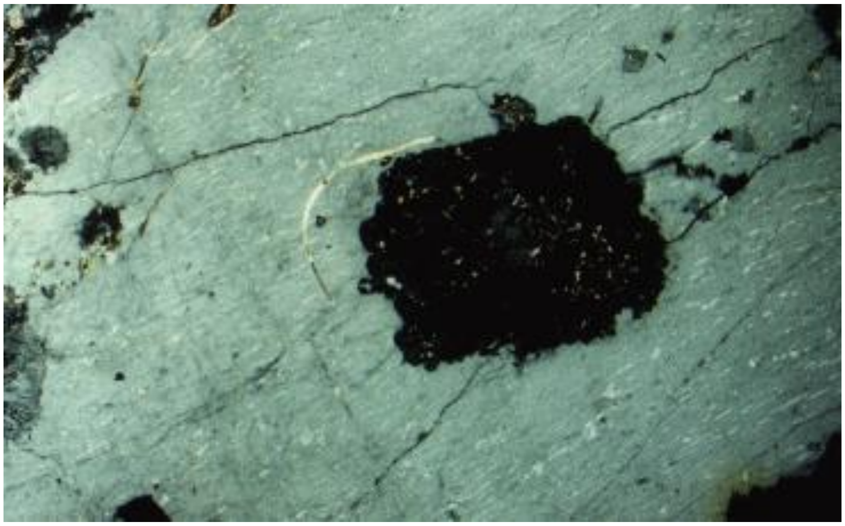

Fig. 18. Perthitic K-feldspar (light gray) has completely replaced the former sodic rim of a zoned plagioclase crystal in the same thin section to leave the plagioclase core (black) as a remnant of unreplaced material. Note tiny myrmekite grains on left border of the K-feldspar. Same thin section as in Fig. 17.

5. ***Quartz-K-feldspar intergrowths and myrmekite*.**

In cataclastically-deformed magmatic plutonic rocks in which the breakage is primarily along grain-boundary seals, K-metasomatism may locally replace rims of zoned plagioclase to form interstitial K-feldspar and *rim myrmekite* (Fig. 19). Where the cataclasis is more intense, causing interior breakage and bending of albite twinning in the plagioclase crystals, K-metasomatism is greater, extending into the plagioclase crystals and causing complete or nearly complete replacements. In such places a second type of quartz-feldspar intergrowth, *wartlike myrmekite*, occurs where the K-replacement is incomplete (Fig. 20 and Fig. 21). In some places gradations occur from rocks containing only rim myrmekite to those containing both rim and wartlike myrmekite to those containing only wartlike myrmekite. Significantly, the maximum coarseness of the quartz vermicules in the myrmekite correlates with the Ca content of the plagioclase in the original, unreplaced, non-myrmekite-bearing magmatic rock. The coarsest vermicules occur in the metasomatized rock where the original plagioclase was the most calcic; see http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf.

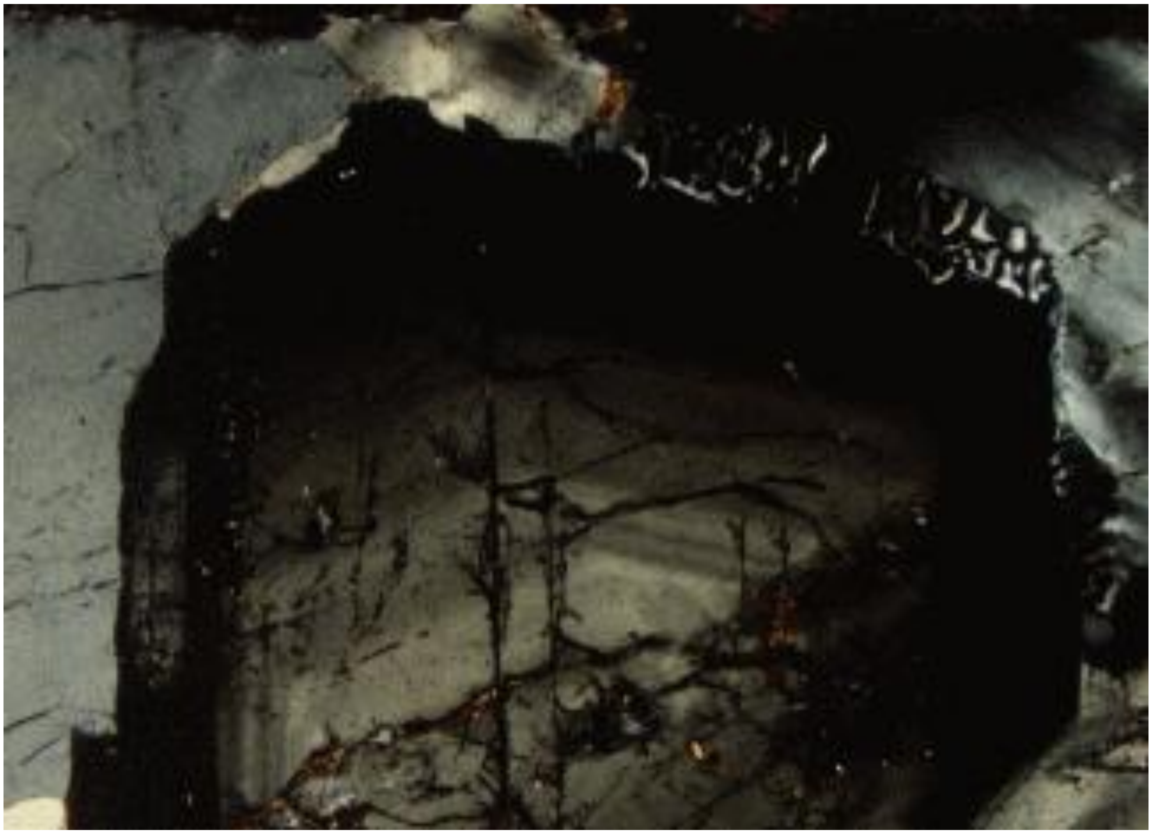

Fig. 19. Rim myrmekite on zoned plagioclase against interstitial microcline (gray and black).

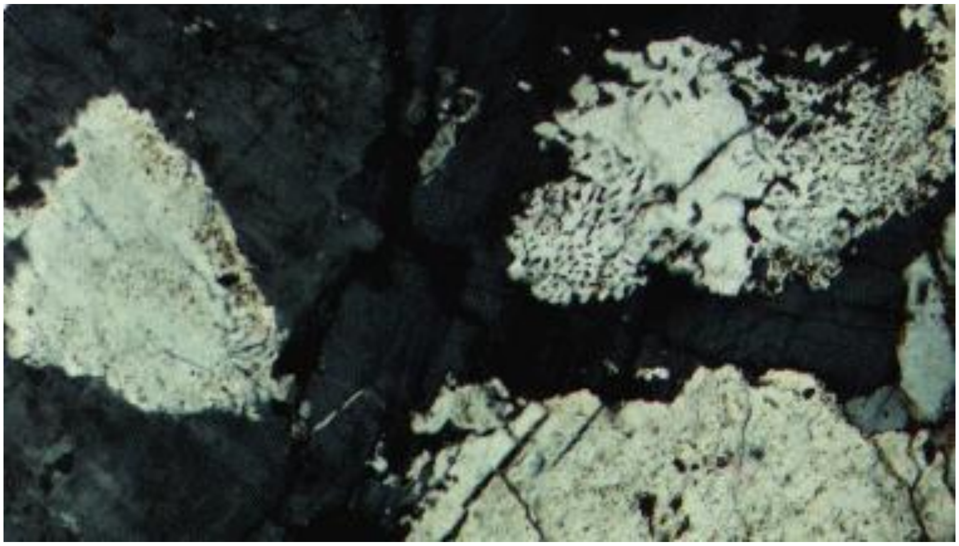

Fig. 20. Wartlike myrmekite with tiny quartz vermicules (black) in plagioclase (cream) surrounded by K-feldspar (dark gray; top and left). K-feldspar encloses, penetrates in veins, and replaces plagioclase (cream-gray, light gray). Large plagioclase islands are optically continuous with adjacent tiny islands (blebs) of plagioclase in microcline. Tiny biotite crystals (light tan) are poikilitically enclosed in plagioclase (bottom). From early stages of replacement of Gold Park diorite near Twentynine Palms, California, USA.

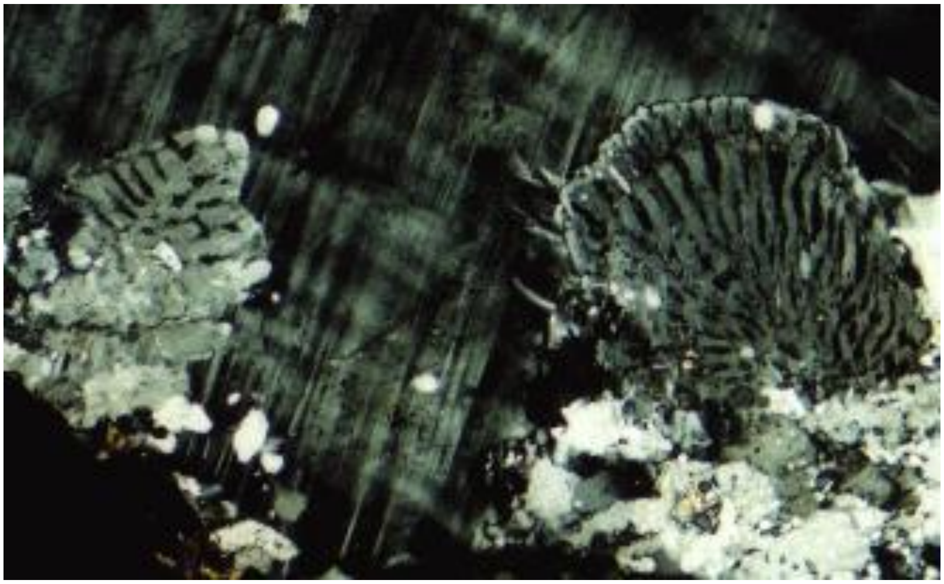

Fig. 21. Wartlike myrmekite with intermediate-sized quartz vermicules (black) in plagioclase (gray) surrounded by K-feldspar (gray, black, cross-hatch pattern). Tiny quartz ovals (white); magnetite (solid black); biotite (brown). From megacrystal quartz monzonite near Twentynine Palms, California, USA.

In some places where K-feldspar replaces plagioclase from the exterior inward, as in a porphyry copper pluton near Ajo, Arizona, no rim or wartlike myrmekite is formed (Wadsworth, 1968, 1975). Exterior replacement occurs because of strong and continuous deformation, breaking grain-boundary seals, and because abundant boundary fluids permit space for expansion of the K-feldspar lattice and ease in which Ca and Na can be subtracted. Where only interior replacements occur, space must be created inside the deformed plagioclase for the expanded lattice of the less-dense K-feldspar to grow because bordering crystals held in place by rock pressure do not permit expansion of the K-feldspar beyond the former plagioclase border.

A third type of quartz-feldspar intergrowth occurs in metasomatic granites where the irregular subtraction of Ca, Na, and Al from deformed plagioclase crystals causes an imbalance in the relative amounts of residual Al and Si. More Si remains than can fit into the lattice structure of the K-feldspar that replaces the plagioclase. This results in *ghost myrmekite,* either as tiny quartz ovoids in remnant albite islands in the K-feldspar or tiny quartz ovoids in clusters without albite hosts in the K-feldspar Fig. 22 and Fig. 23). These quartz ovoids are generally smaller than the rounded quartz blebs that occur in micrographic granite and are associated with wartlike myrmekite, whereas micrographic textures occur in rocks either where myrmekite is absent or as remnants where early K-feldspar replacement have started to form rim myrmekite.

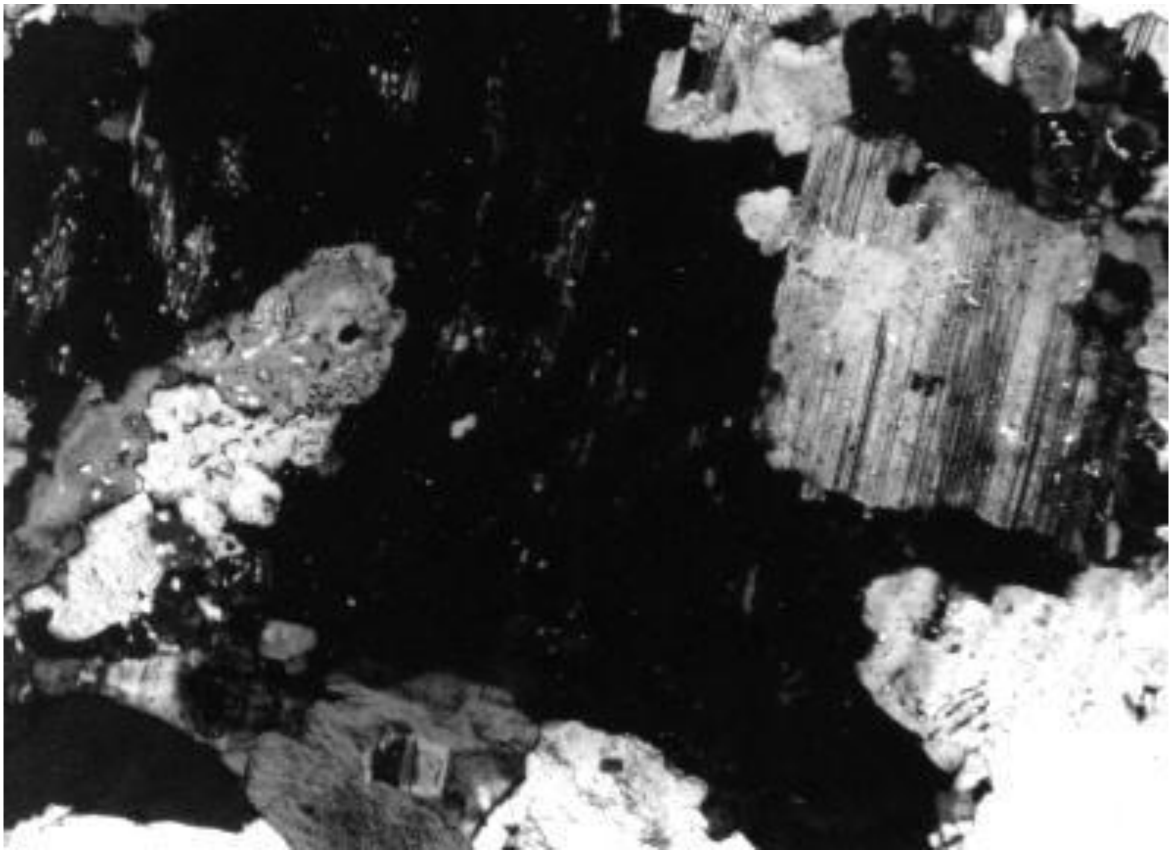

Fig. 22. Ghost myrmekite (tiny quartz blebs, white; upper left quadrant and center) in microcline (black). Albite-twinned plagioclase (tan, left side) is optically parallel to islands of incompletely replaced plagioclase containing tiny quartz blebs (white) which occur scattered from left to right through 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 (upper right quadrant) is still distinct. The inclined, elongate, rounded grain (lower right quadrant) in microcline is myrmekite. From granodiorite in Sierra Nevada, California.

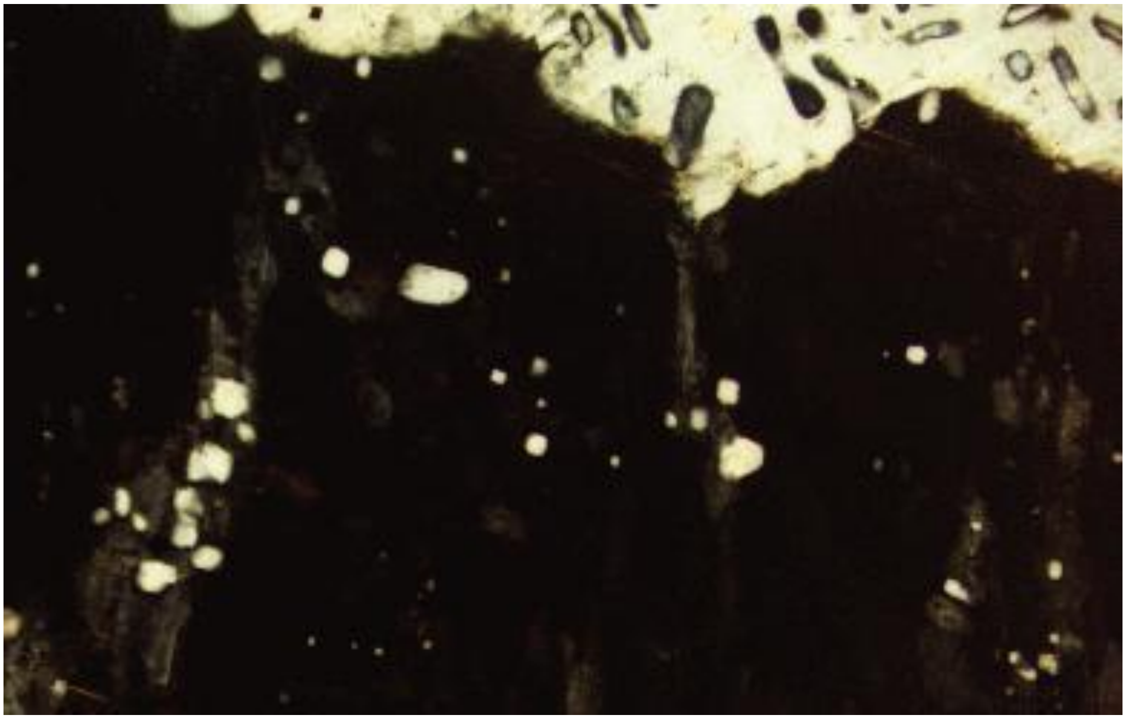

Fig. 23. Ghost myrmekite, occurring as tiny quartz inclusions in K-feldspar (black) and in albite (gray, left side) of the same size as the quartz vermicules in wartlike myrmekite (top edge; white with dark quartz vermicules) between the K-feldspar and non-quartz-bearing plagioclase (outside the view, top edge). Quartz islands are larger than in Fig. 22. From the Rudidoux Mountain leucogranite, California, USA.

A fourth type of quartz-feldspar intergrowth occurs where renewed deformation cataclastically breaks crystal-boundary seals. Granulated quartz grains that are formed along the crystal boundary are enclosed in the K-feldspar as the K-feldspar continues to grow and replace adjacent minerals (Fig. 24).

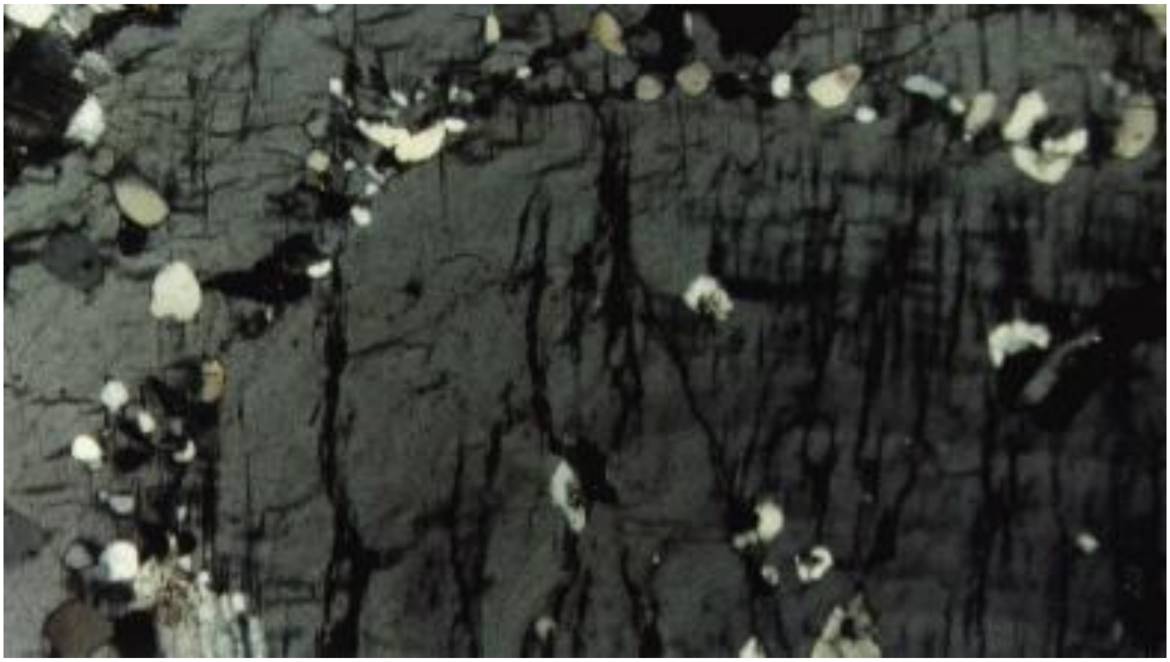

Fig. 24. K-feldspar (dark gray) with granulated inclusions of quartz granules (white, cream) along former curved border of the K-feldspar crystal.

A fifth type occurs in rocks which have been subjected to intense granulation and replacement. For example, diorite at Twentynine Palms, California, in which the constituent plagioclase is strongly cataclasticly broken, the fragments are surrounded and replaced by microcline and myrmekite. The microcline here grows to become megacrysts, changing the diorite into quartz monzonite. Where this occurs, more than 50 vol. % of large K-feldspar megacrysts (2-5 cm long) are filled with aggregates of broken quartz, plagioclase, and myrmekite (Fig. 25).

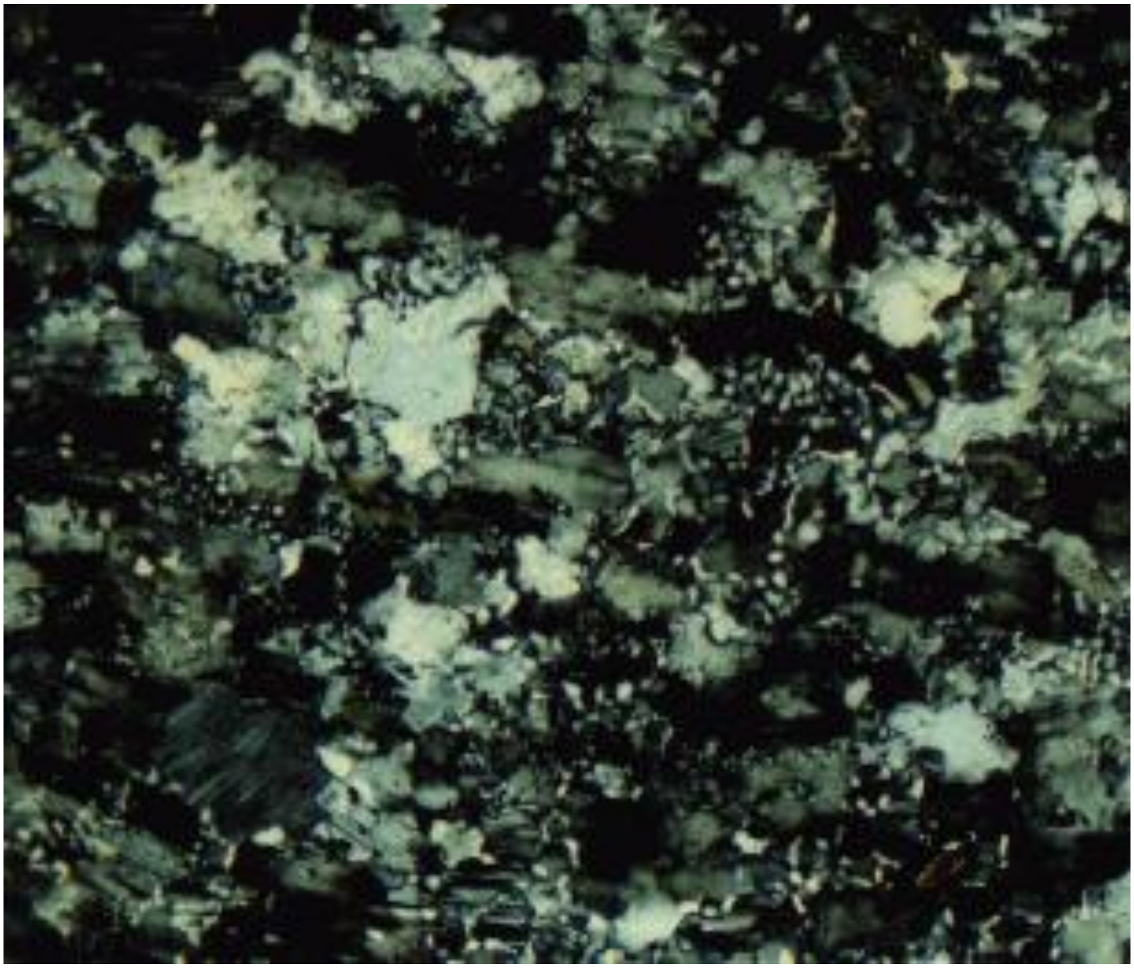

Fig. 25. Aggregate angular inclusions of myrmekite, quartz, and plagioclase in a small portion of a large K-feldspar megacryst at Twentynine Palms, California, USA.

This myrmekite is formed in earlier stages where incomplete replacement of plagioclase occurs. The early replacements are revealed by K-feldspar islands in the large K-feldspar megacryst which have optic orientations different from that of the larger crystal which grows around and encloses all the fragments. In some places, broken fragments of ground-mass minerals occur in a vein-like stringer which extends into the K-feldspar megacryst on one side, through the megacryst where K-feldspar grows around the ground-mass fragments, and then into the ground mass on the other side. The K-feldspar crystal, however, shows no evidence of deformation or being offset by the forces that caused the granulation in the vein-like stringer. The K-feldspar clearly is younger than the cataclasis. See http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf.

Abundant inclusions can be found in K-feldspar crystals in magmatic rocks, but there, the inclusions include all the earlier-formed, high-temperature minerals in the rock. In the Twentynine Palms quartz monzonite, although hornblende is abundantly found in the ground mass, *it is missing among the fragmented inclusions inside the K-feldspar* except for remnants at the rims, and the remnants contain quartz sieve textures.

6. *Quartz sieve textures in biotite and hornblende*.

In early stages of metasomatic replacements of deformed magmatic rocks, the ferromagnesian silicates tend to be affected sooner than the plagioclase, but in later stages all minerals are affected. Across the transitions between unreplaced and replaced rocks, pyroxene and olivine disappear as the quartz content increases, but generally, there is no obvious evidence that these ferromagnesian silicates have been replaced by quartz. Hornblende and biotite, however, may contain a poorly-developed quartz sieve texture (Fig. 26). Such quartz sieve textures are *absent in undeformed portions of the primary igneous rocks*, so it is clear that the quartz is a function of deformation and replacement and *not* the result of primary crystallization from a magma.

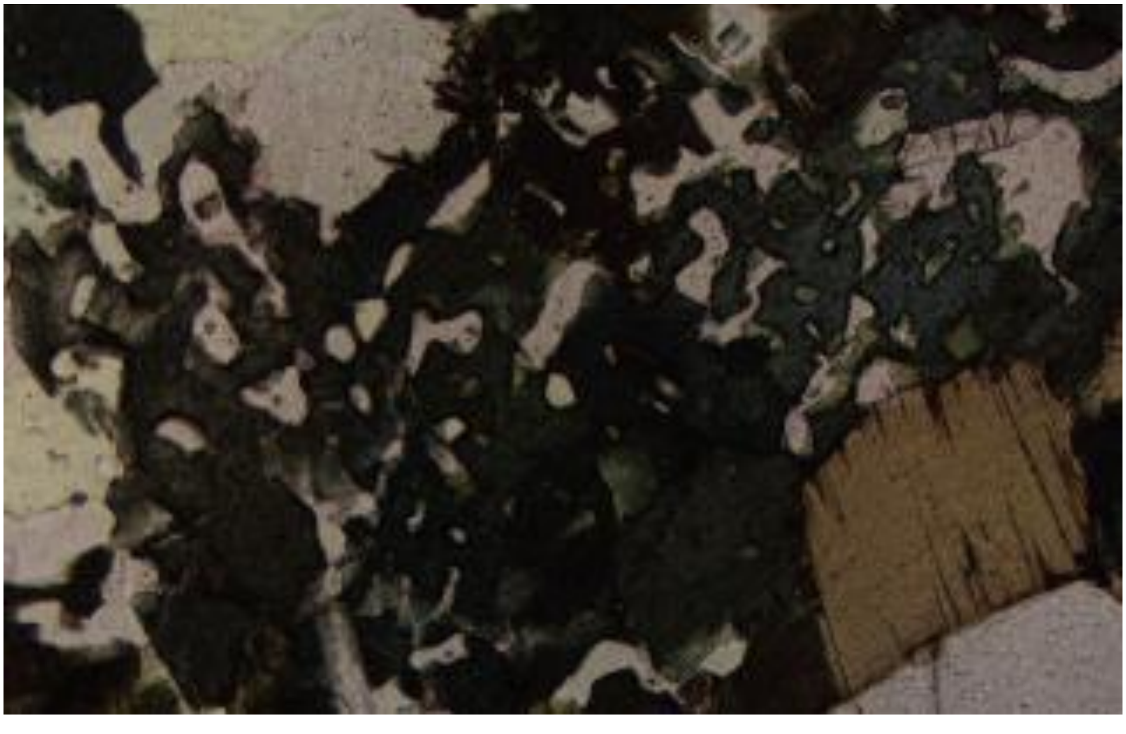

Fig. 26. Quartz sieve textures (white) in hornblende (grayish green). Coexisting biotite (tan) borders the hornblende. From Thorr pluton in Donegal granites of northwestern Ireland.

In some rocks, instead of biotite disappearing because of replacements by quartz, both biotite and quartz are formed where K replaces orthopyroxene. In that case, a *biotite-quartz symplectite* of vermicular quartz in biotite is created which can be similar in appearance to the quartz sieve texture where biotite is replaced by quartz.

7. ***Association with low-temperature ferromagnesian silicates and aluminosilicates; absence of high-temperature pyroxenes, olivine, and calcic plagioclase*.**

Because metasomatic granites generally form at temperatures below 600º C, minerals crystallized at higher temperatures tend to disappear, and minerals stable at temperatures below 600° C are formed in their place. Such minerals include biotite, muscovite, epidote, sphene, garnet, sillimanite, andalusite, kyanite, and cordierite.

Because fluids that cause the metasomatism are less efficient in removing Ti and Al than in subtracting Ca, Mg, and Fe from the original magmatic rocks, the metasomatic granites tend to retain some Ti in sphene (http://www.csun.edu/~vcgeo005/Nr18LyonMtn.pdf) or to contain more Al than can fit into the feldspars. Therefore, the metasomatic granitic rocks become peraluminous, containing muscovite and/or garnet. The occurrence of Al-rich minerals in metasomatic granite is common where the original rock was a magmatic calcic diorite or gabbro in which the plagioclase is relatively Ca- and Al-rich, but Al-rich minerals can also be found in metasomatic granites where the original rock was metasedimentary, containing abundant muscovite and biotite, as in the Cooma granodiorite in Australia (Collins, 1993).

Magmatic rocks, which have assimilated pelitic metasedimentary rocks, can also contain Al-rich minerals, and because the stability of fields for garnet and cordierite extend above the solidus for granite, these minerals can also be legitimate magmatic constituents. On that basis, the presence of Al-rich minerals does not necessarily mean that the granite is metasomatic or magmatic in origin, but their presence is characteristic of some metasomatic granite.

8. ***Absence of evidence for magma mixing*.**

Where contacts between a metasomatic granite and a more-mafic igneous rock exist, hybrid rocks along the contacts in which elements from both rocks diffuse into each other without some elements being lost from the system do NOT occur.

9. *Absence of assimilation of enclaves*.

Enclaves in metasomatic granites can either (a) be island remnants of undeformed portions of the original magmatic rock that did not become deformed and replaced or (b) fragments of foreign rock that was originally in the magmatic rock and which also did not get replaced. Where replacement of an enclave of either type occurs, the enclave becomes progressively more felsic than other unreplaced enclaves, and the *adjacent granite is NOT enriched in mafic components*. This is in contrast to enclaves that are assimilated in magmatic granite in which enrichments in mafic components forms a hybrid mafic rock.

10. *Modifications of comb layering and gravitational structures*.

The plagioclase in comb layers or in layered rocks can be replaced by K-feldspar in myrmekite-bearing granite, so that a layered structure is *inherited* from a former magmatic rock. For example, Finch et al. (1990) reported replacement of pyroxenes by hornblende and biotite in layered rapakivi granite in Greenland. The replacements occurred along zones of deformation, and the hornblende and biotite contain quartz symplectites. Plagioclase crystals in the felsic layers, however, could have also been replaced by microcline and myrmekite with coarse quartz vermicules. The coarse quartz vermicules in the myrmekite would correlate with the former, relatively-high Ca-content of the original plagioclase in the layered magmatic rock.

11. *Absence of evidence for anatexis*.

Where granitic veins and pods occur in more mafic plutonic rocks, the lack of enrichment of mafic components in the rock adjacent to the granite, as in melanosomes or restites, supports a possible metasomatic origin for the granite. This also applies to the absence of partial melting of mafic enclaves. That is, instead of losing felsic components during partial melting, the *enclaves lose their mafic components*, gain felsic components, and become ghost images, consisting of more granitic remnants rather than mafic-enriched remnants. An example of ghost enclaves occurs in the eastern Sierra Nevada of California in portions of the myrmekite-bearing facies of the Tungsten Hills quartz monzonite adjacent to the Lamarck granodiorite (Bateman, 1965, pages 81-88). Locally, deformed portions of the quartz monzonite have undergone K- and/or Na-metasomatism, and former mafic enclaves have been affected by these metasomatic fluids to become more-felsic, myrmekite-bearing, ghost images. Where Na-metasomatism is dominant rather than K-metasomatism, myrmekite is absent because Na consumes excess Si, and albite granite is formed. Bateman (1965, page 87) attributed the albite granite to assimilation of a salt layer from metasediments, although no salt beds have ever been found in nearby pendants. He made no mention of K-metasomatism or assimilation, but assumed that the K-feldspar was primary. The presence of myrmekite, however, suggests that K-metasomatism has occurred.

12. *Absence of miarolitic cavities and gradations to rhyolite*.

The absence of magmatic features, such as miarolitic cavities and gradations to rhyolite, is not a definitive test, but gives permissive evidence that a granitic rock could be metasomatic in origin.

Non-definitive features

Roddick (1982) criticized the intransigent position for preserving a "magmatic-only" model for pluton-sized granite masses and the illogical reasoning used in its support. He described a number of different popular criteria that lack logic when examined in detail. These criteria include: "sharp contacts and cross-cutting relationships; dikes emanating from a pluton; wall-rock deformation, migmatites; fine-grained margins; homogeneity (and heterogeneity); foliation or its absence; strontium isotope ratios; oscillatory zoning; synneusis structure; euhedralism; and volcano-pluton relationships." The following comments supplement those made by Roddick (1982) in regards to criteria that are non-definitive relative to determining the origin of a granite body. Not all of the inconclusive criteria that he mentioned are discussed here, and some new ones have been added.

1. *Sharp contacts and cross-cutting relationships*.

Intrusive bodies commonly have sharp contacts and cross-cutting relationships with respect to their wall rocks, but zones of deformation in fault zones also commonly have sharp boundaries and cross-cutting relationships relative to the adjacent unbroken rocks. This means that metasomatic fluids can enter the granulated and brecciated fault zones, replacing and recrystallizing the broken minerals up to sharp contacts. In this way the replacement is not necessarily at right angles to a contact but could be parallel to it. Therefore, gradations between replaced and unreplaced rocks in irregular patterns across an interval of several centimeters or meters need *not* be present. Moreover, the replaced, solid rock could be mobilized plastically because of tectonic forces, intruding along discordant contacts. Even where magmatic bodies have intruded and developed sharp contacts and cross-cutting relationships, these features could be preserved while both the former magmatic rocks and the wall rocks are subjected to K-metasomatism. For example, in the Twentynine Palms area of California, diorite was converted to quartz monzonite containing K-feldspar megacrysts as the adjacent Precambrian Pinto gneiss also developed K-feldspar megacrysts; see http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf.

2. *Homogeneity and heterogeneity*.

Large, homogeneous, massive granite masses are often cited as evidence for a magmatic origin. Many magmatic bodies are homogeneous because of thorough mixing of the melts, but that same homogeneity can also be inherited during metasomatism so that the replacement granites are also homogeneous. On the other hand, many plutonic igneous rocks have a primary heterogeneity, and, therefore, this heterogeneity could also be inherited when they are converted to metasomatic granites.

3. *Euhedralism*.

It is certainly true that euhedral crystals are common in magmatic rocks, but when the magmatic rocks are replaced, the metasomatic fluids in many places replace the euhedral minerals from the interior outward. In that process, the replacement minerals inherit the euhedral shapes of the former crystals as well as igneous textures and structures. Moreover, other minerals, such as garnet and sphene, may develop euhedralism because of the great bond strengths of their constituent elements, without requiring that the garnet or sphene be crystallized from melts. Overgrowths that produce euhedralism of zircon crystals are commonly supposed to be the result of growth in magma, but these overgrowths could also form in solid but deformed metasomatic granite because of the release of trace zircon from ferromagnesian silicates that are replaced by quartz.

4. *Oriented crystal inclusions in K-feldspar*.

Oriented inclusions of biotite, plagioclase, and quartz whose faces are parallel to possible faces of the K-feldspar crystal (Fig. 27) might also be expected to occur as a K-feldspar crystal grows in a liquid. Concentric zonation of crystal inclusions, however, is not necessarily a useful criterion for establishing a magmatic origin for granite because it may be possible to produce such configurations as the result of preferred replacements of crystals whose lattice orientations are not parallel to the K-feldspar lattice, while leaving unreplaced those crystals whose orientations are parallel to the K-feldspar lattice. Dickson

(1996) also suggests that both the plagioclase inclusions and the orthoclase can result from replacement processes (Fig. 28).

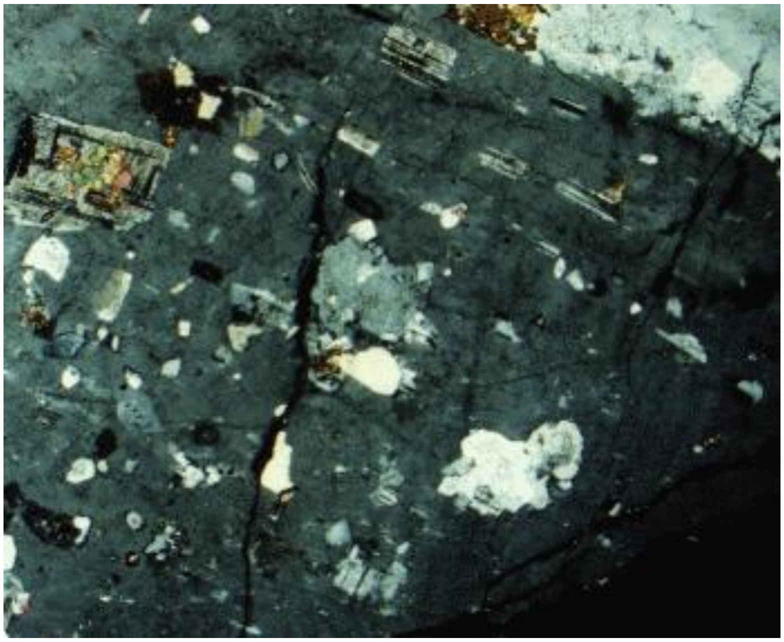

Fig. 27. Oriented inclusions of plagioclase, quartz, and biotite in K-feldspar megacryst (gray) in Precambrian Pinto gneiss near the megacrystal quartz monzonite at Twentynine Palms, California, USA (from Rogers collection, sample 17087).

Fig. 28. Oriented inclusions of plagioclase in Ba-zoned K-feldspar, Papoose Flat pluton, California, USA (magnification 114x). Photograph used with permission of Frank Dickson.

5. *Disoriented enclaves*.

Angular enclaves in plutonic rocks, which have a fabric that is disoriented relative to the fabric in the wall rocks, do not necessarily indicate that the host rock is magmatic or metasomatic. Forceful injection of either magma or a plastic hot, solid could incorporate broken fragments from wall rocks. Furthermore, fault zones in a magmatic rock could also produce disoriented fragments by brecciation and rotation. In any case, fluids could subsequently replace the host rock to form metasomatic granite without replacing the disoriented enclaves. On the other hand, if the enclaves have a foliation or other structure that is parallel to that in the wall rocks, then the granite is likely derived from the wall rock material by metasomatic processes, leaving islands of unreplaced remnants of the wall rock in the granite. See discussion by Collins (1988, p. 126-128).

6. *Pegmatites and aplite dikes*.

Assumptions are commonly made that granitic pegmatite and aplite dikes are late-stage differentiation products of solidifying granite magma. Their sharp contacts, contrasting light color against darker wall rocks, relatively felsic "eutectic" compositions, and different mineral compositions from that in their hosts seem to offer strong support for a magmatic origin. Caution must be used, however, because in some places, pegmatite and aplite dikes can be traced along strike through cataclastic transitions into relatively-mafic igneous rocks. In the transitions toward the pegmatite dikes, the plagioclase in the fine-grained, cataclastically-broken mafic rock is gradually replaced by K-feldspar and myrmekite, and the ferromagnesian silicates are replaced by quartz. Therefore, the granite pegmatite and aplite dikes represent replaced and recrystallized mafic rock rather than granitic magma introduced from an outside source. For example, see discussions of pegmatites in the Pala area and in the San Gabriel Mountains (Collins, 1988, pages 48-49, 76-77).

In the Pala pegmatite area, although myrmekite is a common constituent in the transition rocks from the mafic rock to the pegmatite, myrmekite is absent in the pegmatites. Its absence there suggests that the replaced and recrystallized rock melted after the rocks were converted to eutectic compositions. Compositions of coexisting minerals indicate high-temperatures of crystallization above the eutectic, and, therefore, former felsic minerals that were formed by replacement processes below the melting interval for granite in the transition zone likely were melted in the pegmatite zone as temperatures rose above eutectic conditions.

Pegmatites and aplites in other localities contain myrmekite and, therefore, were formed by replacement processes below melting temperatures; see discussion of pegmatites in the Cargo Muchacho Mountains (Collins, 1988, p. 126-129).

In still other localities, many pegmatite and aplite dikes are formed by direct crystallization from residual magmatic fluids or result from anatexis and migration of felsic components in zones of relatively low pressure without any prior metasomatism occurring. Thus, the pegmatite and aplite dikes can have either magmatic or metasomatic origins.

7. *Contact metamorphism*.

High-temperature minerals (sillimanite, garnet, and cordierite) may be produced by thermal metamorphism of pelitic wall rocks around plutons that have been emplaced as hot magmas. Such a contact metamorphic aureole is proof of magma emplacement but is not proof that later the pluton cannot be converted to granite by metasomatism at temperatures below eutectic conditions; see http://www.csun.edu/~vcgeo005/Nr10Donegal.pdf in this web site, describing the Donegal granites in northwestern Ireland.

8. *Cataclasis or deformation where K-feldspar is present*.

Because many granites crystallize from melts, they are massive and lack any evidence of cataclasis. Cataclasis is necessary to open pore spaces for fluids to enter and cause metasomatism. Therefore, the absence of any evidence for cataclasis gives permissive evidence that a granite body could be derived from magma. Nevertheless, some metasomatic granite that was formerly cataclastically-broken magmatic rocks may show no outward appearance of deformation. Their massive appearance can occur because recrystallization heals the fractures so that most evidence for cataclasis is destroyed. An example exists in some massive granites that still retain myrmekite, for which the myrmekite is the only clue to the former cataclasis; for example, the Fitchburg granite complex in Massachusetts, USA (Zartman and Naylor, 1984).

In other places where deformation is strong, augen structures can be created with C- and S-structures (Simpson and Wintsch, 1989). Vernon (1986, 1990) believed that all augen K-feldspar crystals are former phenocrysts, but that need not be true. If the augen or megacrysts were truly former phenocrysts, then in regions that lack deformation, igneous fabrics should still remain and contain large, undeformed, K-feldspar crystals without tails. On the other hand, if the K-feldspar augen or megacrysts are porphyroblasts and have a metasomatic origin, then transitions from undeformed rock lacking K-feldspar to the rock containing the K-feldspar augen or megacrysts should show the gradual appearance of K-feldspar with myrmekite borders and their absence in the original undeformed igneous rocks; see http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf and http://www.csun.edu/~vcgeo005/Nr12SantaRosa.pdf. Without knowledge of the transitional changes, an investigator could be led to believe that the K-feldspar crystals are primary and magmatic in origin.

9. *Orthoclase versus microcline.*

Orthoclase is the original K-feldspar in magmatic granitic rocks, but later deformation may cause the orthoclase to recrystallize as microcline (all or in part). In many plutons during late stages of solidification, but where magma is still present, plastic deformation creates flow structures, schlieren, foliation, and/or lineation, particularly near margins of the pluton, and the orthoclase in such deformed magmatic rocks lacks myrmekite.

In rocks that have been deformed at temperatures below eutectic conditions, K-metasomatism can create K-feldspar megacrysts by replacement processes. Such megacrysts generally are composed of microcline instead of orthoclase, although formation of orthoclase by replacement processes may occur, as in the Cooma pluton (Collins, 1993). In any case, the K-feldspar (microcline or orthoclase) megacrysts that are formed by replacement processes are bordered by myrmekite. By itself, orthoclase or microcline is not definitive as to the magmatic or metasomatic origin of a plutonic rock, but if myrmekite is present, then a metasomatic origin is indicated.

10. *Sr isotopic ratios and supposed elemental mantle signatures.*

As pointed out by Roddick (1982), high initial $^{87}Sr/^{86}Sr$ ratios in granite almost automatically are interpreted by many geologists to be the result of anatexis of continental crustal metasedimentary rocks while low ratios are supposed to indicate derivation from differentiated mantle magma. No matter what the ratio, it is just assumed that the granitic rock magmatic in origin. In reality, the ratio is meaningless as far as a magmatic or metasomatic origin is concerned. Fluids that bring in K to create metasomatic granites also bring in Rb while subtracting Sr with Ca; see discussion of Sr-Rb isotopic studies of the Isabella pluton (Collins, 1988, pages 191-200). These processes affect the initial $^{87}Sr/^{86}Sr$ ratios and have nothing to do with magmatism or sources of magma. Moreover, very low initial

^{87}Sr/^{86}Sr ratios can also indicate a low-ratio source, simply caused by the escape of Rb (Roddick, 1982).

Granitic rocks have been said to be S-, I-, A-, or M-types or to have been formed in particular settings on the basis of having different kinds of trace-element contents. But many granitic rocks have compositions that fall on boundaries between the supposed classifications, which convolute the interpretations of their sources. What then? Do these granites with ambiguous data, for example, have a part sedimentary and a part mantle source? Ambiguous data could also result because of differential movements of elements during metasomatism that would disrupt the elemental abundances. In that way the supposed signatures of their sources are destroyed. What remains is partly inherited from the original magmatic rock, but some elements are introduced and some, subtracted. In any case, the element content of a granitic rock is not necessarily an indication of magmatism or the source rock.

11. *Stoping.*

Where the configuration of the roof rocks on granitic plutons have structures (e.g., foliation, bedding, fold trends) that project discordantly into the granite along angular contacts and where there is no evidence for assimilation in the granite, some rocks must be missing that obviously extended at one time into the space now occupied by the granitic rocks. It is logical that stoping in a liquid (melt) whose density is less than that of the roof rock explains the structural relationships and provides evidence of the magmatic origin of the granitic rocks. An intruded, hot solid of possible metasomatic origin would be too dense for roof rocks to founder, settle, and disappear by stoping. Nevertheless, stoping as a means of emplacement of magma says nothing about what can happen following emplacement. The magmatic rocks could later be modified by metasomatism and become a more granitic rock than was originally intruded as a melt. Therefore, stoping, by itself, cannot be a strict criterion for the total magmatic origin of the rock.

Discussion

On the basis of the different characteristics of magmatic and metasomatic rocks, a new look at the "granite problem" is in order. Former, seemingly logical arguments against producing large-scale metasomatic granite bodies may no longer be valid.

1. *Objections to large-scale metasomatism.*

Objections to creating large granite bodies by metasomatism have occurred primarily because of the experimental work of Bowen (1948) and Tuttle and Bowen (1958). In their studies of the Qz-Ab-Or system these investigators observed that under conditions of extensive fractional crystallization in a natural system, all silica-saturated magmas migrate to a lowest temperature point. Because most granites have compositions that concentrate near this low-temperature invariant point(s) in this system, the argument was made that the bulk compositions of all granites are controlled by crystal-silicate melt equilibria. Therefore, all large granite bodies must be magmatic in origin.

Further arguments were presented that a metasomatic origin (or granitization) is discredited because highly-variable metasomatic fluid compositions that would be expected to occur (1) should not result in the restricted compositional concentrations in granite and (2) should not be able to produce massive granites of relatively uniform composition. In the minds of most modern geologists, these arguments clinched the validity of the magmatic hypothesis. The logic of these arguments has appeared so insurmountable by many petrologists that they now turn a deaf ear to any proposals that favor a metasomatic origin. They have concluded that all granites of plutonic dimensions are magmatic, and, therefore, no further proof or discussion of origin is needed in any articles describing granites. For them, it is a fact that granite bodies are magmatic.

The observed relationships in *natural rocks*, however, show that these arguments and beliefs are flawed. An analogous situation illustrating a flawed hypothesis occurred when it was once said that a bumble bee`s body was too large and massive relative to the size of its tiny wings for the bee to fly. The theory seemed to be correct, but the bumble bee did not know that it could not fly and flew anyway. Likewise, the rocks do not "know" that the experimentalists and petrologists have said that such rocks cannot be metasomatized, and so large-scale replacement occur anyway.

2. *Flaws in the arguments for the magmatic origin of all plutonic granitic rocks*.

A flaw occurs in the first argument concerning the restriction of metasomatic rocks to granite compositions because the emphasis of this argument is concentrated on granite being the sole metasomatic product. In fact, metasomatic granite is only one of many different products in a continuum of generated metasomatic rocks. Granite just happens to be close to the end-product of that continuum. In extreme cases of metasomatism, large masses of quartz can be produced. See studies of quartzite masses in the Killarney granite (Hunt et al., 1992, pages 316-323).

The continuum of metasomatic rock types is shown by the following example of the large-scale modification of a theoretical magmatic diorite. At one end of the continuum, the modification could be minor and nearly isochemical, resulting in interstitial traces of K-feldspar and rim myrmekite. In that case, the diorite remains a diorite, but seems to have minor deuteric alteration. Farther along the continuum, in other places, the metasomatism could be more extensive, and the diorite could be converted to quartz monzonite or granodiorite. At the other end of the continuum, metasomatism could be even greater, and a granite composition could be achieved. Thus, the composition of the metasomatic produce is *not restricted* to granite compositions which Tuttle and Bowen found to be improbable, but is *variable as these investigators said it should be*.

It is not surprising that the compositions of both metasomatic and magmatic granites plot at the low-temperature invariant point(s) in the Qz-Ab-Or system, because their constituent minerals are the same and stable under those conditions, just as granodiorite or quartz monzonite of either magmatic or metasomatic origin have mineral assemblages that are the same and stable in or near their own low-temperature invariant point(s). Although the names are the same, each rock type achieves its same mineral composition by different routes. To suggest that the final, stable, rock composition can be achieved by only one route, through magmatic differentiation, is not logical. Likewise, as many petrologists seem to imply, suggesting that a pluton emplaced during the Precambrian, some 3.5 billion years ago, would remain unchanged after many forces of tectonism and upheavals, defies reason.

But the process does not end here. Many granitic rocks formed by metasomatic processes below melting temperatures may later melt because (1) volumes of introduced hydrous fluids, enabling metasomatism, can increase to the point that the system is saturated with water, (2) the temperature rises above eutectic conditions, or (3) the pressure becomes less because the metasomatic granite body has been mobilized to rise to higher levels in the crust. Therefore, because conditions for melting are so easily achieved, it is not unexpected that most granites are magmatic and plot near the low-temperature invariant point(s). Nevertheless, experimental studies show that at higher pressures more water is needed to saturate a system than at lower pressures, and, therefore, because high pressures would tend to prevent introduction of additional water necessary for melting to begin, metasomatism would be favored over magmatism in some places.

This favoritism occurs in spite of the fact that the combination of higher pressures and increased water content causes the temperature of first melting to be lowered.

The second argument used to show that large-scale metasomatic granitic bodies cannot be produced by variable metasomatic fluids can also be shown to be flawed, when comparisons are made with other processes involving fluids of variable composition that affect magmatic plutonic rocks. In weathering processes in the range of 0-200º C, for example, the alteration of cores of plagioclase to clay, sericite, and/or calcite is caused by *variable hydrous fluids* and results in a rock that is variably weathered, depending upon the accessibility of the fluid to individual crystals. In final stages, however, the magmatic rock can be *uniformly weathered*, even though the fluids causing the alterations were quite variable. *All high temperature minerals are eventually converted to those stable at the lower temperature range*.

Similar arguments can be applied to magmatic rocks that are altered by hydrothermal solutions in the range of 200-400º C. In this temperature range, microcline and myrmekite do not form, and the metasomatic changes that occur are associated with the formation of hydrated minerals (e.g., muscovite, chlorite, and epidote). And even though the fluids may be quite variable, the final product could result in a uniform alteration of a former magmatic rock.

On the basis of these comparisons, there should not be any valid objections that variable metasomatic fluids can also cause the conversion of magmatic rocks into granitic rocks containing K-feldspar and myrmekite in the temperature range of 400-600186 C. Why should there be a "black hole" preventing alterations at these temperatures? Regardless of what the beginning rock composition is, a granodiorite, tonalite, diorite, or gabbro, the final metasomatic products are minerals that are *stable in the temperature range of 400-600º C*. In early stages different amounts of metasomatism would occur from place to place and from crystal to crystal, but ultimately, most of the rock would obtain a relatively uniform appearance, depending upon the extent of deformation and cataclasis, and the kind of rock that is produced would depend upon the availability of K and Si in the metasomatic fluids. In most places, metasomatism is so complete that it is a problem to find remnants of the original rock which are undeformed and unreplaced. But in any case, the variability of the metasomatic fluids is expected and produces a continuum of rock types with transitional gradations to unreplaced magmatic rocks.

The final argument that variable metasomatic fluids cannot produce large massive granite bodies is also false. Where continued stresses are applied while metasomatism is occurring, foliation is enhanced, but where the rocks are cataclastically broken but then are no longer under stress, the recrystallization that occurs during the replacement process will eliminate any foliation and produce a massive-appearing rock.

Metasomatic granitic rocks formed from metasedimentary rocks

The argument that large granite masses do not result from the granitization of metasediments is likely correct in most places. Where hot magmas are intrusive into metasedimentary rocks, metasomatism of the wall rocks does not occur. Instead, the heat and released hydrous fluids may cause partial melting of the metamorphic rocks, forming lit-par-lit gneisses. Or, the heat may produce contact metamorphism, creating an aureole of higher-temperature mineral species in the wall rocks. During the recrystallization to produce these new metamorphic minerals, generally any pore spaces are eliminate so that it is difficult for potential emanating fluids from the magma to migrate through the rocks and cause metasomatism. But in regions where intense, repeated deformation occurs, creating opening for fluids to enter, metasomatism could take place. An example is the strong deformation and isoclinal folding of the metasedimentary rocks surrounding the Cooma pluton in Australia (Munksgaard, 1988). Adjacent to the pluton (north end), these foliated and metasomatized wall rocks can be seen to become progressive sheared toward the pluton until they become homogenized rock, lacking foliation in the pluton. Myrmekite on the K-feldspar and other replacement features are continuous from the wall rocks into the pluton, so that it is apparent that melting temperatures were never reached during this homogenization (Collins, 1993).

For the most part, metasediments are probably converted to granites by melting processes during underplating by hot basalt magma rather than by metasomatism (e.g., Wiebe, 1996). In order for large-scale metasomatism to be accomplished, large volumes of fluids are needed, and such fluids are more likely to be found in deep sources that follow the same conduits through which rising magmas have moved than to be derived from metasedimentary sources. Breakdown of hydrous minerals during high-grade metamorphism may provide enough fluids to cause local minor replacements of plagioclase by K-feldspar and myrmekite in some sheared and deformed high-grade gneisses (metapelites), but replacements for the most part would be insufficient to convert these gneisses into granite. What generally is formed are garnet-sillimanite or garnet-sillimanite-cordierite or biotite-cordierite gneisses rather than metasomatic granite, although formation of small bodies of granite in advanced stages of metasomatism is possible. See Collins (1993) and discussions of garnet-sillimanite gneisses created from deformed diorite and gabbro in Colorado (Collins, 1988; and http://www.csun.edu/~vcgeo005/Nr11Gold.pdf).

Conclusion

The progressive changes from unaltered rock to metasomatic rock as revealed by (1) the conversion of ferromagnesian silicates to quartz, (2) the interior replacement of plagioclase by K-feldspar and myrmekite, (3) the creation of ghost myrmekite in the K-feldspar, (4) the remnant plagioclase inclusions in K-feldspar which are optically parallel to adjacent plagioclase crystals, (5) the unequal distribution of feldspar lamellae in perthite and antiperthite, (6) the correlation of maximum size of quartz vermicules in myrmekite with the Ca-content of the original plagioclase in unreplaced rocks, (7) the destruction and disappearance of high-temperature minerals, and (8) the lack of evidence for melting are all characteristic features of metasomatized rocks formed in the temperature range of 400-600º C. Such features are observed to occur in a plutonic scale, just as similar features occur in a plutonic scale that result from weathering or hydrothermal alterations at lower temperature conditions. Because silicate minerals that form in the range of 400-600º C are those that contain Si, Al, K, and Na in preference to Mg, Ca, and Fe, the latter elements tend to be removed in escaping fluids while the former are introduced and/or concentrated and retained in the granite. Deformation that breaks crystal boundary-seals and bends and fractures crystal lattices is essential to produce avenues for fluid migration. Temperatures must be less than that which would produce melting, and fluids moving through the rock must be in concentrations below that which would saturate the rock with water and cause melting. The subtracted soluble elements (Ca, Mg, Fe) must be transported in hydrous fluids upwards to lower pressure sites and may eventually become mixed with oceanic waters. The large volumes of released Mg may cause dolomitization of limestones; the iron may form banded iron ores.

The myth that granite bodies of large dimensions cannot be formed by metasomatic processes needs to be put to rest. Too many plutons have been subjected to strong deformational forces for them to remain unchanged through time. What is important to realize is that crystallization of magma need not fix its elemental composition, as in the closed system of an experimental "bomb," but following crystallization of a pluton, deformation and introduction of hydrous fluids could cause vast elemental changes. Thus, the differentiation of a plutonic mass to more granitic facies could be accomplished as much by magmatic processes as by metasomatic alterations. That is, crystal settling of dense mafic minerals in magma need not be necessary to make cores and tops of pluton more granitic − just introduction of Si and K in hydrous fluids in deformed places. Late-stage metasomatism could create more granitic rocks, which could re-melt, and each successive melt could solidify and be modified by metasomatic fluids. The continued rise of a solid pluton after solidification, because the rock is less dense than the surrounding rock, could produce deformation and fracturing in the plutonic rock, necessary to allow the hydrous metasomatic fluids to enter (Collins, 1988; Hunt et al., 1992). In repeated cycles of magmatism, deformation, metasomatism, and re-melting, concentrically zoned plutons could be produced, such as occurs in the Rosses pluton of the Donegal granites of Ireland (Pitcher et al., 1987) or the Tuolumne series in the Sierra Nevada of California (Bateman and Chappell, 1979).

Large volumes of hydrous fluids have existed in fractured plutons to cause nearly isochemical alterations and weathering on a large scale. Why not also larger volumes of metasomatic fluids whose temperatures are higher?

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