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26. THE MICROCLINE-ORTHOCLASE CONTROVERSY --- CAN MICROCLINE BE PRIMARY?

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Introduction

A common perception among petrologists has persisted that microcline is always derived from orthoclase (a high-temperature mineral), and, therefore, all microcline-bearing granites of large dimension have crystallized from a magma. This perception is based on studies of Laves (1950) who suggested that the gridiron twinning in microcline can *form only by inversion from the high-temperature lattice in orthoclase because of the peculiar relations between pericline and albite twinning in microcline*; see also MacKenzie (1954). In magmatic rocks, primary orthoclase will under certain conditions invert to secondary microcline because of the ordering of (Si, Al) atoms during the unmixing of Na and K phases to form perthite. This inversion is quite sluggish, however, and rarely, can a pluton be found, if ever, in which gradations occur from unaltered orthoclase to places where all orthoclase is completely inverted to microcline. Complete gradations occur, however, in some Precambrian granulites, but in these rocks deformation and shifting to lower grade metamorphic conditions (lower T-P) likely aids the total inversion of orthoclase to microcline (Eskola, 1952). Nevertheless, microcline does not always have to result from an orthoclase inversion. Considerable geologic, textural, and temperature evidence exists, demonstrating that microcline can form as *a primary mineral* at temperatures below the solidus where there is absolutely no support for the hypothesis that orthoclase was first formed at higher temperatures as a precursor to this microcline.

Geologic and textural evidence

Some of the geologic and textural evidence for the formation of primary microcline occurs in the Rocky Hill stock (http://www.csun.edu/~vcgeo005/Nr24TwoStyles.pdf) and in the Woodson Mountain granite (http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf, http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf, http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf). In the Woodson Mountain terrane, *the progressive stages of interior replacement of plagioclase by microcline in diorite devoid of K-feldspar across a zone of deformation into myrmekite-bearing granite demonstrate that no melt was ever present in which primary orthoclase crystals grew and later inverted to microcline*. During early alterations of deformed plagioclase in the diorite, disruption of zoning and disappearance of albite-twinning occur as Ca and some Al are subtracted from the plagioclase lattice. This subtraction eventually creates nano-sized holes (Fig. 4a and Fig. 4b in http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf) and prepares the crystal for K-replacement. The differential losses of Ca and Al from place to place cause local variations in lattice structures and atomic compositions, so that when the introduced K begins to recrystallize in the plagioclase lattice as a K-feldspar, the residual Si and Al atoms become re-ordered, distorting the lattice and producing the gridiron twinning characteristic of microcline. In that way, primary triclinic microcline is formed naturally from the primary triclinic plagioclase rather than by inversion from the lattice of a high-temperature, monoclinic orthoclase.

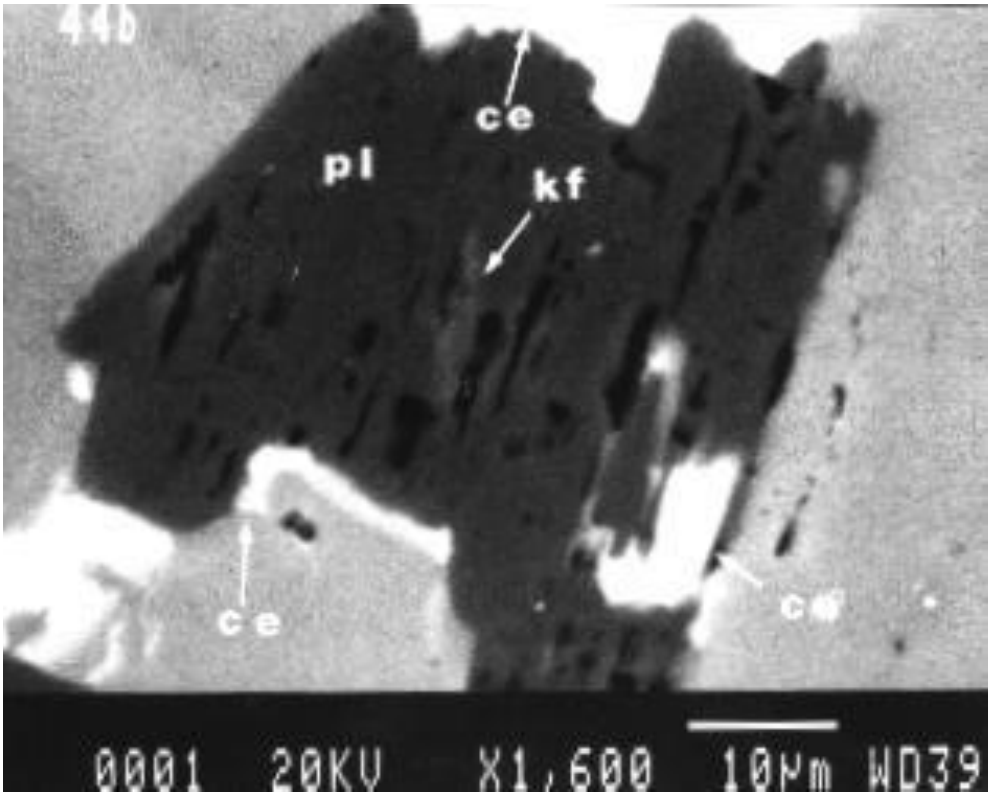

Fig. 4a in Nr2Myrm.pdf. This scanning-electron photomicrograph is an image in the center of a soda-rich core of a plagioclase crystal magnified 1,600x. The

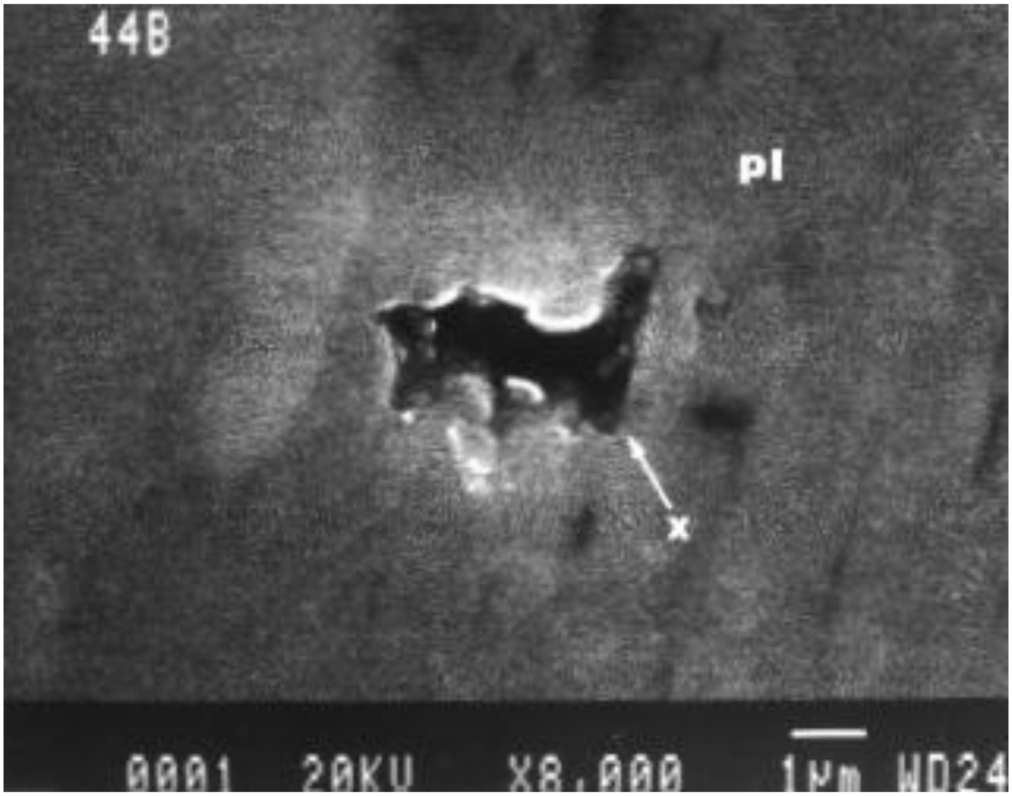

Fig. 4b in Nr2Myrm.pdf. This scanning-electron photomicrograph is from the same area as in Fig. 4a but now magnified 8,000x. The "x" points to a hole (black) bordered by concentrations of K (light gray). See article for more information

Therefore, although it is true that orthoclase crystallized from magma can invert to microcline, it is not necessarily true that all microcline results from the inversion of magmatically derived orthoclase. Moreover, microcline formed by replacement of plagioclase can be Carlsbad-twinned and obtain this twinning by inheritance of the Carlsbad-twinning in the original plagioclase (see Fig. 6 in http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf; Fig. 7 and Fig. 8 in http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf, and Fig. 8 in http://www.csun.edu/~vcgeo005/Nr13Rubidoux.pdf). What is essential for primary microcline to form is that the temperature is below the solidus and that interior K-replacement of deformed plagioclase occurs.

Fig. 6 in Nr3Myrm.pdf. This photomicrograph shows a remnant zoned plagioclase crystal in the massive, pink, Cape Ann granite several meters from the contact with the Salem diorite. The plagioclase is Carlsbad-twinned and has a weathered, sericitized calcic core. This crystal is similar in size and shape to Carlsbad-twinned plagioclase crystals in the diorite. In other places the Carlsbad-twinned plagioclase crystals are deformed and replaced progressively by microcline and wartlike myrmekite, and the microcline inherits its Carlsbad twinning from the former plagioclase.

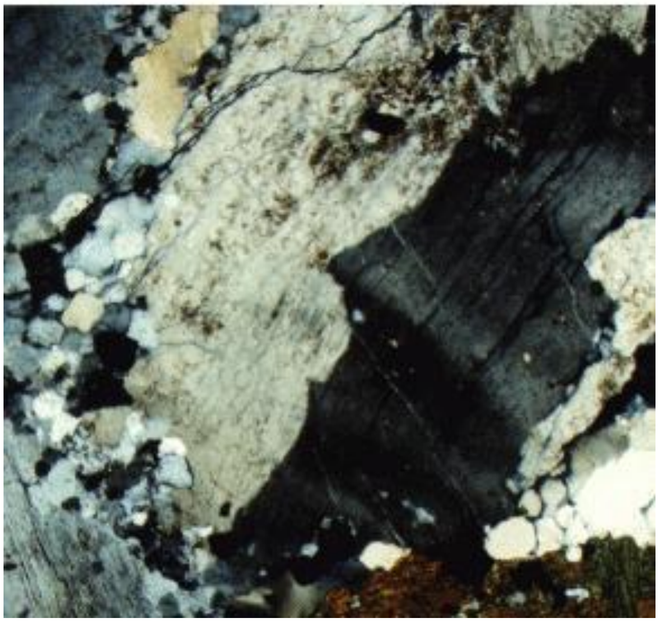

Fig. 7 in Nr9Twenty.pdf. Felsic diorite, showing deformed (bent) Carlsbad- and albite-twinned plagioclase crystal (light and dark gray). Other large plagioclase crystals (left side) have cataclastically broken grain boundaries. Hornblende crystal (brown, bottom) is adjacent to tiny grains of quartz (clear white). Microcline (light gray) is in earliest stages of replacement of deformed plagioclase and occurs as a few tiny irregular blebs just above the hornblende and quartz in the bottom part of the deformed plagioclase. Microcline is much less than 1 vol. % of the rock.

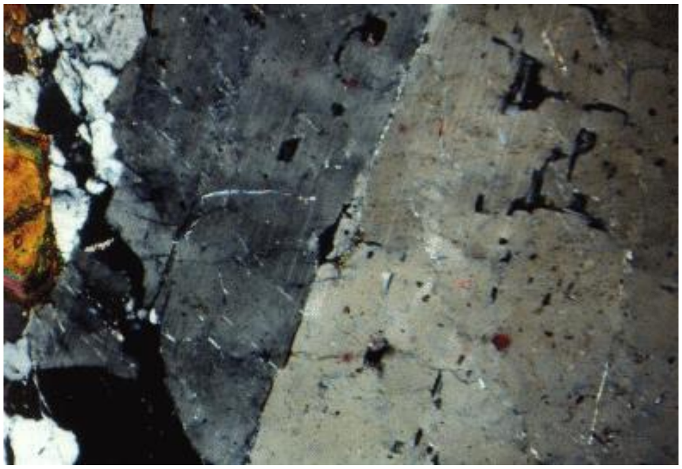

Fig. 8 in Nr9Twenty.pdf. Felsic diorite shows slightly deformed (fractured) Carlsbad- and albite-twinned plagioclase crystal (cream gray and gray) that fills most of image. Tiny irregular islands and veinlets of microcline (black-gray) replace portions of both halves of the Carlsbad-twinned plagioclase crystal.

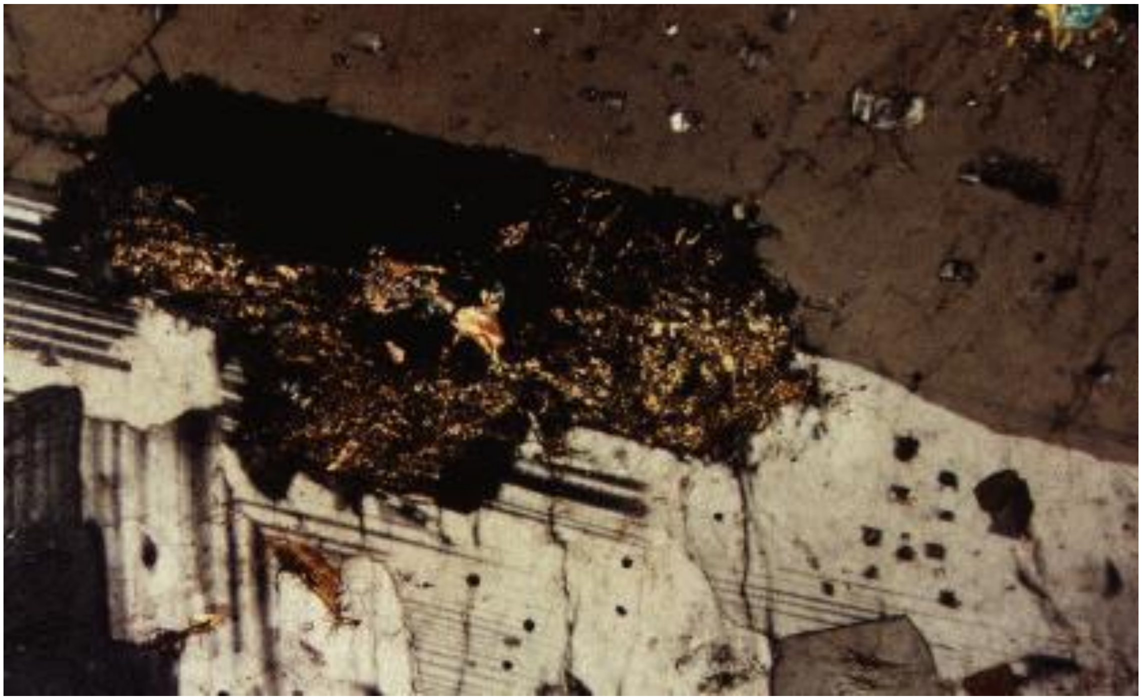

Fig. 8 in Nr13Rubidoux.pdf. Carlsbad- and albite-twinned, zoned plagioclase in Bonsall tonalite. Relatively calcic core (black, altered to sericite) of plagioclase is surrounded by a broad, relatively sodic rim. Plagioclase rim has irregular or rectangular islands of K-feldspar (black, or gray-white gingham-pattern). Biotite (brown); muscovite (blue and yellow).

Additional geologic and textural evidence for the primary origin of microcline is found in many different terranes besides the Rocky Hill stock and the Woodson Mountain granite. In the transition from felsic Gold Park diorite to the megacrystal Twentynine Palms quartz monzonite, undeformed plagioclase crystals contain irregular islands of microcline (Fig. 8 in Nr9Twenty.pdf). Farther along the transition toward quartz monzonite, progressive replacements by microcline occur until the plagioclase crystals are almost entirely replaced by microcline. In some places this microcline becomes megacrysts as much as 16 cm long. *No orthoclase was found in studies of more than 100 thin sections* of the megacrystal quartz monzonite, including sections through 12 megacrysts. In some thin sections, however, cut parallel or nearly parallel to the "a" or "b" crystallographic axes of either the small or large megacrysts, the K-feldspar does not show gridiron twinning, and, therefore, gives the appearance of being untwinned orthoclase. When such crystals were cut at angles that intersected the "c" axis, however, the crystals *always showed gridiron twinning across the whole crystal*. Because there is no evidence for orthoclase anywhere in this quartz monzonite or its transition to unaltered diorite, it is reasonable to assume that *orthoclase was never present* and that primary microcline was formed by replacement processes directly from the altered and deformed plagioclase lattices rather than by inversion from former orthoclase.

The complete absence of orthoclase was noted by Marmo (1955, 1958ab) in Sierra Leone in western Africa and in Finland. In both of these terranes, microcline coexists with albite in Precambrian granites, and no orthoclase is found anywhere. Gysin (1948, 1956) found similar relationships in granites in the Alps and the Himalayas. Marmo also suggested that the microcline was primary and formed by K-metasomatism rather than by magmatic processes and inversion from orthoclase. Schermerhorn (1961, 1956) criticized this interpretation, but Marmo (1961) logically answered these criticisms, emphasizing the facts that (1) such granites had both magmatic (intrusive) and metasomatic characteristics and (2) the coexistence of low-temperature microcline and albite and the *total absence* of orthoclase are illogical partners for an origin solely by magmatic processes. Another example of one of these Precambrian microcline-bearing granites in Finland is granite exposed along a highway extending south of Helsinki (Fig. 1). Remnants of unreplaced former diorite remain in this rock (Fig. 2), and plagioclase grains are replaced in their interiors by microcline (Fig. 3) and Fig. 4), as in the Rocky Hill stock and the Woodson Mountain granite.

Fig. 1. Dynamited highway exposure of Precambrian granite and remnant diorite, south of Helsinki (near Ilmailutie, Helsinki-Vantaa airport). Remnants of vertical drill-holes extend through the exposure.

Fig. 2. Close-up of highway exposure, showing granite replacing foliated diorite. Granitic veins have unmatched walls, and blocks of diorite are not physically displaced or rotated by the penetrating granite. Both features are typical characteristics of replacement processes.

Fig. 3. Plagioclase grain replaced in its interior by microcline

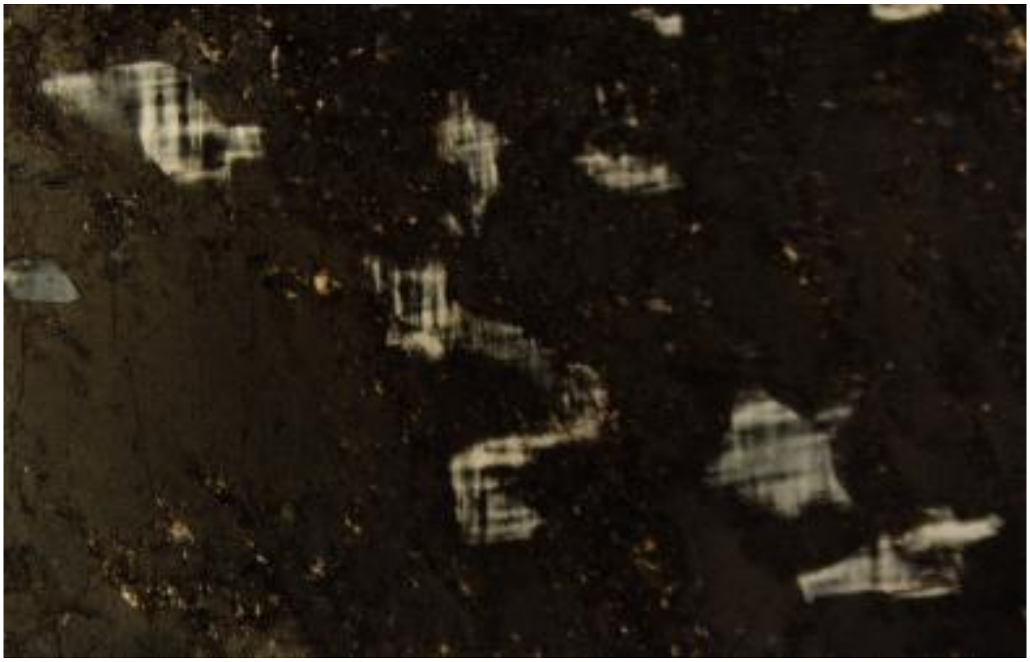

Fig. 4. Plagioclase grain replaced in its interior by microcline.

Myrmekite is relatively common with intermediate-sized quartz vermicules and is typical of places where plagioclase in diorite is replaced by microcline (Fig. 5, Fig. 6, and Fig. 7) (Collins, 1988). Biotite is also replaced by vermicular quartz and microcline (Fig. 7). The occurrence of these microcline islands in only a few of the plagioclase crystals in a thin section is atypical of antiperthite formed by unmixing of a high-temperature alkali feldspar crystallized from a melt.

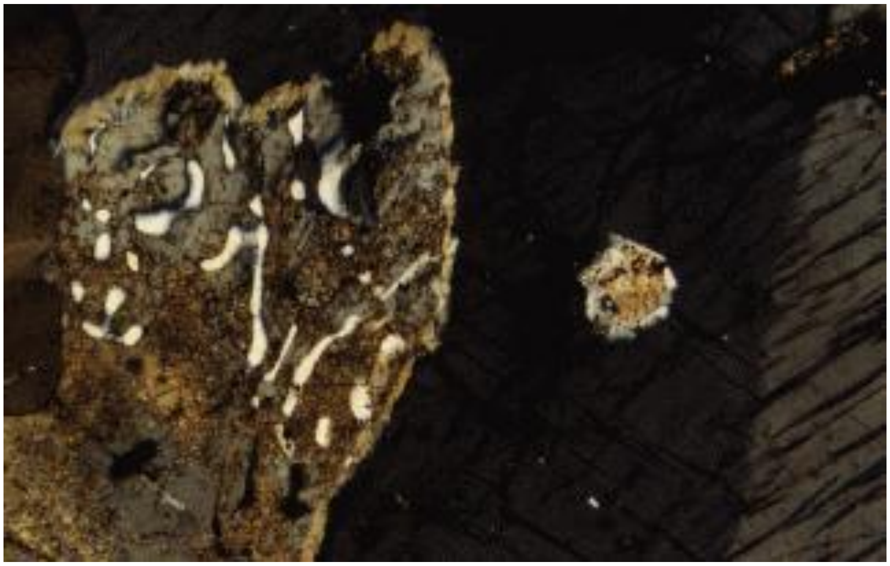

Fig. 5. Myrmekite with intermediate-sized quartz vermicules.

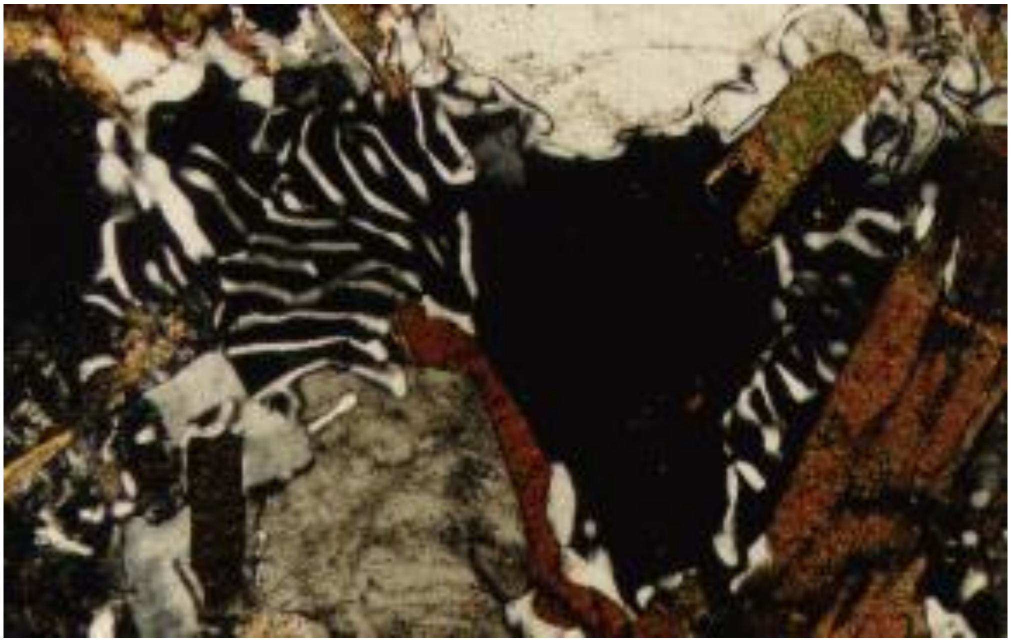

Fig. 6. Myrmekite with intermediate-sized quartz vermicules.

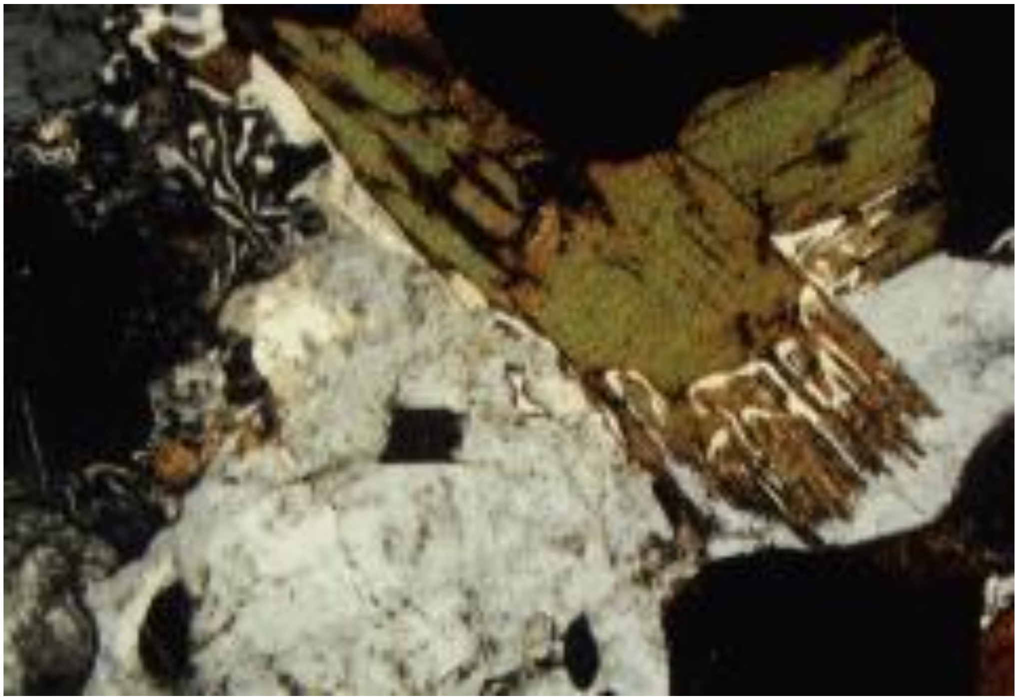

Fig. 7. Quartz sieve texture in biotite.

Other examples of the formation of primary microcline by K-replacements of plagioclase occur in the Sharpners Pond tonalite and the Marlboro Formation in Massachusetts, the Ponaganset augen gneiss in Rhode Island, the Strontian and

Ratagain plutons in Scotland, and in many granitic terranes described in other presentations in http://www.csun.edu/~vcgeo005/index.html. Illustrations of K-feldspar in the other presentations in http://www.csun.edu/~vcgeo005/index.html, however, generally show the microcline at an extinction position, which renders the K-feldspar black so that the gridiron twinning cannot be seen. Nevertheless, the optically black K-feldspar in these illustrations is microcline. See illustrations of earliest stages of primary microcline replacements in the Sharpners Pond tonalite Fig. 4 in http://www.csun.edu/~vcgeo005/Nr20SilicaPump.pdf; in the Marlboro Formation in Fig. 18 in http://www.csun.edu/~vcgeo005/Nr21Three.pdf; in the Ponaganset augen gneiss in Fig. 6 in http://www.csun.edu/~vcgeo005/Nr22Ponaganset.pdf; in the Cluanie pluton in Fig. 10 in http://www.csun.edu/~vcgeo005/Nr23Scotland.pdf, and in the Ratagain pluton in Fig. 19 in http://www.csun.edu/~vcgeo005/Nr23Scotland.pdf.

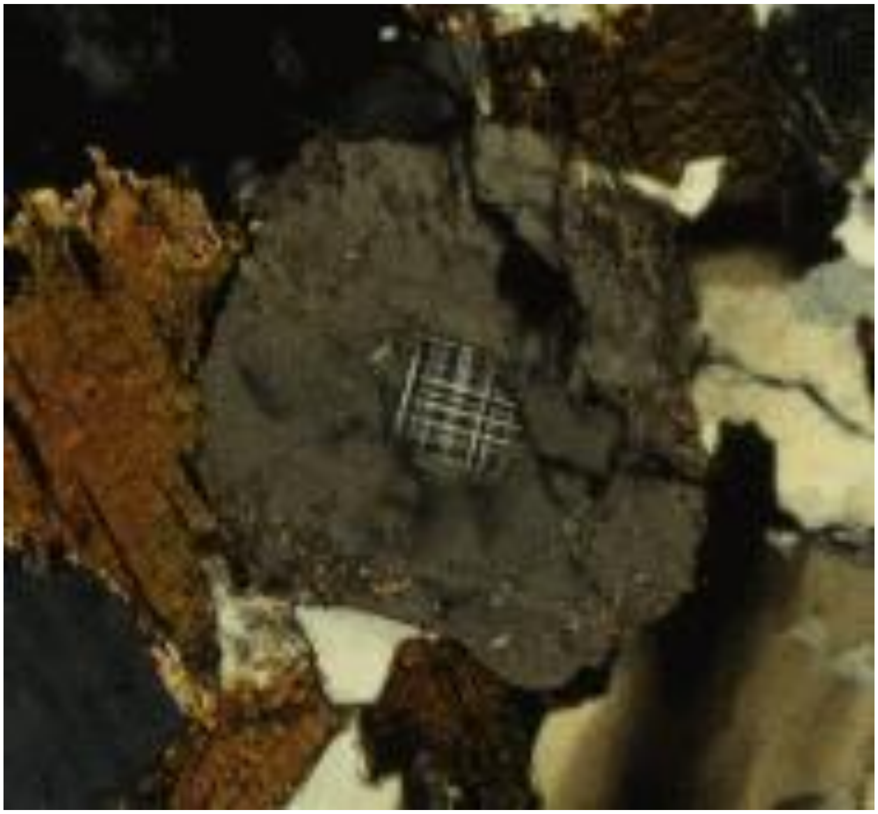

Fig. 4 in Nr20SilicaPump.pdf. K-feldspar (cross-hatch pattern) in the core of a plagioclase crystal (tan) in granodiorite. Quartz (wavy extinction, cream), biotite (brown). Sample is from a transition zone between tonalite and granodiorite.

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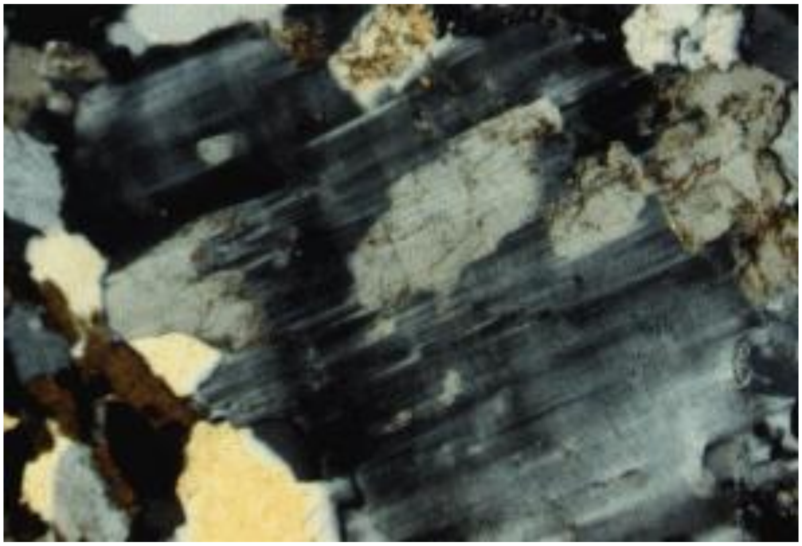

Fig. 18 in Nr21Three.pdf. K-feldspar (gray and black, cross-hatch twinned) with remnants of plagioclase (tan) which extend through the K-feldspar in parallel optical continuity.

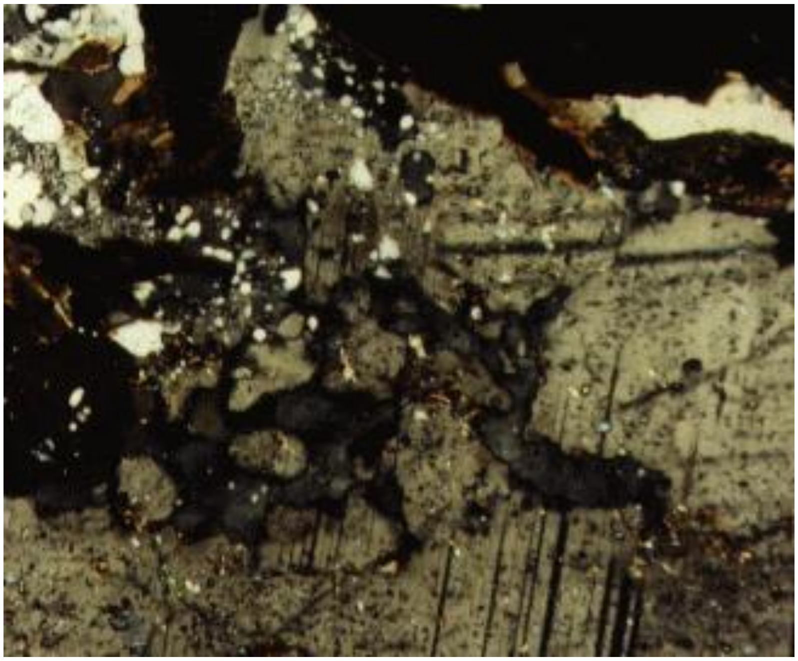

Fig. 6 in Nr22Ponaganset.pdf. Fractured, albite-twinned plagioclase (tan) in which the fractures are filled by K-feldspar (dark gray). Adjacent plagioclase is locally myrmekitic, containing quartz ovals (white). Biotite (brown).

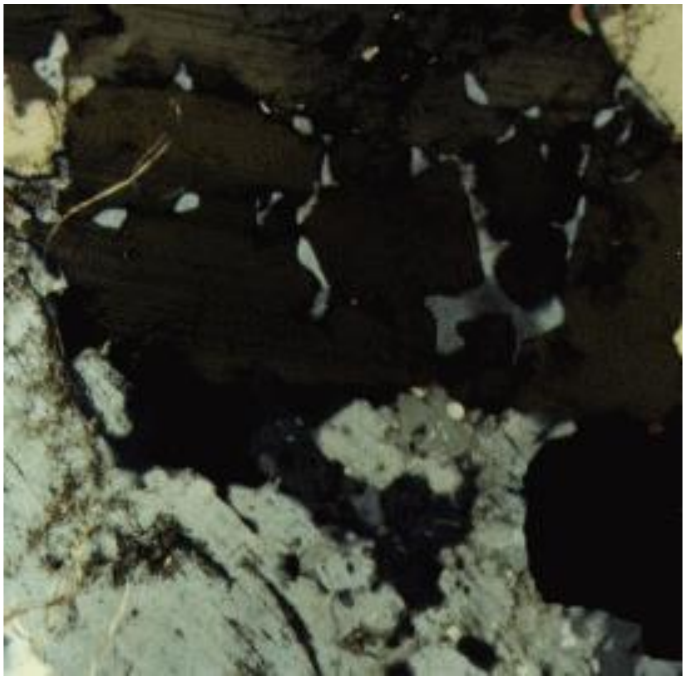

Fig. 10 in Nr23Scotland.pdf. Albite-twinned plagioclase (top; tan) is penetrated along fractures by K-feldspar (white, gray). Plagioclase (light gray; bottom) is also penetrated by K-feldspar (dark gray) along fractures. Cluanie pluton.

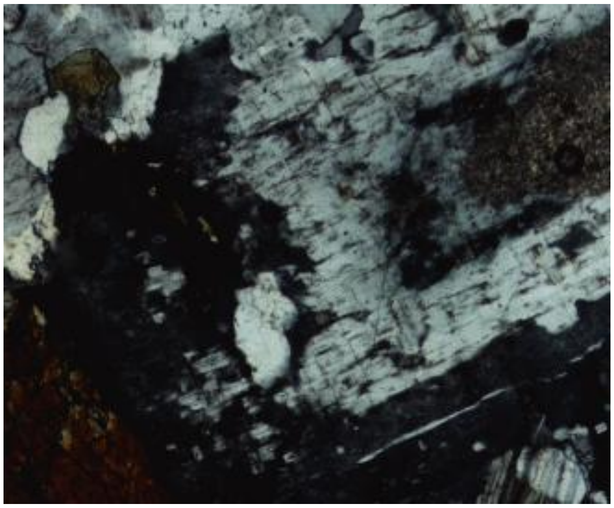

Fig. 19 in Nr23Scotland.pdf. Large zoned plagioclase (light gray) with sericitized central core (right side, brownish). Island remnants of the outer broad rim of the plagioclase occur in perthitic K-feldspar (black). Elongate oval area (white) enclosed by K-feldspar (left of large plagioclase crystal) is myrmekite; see Fig. 21. Hornblende (brown, lower left). Ratagain pluton.

See illustrations of late-stage primary microcline replacements in the Sharpners Pond tonalite in Fig. 6 in http://www.csun.edu/~vcgeo005/Nr20SilicaPump.pdf; and in the Marlboro Formation in Fig. 23 in http://www.csun.edu/~vcgeo005/Nr21Three.pdf. Another excellent example of progressive interior replacement of plagioclase by primary microcline occurs in granite near Central City, Colorado (in Fig. 6 in http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf). *It is noteworthy that all of these microcline-bearing granites are associated with myrmekite*.

Fig. 6 in Nr20SilicaPump.pdf. K-feldspar (shades of gray, cross-hatch pattern, upper right) penetrating and replacing the rim of a zoned and altered plagioclase crystal along irregular fractures. A ragged biotite crystal (dark brown) occurs in the plagioclase. Sample is from granodiorite.

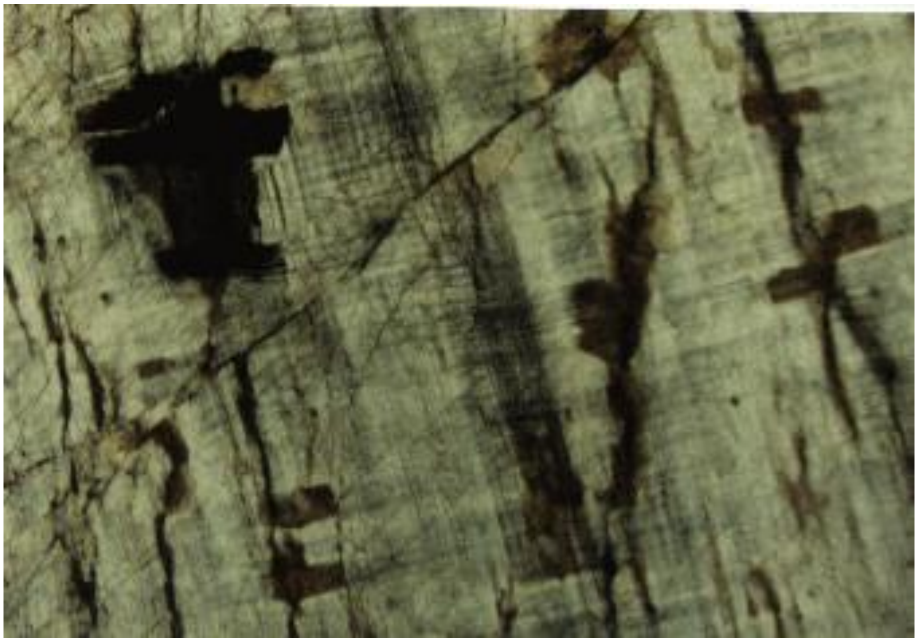

Fig. 23 in Nr21Three.pdf. K-feldspar (shades of gray, cross-hatch twinning), enclosing bent and broken, albite-twinned, plagioclase islands which are in optical continuity (tan, rectangular, and black and gray).

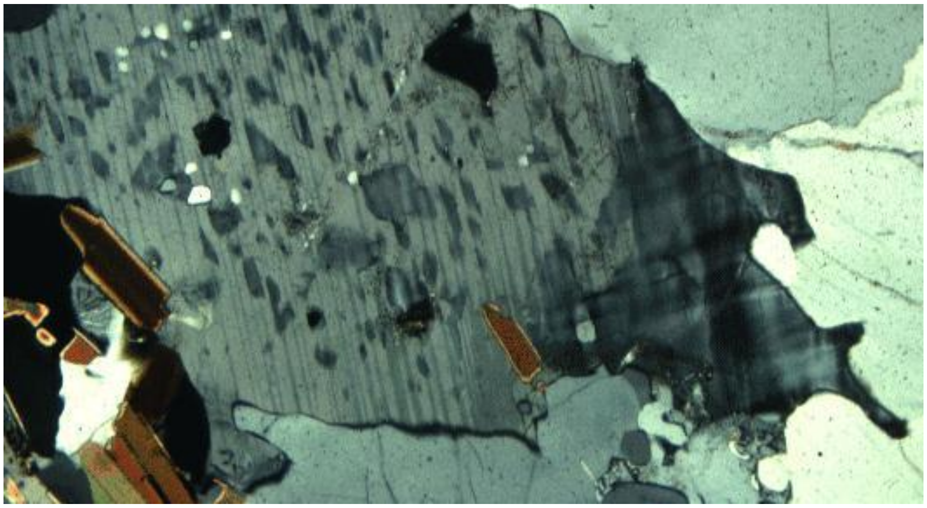

Fig. 6 in Nr2Myrm.pdf. Microcline (dark gray, grid-twinning) in this photomicrograph from myrmekite-bearing granite is in a more advanced stage of replacement of plagioclase. Plagioclase (light tan) in the center and upper left has been completely replaced by K-feldspar (lower right). Note that the albite twinning of the grid-twinning in the microcline is parallel to the albite twinning in the plagioclase.

Crystal settling as evidence

Finch and others (1990) describe unique layered rapakivi granite in south Greenland in which mafic layers (composed of pyroxenes, hornblende, and biotite) alternating with felsic layers (composed of plagioclase, microcline, myrmekite, and quartz) are suggested to result from crystal settling in a fluorine-rich *granitic melt*. But how can settling occur in a viscous granite magma when low density K-feldspar crystals (G = 2.56) would have to sink through a denser magma that still had enough Fe, Ca, and Mg to crystallize high-density pyroxenes and hornblende (G = 3.0-3.2)? How also can the magma composition swing abruptly from being silica-rich (to produce the microcline and quartz) to being silica-poor (to produce the ferromagnesian silicates)? And how can this alternating process be repeated in short intervals to produce the different layers, only a few centimeters apart? Moreover, if the layered granite were formed from magma, orthoclase should be the K-feldspar present in the felsic layers, and none is present --- *only microcline*.

Finch and others (1990) indicate that in deformed portions of the mafic layers, the pyroxenes and hornblende are replaced by biotite. Why should one type of layer in the granite be deformed and replaced and not the other? It is *far more logical that both layers would be deformed and replaced at the same time*. The presence of microcline and myrmekite suggests that the layered granite was once really a *former layered gabbro* in which K-bearing fluids moved through zones of deformation to cause biotite to form in the mafic layers and to create myrmekite and primary microcline in the felsic layers. In that case, orthoclase would never have been present in the gabbro or granite, and the microcline would have formed rather than orthoclase under the subsolidus conditions in which the deformation occurred. Moreover, if periodic crystal settling of high-temperature ferromagnesian silicates, such as pyroxenes, were to occur in granite magmas and alternate in short intervals with settling of felsic minerals, one would expect to find this occurrence to be common elsewhere, and *that is not the case*. It should also be emphasized that most rapakivi granites are large massive bodies, lacking any layered appearance and have a primary magmatic origin rather than a metasomatic origin.

Temperature evidence from metamorphic rocks

Evidence for the origin of primary microcline is also indicated by the relatively low temperatures in which the microcline is formed, well below the field of stability for orthoclase. An example is found in the paragneisses in New York (USA). Along the northwestern border of the Adirondack massif in New York are paragneisses consisting of muscovite, biotite, plagioclase, and quartz. Toward the massif these rocks have been progressively recrystallized from lower amphibolite- to granulite-grades of metamorphism (Engel and Engel, 1958, 1960). From measurements on such geothermometers as FeS in sphalerite, Na- and K-proportions in coexisting K-feldspar and plagioclase, magnesian contents of calcite in marble, and TiO_2 in magnetite, temperature values were obtained that ranged from as low as 375º C, farthest from the massif, to about 600º C, adjacent to the massif (Engel and Engel, 1958, 1960). Progressively across the metamorphic zones, beginning in rocks whose temperatures were near 500º C, muscovite and biotite in the paragneisses *recrystallized to form* garnet, quartz, and microcline. In that process microcline replaced some plagioclase grains while other plagioclase grains were recrystallized as relatively more-sodic plagioclase and/or myrmekite. Generally, plagioclase, ranging from An_{30} to An_{60} in lower-grade metamorphic rocks, was recrystallized to ranges from An_{10} to An_{30}. At granulite grades of metamorphism near the massif, much of the microcline lost its gridiron twinning and was assumed by Engel and Engle (1958, 1960) to have converted to orthoclase. At any rate, the temperature of 500º C, where microcline was formed, is well below melting conditions and below the temperature at which orthoclase forms. On that basis, it is clear that *orthoclase was never present as a primary mineral which crystallized from a melt in the paragneisses* and from which the microcline could have theoretically inverted. Orthoclase only appeared when temperatures reached high enough for its formation.

Orthoclase formed by subsolidus replacements in metamorphic rocks

Another example of a metamorphic terrane in which higher temperatures of metamorphism have converted microcline into orthoclase is reported by Rao (1960). He found that microcline in the Precambrian gneisses near Oslo, Norway, became increasingly disordered as the contact with a nordmarkite was approached, and near the contact the microcline was converted to a sanidine-like form.

Heier (1956) described a metamorphic sequence from Orsdalen, Norway, grading from a greenschist through a granulite facies. In this terrane, augen gneisses are gradational to amphibolites, and the plagioclase of the amphibolite shows progressive K-replacement with increasing degrees of metamorphism. Microcline is first produced in antiperthite by interior replacement of plagioclase. Next, in intermediate grades of metamorphism, the plagioclase crystals are converted to perthitic microcline bordered by myrmekite. In the highest grades of metamorphism perthitic orthoclase is formed, also bordered by myrmekite, illustrating that *not all orthoclase (or sanidine) is formed by crystallization from magma*.

Eskola (1952) reports that conversion of microcline to orthoclase is common in many granulite terranes (and vice-versa). It logically follows that if temperatures and pressures rise sufficiently to cause primary microcline to convert to orthoclase under subsolidus conditions, then in some terranes, temperatures could rise high enough eventually to cause melting, with the formation of magma. After crystallization of the magma, *primary magmatic orthoclase* would be formed, and *under such conditions myrmekite would not be expected*.

Perthite, microcline, and orthoclase

Existing theory for the origin of plagioclase lamellae in microcline or orthoclase to form perthite is that plagioclase lamellae generally result from unmixing of Na (and Ca) from high-temperature alkali feldspar (Tuttle, 1952). Other origins of perthite include simultaneous crystallization of a potassium-rich and a sodium-rich feldspar (Anderson, 1928; Wallace, 1956), replacement of plagioclase during late deuteric potassium metasomatism (Heier, 1955, 1956, 1957; Robertson, 1959), and replacement of primary orthoclase or microcline by plagioclase (see http://www.csun.edu/~vcgeo005/Nr18LyonMtn.pdf). But what about perthitic microcline (or orthoclase) formed during subsolidus K-replacement of plagioclase? In that case, the plagioclase islands or lamellae in the perthite are residual remnants of the former plagioclase or result from the displacement and/or recrystallization of Na and Ca in the former plagioclase crystal. Whether plagioclase islands or lamellae in the K-feldspar are coarse or fine is a function of the An-content of the primary plagioclase. The more calcic the primary plagioclase that has been replaced, generally the coarser are the plagioclase lamellae in the perthite. Examples of perthitic microcline with coarse plagioclase lamellae formed by K-replacement occur in the charnockites of India (Ramaswamy and Murty, 1968, 1972) and in mangerite at Raftsund, Lofoten-Vesteralen, Norway (Griffin et al., 1974). Examples of perthitic orthoclase containing extremely tiny plagioclase lamellae occur in the Cooma pluton (Collins, 1996). Noteworthy is that these perthitic microcline- and orthoclase-bearing rocks are also associated with myrmekite.

Origin of granites

It is well understood that granites can form in many different ways. (1) Melting of sediments of appropriate composition, (2) partial melting (anatexis) of granitic components of mafic rocks and separation (migration) of this granitic melt to form a magma, and (3) crystal settling of mafic components (magmatic differentiation) in a magma are three generally accepted hypotheses. During magmatic differentiation, K, Na, and Si are enriched in the top of a magma chamber as earlier-formed, higher-temperature, heavy crystals enriched in Ca, Mg, and Fe settle. These K-, Na-, and Si-rich fluids may continue to rise in a magma, however, as illustrated by the Cornelia pluton at Ajo, Arizona (http://www.csun.edu/~vcgeo005/Nr24TwoStyles.pdf) even after most of the magma has solidified, and crystal settling is no longer possible. These fluids caused late-stage resorption and replacements of earlier formed plagioclase to produce orthoclase, albite, and quartz. It logically follows that if such fluids can rise in a melt (magma), why cannot they also continue to rise after the pluton has completely solidified, provided that deformation and fracturing open avenues through which the fluids could move? In that case, K- and Si-bearing fluids could continue to enrich the tops of plutons so that additional K-feldspar (microcline) and quartz would form instead of orthoclase. Examples are the deformed granitic cores of the zoned Scottish plutons and the Rocky Hill stock, which are enriched in primary microcline (see http://www.csun.edu/~vcgeo005/Nr23Scotland.pdf and http://www.csun.edu/~vcgeo005/Nr24TwoStyles.pdf). Another example is the Gold Butte rapakivi granite in Nevada. Here, volumes of K-feldspar megacrysts, bordered by myrmekite, increase from 30% in lower portions of the pluton to nearly 70% near the top (Fryxell et al., 1992). Therefore, upward enrichment in K-feldspar may not be due to the floating upwards of crystals in a melt but to K-replacements of former already-crystallized plagioclase crystals.

Points to ponder

The geologic evidence presented in examples in this web-site raises some serious questions regarding existing theories for the origin of granite and microcline.

(1) If all microcline results from inversion from orthoclase, why is a complete transition from orthoclase to microcline rarely (if ever) seen in a granite pluton?

(2) Why also do some granites, even billions of years old, have nearly *pure orthoclase*. One must conclude that the process of inversion is incredibly slow.

(3) But, if the conversion of orthoclase is so slow, why do some younger granites have pure microcline without even a trace of orthoclase, particularly if the fabric in the granites does not seem to show any evidence for deformation? Why also is myrmekite commonly associated with this microcline?

(4) Why, in deformed plutonic rocks containing fractured plagioclase in a transition from more-mafic to felsic rocks, is microcline the first K-feldspar to appear without a trace of orthoclase? Why also is microcline the first K-feldspar to appear in mica-bearing paragneisses undergoing increasing grades of metamorphism with no signs of orthoclase until the granulite grade of metamorphism is reached?

(5) If at temperatures below 500º C, K-metasomatism can cause cores of zoned plagioclase crystals to be replaced by sericite on a plutonic scale, and if at temperatures above 600º C, K-metasomatism can cause plagioclase to be replaced (resorbed) to form orthoclase (as in the Cornelia pluton, http://www.csun.edu/~vcgeo005/Nr24TwoStyles.pdf), why should the range of 500 to 600º C be a gap in which no large-scale K-metasomatism can occur?

When the above five points are considered, basic logic strongly suggests that existing paradigms about origins of granite, microcline, and myrmekite need to be re-examined. Geologic textural evidence demonstrates that microcline can form by replacement processes at temperatures below the solidus from primary plagioclase instead of solely by inversion from orthoclase. Therefore, the idea that all microcline-bearing granites are the result of solidification from magma needs to be rejected.

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