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51. Felsic and mafic magma commingling accompanied by Ca-metasomatism of xenocrysts, followed by K-metasomatism of solidified felsic tonalite to form quartz monzonite and granite in the Chief Lake granitic complex south of Sudbury, Ontario, Canada

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Abstract

South of Little Raft Lake in the Chief Lake granitic complex, south of Sudbury, Canada, Na-rich, felsic magma locally commingled with a Na-rich mafic magma. In addition, subhedral quartz and large sodic plagioclase phenocrysts floated-off from the felsic magma to become isolated xenocrysts in the mafic magma. Reactions of the quartz xenocrysts with the relatively more-calcic mafic magma produced rims of tiny amphibole crystals. Ca-metasomatism of borders of the sodic plagioclase xenocrysts by mafic magma locally resulted in aggregate myrmekite rims with tiny quartz vermicules, intermeshed with tiny amphibole crystals. The mafic magma crystallized as a fine-grained mafic tonalite containing more than 30 volume percent biotite, and locally, the felsic magma crystallized as coarse-grained felsic tonalite in small, agmatitic patches and veins in the mafic tonalite. Following this crystallization, portions of the mafic tonalite and agmatite were enclosed as large enclaves in a much larger mass of felsic tonalite magma. After all magmatic rocks were solidified, cataclasis allowed fluids to move through microfractures and release K from the abundant biotite. This K was then precipitated as K-feldspar (microcline) that replaced deformed plagioclase crystals, (a) in xenocrysts in the mafic tonalite, (b) in patches of coarse-grained felsic tonalite in agmatite, and (c) in the larger mass of coarse-grained felsic tonalite that enclosed the large enclaves. In this way, the compositions of the felsic agmatite patches and the larger felsic tonalite masses were locally changed into quartz monzonite and granite, depending upon the degree of K-metasomatism. Similar metasomatic modifications of magmatic quartz diorite and quartz monzonite also occur in the Chief Lake granitic complex north and northeast of Wavy Lake, but

the felsic tonalite here in agmatite lacks any signs of K-metasomatism. The metasomatically modified granitic rocks in the Little Raft Lake and Wavy Lake areas become models for creation of all the various granitic facies of the Chief Lake complex in which cataclastically deformed portions of primary quartz diorite masses of magmatic origin were converted to quartz monzonite and granite. In each of these places, myrmekite with tiny quartz vermicules provides additional evidence for K-metasomatism.

Introduction

The Chief Lake granitic complex (Fig. 1), south of Sudbury, Ontario, Canada, consists mostly of quartz monzonite and quartz diorite, but locally contains megacrystal granite, mafic tonalite, felsic tonalite, and agmatite. (Agmatite is intermingled mafic and felsic tonalite.)

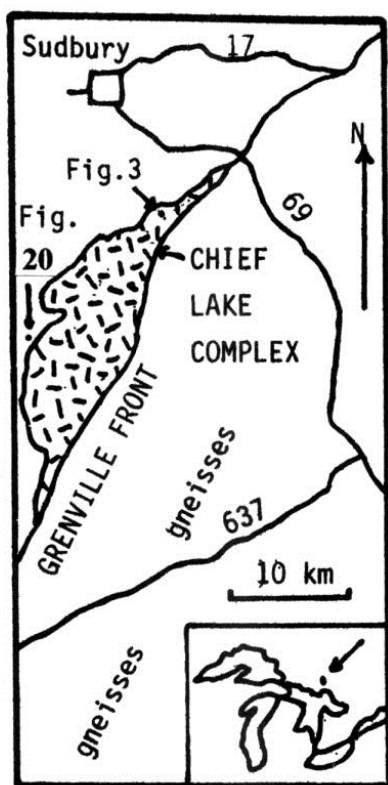


Fig. 1. Simplified geologic map showing general location of the Chief Lake granitic complex, south of Sudbury and west of the Grenville Front (after van Breemen and Davidson, 1988). Locations of Fig. 3 and Fig. 20 along west and north edges of the complex are also shown.

This complex has been studied by a number of investigators (e.g., Phemister, 1960; Henderson, 1967; Clifford, 1990; Davidson and Ketchum, 1993, 1999; Davidson, 2002; and others listed in references by these persons). All except Phemister (1960, 1961; Grant et al., 1962) have considered this complex to be entirely magmatic in origin. Phemister (1960, 1961; Grant, et al., 1962) thought that the complex was formed by regional granitization of gabbro and quartzite in which the K came from a distant outside source. However, normally zoned plagioclase crystals, angular enclaves of metasedimentary wall rocks and Nipissing gabbro, and narrow dikes projecting from the complex, tens of meters into these wall rocks, attest to the emplacement of the various granitic facies as magma. On the basis of these relationships, Henderson (1967) disagreed with Phemister's (1960, 1961) model of regional granitization for the origin of the Chief Lake complex. Nevertheless, Henderson (1967) described contact K-metasomatism in several areas in which the source of K was local. He suggested that microcline megacrysts and disseminated crystals of quartz in what he called "metagabbro" (not the Nipissing metagabbro) were created by K- and Si-metasomatism and that megacrysts of microcline of the same size in adjacent quartz monzonite of the Chief Lake body were *phenocrysts* (Fig. 2, photo, Plate 2B of his Ph.D thesis, 1967).

One of the local K-metasomatized areas (Fig. 2) occurs in large enclaves of the "metagabbro" and agmatite in a small megacrystal granite mass, south of Little Raft Lake. Henderson (1967) did not describe the petrography of the "metagabbro," and he probably called it that on the basis of its black color. However, this mafic rock is quartz-bearing, biotite-rich (>30 vol. %), and hornblende-poor and contains sodic plagioclase (An₁₀₋₃₀), and, therefore, is not "metagabbro" but mafic tonalite. This mafic tonalite is a facies of the Chief Lake granitic complex (oral communication, A. Davidson, 1999), and the combination of the mafic tonalite, agmatite, and the megacrystal granite is referred to by him as the Raft Lake unit (Davidson, 2002).



Fig. 2. Massive, coarse, pink granite (top) overlying fine-grained mafic tonalite (black) containing scattered feldspar megacrysts. A lenticular dike-like mass of coarse granite occurs in the middle of the fine-grained mafic tonalite. Outcrop is along the northern edge of the granite body, south of Little Raft Lake (Fig. 1 and Fig. 3). For scale, the chisel is 20 cm long.

The Chief Lake granitic complex occurs in and adjacent to the Grenville Front, which is a wide quasi-boundary zone between strongly deformed Grenville rocks and older Huronian metasedimentary rocks north of the complex (Fig. 1).

Because of the strong deformation that occurs in this zone, it is logical to expect that localized metasomatic changes and recrystallization could have occurred following crystallization of the complex. Henderson's observation that K-metasomatism had occurred to produce K-feldspar megacrysts in this fine-grained tonalite of the Chief Lake complex (Fig. 2) bears consideration. Evidence supporting K-metasomatism in tonalite near Little Raft Lake is given below.

LITTLE RAFT LAKE AREA

Large enclaves in granite

Fine-grained, biotite-rich, mafic tonalite masses, as much as 150 meters long and 20 or more meters wide, occur as enclaves in a megacrystal granite south of Little Raft Lake (Fig. 3); enclaves are not shown on figure because of scale. In these places agmatitic, white to gray, coarse-grained, felsic tonalite patches, devoid of K-feldspar and generally less than a meter wide, are intermingled with the mafic tonalite (Fig. 4). Curved veins of felsic tonalite extend from these patches, gradually narrowing and disappearing in the mafic tonalite. The contacts are commonly cusped and sharp (Fig. 4), but in a few places are jagged (Fig. 5). Although the felsic tonalite pinches out in narrow curved veins in the mafic tonalite, it is difficult to determine relative ages of the two magmas. Outside the Little Raft Lake area evidence of magma commingling is present where a finer-grained chill zone in the mafic tonalite against the felsic tonalite suggests that hotter mafic tonalite was injected into cooler felsic tonalite; see Davidson (2002, Fig. 3C).

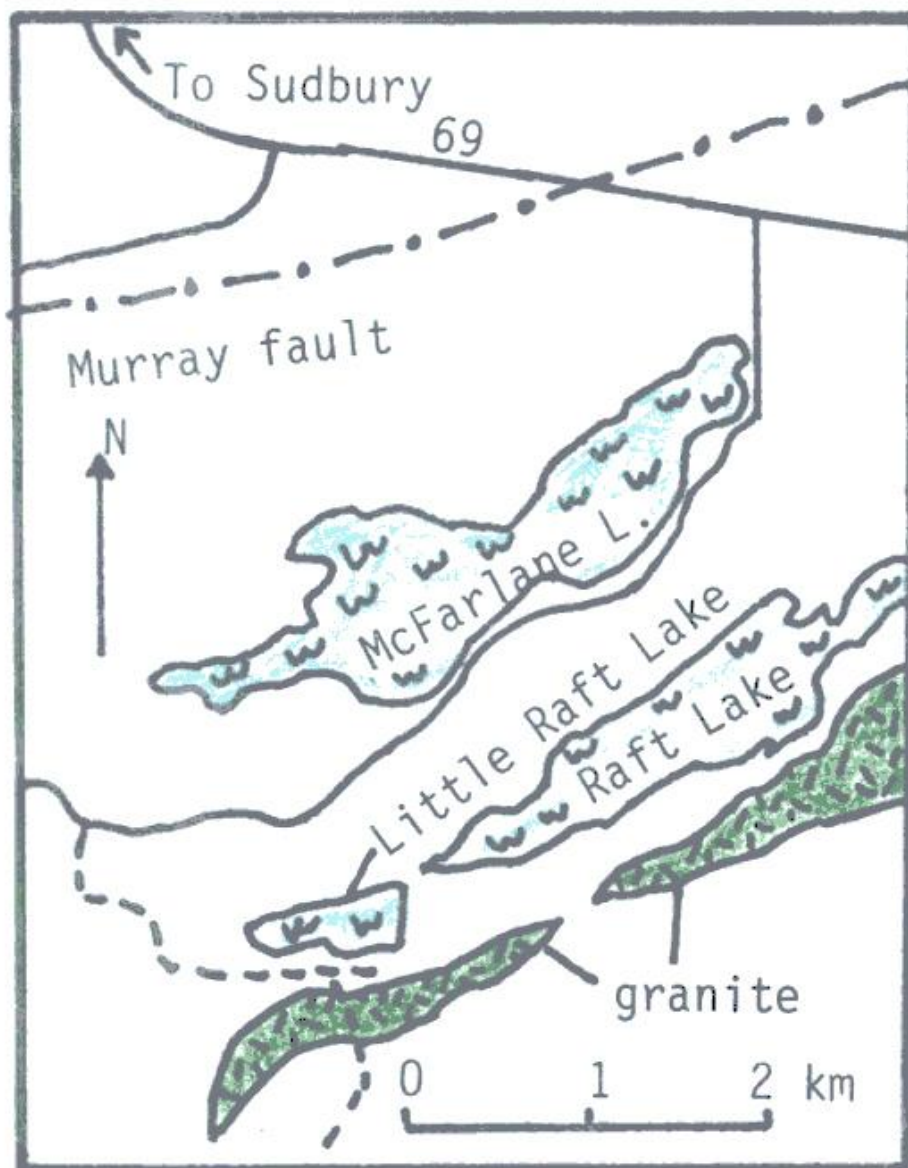


Fig. 3. Simplified geologic map, showing granite (light green, randomly dashed lines) containing large agmatite enclaves (not shown), that occurs south of Little Raft Lake. This granite body occurs along the north edge of the Chief Lake granitic complex (after Davidson and Ketchum, 1993) and also includes felsic and mafic tonalite. Other rock types bordering the granite body have been omitted from the map. Figures 2 and 4-16 show (a) images of outcrops on the north edge of a ridge west of the gravel road (dashed line) that traverses the granite body and (b) photomicrographs of thin section textures in samples collected in this same area.

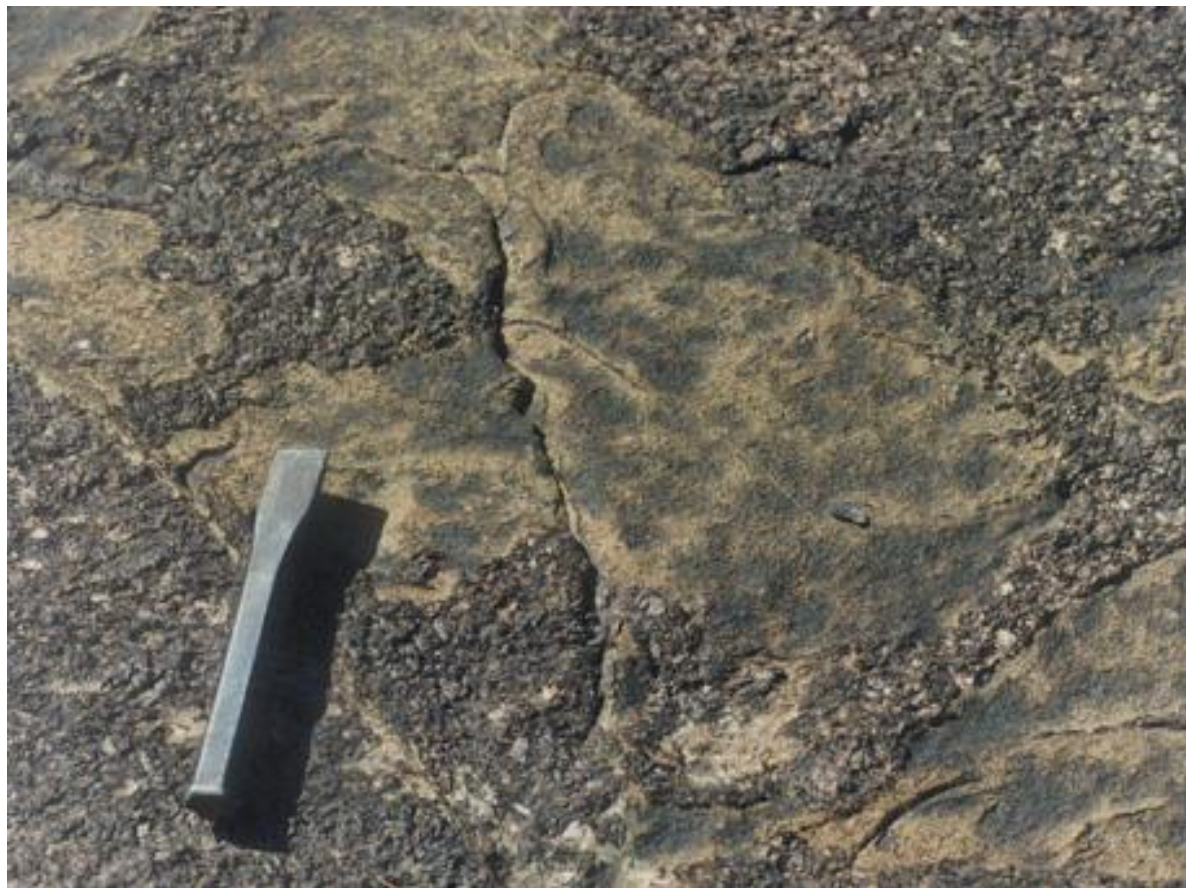


Fig. 4. Fine-grained, mafic tonalite (tan and black) intermingled with curved, white, coarser-grained, felsic tonalite crusted by a dark alteration surface. Chisel is 20 cm long.

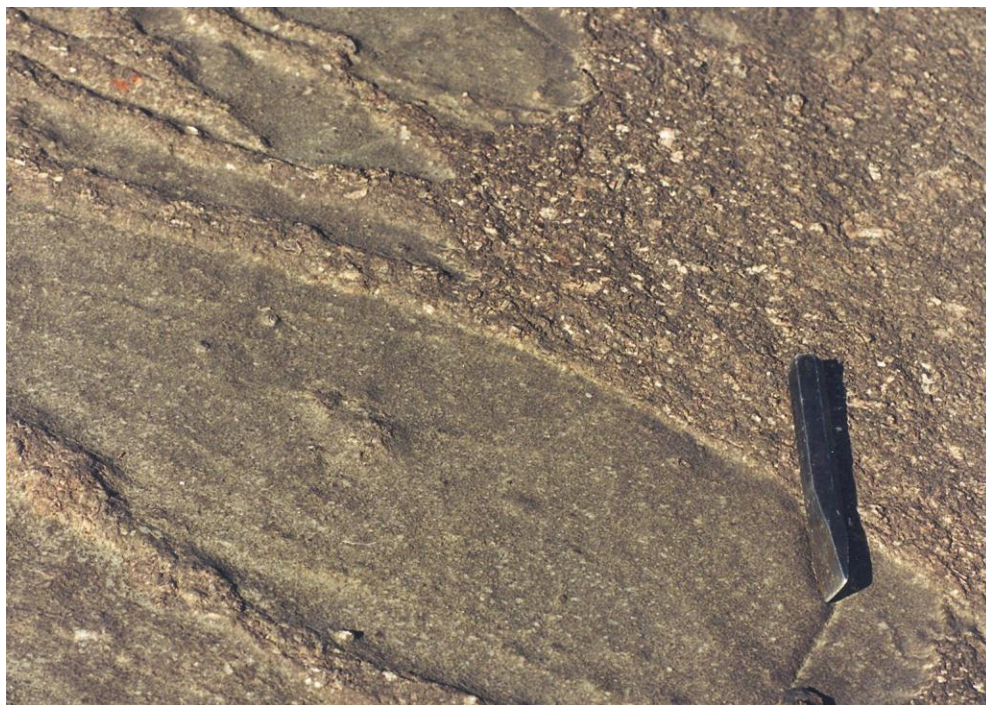


Fig. 5. Fine-grained mafic tonalite interfingering with coarser-grained felsic tonalite, perhaps as co-mingling magmas.

Where the mafic tonalite is slightly coarser grained, hornblende is present. Isolated, pink crystals (0.5 cm long) in this coarser mafic tonalite are sericitized plagioclase rather than pink K-feldspar. Locally, gradations occur from fine-grained, hornblende-bearing, biotite tonalite to hornblende-absent, biotite tonalite, containing plagioclase phenocrysts that gradually increase in abundance (up to 50 volume percent) and size (up to 2 cm long; Fig. 6). (Davidson (2002) also reported that interior parts of the mafic tonalite masses grade to hornblende gabbro that contains relict augite.) In some places accessory magnetite grains are bordered by titanite rims. The plagioclase is sodic (An_{10-20}) and slightly zoned. Minor quartz and epidote are present.



Fig. 6. Concentrations of megacrysts of plagioclase in a dark, fine-grained biotite tonalite. A late chloritized, mylonitized shear zone cuts through the rock above the Canadian penny.

In some non-agmatite places, the fine-grained mafic tonalite contains isolated, scattered, large pink feldspar megacrysts. Some of them are pink microcline instead of plagioclase (Fig. 7 and Fig. 8), and locally, the pink microcline crystals are rimmed by white plagioclase (Fig. 9 and Fig. 10).



Fig. 7. Close up of the middle portion of Fig. 2, showing a coarse granite lens (top), mafic tonalite (middle) containing plagioclase and microcline megacrysts, and fine-grained mafic tonalite lacking microcline megacrysts (bottom). Canadian penny for scale.



Fig. 8. Fine-grained mafic tonalite containing scattered microcline megacrysts replacing plagioclase crystals. This rock is about 30 meters southwest from photo in Fig. 2. Chisel is 20 cm long.



Fig. 9. An isolated feldspar megacryst from same area as in Fig. 8. Note pink K-feldspar core and white plagioclase rim. Canadian penny for scale.



Fig. 10. Outcrop. At the top is fine-grained mafic tonalite; in the middle, coarser mafic tonalite containing intermediate-sized feldspar megacrysts with pink microcline cores and white or gray plagioclase rims; and at the bottom, coarse pink granite. This exposure is on the northwest (back-right) side of the same outcrop shown in Fig. 2. Chisel is 20 cm long.

Xenocrysts of plagioclase and quartz

Because of the contrast between the tiny white plagioclase laths in the fine-grained mafic tonalites in the Little Raft Lake area and the large isolated pink feldspar crystals (Fig. 7, Fig. 8, Fig. 9, and Fig. 10), these megacrysts are likely xenocrysts that "floated off" from a felsic magma and mixed into the mafic magma during magma commingling (in the manner described by Pitcher, 1997, p. 127-129; personal communication, Davidson, 1999; Davidson, 2002). Moreover, associated subhedral quartz crystals may also be xenocrysts. These quartz crystals are surrounded by reaction rims of crudely radiating green amphibole (Fig.11). Where the feldspar megacrysts are plagioclase, they have clear, oscillatory-zoned cores lacking albite twinning, surrounded by a broad zone (within the original grain outline) that has a peculiar mottled texture (Fig. 12). This mottled zone consists of myrmekite aggregates with very tiny quartz vermicules which are intermeshed with tiny amphibole crystals (Fig. 13).

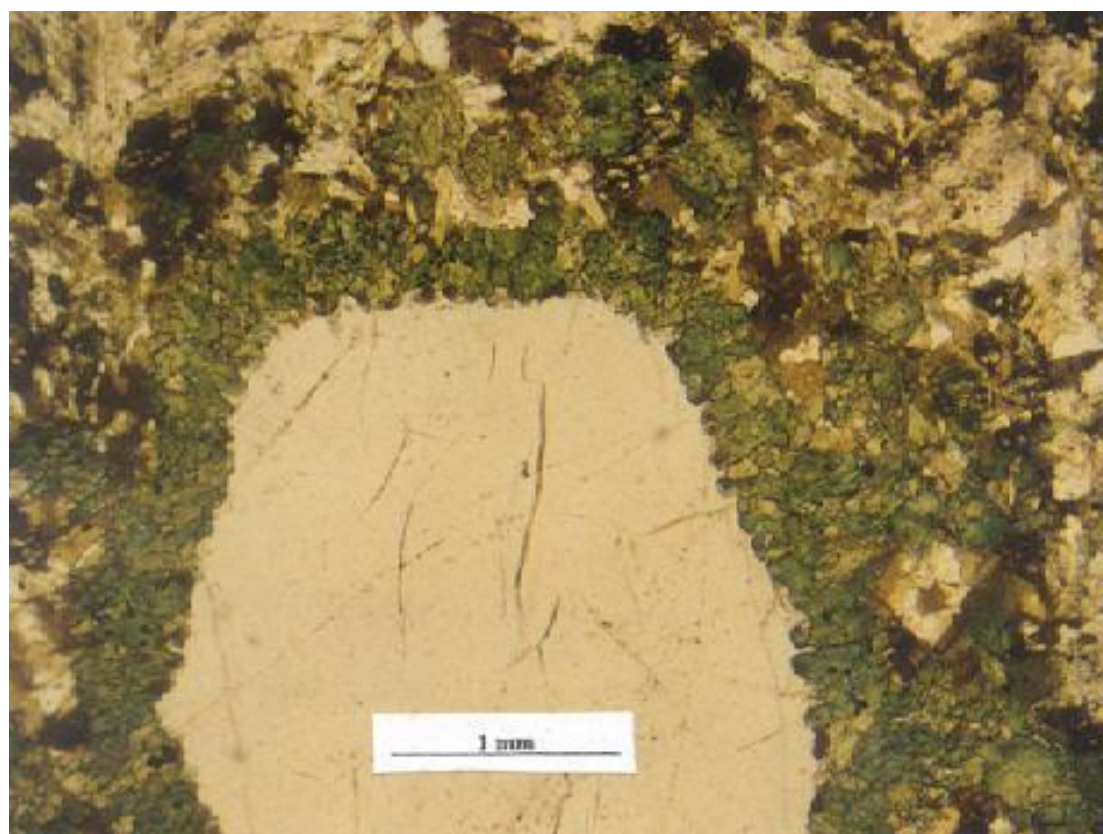


Fig. 11. Photomicrograph (100x) in plane light of a quartz xenocryst with a reaction rim of tiny green amphibole crystals in a ground mass of fine-grained biotite, hornblende, quartz, and sodic plagioclase in mafic tonalite. Thin section from a sample collected obtained by A. Davidson.

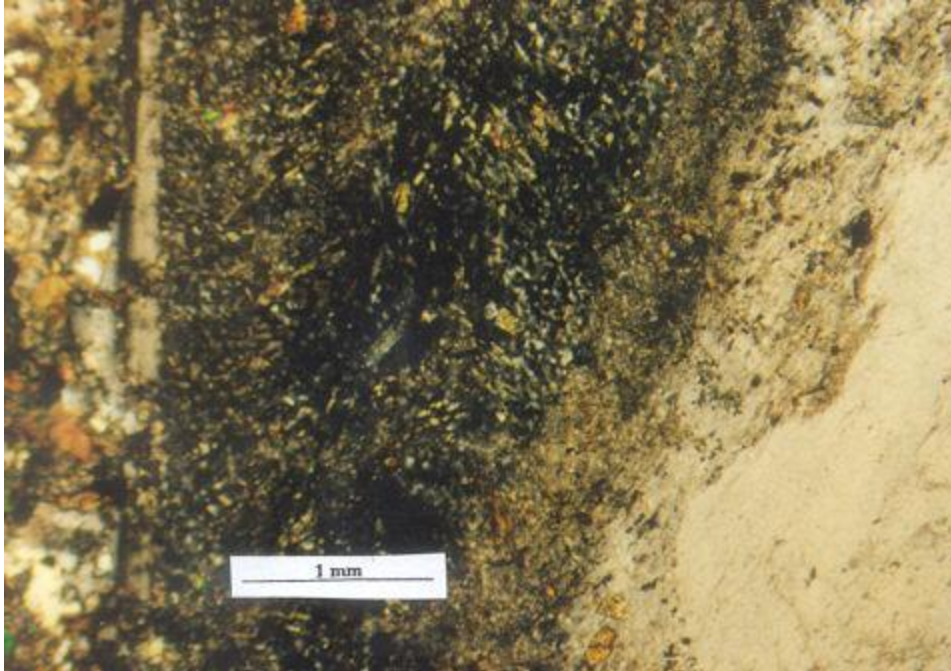


Fig. 12. Photomicrograph (100x). Unaltered sodic plagioclase core (right side) is bordered by two narrow zones of altered plagioclase (brownish), showing progressive early stages of losing sodium and being replaced by calcium and aluminum. Farther to the left in the center (black) is a broad zone containing myrmekite and traces of amphibole laths. Against the myrmekite zone (left side) is a thin unaltered plagioclase rind, outlining the shape of the former shape of the plagioclase crystal. Farthest to the left is the host, fine-grained, mafic tonalite containing plagioclase, biotite, and hornblende.

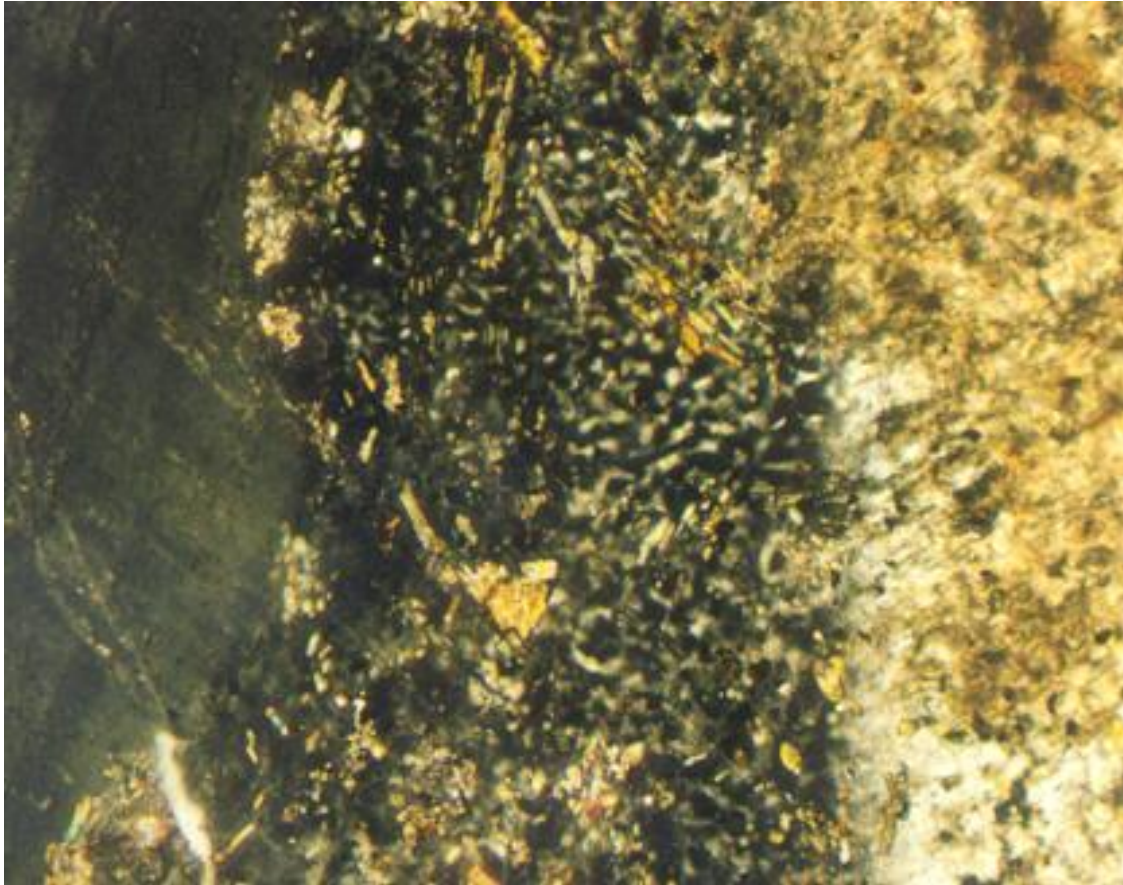


Fig. 13. Photomicrograph (400x) of myrmekitic zone adjacent to unaltered sodic plagioclase core (gray to black).

In some places the myrmekitic zone encloses remnants of the unaltered plagioclase core having parallel optical continuity (Fig. 14). Outside this myrmekitic zone is a very narrow, clear, normally-zoned growth rim of plagioclase (albite-oligoclase) adjacent to the rock matrix (Fig. 12). The matrix, itself, is "messy," with clear, twinned, relatively calcic plagioclase laths and their altered equivalents, plus ragged biotite, amphibole, opaque oxide with titanite rims, and secondary epidote. These mineral relationships and textures support the hypothesis that the large plagioclase crystals (1 to 2 cm long) are xenocrysts for the following reasons.

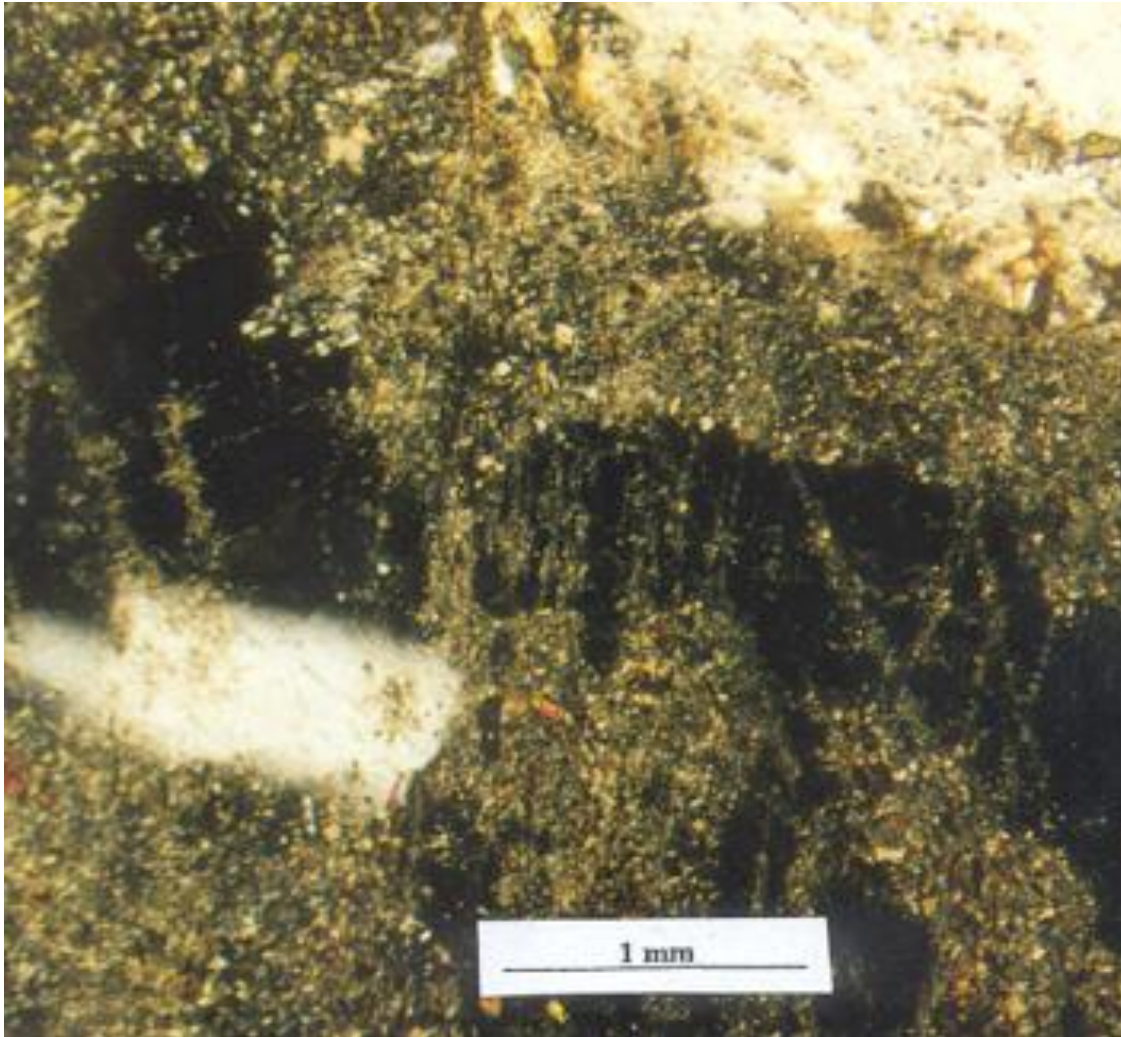


Fig. 14. Photomicrograph (100x) of island remnants of unaltered, optically-continuous, sodic plagioclase (black and small white area) in a sea of myrmekite and tiny amphibole needles (brownish).

Because the mafic tonalite is slightly more calcic than the felsic tonalite; as indicated by the presence of amphiboles in the mafic tonalite and their general absence in the felsic tonalite, the floating-off of quartz and plagioclase crystals from a felsic magma into a mafic tonalite magma would result in reaction rims between these introduced foreign crystals and the more calcium-rich mafic magma. The Ca-bearing amphibole crystals, needing silica, would nucleate around the quartz crystals (Fig. 11). The introduced, oscillatory-zoned, more-sodic, plagioclase crystals with even more-sodic rims would be out of equilibrium in the higher-temperature, more calcium-rich, mafic magma. Therefore, calcium and some aluminum in this magma would replace some of the sodium and silicon in the sodic plagioclase crystals, and this Ca-metasomatism would be from the

exterior of the crystals inward. The result would be a relatively more-calcic plagioclase border-zone surrounding unaltered cores. However, because the more-calcic plagioclase requires less silica in its structure than is present in the more-sodic plagioclase, silica is left over to form tiny quartz vermicules in myrmekite (Fig. 13). See Collins (1997d; <http://www.csun.edu/~vcgeo005/Nr4CaMyrm.pdf>) for other kinds of myrmekite production during Ca-metasomatism.

The introduction of small amounts of iron and magnesium with the calcium and aluminum into the sodic plagioclase would also result in scattered tiny amphibole crystals that would use up some of the released silica rather than forming quartz vermicules. This would explain why quartz vermicules in the peculiar mottled zone in the plagioclase xenocrysts are very tiny and not always readily visible.

Xenocrysts of K-feldspar?

If the large plagioclase crystals are xenocrysts, are the coexisting large K-feldspar crystals also xenocrysts that floated-off from the felsic magma? Or, could they be primary phenocrysts in the mafic tonalite? Or, alternatively, could they be xenocrysts of primary plagioclase crystals that have been replaced by microcline?

That the large K-feldspar crystals are **not** primary orthoclase phenocrysts that crystallized from mafic tonalite magma and which later were inverted to microcline can be ruled out as former phenocrysts for the following reasons. (1) The dominant feldspar species in the fine-grained mafic tonalite is plagioclase, and (2) no K-feldspar also occurs interstitially in the ground mass as would be expected if the K-feldspar megacrysts were primary and crystallized when the cooling mafic magma reached the solidus at eutectic conditions. Therefore, the large K-feldspar crystals must have formed by some secondary process.

If the K-feldspar megacrysts were xenocrysts of primary K-feldspar, floated-off from the same felsic magma that also released the above subhedral quartz and relatively large plagioclase xenocrysts, then they should have been former zoned orthoclase and have evenly distributed albite perthite lamellae, and *that is not the case*. Moreover, if large orthoclase crystals were floated-off from a *hornblende-free*, felsic magma, they should *not* enclose hornblende crystals like those found in the mafic tonalite, and *they do*. Furthermore, their borders should be sites (sources of potassium) where biotite crystals would nucleate from mafic magma, and that is not the case. Finally, although myrmekite occurs on the borders of some of the large K-feldspar crystals, this myrmekite differs from that found on the borders of

the large plagioclase crystals. If the myrmekite were formed by Ca-metasomatism of K-feldspar xenocrysts (like that for plagioclase in Fig. 12 and Fig.), then the myrmekite should occur in aggregate masses that surround the K-feldspar crystals on all surfaces. Instead, the myrmekite grains on the borders of the K-feldspar crystals are generally few and isolated, and the plagioclase of the myrmekite is in optical continuity with adjacent, larger, quartz-free plagioclase outside the K-feldspar crystals. If the myrmekite grains bordering the K-feldspar megacrysts were formed by exsolution from a former orthoclase xenocryst, then the dominant feldspar in the megacrysts should be K-feldspar, and that is not the case in all places. For example, where K-feldspar first appears in plagioclase megacrysts, it occurs as irregular islands in the interiors where microfracturing of the plagioclase permitted introduction of K-bearing fluids.

Therefore, on the basis of all the above reasons, the microcline megacrysts in the fine-grained mafic tonalite (Fig. 5, Fig. 7, Fig. 8, and Fig. 9) cannot be xenocrysts or primary orthoclase phenocrysts that inverted to microcline. Some of them must have formed by K-replacements of former plagioclase crystals (xenocrysts) that floated-off from a felsic magma, while others must have also formed by K-replacement of deformed ground mass plagioclase crystals in the mafic tonalite that are interlocked with hornblende and/or biotite crystals. Photomicrographs that show textures which support K-metasomatism as a means of producing the K-feldspar are provided in a later section.

Kinds of deformation in the rocks

The different rocks in the "granite" mass south of Little Raft Lake (Fig. 3) have been subjected to different kinds of deformation which have affected the ways in which their minerals and textures have been modified. A late deformation cuts through all the rocks in the Chief Lake complex, locally creating narrow, mylonitized, shear zones (Fig. 6) or broad mylonitic shear zones (tens of meters wide) that are associated with thrust faults in the Grenville Front (Davidson, 2002). This late deformation creates mineralogical and textural changes that are unrelated to earlier kinds of deformation, and these mylonitic rocks are not further discussed.

Much of the fine-grained mafic tonalite in the agmatite and adjacent large mafic enclaves is not deformed, but some coarse-grained felsic rocks in the agmatite, some parts of the mafic tonalite in the large enclaves containing large K-feldspar crystals, and large portions of the large felsic mass surrounding the large mafic enclaves are cataclastically deformed in early episodes of deformation. Deformation in these places is not planar and mylonitic, as in Fig. 6, but a cracking

and jostling of grain fragments with little to no lateral translation. Moreover, this kind of cataclasis occurs in the pink coarse-grained, microcline-bearing, quartz-monzonite agmatite patches and not in the white coarse-grained felsic tonalite veins which extend from the pink patches into the enclosing undeformed mafic tonalite (Fig. 4 and Fig. 5). In the fine-grained mafic tonalite, the tiny laths of white, sodic plagioclase grains occur in random orientation and show no outward signs of recrystallization or deformation. In each rock type where the early deformation has occurred, K-metasomatism has modified the composition of the rocks. In the following sections, evidence in photomicrographs for K-metasomatism is examined (1) in the felsic tonalite in the agmatite, (2) in the mafic tonalite in the large enclaves, and (3) in the large mass of coarse-grained felsic tonalite surrounding the large enclaves.

K-metasomatism in felsic tonalite in agmatite

The veins and patches of felsic tonalite in the agmatite in the Little Raft Lake area (Fig. 3) locally grade from white in the narrow veins to pale pink in the larger patches (Fig. 4; unfortunately, the pink color cannot be seen in the photo). When seen in thin section, these pink patches are cataclastically deformed and contain microcline, thereby converting the former white felsic tonalite into quartz monzonite or granite. In these places in a given thin section, undeformed Carlsbad-twinned plagioclase crystals are devoid of microcline, whereas adjacent Carlsbad-twinned plagioclase of the same size that are slightly microfractured have irregular islands of microcline randomly scattered throughout the crystals; or, in some places, in one half of a twin but not the other. Still other Carlsbad-twinned crystals of the same size are almost entirely microcline (Fig. 15 and Fig. 16) and locally are bordered by wartlike myrmekite with tiny quartz vermicules (not shown in Figs. 15 and 16).

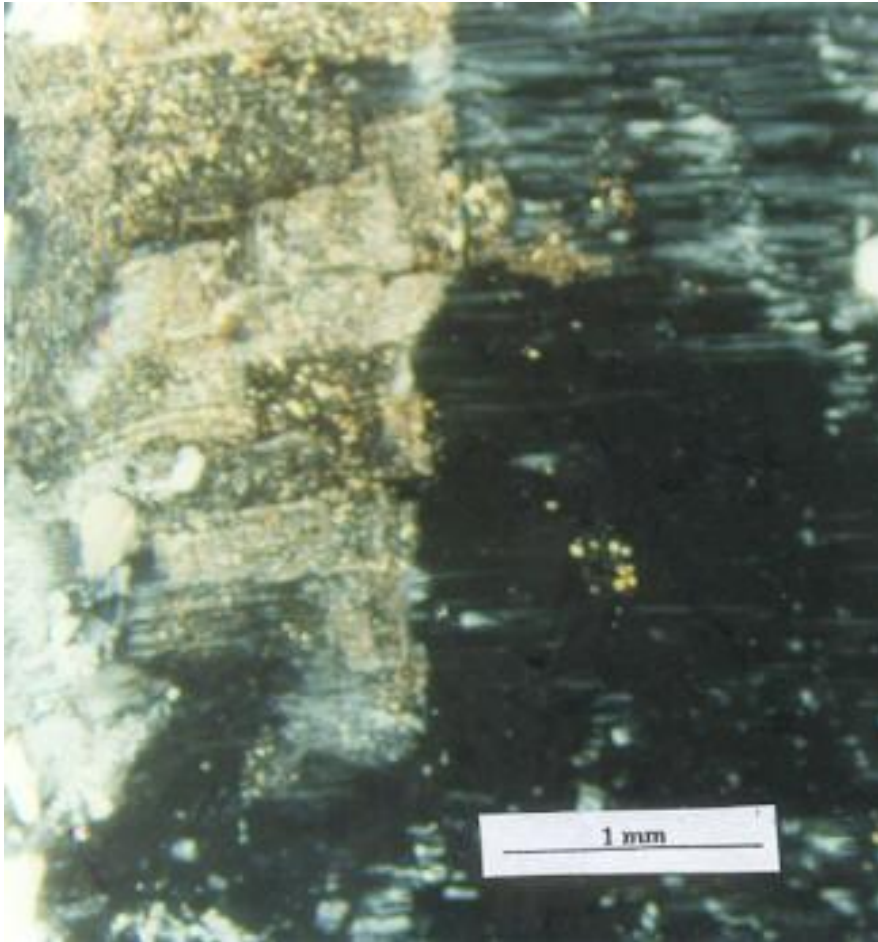


Fig. 15. The altered plagioclase grains (brown speckled; albite-twinned; left side) were likely part of a former larger plagioclase crystal before being broken into smaller blocks. This crystal would have extended into the area now occupied by microcline (black; right side). A relatively sharp boundary occurs on the photo from the top vertically downward between the plagioclase (left side) and the microcline (right side), black and gray). However, a portion of the speckled-brown plagioclase projects into the dark microcline as an irregular pointed remnant that sticks out from the vertical edge. This remnant suggests that K-replacement of adjacent plagioclase has occurred because such textures are not commonly seen where both feldspars crystallize from melt. In the lower left corner of the photo, the microcline (black) can be seen to penetrate (upward and to the left) into the altered plagioclase along an irregular fracture. In the microcline (right side), island remnants of plagioclase with albite-twin lamellae are aligned parallel with the twin lamellae of the speckled grains outside the microcline (left side), and still more aligned remnants are abundant beyond what is seen in the photograph.

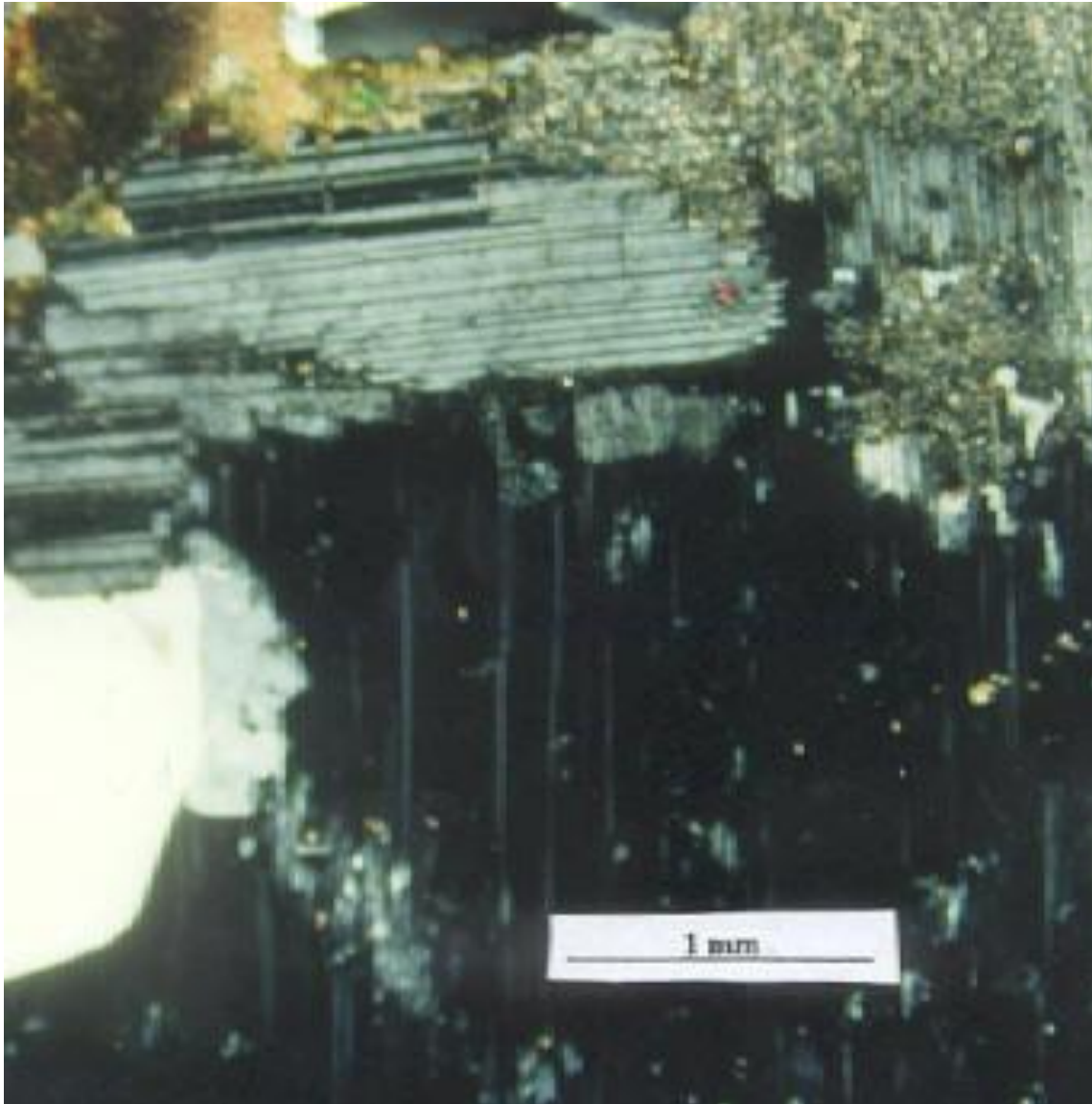


Fig. 16. An albite-twinned plagioclase grain (top center with horizontal twin lamellae) is penetrated by microcline (black) along the lower edge and then upward along an irregular fracture at the right end. Remnant albite-twin lamellae project like teeth of a comb into the microcline (black) at the right end of this plagioclase crystal.

Because of the restriction of the microcline to pink felsic patches in the agmatite and not in white veins extending from these patches, it is unlikely that the microcline was formed during the initial magma commingling between the mafic and felsic parts of the agmatite. (This correlation between color, deformation, and the presence of K-feldspar is supported by the absence of K-feldspar in white felsic patches and veins in undeformed agmatite near Wavy Lake, discussed in a later

section.) Regardless of whether felsic magma with K-feldspar crystals was injected into a mafic magma or vice-versa, such K-feldspar crystals should be expected to occur in *both* the felsic patches and their connecting veins, if the K-feldspar were crystallized from the original melt, and they do not.

In the transition from the white veins to the pink patches, the first appearance of microcline is in irregular interior islands in microfractured albite- and Carlsbad-twinned plagioclase grains. These microcline islands are not systematically distributed but occur randomly in the cores or on one side of a plagioclase crystal and not the other. These relationships are *atypical* of K-feldspar-plagioclase intergrowths in magmatic rocks where relatively uniform distributions of both feldspars within a crystal are found as perthitic lamellae or where early-formed plagioclase crystals with well-developed faces are enclosed in the later-formed larger K-feldspar crystals.

Significantly, farther into the pink patches away from the white veins where the K-metasomatism of the plagioclase is more advanced and forms the microcline megacrysts, the tiny irregular islands of plagioclase enclosed in the microcline are not oriented in concentric zonal patterns from cores to rims in which the longer dimensions of the plagioclase crystals are aligned parallel to possible faces of orthoclase phenocrysts growing in a melt. Instead, the parallelness of lattice structures in these irregular islands is with the lattice structure in remnant plagioclase grains outside the microcline (Fig. 15 and Fig. 16). Such relationships provide support for the metasomatic origin of these microcline-plagioclase intergrowths.

K-metasomatism in mafic tonalite in the large enclaves

Outcrops of the mafic tonalite that contain scattered plagioclase and microcline megacrysts look massive and undeformed (Fig. 8 and Fig. 9). Nevertheless, thin sections of mafic tonalite samples that have microcline megacrysts show these tonalites are cataclastically broken, *whereas thin sections in mafic tonalite lacking microcline megacrysts but containing plagioclase megacrysts, show that such tonalites lack cataclasis*. In transitions to tonalites showing increasing amounts of cataclasis, the plagioclase grains show increasing deformation (cracking) and progressive interior replacement by microcline.

In the mafic tonalite, as in the felsic veins in the commingled agmatite, wartlike myrmekite occurs in some places on the borders of the plagioclase remnants adjacent to the microcline megacrysts. In addition, some plagioclase

islands enclosed in the microcline contain ovoid quartz blebs of the same maximum size as the tiny quartz vermicules in the myrmekite (Fig. 16); see "*ghost myrmekite*" in Fig. 11 of Collins (1997b; <http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf>) and Hunt et al., (1992) and Collins (1988).



Fig. 11 in Nr2Myrm.pdf. "*Ghost myrmekite*" also occurs in this photomicrograph of Rubidoux Mountain leucogranite. At the extinction position for microcline (black), clusters of quartz blebs (white) occur in faint traces of remnant plagioclase or as isolated oval islands in the microcline. The maximum sizes of the quartz blebs in the microcline match the maximum diameters of quartz vermicules in myrmekite (left side) where plagioclase is white and quartz vermicules are gray.

All these textural relationships suggest that the microcline megacrysts have replaced former microfractured plagioclase grains in the mafic tonalite and could *not* have formed by inversion from primary orthoclase; see website article Collins (1998; <http://www.csun.edu/~vcgeo005/primary.htm>). In many places, replacements are so complete that little to no plagioclase remains inside the microcline grains although plagioclase remnants may be preserved along the rims (Fig. 9). Rims tend to be preserved because they are more sodic than plagioclase cores and more stable in the pressure-temperature conditions in which the K-

metasomatism occurs; see Collins (1997b; <http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf>) and Collins (1999; <http://www.csun.edu/~vcgeo005/Nr36Experimental.pdf>).

K-metasomatism in the large coarse-grained felsic tonalite body

Massive pink coarse-grained felsic tonalite that encloses the large enclaves in the Little Raft Lake area and which has been modified by K-metasomatism to form massive pink granite is illustrated in Fig. 2 (top of photo) and Fig 10 (bottom of photo). Here, primary plagioclase crystals are microfractured and penetrated to the core by microcline (Fig. 17). Similar megacrystal granite that appears outwardly undeformed in the field occurs at the southwest end of the granite (Fig. 3), and it also contains large Carlsbad-twinned microcline with islands of plagioclase in optical parallel orientation (Fig. 18 and Fig. 19).

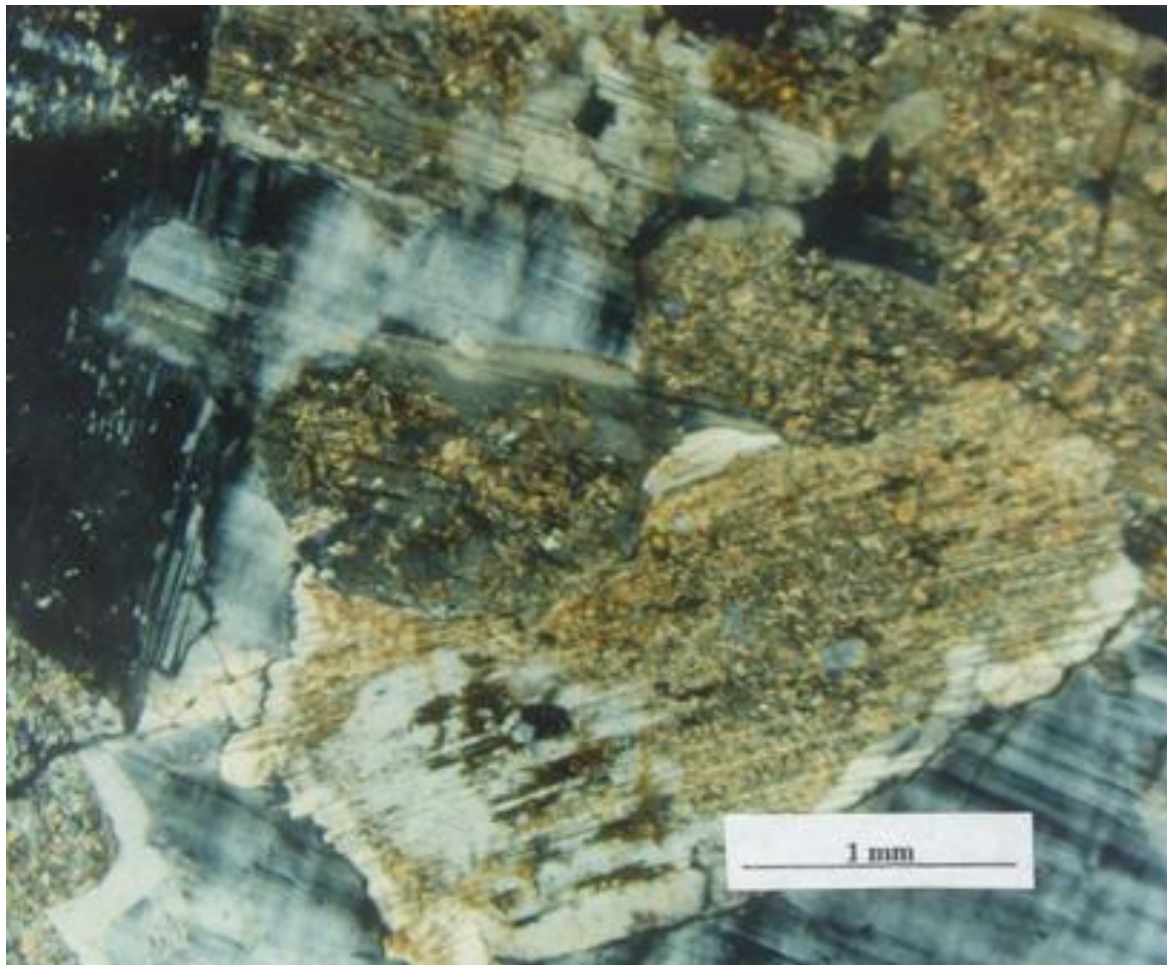


Fig. 17. Note that microcline (grid-twinning; black; upper left, center) penetrates along an irregular fracture to the core of a speckled, albite-twinned plagioclase

crystal (top center and right side). Another plagioclase grain (bottom center) has irregular projections (left end of crystal) which stick out into the adjacent microcline (bottom left). The diagonal truncation by the microcline of the albite-twin lamellae and zoning (altered albitic edge) of this same plagioclase crystal along the bottom right side suggests that a portion of this plagioclase grain has been replaced by the microcline.

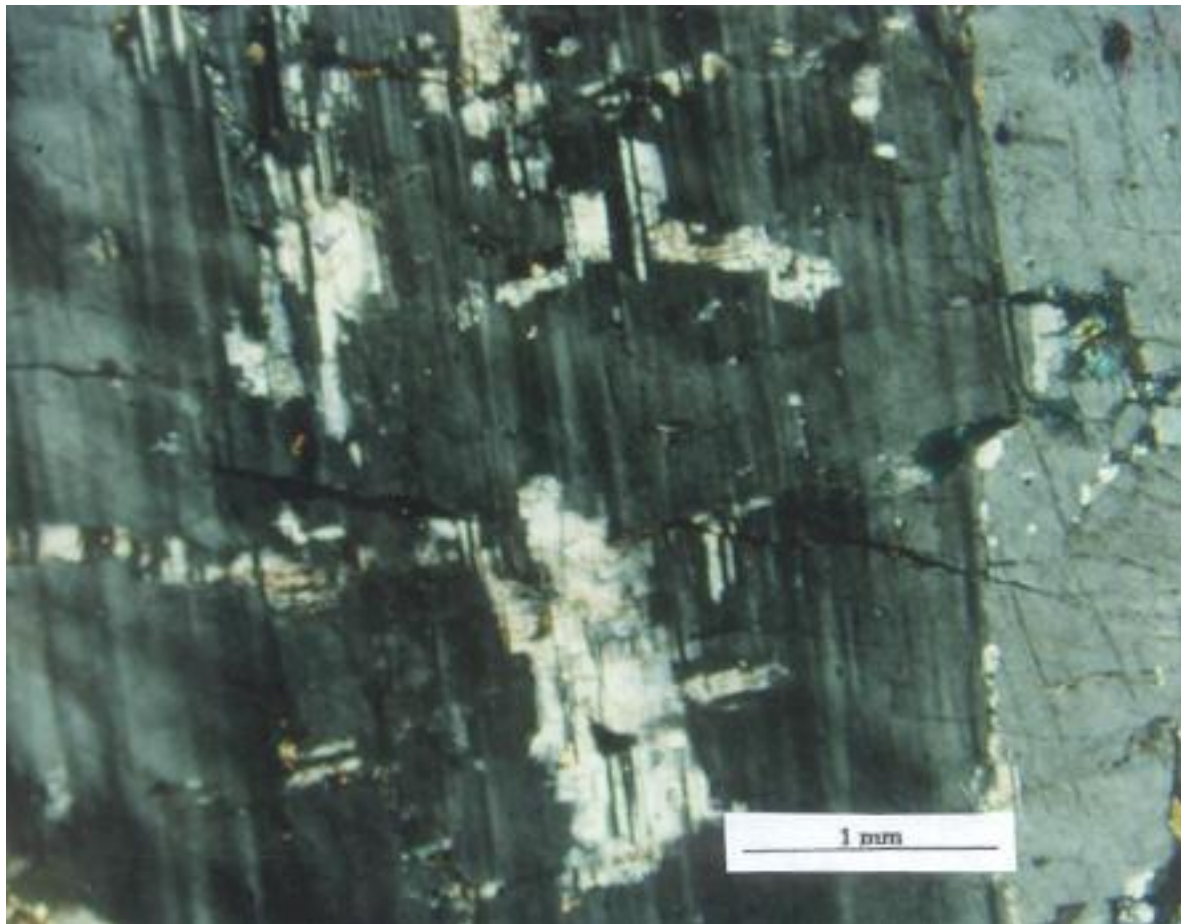


Fig. 18. Carlsbad-twinned microcline with island remnants of a former larger Carlsbad-twinned plagioclase whose albite-twin lamellae are in parallel alignment.

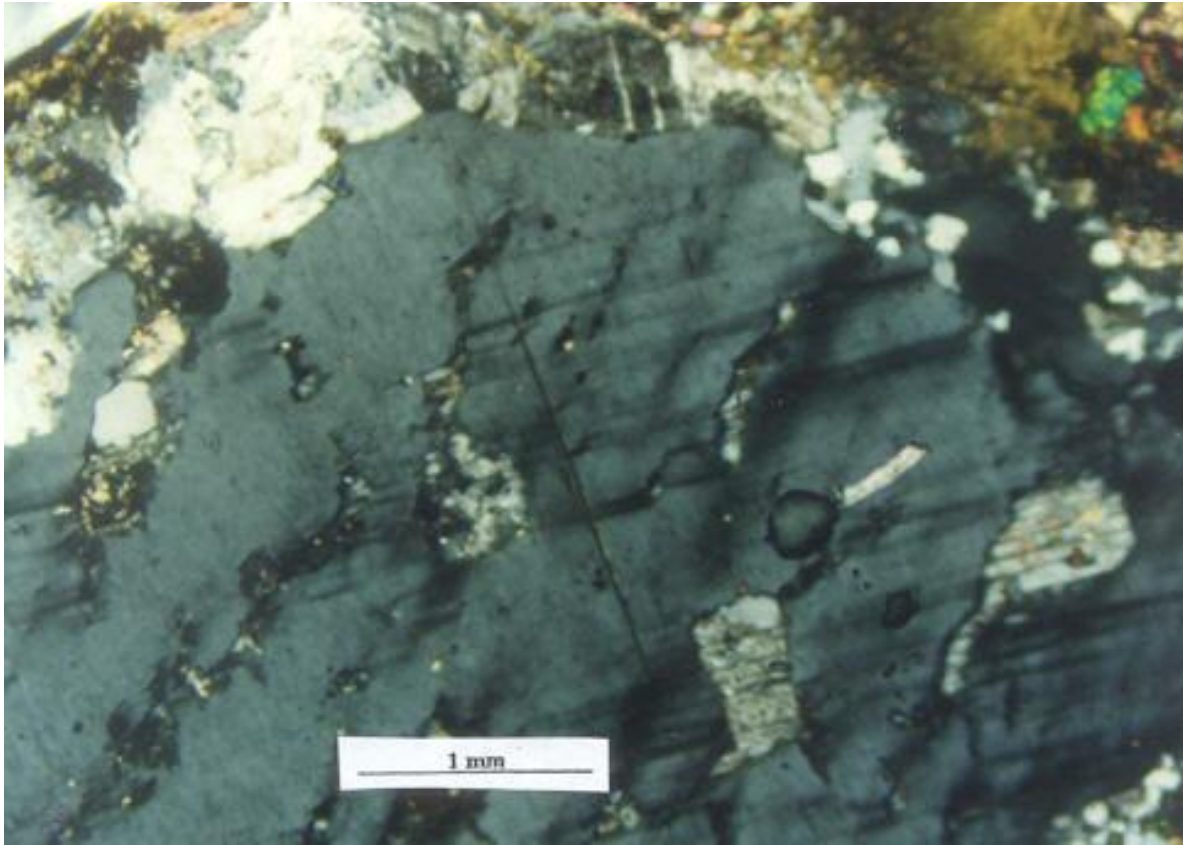


Fig. 19. Microcline projects into a crack in a bordering plagioclase grain (upper left; cream-white). Remnant plagioclase grains occur with parallel alignment. One remnant plagioclase grain (lower right side) has a long tail (lower left corner of plagioclase island) that would not be characteristic of a sub- or euhedral plagioclase crystal that had formed prior to the crystallization of a K-feldspar (orthoclase) crystal from a melt and which would grow around earlier-formed plagioclase crystals. Such a tail would not exist.

These relationships suggest a replacement origin for the megacrystal granite, called the Raft Lake unit by Davidson (2002), although initially this granite was likely emplaced as a magmatic body that crystallized as a coarse-grained, biotite-rich, felsic tonalite, similar to that shown in Fig. 6, but likely containing much less biotite. Because of the ease by which coarse-grained, biotite-bearing tonalites could have been cataclastically microfractured, the former felsic tonalite could have been converted to either quartz monzonite or granite, depending upon the degree of K-metasomatism. The slight cataclasis would make it easy for abundant fluids to move through the rocks and enable K to be shifted from the biotite to form microcline in adjacent microfractured plagioclase. Thus, the K for the metasomatism would have a very local source. The possibility that the megacrystal

granite was formerly a coarse-grained felsic tonalite is supported by the fact that both rocks are gradational to each other, and no boundary between them can be drawn in the field. Both pink rocks look the same in outcrop.

On the basis of the above studies of the felsic and mafic tonalites and their metasomatic modifications in the Little Raft Lake area, comparisons can be made with similar rocks in the Wavy Lake area (Fig. 1 and Fig. 20).

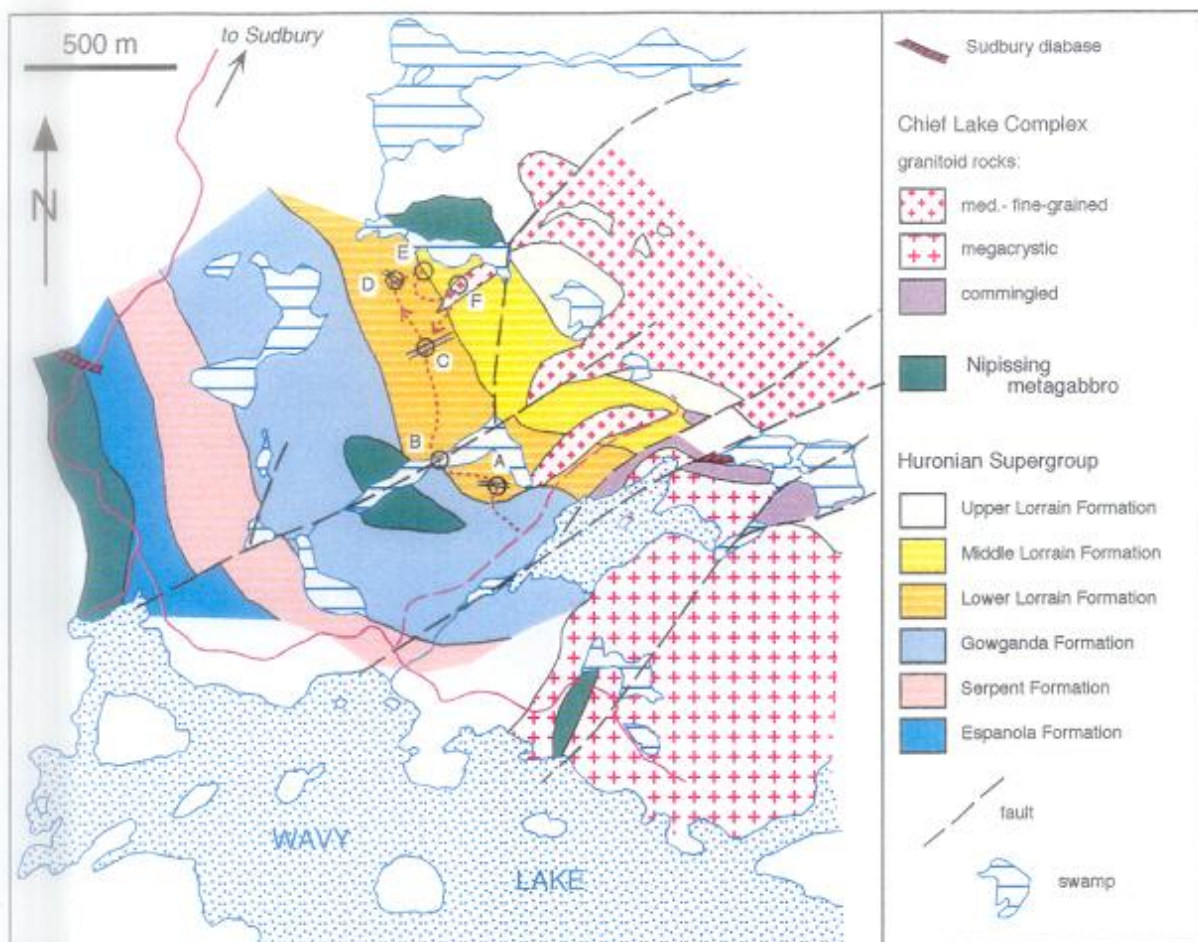


Fig. 20. Geologic map of area north of Wavy Lake, showing portions of the Chief Lake Complex (red pluses), Nipissing gabbro (dark green), the Huronian Supergroup of metasedimentary rocks (various solid colors), and commingled areas of mafic and felsic tonalites or quartz diorites (lavender). Roads are indicated by solid and dashed red lines. Route of a traverse to collecting localities is shown by a dotted red line. Sample sites mentioned in this article are for massive quartz monzonite, gneissic quartz monzonite, and fine-grained border facies (all at site F), a small granitic dike (between sites C and D), and commingled rocks (site C,

agmatite). This unpublished map was drawn by A. Davidson from his field work and aerial photography studies.

WAVY LAKE AREA

Fine-grained mafic tonalite and agmatite

As a comparison for the mafic tonalite and agmatite in the Little Raft Lake area, the characteristics of the fine-grained mafic tonalite and agmatite in the Wavy Lake area provide contrasting relationships. As in the Little Raft Lake area, in some places (site C on Fig. 20), the fine-grained mafic tonalite encloses coarser-grained felsic tonalite along irregular curved (cusped) surfaces in agmatite (Fig. 21).



Fig. 21. Mafic tonalite (black, fine-grained) and felsic tonalite (grayish white, coarse-grained; raised weathered surface crusted with a dark tarnish) are intermingled to form agmatite in an area north of Wavy Lake (Fig. 20). Chisel is 20 cm long.

The fine-grained mafic tonalites vary in composition from place to place, but generally are quite rich in biotite (>30 vol. % or more). Where the mafic tonalite is slightly coarser grained, it also contains hornblende. The plagioclase is commonly sodic (oligoclase, An₂₀₋₃₀, but can be albite (An₁₀₋₂₀). Quartz occurs in some samples but not others. Epidote is locally abundant (>50 vol. %), but generally is about 5 vol. %. Titanite and magnetite are accessories. K-feldspar (microcline) is generally absent, but occasionally occurs interstitially (less than 1 mm in diameter) in trace amounts and lack myrmekite borders. This microcline could have once been primary orthoclase.

The coarse-grained felsic tonalite veins and patches that are enclosed in the dark mafic tonalites of the commingled rocks with curved contacts (Fig. 21) are white to gray because of the abundant white plagioclase crystals. K-feldspar is absent. These plagioclase crystals have both albite- and Carlsbad-twinning, are strongly zoned, and have relatively more-calcic cores although still being quite sodic. Hornblende is absent, but biotite is still relatively abundant but not as abundant as in the adjacent finer-grained mafic tonalites.

Absence of evidence for K-metasomatism in agmatite in the Wavy Lake area

Unlike the Little Raft Lake area, the white, coarse-grained felsic tonalite patches and curved veins in agmatite in the Wavy Lake area are undeformed and contain no pink microcline or myrmekite. Therefore, there is no evidence for K-metasomatism in agmatite in the Wavy Lake area. However, locally the fine-grained, mafic, non-agmatitic tonalite contains a few isolated plagioclase and microcline megacrysts. The microcline megacrysts have unusual patchy plagioclase intergrowths (Fig. 22) that are not characteristic of orthoclase (inverted from microcline) in which simultaneous crystallization of orthoclase and plagioclase in magma results in exsolution spindle lamellae in perthites. Therefore, because of the absence of spindle lamellae and the presence of plagioclase patches in parallel optical orientation, these microcline megacrysts are suggested to result from K-metasomatism along former fractures in plagioclase *xenocrysts* that floated-off from felsic tonalite magma, as in the Little Raft Lake area.

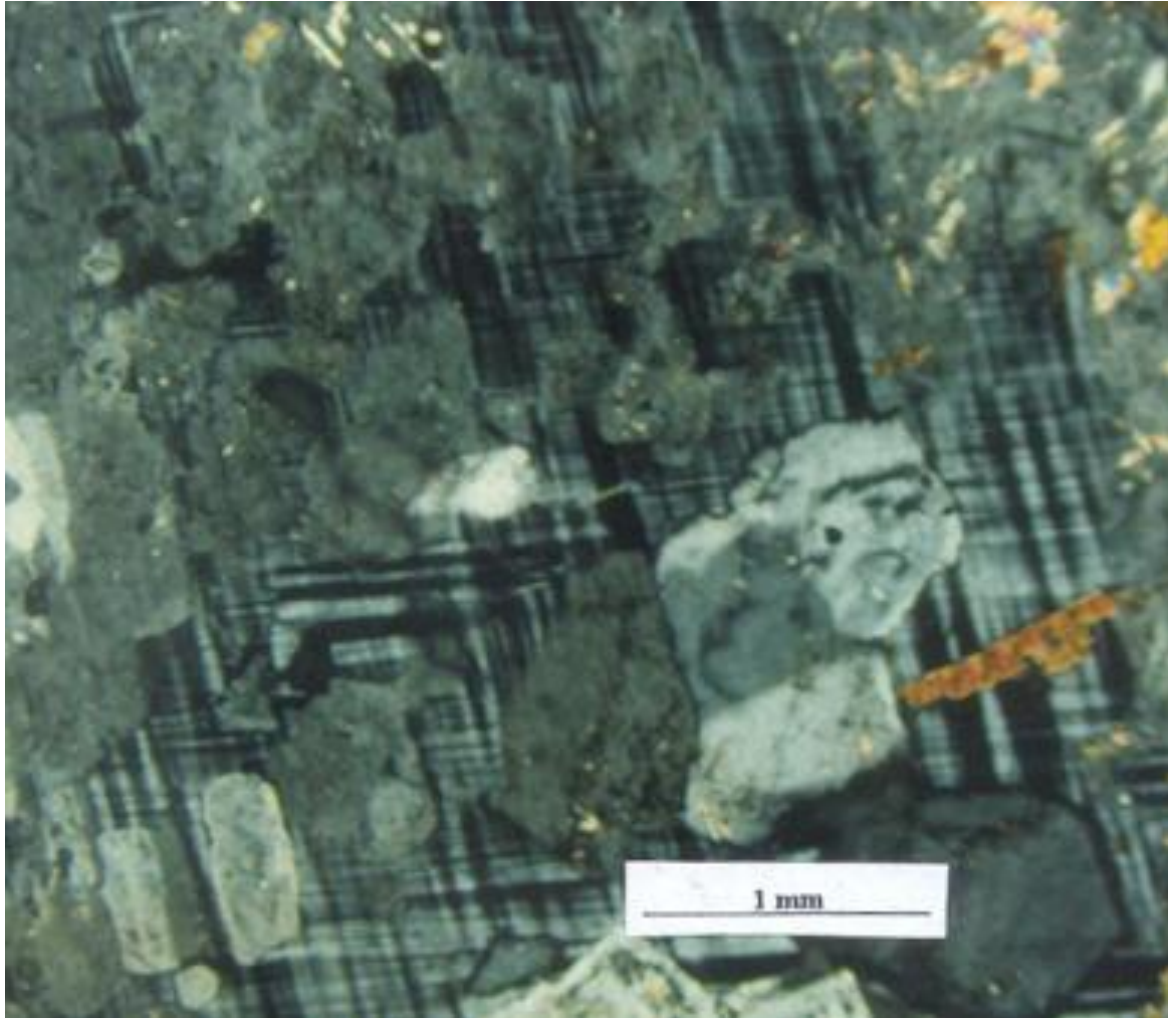


Fig. 22. Portion of plagioclase phenocryst (gray), containing microcline (grid-twinning) in an irregular, patch, network, possibly extending along former fractures in the plagioclase crystal.

The absence of microcline and myrmekite in the coarse-grained felsic tonalite in the agmatite (Fig. 21) and the absence of any deformation in both the coexisting mafic and felsic tonalites in this Wavy Lake area in comparison to the presence of microcline and myrmekite in deformed rocks in the Little Raft Lake area lend support to the hypothesis that the K-metasomatism is a common result that follows deformation of former biotite-rich magmatic rocks. The deformation would have allowed introduction of hydrous fluids to facilitate the metasomatism. On that basis, deformation of other solidified, biotite-rich tonalite or quartz diorite in the Chief Lake complex would also be expected to allow K-metasomatism, causing some of the plagioclase to be replaced by microcline and myrmekite and

converting the rocks into quartz monzonite or granite. Examples are described below.

K-metasomatism in granitic rocks of the Wavy Lake area

Similar K-metasomatism occurs in the much larger cataclastically deformed mass of quartz monzonite of the Chief Lake complex (Fig. 1 and Fig. 20). Protrusions and dikes of this quartz monzonite into the metasedimentary wall rocks are shown in the right-center and site F of Fig. 20 and include (a) massive, undeformed, quartz monzonite, (b) gneissic portions of this granitic rock, (c) a finer-grained border facies, and (d) pinkish granitic dikes (too small to map, between C and D, Fig. 20).

Feldspars in the granitic rocks.

The granitic rocks show different kinds of replacement features in the feldspar, depending upon the grain size, composition, structural relationships, and degrees of deformation of the granitic rocks.

(a) Massive quartz monzonite.

In the massive, coarse-grained quartz monzonite (Fig. 20, site F), albite- and Carlsbad-twinned plagioclase crystals are replaced both in their interiors by islands of microcline (Fig. 23) and along borders of veins of microcline in fractures (Fig. 24). It is illogical that this microcline crystallized from magma in the core of this plagioclase crystal (Fig. 23) because the dominant feldspar in the quartz monzonite is plagioclase and not K-feldspar and *because relatively calcic plagioclase should form first from a magma* and become the cores of larger plagioclase crystals, *not microcline*. Therefore, logically, such microcline formed by replacement processes when the plagioclase crystals were slightly deformed or cracked. Similar replacements of plagioclase cores by microcline can also be seen in Fig. 25 and Fig. 27.

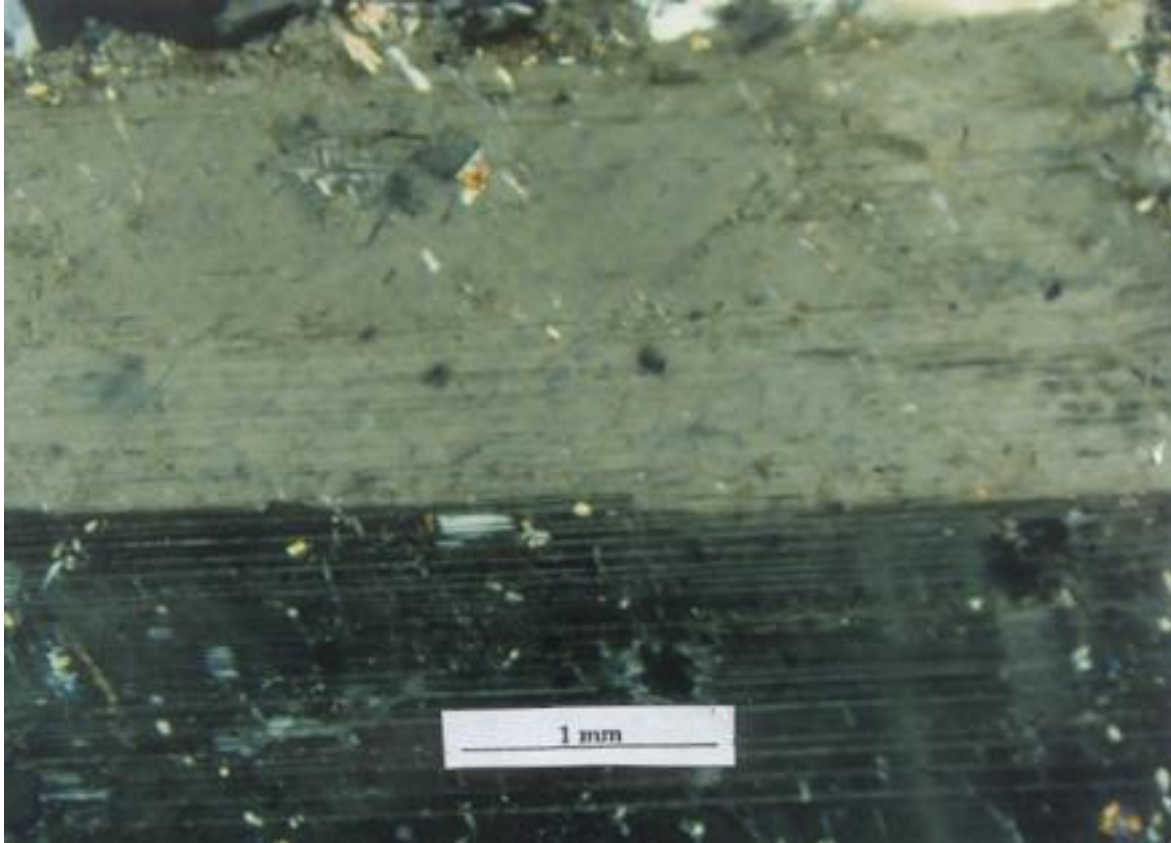


Fig. 23. The Carlsbad- and albite-twinned plagioclase crystal (tannish gray) has irregular islands of microcline (grid-twinning) which are seemingly randomly distributed. Some microcline islands occur in the core of the crystal along the Carlsbad-twin plane. Sericite (bright-colored grains).

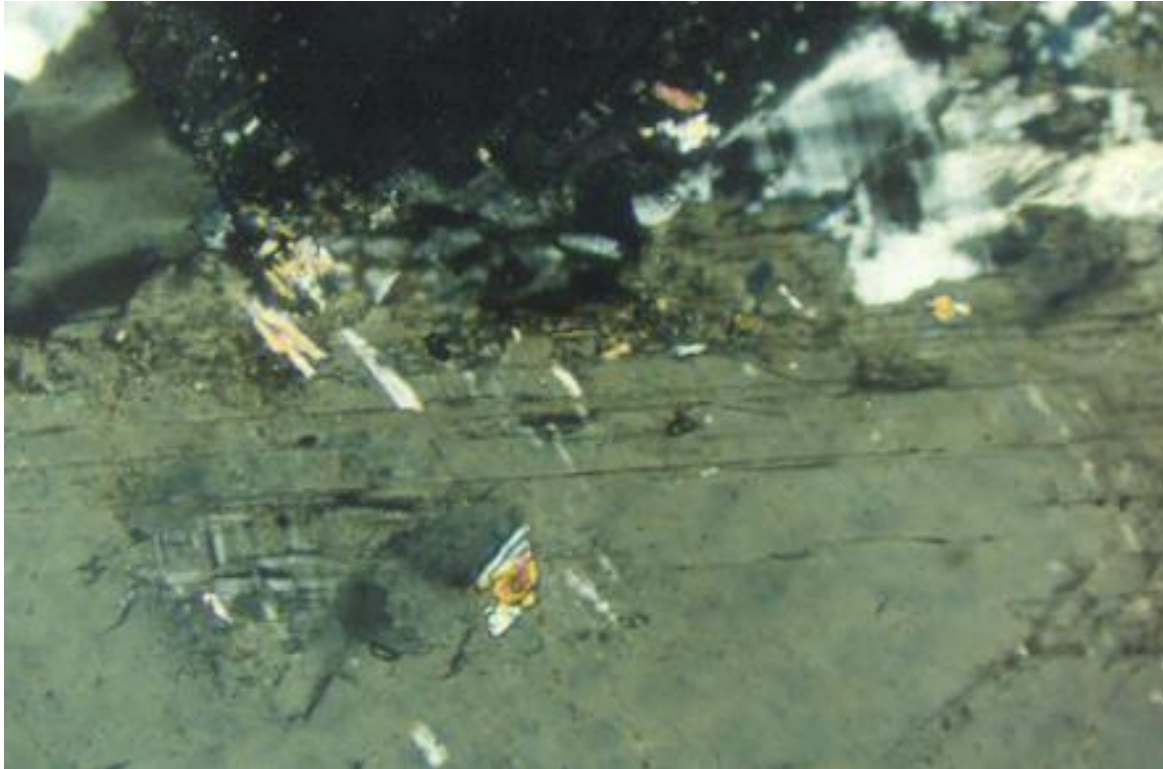


Fig. 24. Enlargement of the upper portion of Fig. 23, showing relationships of bordering grains. In the center of the upper right quadrant, microcline (grid-twinning) can be seen to penetrate the plagioclase (tannish gray) along fractures at the edge of the crystal so that the microcline narrows to two points (above and left of the white quartz grains). The lower pointed wedge of microcline then extends farther into the plagioclase in a thin line. In a similar fashion, the adjacent plagioclase also narrows to two points, each projecting in the opposite direction into the microcline.

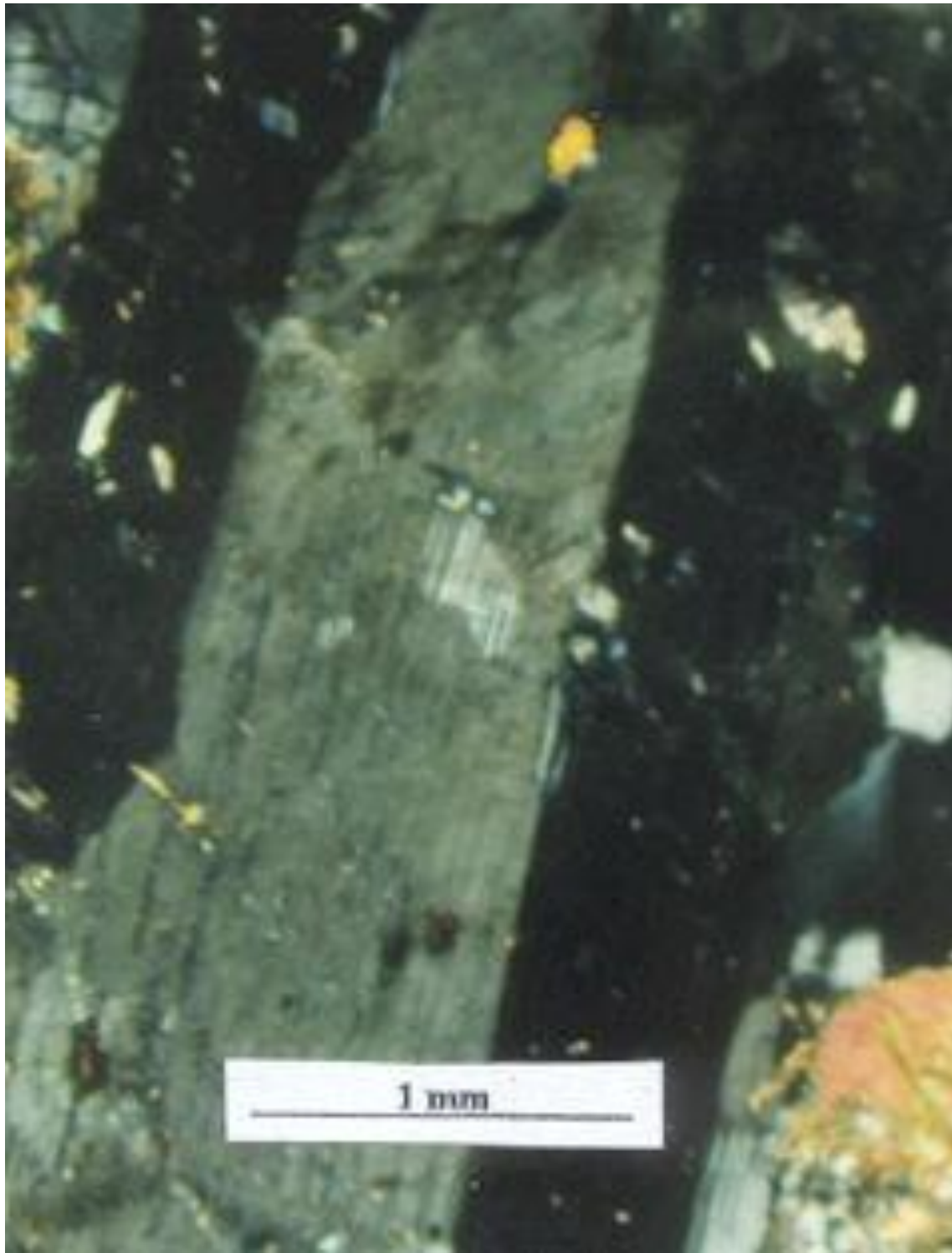


Fig. 25. A plagioclase crystal has two Carlsbad twins that divide the crystal into three parts (black-gray-black). In the central gray area is an irregular microcline patch (grid-twinning).



Fig. 26. Microcline (light gray) is bordered by myrmekite with very tiny quartz vermicules. Note zoned plagioclase (left side) with sericite and epidote in core. Biotite (brown).

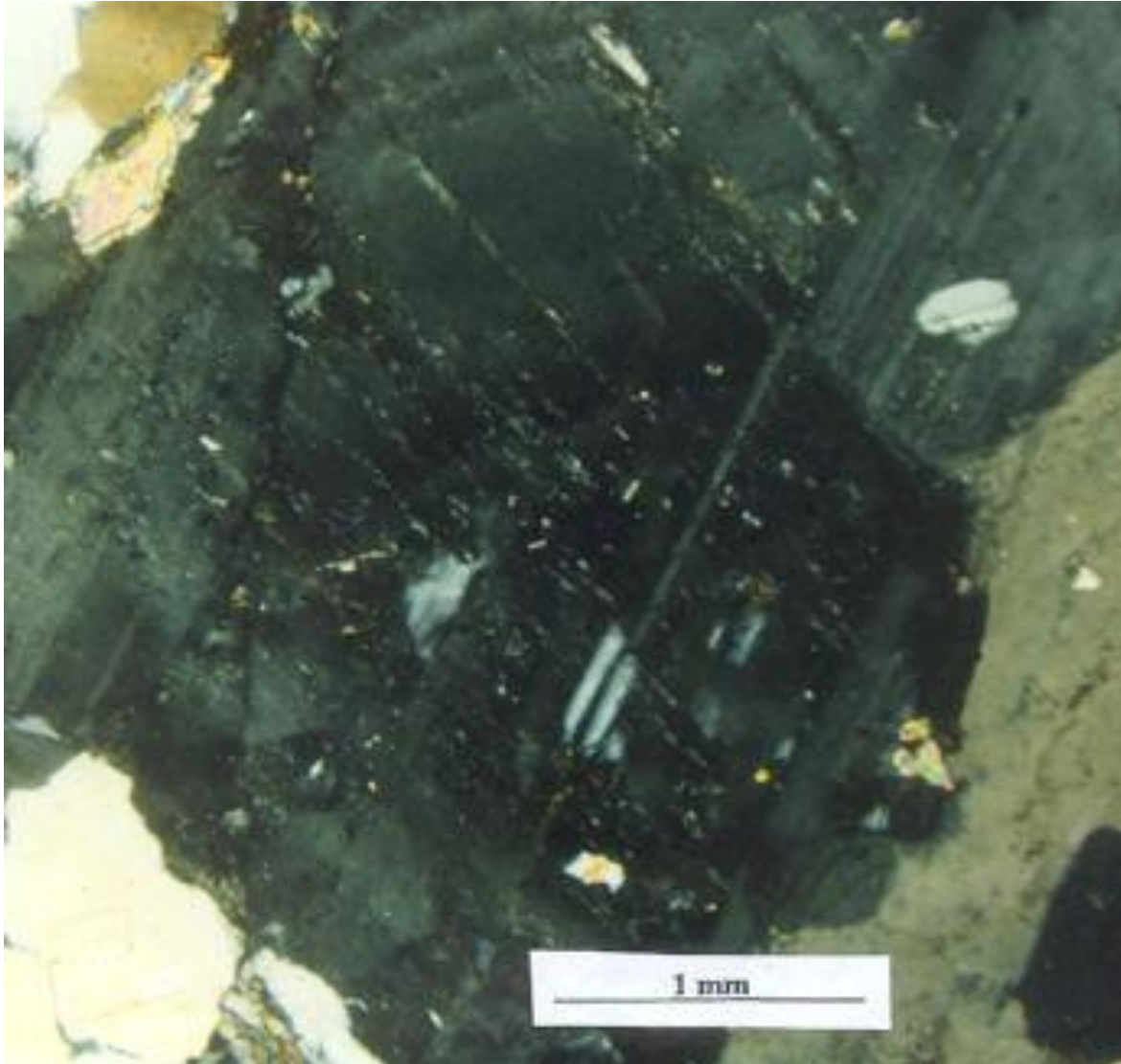


Fig. 27. A strongly zoned plagioclase crystal in which the darkest part (lower right center) is the more calcic core of the grain although it is still quite sodic. In the core are three tiny patches of microcline.

(b) Gneissic quartz monzonite.

The gneissic quartz monzonite (Fig. 20, site F) is adjacent to the massive quartz monzonite and is essentially the same composition and grain size except that deformation has created a foliation. In the gneissic quartz monzonite, similar Carlsbad-twinned plagioclase crystals (as in Fig. 24) are replaced in their interiors by islands of microcline (Fig. 25).

(c) Fine-grained border facies.

The fine-grained border facies (Fig. 20, site F) occurs against metasedimentary wall rocks and adjacent to the above gneissic quartz monzonite. This border facies lacks abundant microcline, and the feldspars are mostly zoned plagioclase. Where microcline is present, it commonly coexists with myrmekite with very tiny quartz vermicules (Fig. 26). Certainly, this rock came in as magma, but after solidification, it must have undergone deformation and some minor amounts of K-metasomatism, as suggested by the presence of myrmekite (Hunt et al., 1992; Collins, 1988).

(d) Granitic dikes.

Isolated narrow, pinkish, granitic dikes, cutting the layering of the metasedimentary rocks and too small to map, occur between sites C and D on Fig. 20. The similarity of the mineralogy in these dikes with that in the aforesaid fine-grained border facies suggests that both are crystallized from the same magma. The plagioclase crystals are sodic, strongly zoned, and occasionally have microcline islands in their cores (Fig. 27). Myrmekite with tiny quartz vermicules occurs between minor interstitial microcline crystals and the plagioclase (Fig. 28). Biotite is abundant; hornblende is absent. Epidote is an accessory.

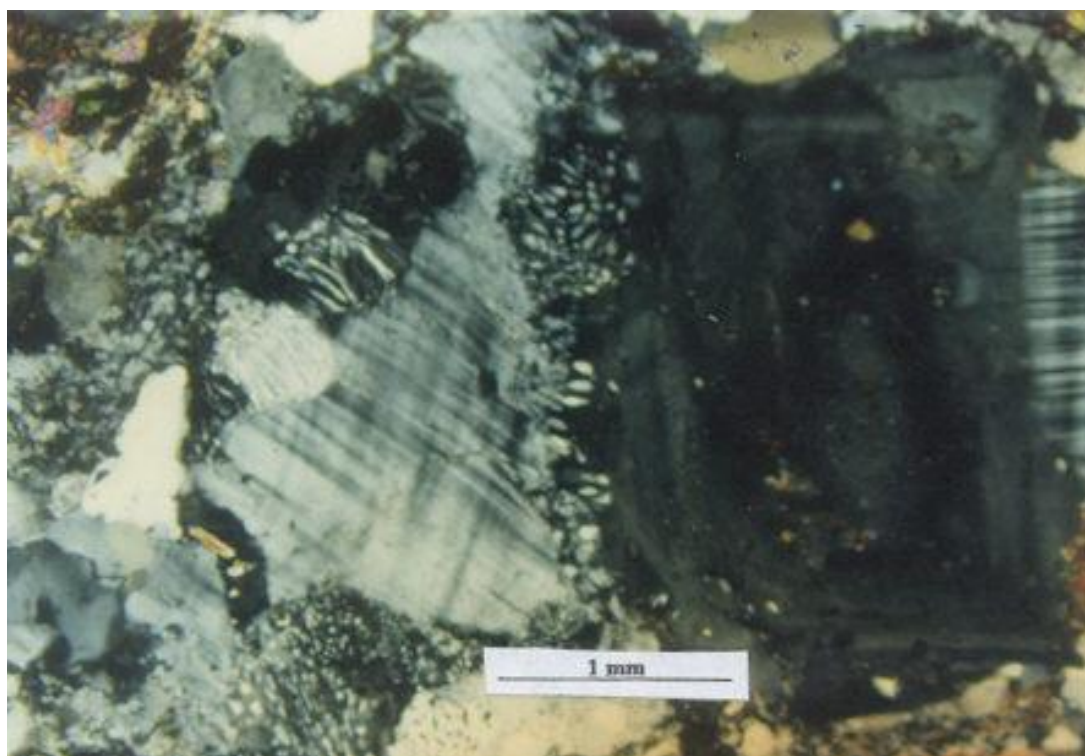


Fig. 28. Myrmekite bordering zoned plagioclase grain (dark; right side) against microcline (grid-twinning). Biotite (brown) and quartz (cream, white, gray).

There is no doubt that these dikes were introduced as magma, but the presence of myrmekite and the occurrence of microcline in the cores of some plagioclase grains suggest that following solidification, deformation allowed hydrous fluids with K to enter and convert some of the primary plagioclase into microcline. The initial magma in the dike as well as in the fine-grained granitic border facies could have been a felsic tonalite with a composition similar to the felsic tonalite in the cusped veins and dikes in the agmatite. The increased amounts of microcline in the gneissic and massive quartz monzonite could be a result of increased amounts of K-metasomatism of the former solidified felsic tonalite (Fig. 23, Fig. 24, and Fig. 25). The source of K need not be from a distant source but come from the abundant biotite in the primary, deformed, solidified tonalites.

Conclusions

The initial emplacement of the various igneous rocks in the northern edge of the Chief Lake granitic complex must have been in the form of Na-rich tonalitic magmas which crystallized with varying amounts of biotite and sodic plagioclase and locally with a little hornblende. The biotite-rich rocks were easily deformed because of the planar cleavage of biotite and its Moh's hardness of 3. The breakdown of biotite released K and water, and the cataclasis opened avenues for fluids to shift the K from the biotite to microcline that replaced deformed plagioclase. These K-replacements can be thought of as auto-K-metasomatism. Enough K is readily available in the primary biotite of the magmatic rocks to produce the microcline without obtaining it from an outside source. In this K-metasomatic process the microcline inherited the Carlsbad-twinning of the primary plagioclase and enclosed remnant fragments of broken plagioclase grains in parallel optical orientation. Where K-replacements of plagioclase were incomplete, myrmekite was formed. This K-metasomatism occurred, not only in the deformed, fine-grained, biotite-rich, mafic tonalites, but also in the coarse-grained tonalites that later became megacrystal granite or quartz monzonite in agmatitic patches or in the larger mass enclosing the mafic tonalite enclaves. The *in situ* sub-solidus formation of microcline (Collins, 1998) was accompanied by increased quartz content in the rock because, as the biotite broke down to release K to form the microcline, silica from the biotite lattice would have been left behind.

Where commingling between early formed mafic and felsic magmas occurred, floating-off of sodic plagioclase phenocrysts and coarse quartz crystals from the felsic magma into the mafic magma resulted in isolated xenocrysts of plagioclase megacrysts and quartz. In this process, (1) the quartz reacted with the

mafic magma to produce amphibole rims, and (2) rims of the sodic plagioclase xenocrysts underwent Ca-metasomatism to form tiny amphibole crystals and aggregates of myrmekite grains with tiny quartz vermicules.

In all places where myrmekite is found bordering the microcline in the biotite-rich rocks, the quartz vermicules are relatively tiny. Where the host rocks also contain hornblende, the quartz vermicules are still tiny but slightly thicker. The tiny sizes of the quartz vermicules in the biotite-rich rocks are expected because of the relatively sodic composition of the coexisting plagioclase (An_{10-30}). The slightly greater thickness of the vermicules, where coexisting hornblende is present, occurs because the plagioclase is slightly more calcic. These size and compositional correlations are confirmed in other terranes where tiny vermicules are found in myrmekite associated with relatively sodic plagioclase, where intermediate-sized vermicules are produced in myrmekite in granite derived from diorite containing still more calcic plagioclase, and where coarse vermicules are produced in myrmekite derived from gabbro where the primary plagioclase has the highest calcium content. See Collins ([1997a](#); [1997b](#); [1997c](#)); (<http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf>; <http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf>; <http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf>) and Hunt et al. (1992); Collins (1988).

Precautions

The evidence for K-metasomatism presented in this article was obtained from only *very tiny* portions of three of the several igneous facies in the Chief Lake granitic complex (Fig. 1), and, therefore, one cannot conclude from this evidence that all other facies in the complex have undergone such metasomatic modifications. Perhaps many were emplaced as magmas that solidified and were not subsequently modified, and some of these could have been primary granite or monzogranite. An example is the Pine Lake unit composed of uniform, fine-grained, leucocratic biotite monzogranite (Davidson, 2002). One sample was collected from this unit, and it lacks myrmekite. However, Henderson (1967) reported myrmekite in most of the samples that he collected, which suggests that K-metasomatism is a common modification of the deformed parts of the various facies throughout the complex, and these modifications could have produced the granite or quartz monzonite compositions, as was observed north and northeast of Wavy Lake (Fig. 20). He also did not identify where the "metagabbro" with K-feldspar megacrysts in his Plate 2B was photographed, so perhaps he found a place where deformed enclaves of the Nipissing metagabbro were subjected to K-

metasomatism as occurs in the deformed mafic tonalite enclaves. Further studies are needed.

Applications

Because numerous magmatic tonalites, quartz diorites, and trondhjemites (plagiogranites) occur in the Canadian Shield in which the plagioclase is as sodic (An_{10-30}) as in the Chief Lake complex, the same kinds of late K-replacements to produce more granitic facies are certainly possible if these rocks were subjected to cataclastic deformation. Many of these rocks contain little biotite, and, therefore, have insufficient K necessary to convert the rocks to more granitic compositions. But those that are rich in biotite and which have been deformed could have some of their plagioclase replaced by K-feldspar to produce quartz monzonite, granodiorite, or granite, depending upon the abundance of K, hydrous fluids, and degree of deformation. Such granitic rocks should be examined with this hypothesis in mind, particularly if any of them are myrmekite-bearing. An example of a myrmekite-bearing, soda-rich quartz monzonite is the Bell Lake pluton south of the Chief Lake complex.

Acknowledgements

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