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34. The K-replacement origin of the megacrystal Lower Caribou Creek granodiorite and the Goat Canyon-Halifax Creeks quartz monzonite --- modifications of a former tonalite and diorite stock, British Columbia, Canada

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Introduction

About 25 km south of Nakusp and 1 km east of Burton, British Columbia, Canada, is a stock whose western half is the Lower Caribou Creek megacrystal granodiorite and whose eastern half is the Goat Canyon-Halifax Creeks fine-grained quartz monzonite (Fig. 1); Hyndman, 1968). Biotite-hornblende tonalite and diorite are additional facies that occur along the border of the stock. Zoned plagioclase in all these rocks indicates a shallow intrusion and relatively rapid crystallization. This stock was called to my attention by Donald Hyndman because the K-feldspar megacrysts in the granodiorite appeared to be orthoclase whereas the smaller K-feldspar crystals in the fine-grained quartz monzonite were microcline. Subsequently, he loaned me 19 thin sections from his Ph.D thesis study (Hyndman, 1968), and these sections provided a broad representation of the textural and compositional variations in both rock types. Because he indicated that the two granitic facies were gradational to each other, this stock offered an opportunity to study the field and textural relationships across the transitions between the rocks having the two kinds of K-feldspar. Following his loan of thin sections, I visited the area and obtained 44 additional samples (and thin sections) across transitions between the two rock types. Examinations of field relationships and both his and my thin sections provide the basis for the conclusions presented in this article.

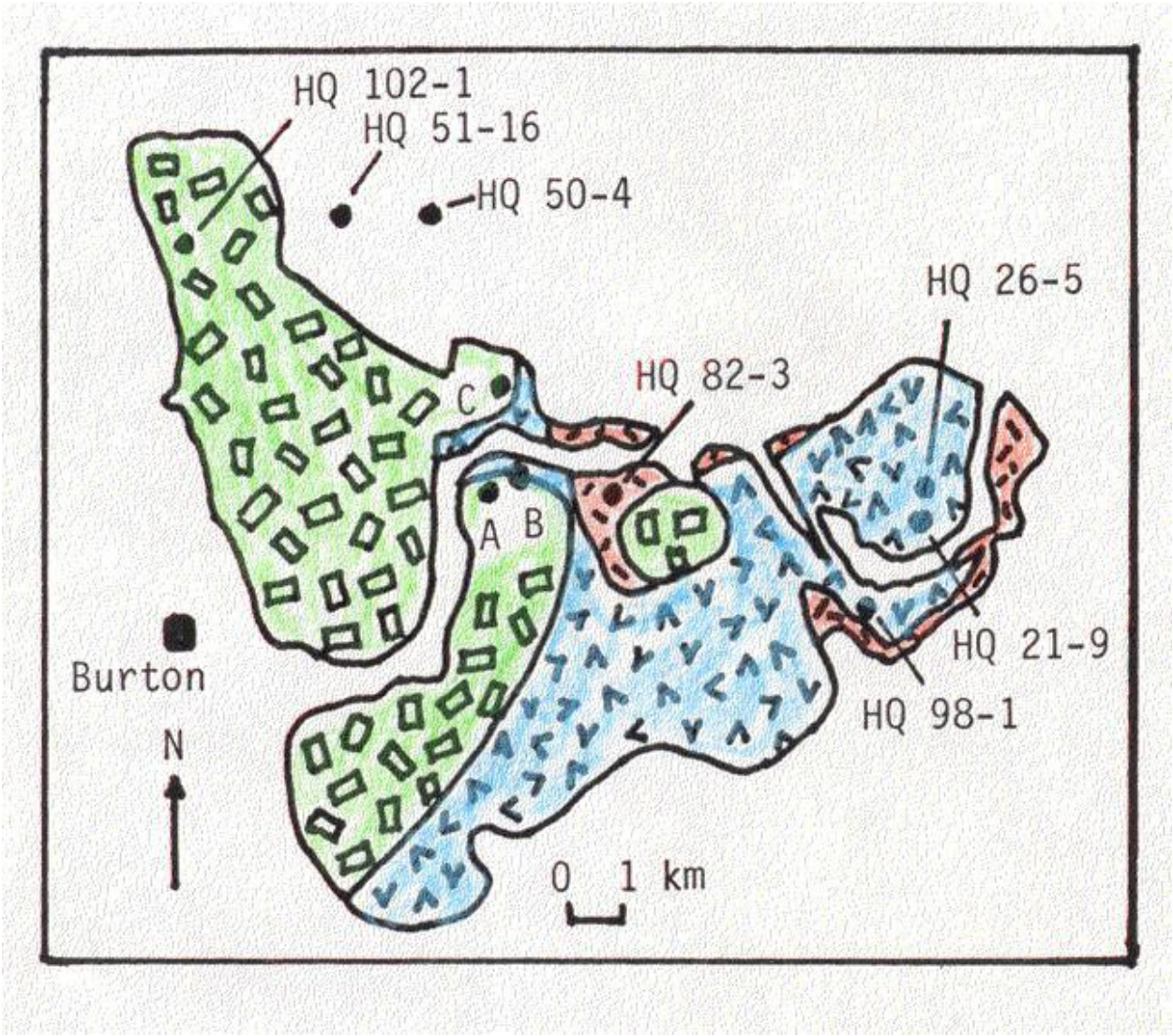

Fig. 1. Geologic map of the stock consisting of the Lower Caribou Creek megacrystal granodiorite (rectangular block pattern; green), the Goat Canyon-Halifax Creeks quartz monzonite (v-pattern; blue), and biotite-hornblende tonalite and diorite border facies (random dash pattern; red); modified after Hyndman (1968 but omitting many other mapped rock types. The highway from Nakusp to Burton and forest roads extending into the map area is not shown. Hyndman's HQ-samples and areas A, B, and C, indicated by solid dots, are discussed in the text.

Field relationships

Before going to the stock near Nakusp, I had imagined from the distribution of rock types on the geologic map (Fig. 1) that the intrusion pattern would be that of a typical zoned pluton created by magmatic differentiation processes. That is,

the rim would be a more-mafic rock, the diorite, and progressively toward the center, the rocks would gradually become more felsic with the quartz monzonite first and finally the megacrystal granodiorite. This seemed logical although the map pattern showed an asymmetric distribution with the diorite primarily along the northeast, east, and southeast sides and the granodiorite on the west side (Fig. 1). I also pictured the contact between the fine-grained monzonite and the megacrystal granodiorite as being a gradual smooth transition, beginning approximately where Hyndman drew the separation line (Fig. 1). On the basis of these assumptions, I was surprised to discover when I arrived that the mapped distribution of the various rocks only existed in a broad sense. The transition westward from the fine-grained quartz monzonite to the megacrystal granodiorite was not a single gradual smooth transition but consisted of several gradual transitions, back and forth, between the two rock types before finally becoming mostly megacrystal granodiorite farther west. Moreover, in this transition interval, in both the megacrystal granodiorite and the quartz monzonite were small unmapped units of diorite. Such details were not essential to Hyndman's study of the larger area that he mapped and were impossible to delineate at the small scale of his map. Nevertheless, the discovery of this distribution of rock types meant that the diorite did not just form on the rims of the pluton but was also present farther into the middle and that a magmatic differentiation model for the origin of the pluton with gradual compositional changes to a more-felsic core was not entirely consistent.

This conclusion was verified when I examined the contact relationships among diorite, fine-grained quartz monzonite, and megacrystal granodiorite in outcrops in area A (Fig. 1). In some places in the transition zone, the megacrystal granodiorite grades into fine-grained quartz monzonite within a few centimeters and then appears to penetrate into the diorite as an intrusive body (Fig. 2, Fig. 3, and Fig. 4). Some of the diorite contains angular disoriented blocks of diorite that vary from light green to dark green to black. The disoriented blocks indicate that the diorite has been strongly sheared, and the blocks have experienced different degrees of alteration to chlorite and epidote. Within the diorite mass, however, locally there are tiny isolated grains or small aggregate patches of pink K-feldspar that have no apparent physical connection to the main granodiorite mass in the sense of being transported there via magma.

Fig. 2. Chloritized and epidotized diorite, penetrated by fine-grained granitic rock which locally contains megacrysts of K-feldspar. Canadian penny provides a scale. Area A, Fig. 1.

Fig. 3. Megacrystal granodiorite (right side) has an irregular contact with a cataclastically deformed diorite, altered by chlorite and epidote (left side). Relatively unaltered and undeformed diorite at bottom of photo has a sharp contact with the granodiorite. Area A, Fig. 1.

Fig. 4. Close-up of contact of fine-grained quartz monzonite and megacrystal granodiorite with the deformed diorite. The close-up area is in the lower left near the black, less-sheared diorite (bottom of photo in Fig. 3). Canadian penny provides a scale. Area A, Fig. 1.

Not all of the diorite is sheared, however. In the same outcrop, a sharp contact of the megacrystal granodiorite against relatively unaltered and unsheared black diorite can also be seen. See the lower part of Fig. 3.

In other parts of the transition zone, the fine-grained quartz monzonite grades into megacrystal granodiorite gradually across several tens of meters. In this gradual transition, the randomly oriented K-feldspar megacrysts that first appear are only 0.5 to 1.0 cm long. Farther into the megacrystal granodiorite, the crystals may increase in size to 2-3 cm long (Fig. 5).

Fig. 5. Massive megacrystal granodiorite, showing random orientation of light pink K-feldspar megacrysts in a matrix of white plagioclase, gray quartz, and black biotite and hornblende. Canadian penny provides a scale. Area A, Fig. 1.

In many places at area B on Fig. 1, in bulldozed road outcrops, the repeated gradual transitions, back and forth, between fine-grained quartz monzonite and megacrystal granodiorite are also found. Here also, diorite or tonalite is found adjacent to the fine-grained quartz monzonite. Contacts are usually relatively sharp, but in a few places are gradational.

At area C on Fig. 1, similar transitions from fine-grained quartz monzonite to megacrystal granodiorite and/or to remnants of diorite and tonalite are also exposed. Here, also, contacts of the granitic rocks against the more mafic rocks tend to be relatively sharp. In a few places megacrysts of K-feldspar occur in the diorite and tonalite within 10 centimeters (or less) from the contact with the megacrystal granodiorite.

Thin section analyses and discussion of the Lower Caribou Creek megacrystal granodiorite

Thin sections of the sheared diorite (Fig. 2, Fig. 3, and Fig. 4), show that portions of this rock are strongly granulated to become a cataclasite in which many of the grains are altered to chlorite and epidote. In the fine-grained quartz monzonite adjacent to the altered diorite (Fig. 2, Fig. 3, and Fig. 4), small microcline crystals (0.5 -3 mm wide) contain angular remnants of plagioclase which are in optical parallel orientation (Fig. 6).

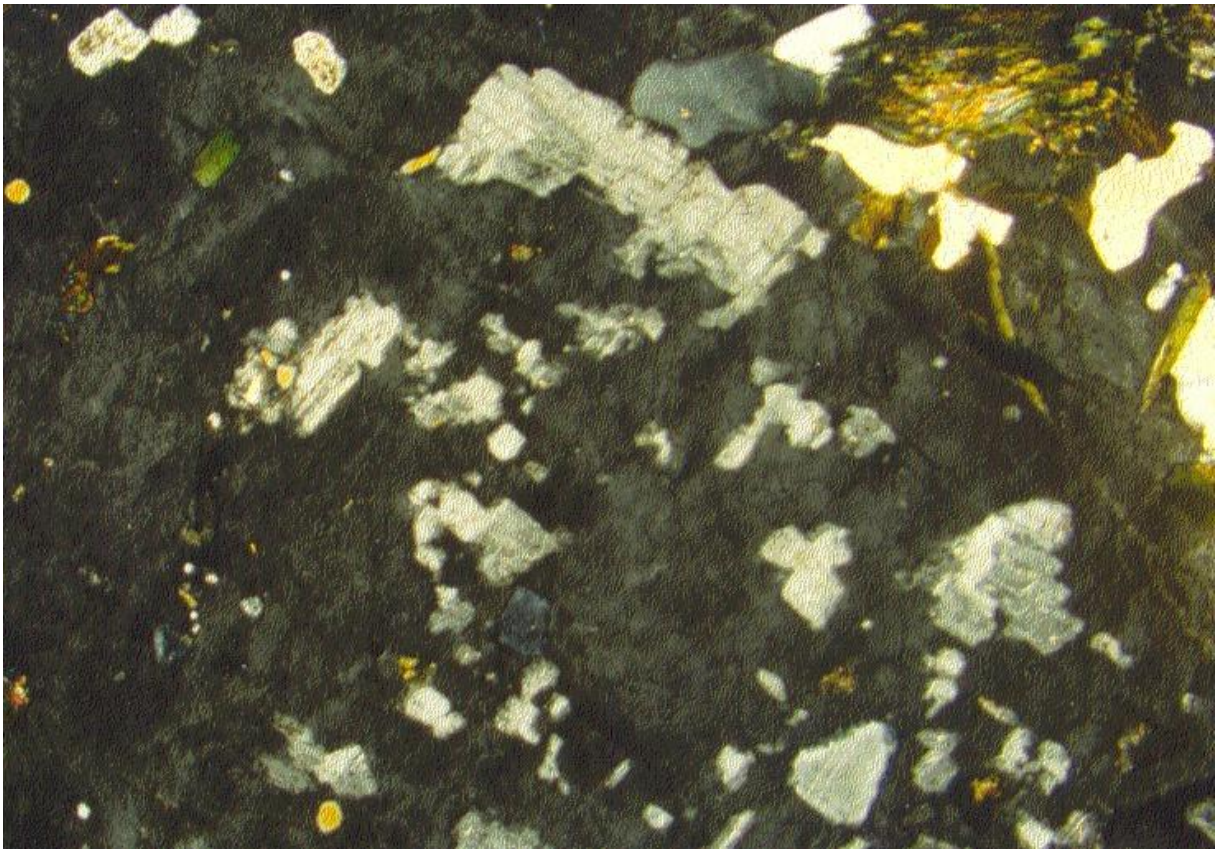

Fig. 6. Microcline (black, dark gray) enclosing irregular islands of albite-twinned plagioclase (light gray) in parallel optical orientation. Area A, Fig. 1.

Where the K-feldspar megacrysts (0.5 to 1 cm) first appear (areas A and B, Fig. 1), the interior remnant islands of plagioclase no longer occur (as in Fig. 6), but tiny islands may remain along the K-feldspar borders in optical parallel continuity with the adjacent larger plagioclase crystal. Moreover, the K-feldspar may extend in veins into the adjacent plagioclase (Fig. 7, Fig. 8, and Fig. 9).

Fig. 7. Microcline (black), penetrating plagioclase (light gray) along veins and enclosing tiny islands of plagioclase (cream white; left of center) which are in optical parallel continuity with the adjacent plagioclase. Area A, Fig. 1.

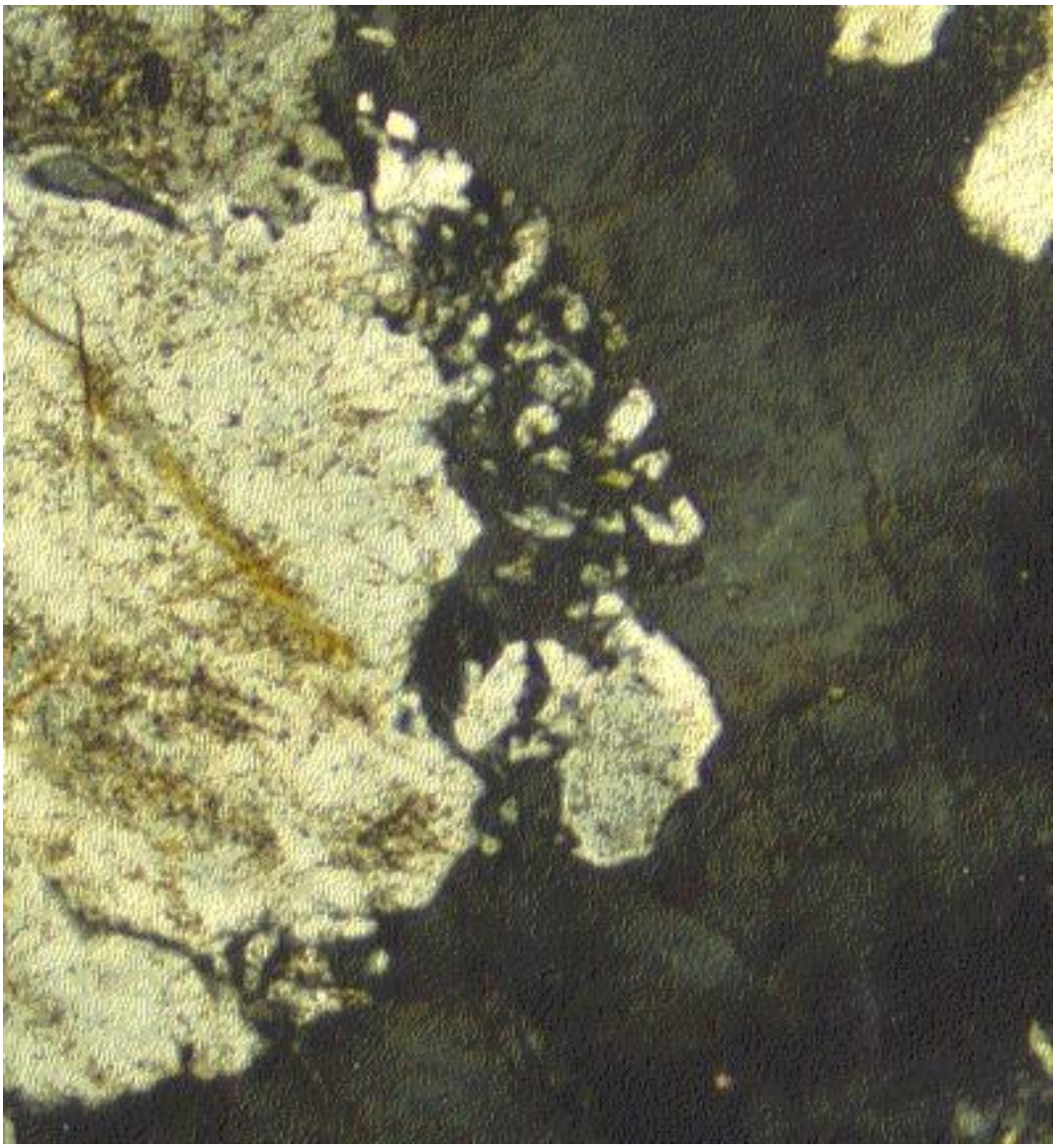

Fig. 8. Microcline (black), penetrating plagioclase (light gray) along veins and enclosing tiny islands of plagioclase (cream white) which are in optical parallel continuity with the adjacent plagioclase. Area A, Fig. 1.

Fig. 9. Microcline (black), penetrating plagioclase (light cream) along veins and along albite-twin lamellae, leaving some lamellae projecting into the microcline. A portion of the plagioclase that is enclosed in the microcline is myrmekitic with tiny quartz ovules. Myrmekite also occurs in upper right. Area B, Fig. 1.

The same textural relationships are found in the fine-grained quartz monzonite and megacrystal granodiorite at area C (Fig. 1) as in areas A and B, except that in area C in a few places megacrysts of microcline also occur bordering diorite or tonalite for the first 10 cm beyond the contact. Here, also, island remnants of optically parallel plagioclase occur in the microcline, and the microcline penetrates the adjacent plagioclase along veins (Fig. 10). Farther into the diorite or tonalite where K-feldspar megacrysts are absent, microcline is interstitial, bordered by myrmekite, and also penetrates broken plagioclase grains along veins or occurs in interiors of deformed plagioclase grains in irregular random islands. Still farther into the diorite or tonalite in undeformed areas, the microcline and myrmekite are absent.

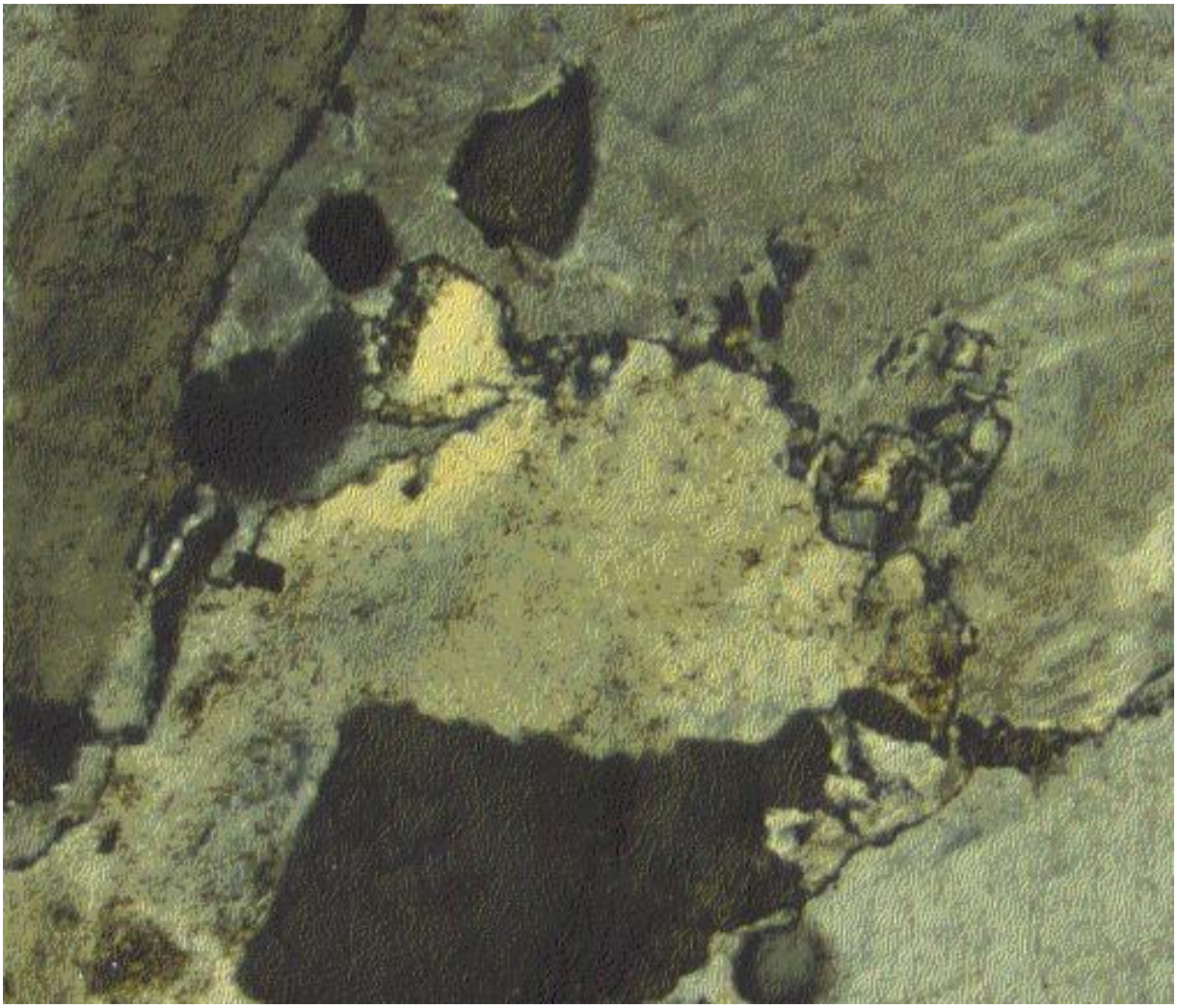

Fig. 10. Microcline (dark gray) enclosing island remnants of plagioclase (light gray; upper right quadrant) in parallel optical continuity with the adjacent larger plagioclase crystal (light gray and cream). Microcline penetrates the plagioclase along a triangular-shaped vein on left side of the plagioclase crystal. Area C, Fig. 1.

Discussion

The absence of microcline and myrmekite in undeformed diorite and tonalite far from contacts with granodiorite or quartz monzonite and their presence in diorite and tonalite with broken or bent crystals suggest that neither the microcline nor the myrmekite are primary but are secondary and resulted from fluids that moved through nano-sized openings in the cracked and deformed grains. If true, the remnant islands of optically parallel plagioclase in K-feldspar (Fig. 6) are broken fragments of a plagioclase crystal that was once in a former deformed

diorite. The incomplete replacements created the island remnants. Because of these micro-replacement textures, the patches and veins of granitic rock that extend into the diorite are not physical injections of magma but avenues where metasomatic fluids have replaced the deformed more-mafic rocks on a macro-scale to create the granitic rocks.

The absence of plagioclase remnants in the K-feldspar interiors where megacrysts first appear (Fig. 7, Fig. 8, and Fig. 9) shows a greater degree of K-replacement than in Fig. 6. Total K-replacement, of course, destroys the evidence for the existence of a former plagioclase crystal. The same characteristics are also found in the megacrystal granodiorite in which the microcline crystals are even larger (2-3 cm long) even though the outward field appearance is that of a massive granitic rock crystallized from a magma (Fig. 5). On that basis, the places in altered diorite which have isolated islands of K-feldspar or granitic patches of K-feldspar (Fig. 2, Fig. 3, and Fig. 4) reveal the early stages of K- and Si-metasomatism of the diorite, which in advanced stages produced the nearby granitic rocks. On the basis of all these relationships, the outcrops of diorite (a few tens of meters wide) in the midst of megacrystal granodiorite and fine-grained quartz monzonite in areas A, B, and C are interpreted to be remnants of former diorite that once filled the volumes now occupied by the two more-granitic rocks.

Support for such K-metasomatism is indicated further by thin-section textures in biotite-hornblende granite and granodiorite dikes which intruded the wall rocks; see sites HQ 51-16 and HQ 50-4 on Fig. 1 that were examined by Donald Hyndman. These dikes were obviously initially magmatic, but later deformation, following solidification, has permitted K-replacements. For example, the zoned, albite- and Carlsbad-twinned plagioclase crystals locally contain irregular but randomly distributed islands of microcline (Fig. 11 and Fig. 12). These islands are interpreted to be early stages of K-feldspar replacement of cracked interiors of the plagioclase. Such cracking cannot be seen in crossed polarized light but likely could be seen in cathodoluminescence studies; see http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf. More extensive K-replacements of similar Carlsbad-twinned plagioclase crystals in the main granodiorite mass would have resulted in Carlsbad-twinned K-feldspar megacrysts that occur there; see http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf. And, of course, these replacements of the plagioclase by the K-feldspar would change the diorite or tonalite composition of the dike into quartz monzonite, diorite, or granite.

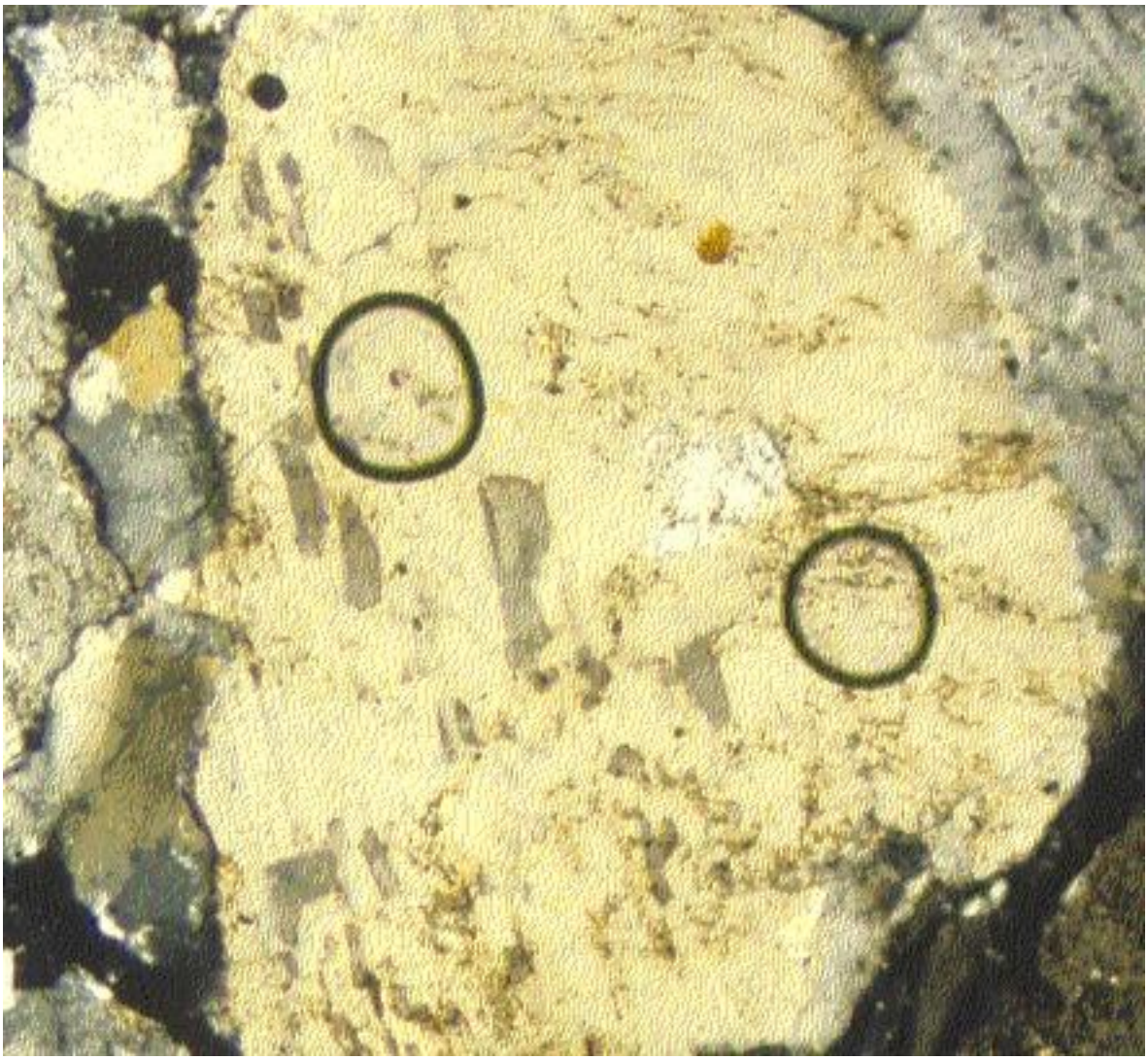

Fig. 11. Plagioclase crystal (cream) has K-feldspar replacement in islands (light gray). (Biotite-hornblende granodiorite dike; sample HQ 50-4; Fig. 1).

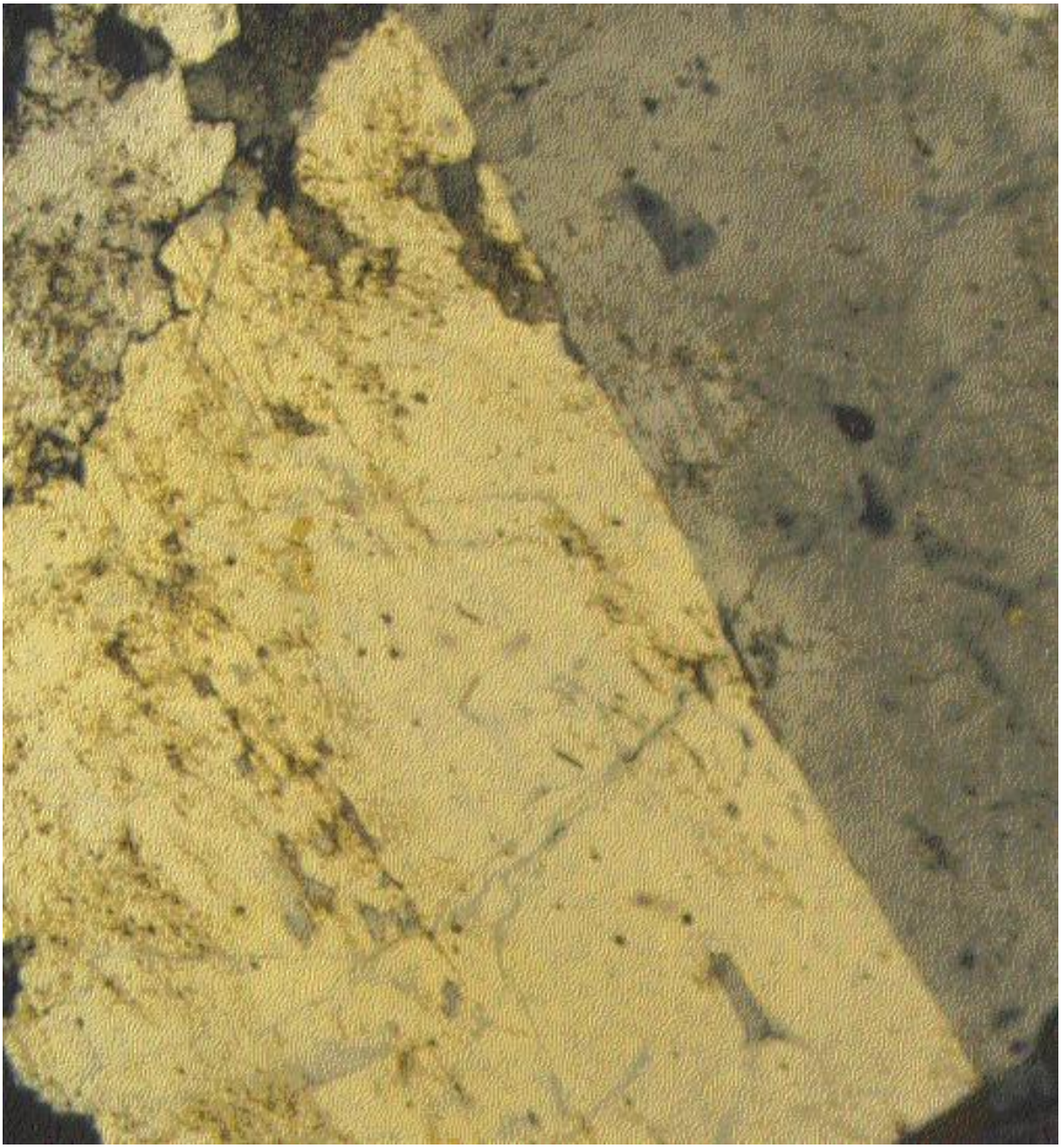

Fig. 12. Carlsbad-twinned plagioclase crystal (cream, gray) has K-feldspar replacements in islands (light gray; near twin plane) and in left half (light gray; lower center and left side). (Biotite-hornblende granodiorite dike; sample HQ 50-4; Fig. 1).

In all places where K-replacement of plagioclase is found, wartlike myrmekite on borders of the K-feldspar is common but generally not more abundant than 0.5 vol. %. In the granitic dikes that cut the wall rocks and in the interiors of the megacrystal granodiorite mass, the quartz vermicules are relatively

tiny (Fig. 13), but near the border of the stock, the quartz vermicules are coarser (Fig. 14). The greater coarseness indicates the more-calcic composition of the original plagioclase in a former more-mafic tonalite or diorite border-facies prior to K-replacement (Collins, 1988a; Hunt *et al*., 1992).

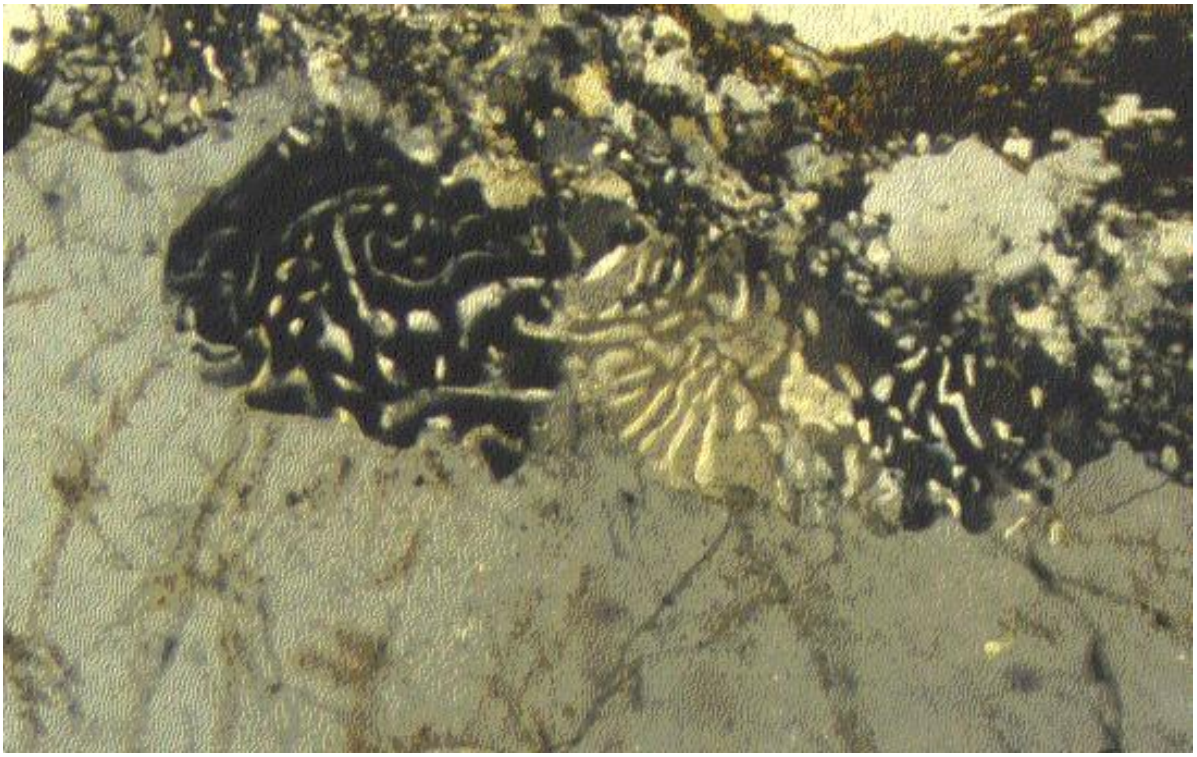

Fig. 13. Wartlike myrmekite in borders of K-feldspar (orthoclase ?) crystal. Quartz vermicules are intermediate to fine in size. Boundary has cataclastic texture. (Hornblende-biotite granite dike; sample HQ 51-16; Fig. 1).

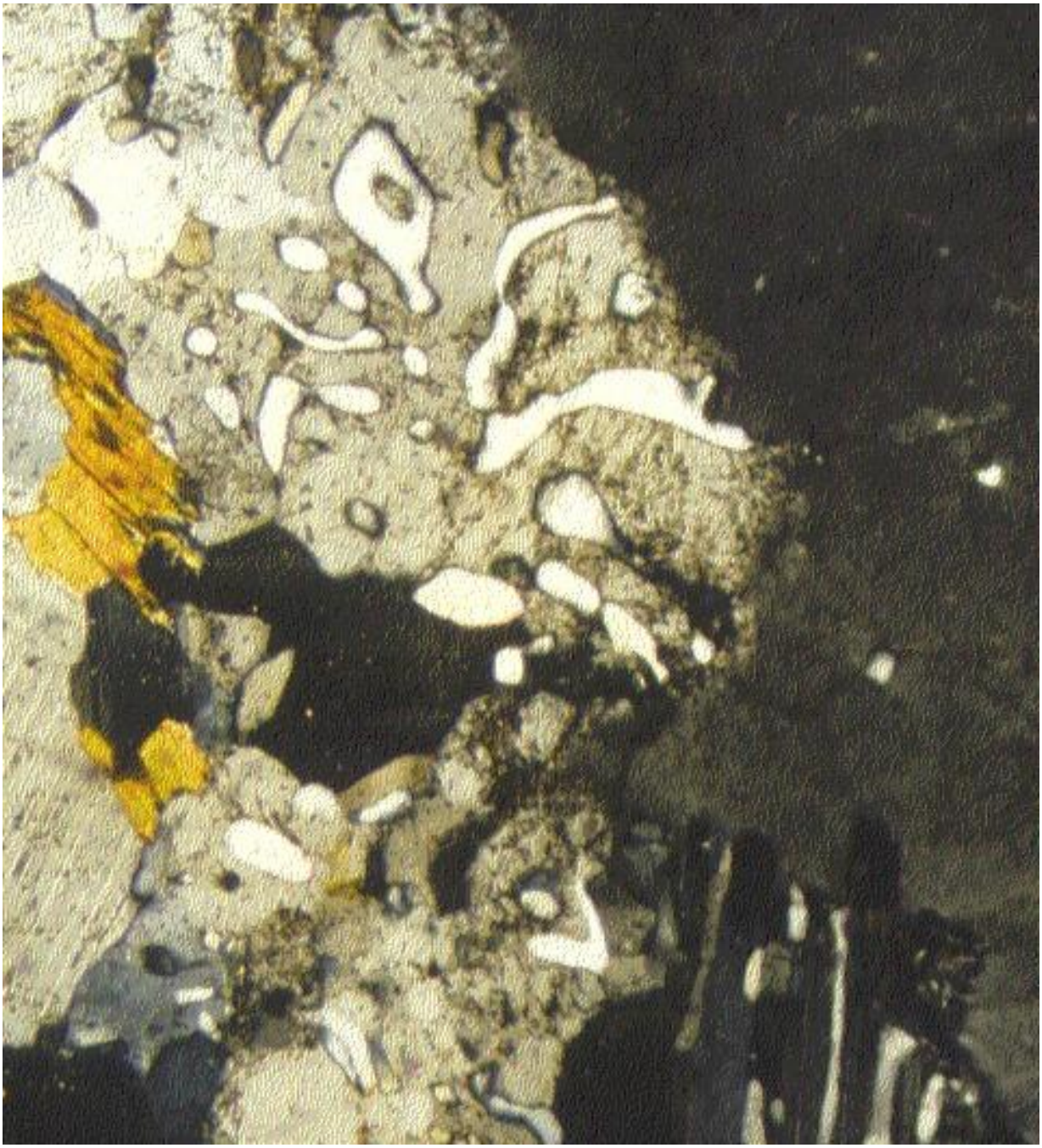

Fig. 14. Myrmekite with coarse quartz vermicules against K-feldspar (orthoclase ?; gray black; right side). Unzoned, albite-twinned plagioclase left side. Biotite (brown). (Hornblende-biotite granodiorite sample HQ 102-1; Fig. 1).

Thin section analyses and discussion of the Goats Canyon-Halifax Creeks quartz monzonite

In the eastern part of the stock in the Goat Canyon-Halifax Creeks fine-grained quartz monzonite (Fig. 1), the same kinds of interior replacements in cores of albite- and Carlsbad-twinned plagioclase crystals by K-feldspar occur as in the Lower Caribou Creek megacrystal granodiorite, except that the grain size is smaller. K-feldspar would not be expected in the cores of zoned plagioclase that was crystallized from magma because such cores should contain relatively more-calcic plagioclase. Therefore, it is clear that the irregular islands of K-feldspar in the cores of zoned plagioclase crystals of this quartz monzonite have been formed by replacement processes (Fig. 15 and Fig. 16).

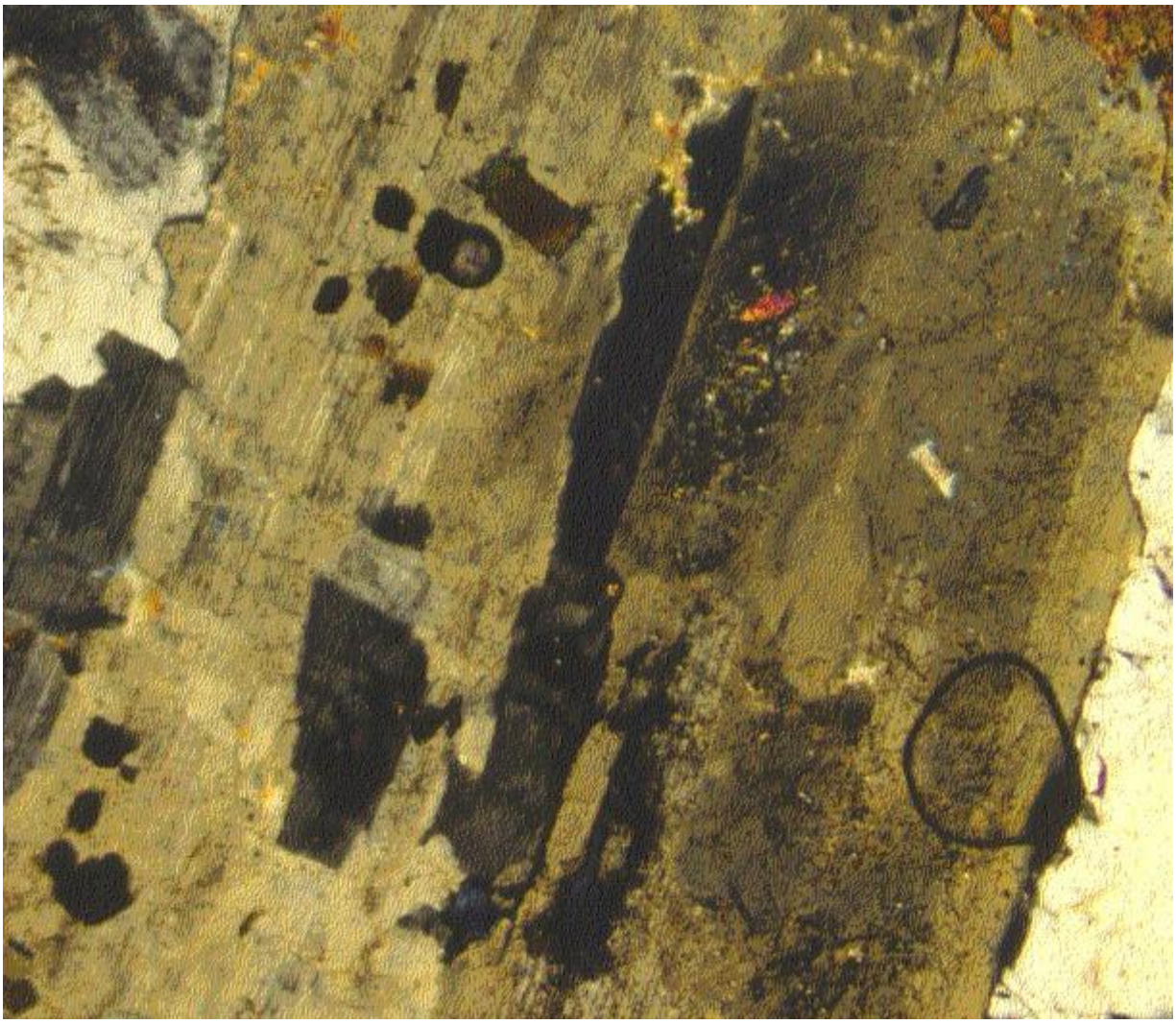

Fig. 15. Zoned, Carlsbad- and albite-twinned plagioclase (tan). Along the Carlsbad twin-plane of the mottled plagioclase, K-feldspar (dark gray, black) replaces the core of the plagioclase crystal. (Hornblende-biotite quartz monzonite; sample HQ 26-5, Fig. 1).

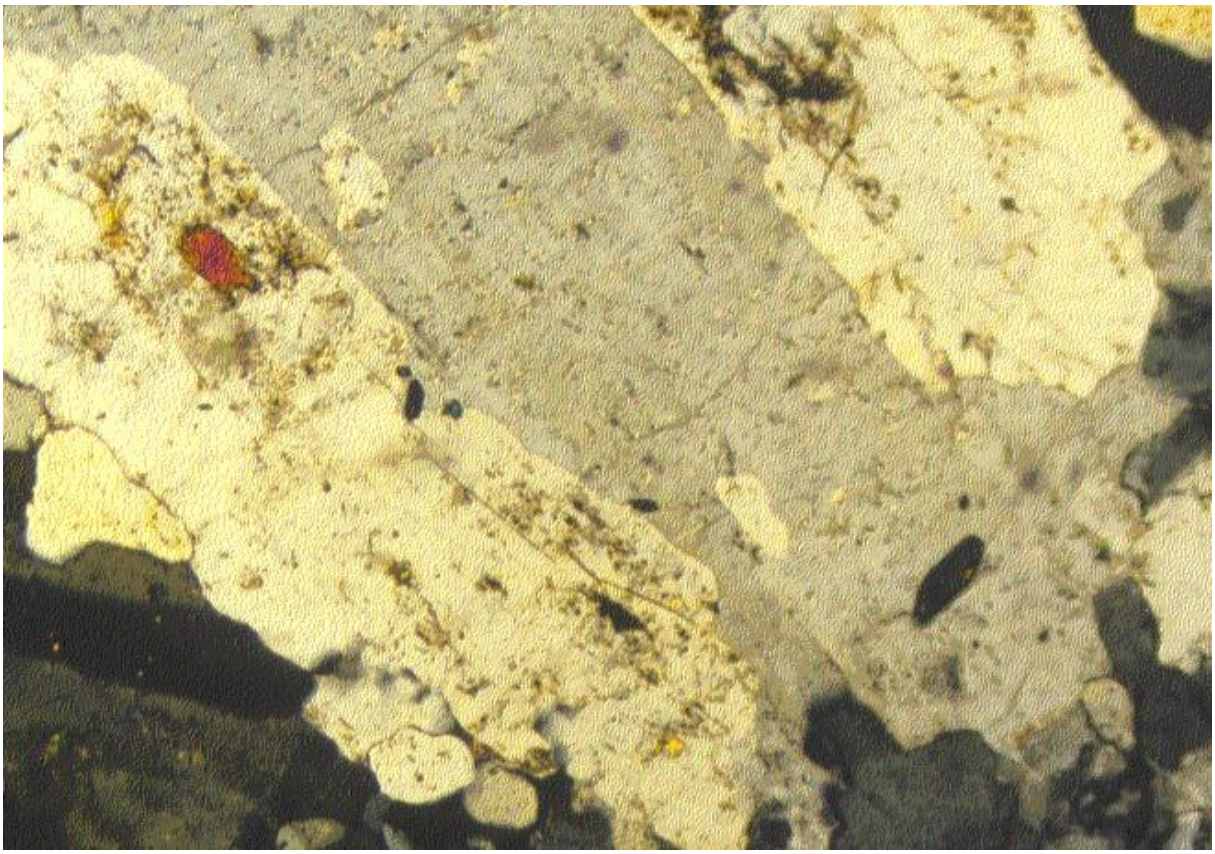

Fig. 16. More advanced stage of microcline (light gray; orthoclase ?) replacing core of plagioclase crystal (cream white). Irregular islands of remnant unreplaced plagioclase occur in the microcline, and these islands are in optical parallel continuity with the outside larger plagioclase crystal. (Biotite-hornblende quartz monzonite; sample HQ 98-1, Fig. 1).

The biotite-hornblende diorite (sample HQ 82-3, Fig. 1) that occurs adjacent to the Goats Canyon-Halifax Creeks quartz monzonite shows early stages of K-replacements (Fig. 17). This relationship is the same as that found in area C mentioned earlier). With just a little more K-metasomatism, the diorite here would have ultimately converted into quartz monzonite (Fig. 18).

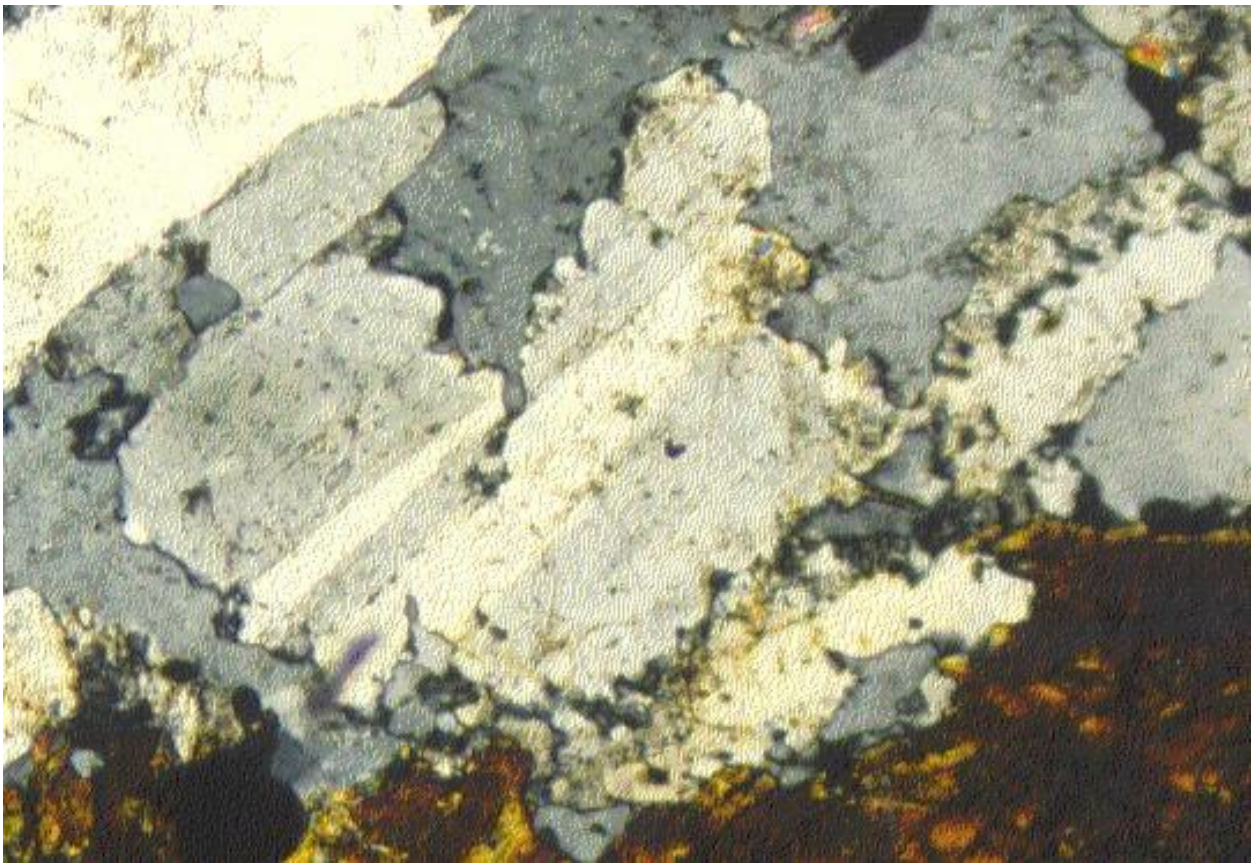

Fig. 17. Penetration and replacement of albite-twinned plagioclase (white; light gray) by interstitial microcline (darker gray) is clearly evident along scalloped edges. Hornblende (brown; bottom). (Biotite-hornblende diorite; sample HQ 82-3, Fig. 1).

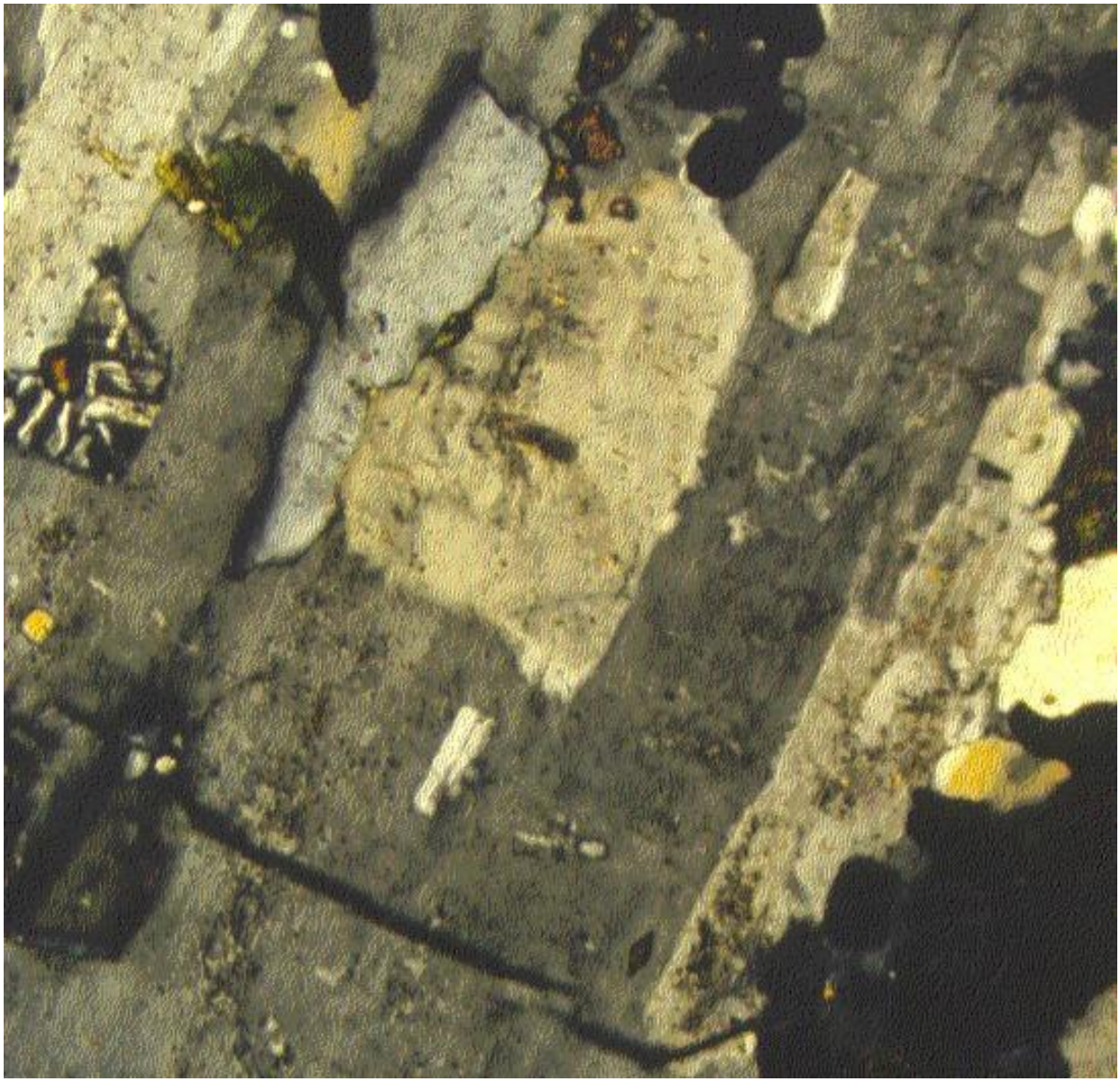

Fig. 18. Microcline (dark gray) with remnant tiny islands of plagioclase (tan) which are optically parallel to albite-twinned plagioclase (tan; right side). (Biotite-hornblende quartz monzonite; sample HQ 21-9, Fig. 1).

Myrmekite in the fine-grained quartz monzonite tends to have vermicules with very tiny quartz vermicules (Fig. 19), indicating the relatively sodic composition of the original plagioclase in the tonalite and diorite prior to the K-replacement that converted these rocks to quartz monzonite (Collins, 1988a; Hunt *et al*., 1992).

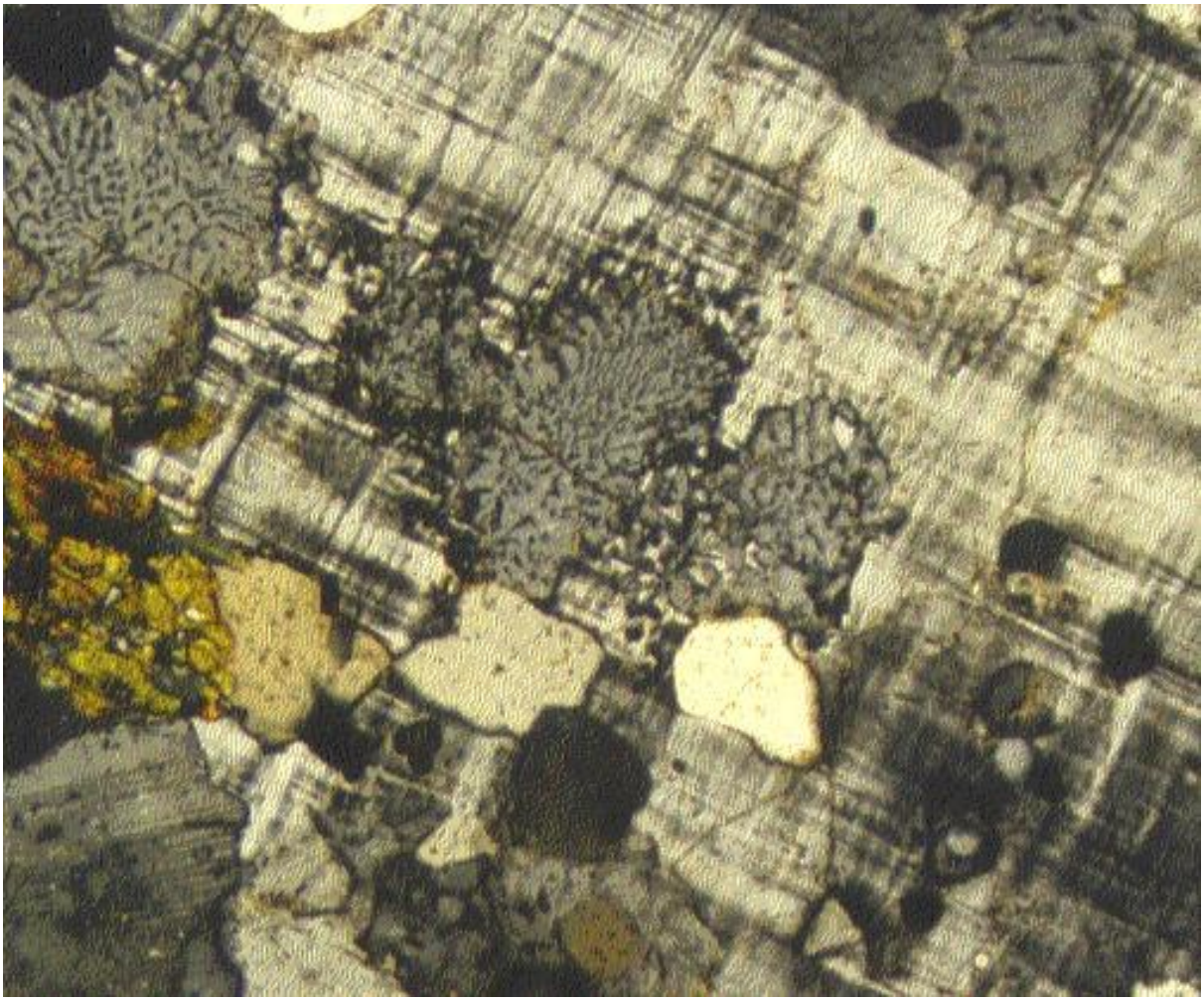

Fig. 19. Myrmekite with tiny quartz vermicules surrounded by microcline (grid-pattern). Quartz (white, gray, cream). Biotite (brown). Hornblende (dark green). (Biotite-hornblende quartz monzonite; sample HQ 98-1, Fig. 1).

In a few places hornblende in the quartz monzonite shows a poorly-developed quartz sieve texture (Fig. 20), indicating that silica has replaced the interiors of some hornblende crystals at the same time that potassium replaced some plagioclase crystals to form microcline (Collins, 1988a). In most places, however, there are few textural clues that the hornblende is replaced by quartz as the rock converts to quartz monzonite or granodiorite.

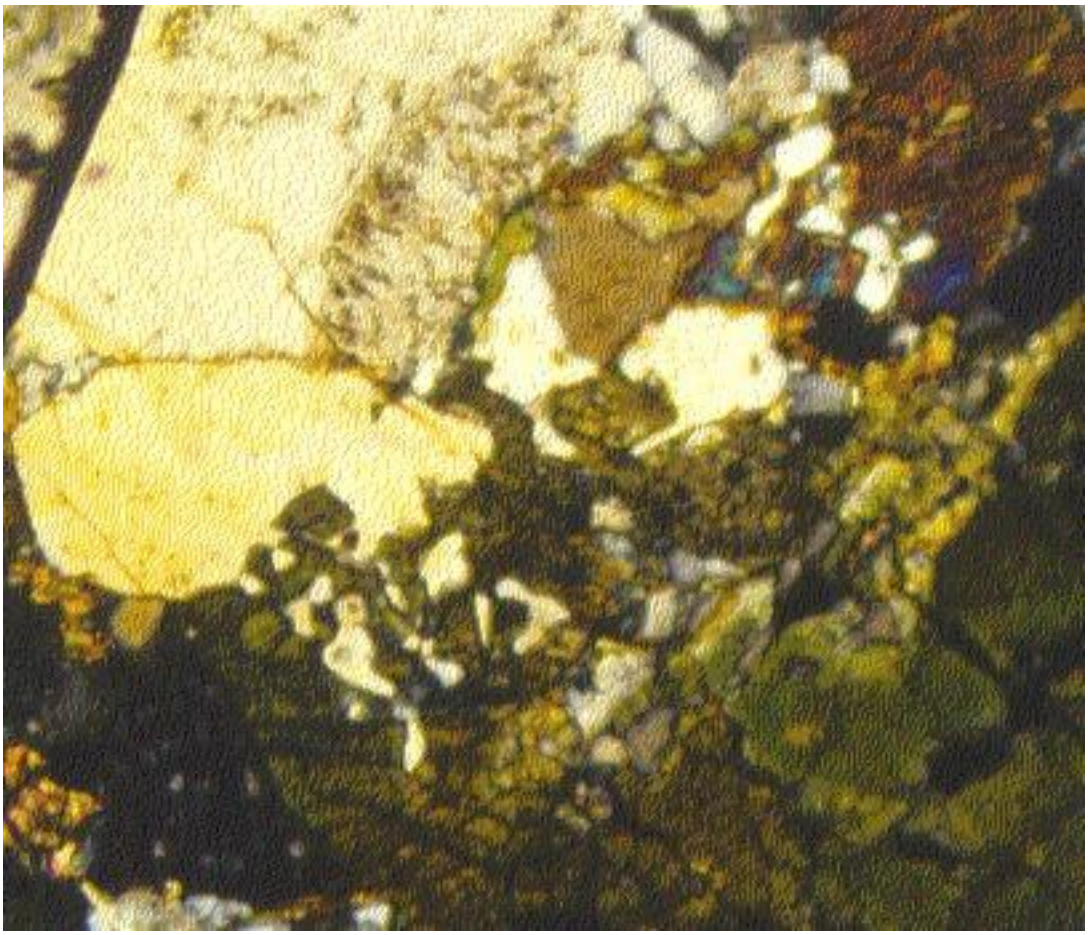

Fig. 20. Quartz sieve texture (white) in hornblende to the right of the yellow quartz grain. Hornblende (brown and dusky green). (Biotite-hornblende quartz monzonite; sample HQ 98-1, Fig. 1).

Discussion of outcrop relationships

If an investigator observed the outcrop that was described and illustrated in the first part of this article (Fig. 3 and Fig. 4) and thought only in terms of magmatism, the relationships seen there would be interpreted as evidence for injection of granitic magma into diorite. The sharp contact against the darker diorite at the bottom of the outcrop, the contrasting mineralogy (dark mafic rock against light-colored felsic rock), and the abrupt transition of the granitic rocks against the deformed chloritized and epidotized diorite would be used as evidence for intrusion of granite magma. But one's model often determines what one sees. Close examination, however, shows (1) that the granitic material in veins is not physically making room for itself by shoving aside the diorite, (2) that isolated islands of K-feldspar and granitic patches in the diorite occur without apparent connection to the main body of the granitic rock (although the third dimension

might allow that to happen), and (3) that there is no evidence that the granitic rock has assimilated large volumes of biotite and hornblende which would make the granitic magma darker at or near the contact.

In some terranes mixing of contemporaneous mafic and felsic magmas occur, but the cataclastic textures in the diorite at this outcrop and the absence of strong deformation in the adjacent granitic rock in combination with the absence of evidence for cross-current diffusion (or assimilation) between the two rock types rule out the mixing of two magmas. The quartz monzonite and granodiorite are certainly younger than the diorite regardless of the origin of the granitic rocks − magmatic or metasomatic.

Although the field relationships (Fig. 3 and Fig. 4) may seem to indicate a magmatic contact to some investigators, the textural studies in thin sections reveal the replacement characteristics. Therefore, this outcrop is quite significant because it shows a ***"replacement front"*** and reveals how abrupt that front can be in terms of the rapid (short-interval) disappearance of most of the hornblende and biotite in the original diorite to produce the more-felsic quartz monzonite and granodiorite. Moreover, the contrast between the sharp and gradational contacts and the appearance of the rocks on either sides of these contacts show that this "front" is controlled by the degree of deformation of the original rocks; see also Roddick (1982). A similar, abrupt, replacement front was also observed in studies of a diorite contact with myrmekite-bearing granite near Temecula, California (Collins, 1988ab).

Conclusions

The field relationships and thin section evidence indicate that the original stock was composed of biotite-hornblende diorite and tonalite. Those facies richer in hornblende and less rich in biotite are the facies which are more competent and which now generally remain as island remnants in the interior of the stock or along its borders. In comparison, those facies richer in biotite and structurally less competent would have been more easily deformed, permitting fluids to enter and cause metasomatism. In that process, the biotite was replaced by silica to form quartz, releasing K, and this K replaced some of the plagioclase to form K-feldspar and myrmekite.

Factors that allowed K-feldspar megacrysts to form could have been (1) a great abundance of biotite to provide sufficient K to produce larger K-feldspar crystals and (2) extensive cataclastic shearing and/or crushing to allow adequate

movements of metasomatic fluids to carry the K to replacement sites. Remnant more-mafic facies in the eastern part of the stock tend to be finer grained, more hornblende rich, and less deformed, and, therefore, in the eastern part, K-feldspar megacrysts did not form, and the amount of K-metasomatism was sufficient to convert the rocks only to quartz monzonite rather than to granodiorite.

Noteworthy is the fact that the quartz monzonite and megacrystal granodiorite in the field show little evidence for deformation (Fig. 5). This is because recrystallization and replacements have annealed the former cataclastic textures except for the enclosed plagioclase fragments in the K-feldspar crystals which are in parallel optical orientation and are remnant evidence for the early history of cataclasis.

In thin sections of **both** the western megacrystal granodiorite and the eastern quartz monzonite, some K-feldspar crystals have grid-twinning, typical of microcline, while others in the same thin section lack grid-twinning, typical of orthoclase. Both K-feldspar types, however, show the same kinds of vein-replacements of adjacent plagioclase crystals or enclose irregular islands of plagioclase which are in optical parallel continuity with an adjacent large plagioclase crystal. The absence of grid-twinning in some places may result from the thin section being cut where the grid-twinning of the microcline is not seen. On the other hand, such crystals could actually be orthoclase. On the basis of the replacement textures that are associated with the orthoclase-like crystals, however, this K-feldspar need not have crystallized from a melt but result where temperatures rose high enough to produce orthoclase during the K-metasomatism. The absence of melting is based on the fact that melting temperatures would have destroyed the coexisting myrmekite; see web site articles http://www.csun.edu/~vcgeo005/Nr24TwoStyles.pdf, http://www.csun.edu/~vcgeo005/Nr26Controversy.pdf, and http://www.csun.edu/~vcgeo005/Nr28Popple.pdf.

Acknowledgements

Much thanks are extended to Donald Hyndman who loaned 19 thin sections of samples that he collected from the Lower Caribou Creek stock during his Ph.D study of this stock and other rocks in a much larger area south of Nakusp, British Columbia. He also provided many helpful comments that assisted in this study. Special thanks are extended to my wife, Barbara, for many excellent editorial suggestions.

ADDENDUM

The following comments are made by Donald Hyndman who agrees with me that K-replacement has occurred in the megacrystal granodiorite and quartz monzonite but suggests that all of the K-replacements were done during late-stages of magmatism. The following are excerpts of communications to me that are pertinent to his alternative interpretations and are inserted with his permission.

"I wonder if some/many of the features that you see/describe could result from a different interpretation. For example, some of the fine-grained 'diorite' in digitate contact with coarser granitic material (Fig. 3 and Fig. 4) could be formed by magma mingling. The mafic magma would chill in the granitic magma while mingling with it. Brittle fracturing and different degrees of chilling of preserved mafic magma would be expected if surrounded by highly viscous and moving felsic magma. The fragments would be broken up by further movement of the viscous granite, and many/most of the pieces would appear angular. Fracturing in a magmatic environment is no problem in a magma in the late stages of crystallization. Its viscosity is unbelievably high, and any movement would place very high stresses on any of the already crystallized fragments or grains.

Iso-crystallization of a granodiorite magma at various pressures and variable water contents would begin with plagioclase, followed by quartz, and end with K-feldspar, as determined experimentally (Robertson and Wyllie, 1971; Whitney, 1975). Under such conditions, K-feldspar would begin crystallization late when water content had built up to approach saturation. Nucleation beginning under those conditions would be inhibited, and diffusion and growth rate fostered, as in pegmatites. Thus, K-feldspar would tend to form a few, large crystals/megacrysts. The K-feldspar, along with amplified water activity, might permit the K-feldspar to replace other minerals enclosed within it. Amount of diffusion depends on the amount of time available, which in turn, is related to the rate of cooling/depth of emplacement. It also presumably depends on the amount of water present during diffusion. Water can be lost from the granitic magma at various stages, such as with decreasing pressure during magma rise, and very quickly.

In the gradational zone between megacryst-bearing granodiorite and the megacryst-free part of the pluton, I recall K-feldspar which is very

poikilitic, containing all of the minerals in the rock. If the K-feldspar replaced these remnants, they would be less abundant in the better-formed megacrysts. Where K-feldspar replaces cores of plagioclase crystals, the more calcic composition in the core could go into solution before precipitation of the more sodic rims. Apparently calcic cores can melt preferentially, without direct access through visible veins to the enclosing magma. This is seen in phenocrysts in many volcanic rocks with glass inclusions.

Where do the mafic constituents go that were in mineral inclusions within the K-feldspar megacrysts? These are in relatively small proportions compared with the felsic constituents. They would likely diffuse into the surrounding magma, and crystallize on the already growing grains of mafic minerals. Also, I would expect that any solid-state fractures that provide avenues of escape of mafic constituents to show a concentration of mafic constituents along the walls of these fractures.

The activity of the metasomatic constituents would presumably be higher with magma present, especially at the higher temperatures with a magma present. Most of the changes would have gone at faster rates and to a greater degree of completion when a melt is present, and at the higher temperatures therein. These comments do not, of course, negate any metasomatic activity at subsolidus conditions. Compared with the rates of diffusion in the magma, however, the rates of diffusion should be orders of magnitude slower in the completely solidified rock which is, of course, also at lower and decreasing temperature.

I am not prepared to argue the origin of myrmekite since I have not studied it to any extent. But an origin inferred from a few occurrences does not necessarily translate to other occurrences at different pressure, temperature, composition, oxygen fugacity, etc."

COMMENT

I agree with Donald Hyndman that there can be K-metasomatism in late stages of magmatism (see http://www.csun.edu/~vcgeo005/NrTwoStyles.pdf), but there is likely a continuum between magmatic replacements and sub-solidus replacements. His emphasis is on magmatic processes; mine is on sub-solidus reactions.

From the appearance of the outcrop (Fig. 3), I cannot tell (**1**) whether granodiorite magma has physically shoved broken fragments of a former, chilled, diorite magma that was once intruded nearly simultaneously with a granodiorite magma or (**2**) whether a hot, plastic-to-brittle, solid granodiorite, formed by replacement of diorite, has shoved broken fragments of diorite which were in the process of replacement. Brittle fracturing may occur in late stages of magma crystallization, but it is equally true for a hot, but cooler solid that was becoming granodiorite by replacement of a diorite. Note that "**cooler solid**" does **not** mean totally solid without abundant micro-fractures because the extensive replacements cannot occur without avenues for fluids to move, just as in magma.

In volcanic rocks replacements of more-calcic cores of plagioclase crystals by solution is along rounded veins that penetrate from the outside inward and not along angular fractures. Replacement of plagioclase by K-feldspar in melts, if it occurs, should be from the exterior inward and not from the interior outward. See http://www.csun.edu/~vcgeo005/NrTwoStyles.pdf which discusses exterior-inward replacements in the Cornelia pluton. In any case, the more-calcic cores are less stable and more likely to be replaced either by magmatic or subsolidus metasomatic fluids, so the fact that replacements of plagioclase cores occur in magmatic rocks does not rule out that it also occurs in fractured solidified rocks.

It may be easier for metasomatism to commence in the very late stages of magmatism rather than wait until the rock is totally solid. In latest stages, the nearly solidified rock could be subjected to forces that would re-open channel-ways by fracturing so that fluids can move again, but the same forces that cause flowage of viscous magma and simultaneous fracturing of previously crystallized rock, could continue after temperatures are below the sub-solidus. The replacements do not stop with the end of magmatism provided that the solidified rock is **micro-fractured**. On that basis, the original granitic magma that is alleged to be granodiorite composition and which is supposed to mingle with and chill a more-mafic diorite magma, may in fact be a progressively-solidifying, K-rich diorite magma that is converted to granodiorite because of the continued fracturing and a continuum of replacements that go on into the subsolidus stages, shifting K in biotite in the diorite to K in microcline or orthoclase.

The real issue is the timing of when the K-feldspar crystals have formed − *late magmatic* or *subsolidus*. Poikilitic inclusions of hornblende, biotite, and plagioclase certainly occur in late-forming K-feldspar crystals that have crystallized from magma, but such inclusions can also occur where K-feldspar has incompletely replaced these inclusions as the K-feldspar replaced plagioclase that

poikilitically enclosed hornblende, biotite, and other plagioclase crystals. Moreover, in poikilitic K-feldspar that has formed by late-stage crystallization from magma, myrmekite is absent. It is absent because in magma, the temperatures are hot enough that granophyric or micrographic quartz-plagioclase intergrowths would have been produced in which the plagioclase has uniform composition. In contrast, the plagioclase in myrmekite in the Lower Caribou Creek granodiorite has variable composition in the same grain, and these compositions are proportional to the thickness of the quartz vermicules.

If magmatic K-feldspar replaces minerals that it normally encloses as poikilitic inclusions, there are no criteria that can be used to counter Donald Hyndman's argument that the displaced elemental components were added to "already growing rains of mafic minerals." However, in no place are there concentrations of mafic constituents along the walls of fractures.

Donald Hyndman is correct that rates of diffusion in solid rock should be orders of magnitude slower than rates of diffusion in magma. But this statement applies to the old false idea of early granitizers that K-metasomatism was achieved by dry diffusion in totally solid rocks which were not fractured. To re-emphasize again − **the K-replacements that occur in the diorite and tonalite that have become granodiorite and quartz monzonite are possible because of breakage of grain boundary seals and nano-sized fractures through the crystals.** Abundant fluids (as is also the case in late-stages of a magma) would enable the K-replacements at subsolidus temperatures, and the total distance of solid-state diffusion is likely no more than a fraction of a millimeter or half the width between tiny fractures in the crystals. Distances of diffusion of elements in crystals at subsolidus temperatures could be less than that which occurs during K-replacements in a magma where fracturing is not as likely. In magmas, the higher temperatures would facilitate more rapid diffusion, but subsolidus temperatures are still plenty high enough near the eutectic values for diffusion to occur.

Finally, in a magmatic model there is still the problem of the formation of myrmekite in the granodiorite and quartz monzonite. Myrmekite cannot be dismissed as not being part of the total process. Donald Hyndman should not be expected to argue the origin of myrmekite since he has not studied it to any extent. However, the model that I have proposed for its origin is not based on just a few occurrences, but now on more than 50 different terranes in which the results are consistent over broad ranges of different pressures, temperatures, compositions, oxygen fugacity, etc. The experimental work of Robertson and Wyllie (1971) and Whitney (1975) are appropriate for showing crystallization trends in magmatic

rocks, but these experiments are done in closed systems (laboratory bombs) in which no myrmekite is formed and cannot be strictly applied to open systems at temperatures below the subsolidus where myrmekite is formed. For similar studies of large-scale K-replacements of deformed diorite that produced megacrystal granitic rocks, see also articles http://www.csun.edu/~vcgeo005/Nr6Waldoboro.pdf and http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf.

The following are some suggestions made by Malcolm Roberts as to why microcline or orthoclase will crystallize and are presented with his permission.

"From what I have read, and the rocks I have studied, the transition from orthoclase to microcline is a kinetic phenomenon, for which a couple of factors seem to decide how fast the process will happen. Firstly, a fluid phase lowers the activation energy for the transformation, and secondly, the composition of the K-feldspar itself decides whether the process will occur or not - the presence of Na in the lattice causes instabilities which promote the transition. Maybe the granodiorite crystallized megacrysts of K-feldspar with very little Na, whilst those in the more mafic quartz monzonite are more Na rich causing it to transform to microcline more rapidly on cooling. I found this among the Querigut rocks - low bulk rock Na/K = orthoclase; higher bulk rock Na/K = microcline (Roberts, 1994). Of course, a fluid would help, but is not entirely necessary."

Comment

Malcolm Robert's hypothesis agrees with the thin section evidence. The Na content appears to be higher in the quartz monzonite than in the granodiorite. This observation is based on extinction angles in albite-twins in the plagioclase and on the smaller maximum size of the vermicules in myrmekite in the quartz monzonite in comparison to that in the granodiorite. Nevertheless, the same results might happen where such K-feldspar crystals are formed by metasomatic processes as that which occurs where they are crystallized from magma. The kinetic phenomenon should be the same in either place and might be facilitated by the fluids causing the metasomatism.

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