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23. A CLOSE SCRUTINY OF THE "NEWER GRANITES" OF THE CALEDONIAN OROGEN IN SCOTLAND

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Introduction

The following discussions and interpretations are based on an analysis of 58 thin sections of samples collected during the EuroGranites '97 field trip, Sept. 4-10, 1997, in which 32 participants examined several predominantly I-type granites in eastern and southeastern Scotland (Fig. 1). Except for the Loch Ainort and Dunan granites in the Isle of Skye, these granites belong to the "Newer Granites" that were emplaced 395-435 Ma at the end of the Caledonian orogeny (Stephens, 1997). The field evidence clearly indicates that all of the granitic plutons had a primary magmatic origin, but thin section analyses suggest that following the solidification of most of these plutons, subsequent deformation permitted introduced fluids to cause large-scale changes. This is true for the Strontian, Cluanie, Ratagain, Garabal Hill, Criffell, Fleet, and Loch Doon granitic plutons. The following sections present preliminary observations that support the need for additional studies.

Fig. 1. Outline map of Scotland, showing locations of several "Newer Granites" visited on the EuroGranites '97 field trip, September 5-10, 1997. These include the Strontian, Cluanie, Ratagain, Garabal Hill, Criffell, Fleet, and Doon plutons (after Stephens, 1997).

1. Strontian pluton

The outer, non-porphyritic facies of the Loch Sunart hornblende-biotite granodiorite (Fig. 2) contains zoned plagioclase that poikilitically encloses early-formed crystals of hornblende and biotite. The mineral relationships and the occurrence of angular enclaves of diorite and meladiorite are characteristic of crystallization from a melt and are in agreement with a magmatic origin. However, although a small percentage of K-feldspar is present (1-3 vol. %), none of it is either in interstitial orthoclase or as antiperthite lamellae as would be expected for magmatic K-feldspar. What is observed is that the K-feldspar (microcline) occurs only where it penetrates deformed plagioclase crystals along fractures (Fig. 3 and (Fig. 4), and not in undeformed crystals. Because of the unmatched walls of the fractures, the K-feldspar *must have come in and replaced* the plagioclase rather than having crystallized from a liquid (melt) in that space. Moreover, the brittlefracturing of the plagioclase indicates that temperatures were *below the melting conditions*. On this basis similar relationships in other plutons will be interpreted as replacement and not crystallization from a melt. Between the K-feldspar and the plagioclase, myrmekite with tiny quartz vermicules commonly occurs.

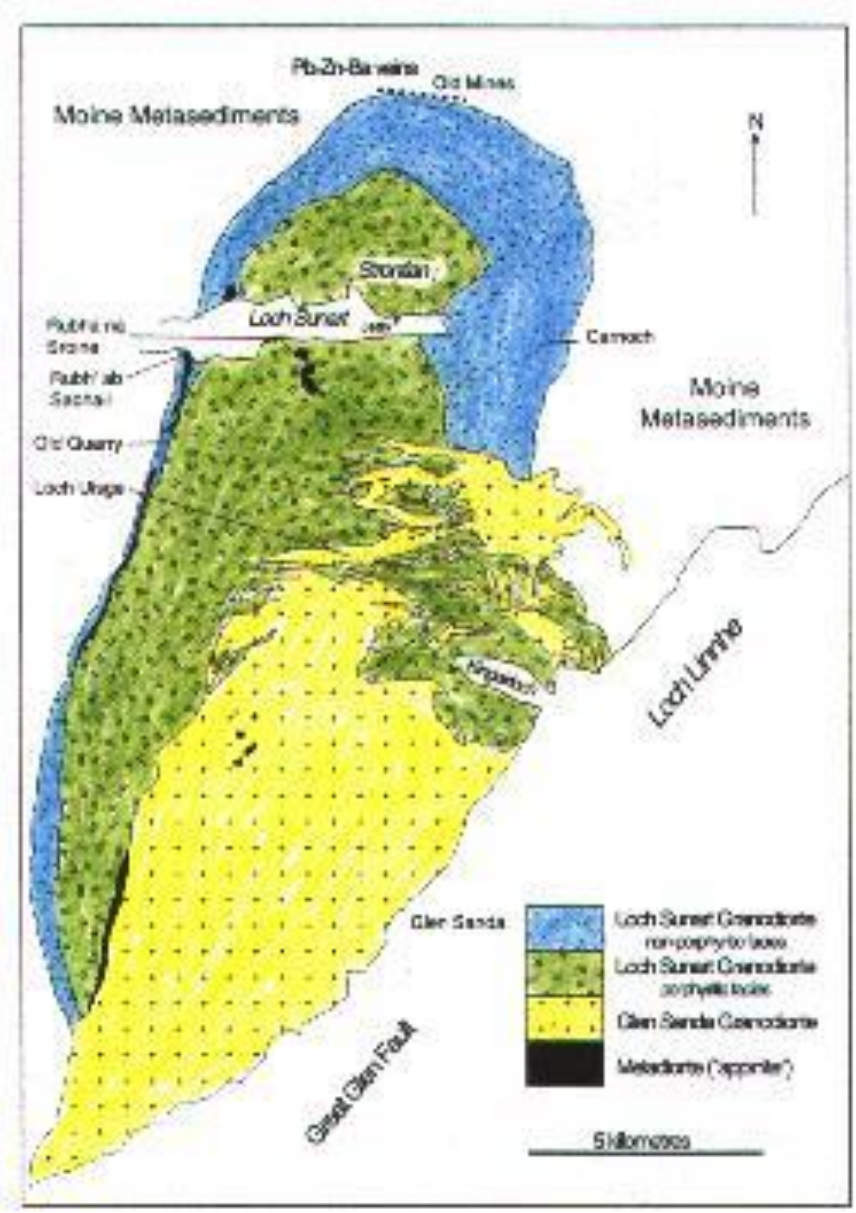

Fig. 2. Petrological map of the Strontian pluton, showing the main zones and localities that were visited (after Stephens, 1997, with revisions of map from MacGregor and Kennedy, 1932). Loch Sunart granodiorite (non-porphyritic, blue); Loch Sunart granodiorite (porphyritic, green); Glen Sanda granodiorite (yellow); meladiorite ("appinite," black).

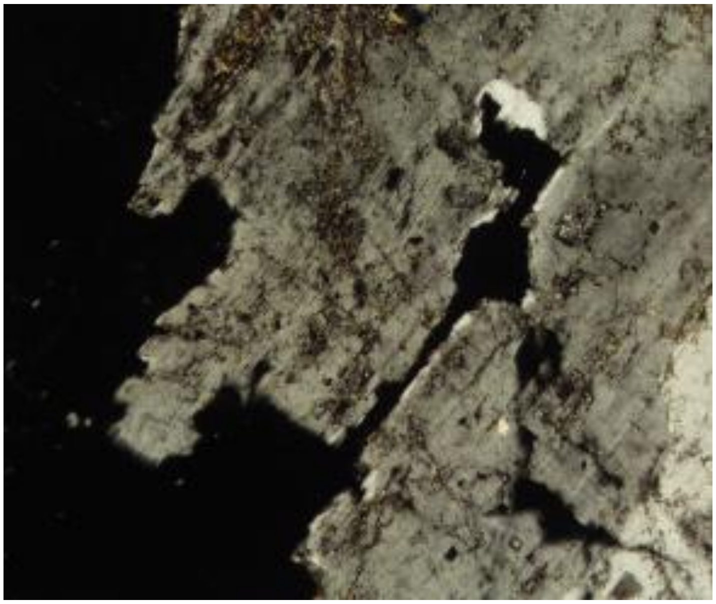

Fig. 3. Plagioclase (light gray and white, speckled with tan, sericite alteration) is penetrated along fractures by K-feldspar (black; center and right of center and in lower right in interior of plagioclase). Also K-feldspar (gray) occurs in the interior of plagioclase (white) in lower right corner. Loch Sunart granodiorite, non-porphyritic facies. Strontian pluton.

Fig. 4. K-feldspar (center, light gray) penetrating albite-twinned plagioclase (left side) adjacent to K-feldspar (dark gray) extending into albite- and Carlsbad-twinned plagioclase (center, right side). Below is biotite (brown) with tiny quartz crystals (white). Larger quartz grains (gray and cream) are adjacent to the biotite. Loch Sunart granodiorite; non-porphyritic facies. Strontian pluton.

Quartz also occurs as tiny blebs in hornblende and biotite, forming a quartz sieve textures (Fig. 5). Quartz is a late stage mineral in magmatic processes. It would not be expected to crystallize *early in the interiors* of the high-temperature hornblende crystals. Therefore, the quartz as well as the K-feldspar must have been formed in processes that affected the magmatic rocks *after they were solidified* and subjected to deformation (Collins, 1988a; Hunt et al., 1992). See http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf, http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf, http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf, and http://www.csun.edu/~vcgeo005/Nr10Donegal.pdf.

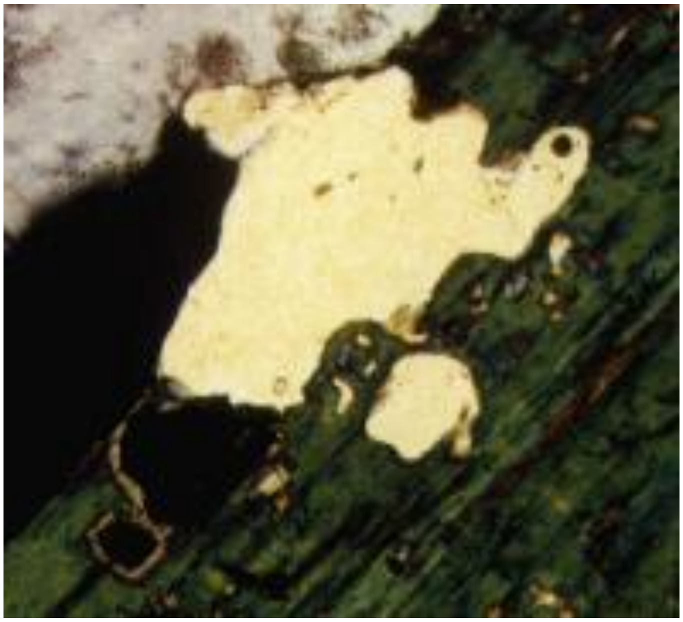

Fig. 5. Hornblende (green) with quartz (cream white) in a poorly-formed quartz sieve texture. Loch Sunart granodiorite, non-porphyritic facies.

Where the non-porphyritic facies grades eastward to the porphyritic facies along the north shore of Loch Sunart (Fig. 2), the ferromagnesian silicates and zoned plagioclase in the ground mass look essentially the same. The K-feldspar and some of the plagioclase, however, no longer look the same. The K-feldspar has penetrated farther into fractures, replacing the plagioclase so that large undeformed crystals of K-feldspar occur leaving only remnants of unreplaced plagioclase. These small remnants have *parallel optical continuity with larger unreplaced portions* of the plagioclase (Fig. 6). Myrmekite again commonly borders the K-feldspar (Fig. 7). Because of the presence of the larger K-feldspar crystals, this granodiorite is described as a porphyritic facies, but the K-feldspar crystals are not phenocrysts but metacrysts.

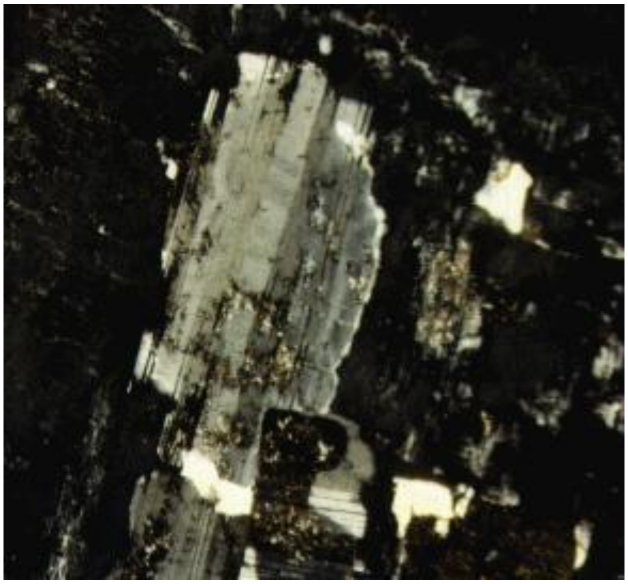

Fig. 6. Coarse K-feldspar (dark gray to black) penetrating albite-twinned plagioclase (center, light gray and tan). Remnant islands of this plagioclase occur in the K-feldspar (right side) in parallel optical continuity. Loch Sunart granodiorite, porphyritic facies.

Fig. 7. Sericitized, albite-twinned plagioclase (left side) with myrmekite borders against K-feldspar (black, right side). Larger quartz crystals (white and cream), sphene (diamond, brown), and hornblende (brown, right corner). Loch Sunart granodiorite, porphyritic facies.

In the central zone of the porphyritic Loch Sunart granodiorite near the jetty (Fig. 2), a dike containing large (2-cm long) euhedral K-feldspar occurs. These crystals differ from the K-feldspar metacrysts and clearly crystallized from a melt. They are *orthoclase* (rather than microcline), and they contain *concentrically* oriented inclusions of plagioclase in zones parallel to possible faces of the K-feldspar crystal as it grew in the melt (Fig. 8).

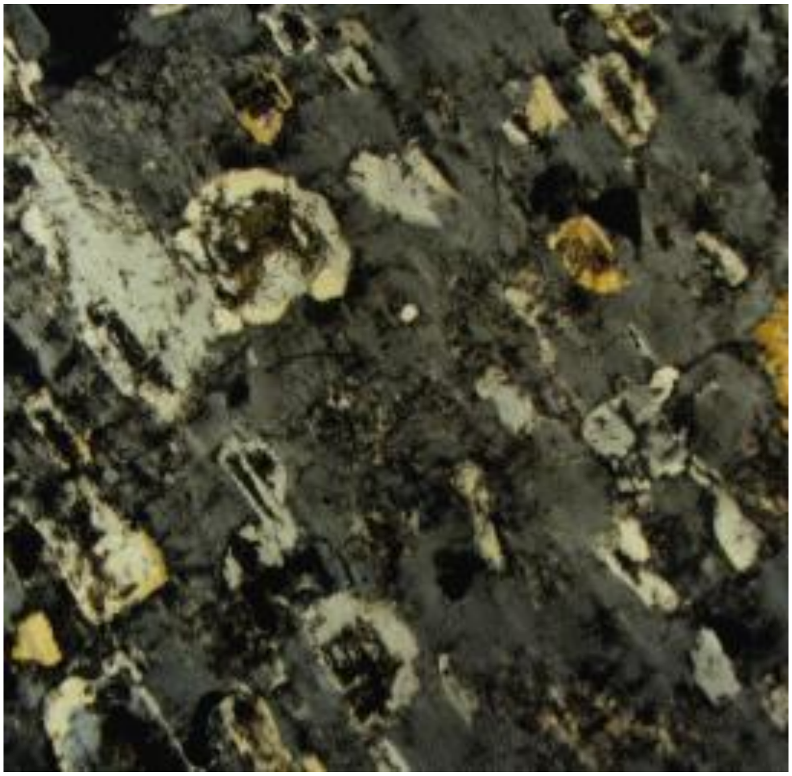

Fig. 8. Portion of megacryst of K-feldspar (orthoclase, gray) with concentric zonation of bands of tiny plagioclase inclusions. Inclusions are albite twinned and rimmed by albite. Loch Sunart granodiorite, porphyritic facies; at jetty site.

In other places in this same locality (not in the dike), the porphyritic granodiorite contains large K-feldspar (microcline) that lacks such oriented inclusions and is like that observed in the transition from the non-porphyritic to the porphyritic facies described above. This latter K-feldspar (microcline) is bordered by myrmekite. The magmatic dike of porphyritic granodiorite may have one of two possible origins. Either (1) the orthoclase-bearing dike was derived from primary magma that had differentiated to this granitic composition or (2) the dike represents secondary magma, produced by re-melting of former diorite after it was deformed and replaced by K-feldspar, as described above (Collins, 1988; Hunt et al., 1992). Melting, however, destroys any evidence of prior metasomatism so that deciding which hypothesis is correct is not readily possible. Nevertheless, the progressive changes inward from the margin of the pluton with increasing replacement by K-feldspar and probable increasing deformation logically suggest that re-melting and mobilization of magma into large fractures (dikes) could have occurred, and that the differentiation toward more felsic composition could be achieved by metasomatism rather than by crystal settling of mafic components.

A sample of the Glen Sanda biotite granodiorite (Fig. 2), collected on the road from Loch Uisge to Kingairloch, shows little evidence for a deformational fabric in the field. In addition, orthoclase crystals containing concentrically oriented inclusions of plagioclase, similar to that in the porphyritic Loch Sunart granodiorite (Fig. 8), are also present. Therefore, both the orthoclase and the coexisting zoned plagioclase in the Glen Sanda granodiorite support the magmatic origin of this rock. Nevertheless, K-feldspar (microcline) crystals in fractured plagioclase and myrmekite (Fig. 9) are locally present. More samples are needed from areas that are transitional to the Loch Sunart granodiorite in order to resolve the history of this rock.

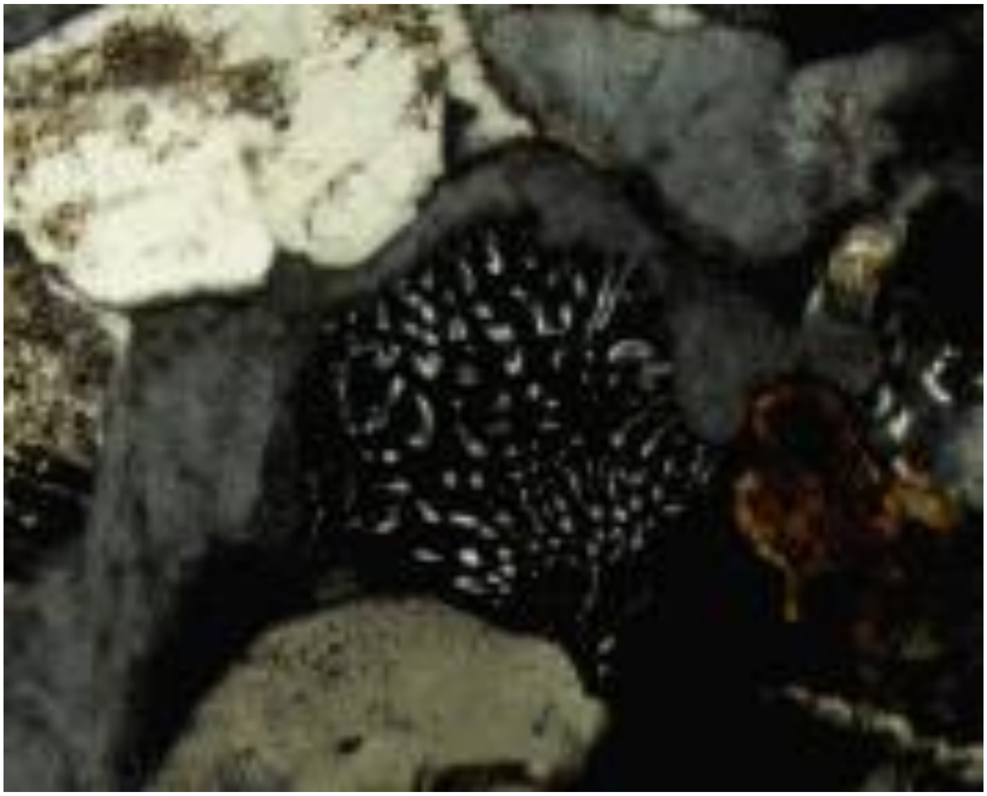

Fig. 9. Myrmekite (center) in Glen Sanda granodiorite. Poikilitic K-feldspar (gray) surrounds sericitized plagioclase crystals. Biotite (brown); quartz (cream). Strontian pluton.

2. Cluanie pluton

The Cluanie pluton clearly has a primary magmatic origin because of the presence of zoned plagioclase crystals. Many plagioclase crystals, however, are broken and contain irregular islands of K-feldspar (Fig. 10) or are penetrated and replaced by K-feldspar along fractures (Fig. 11 and (Fig. 12). In the large K-feldspar crystals (1-2 cm long), remnant islands of plagioclase retain parallel optical continuity with adjacent plagioclase outside the K-feldspar (Fig. 13). Myrmekite is common (Figs. 11, 12, and 13). These features again suggest that the K-feldspar is late and formed by replacement processes following solidification of the magma.

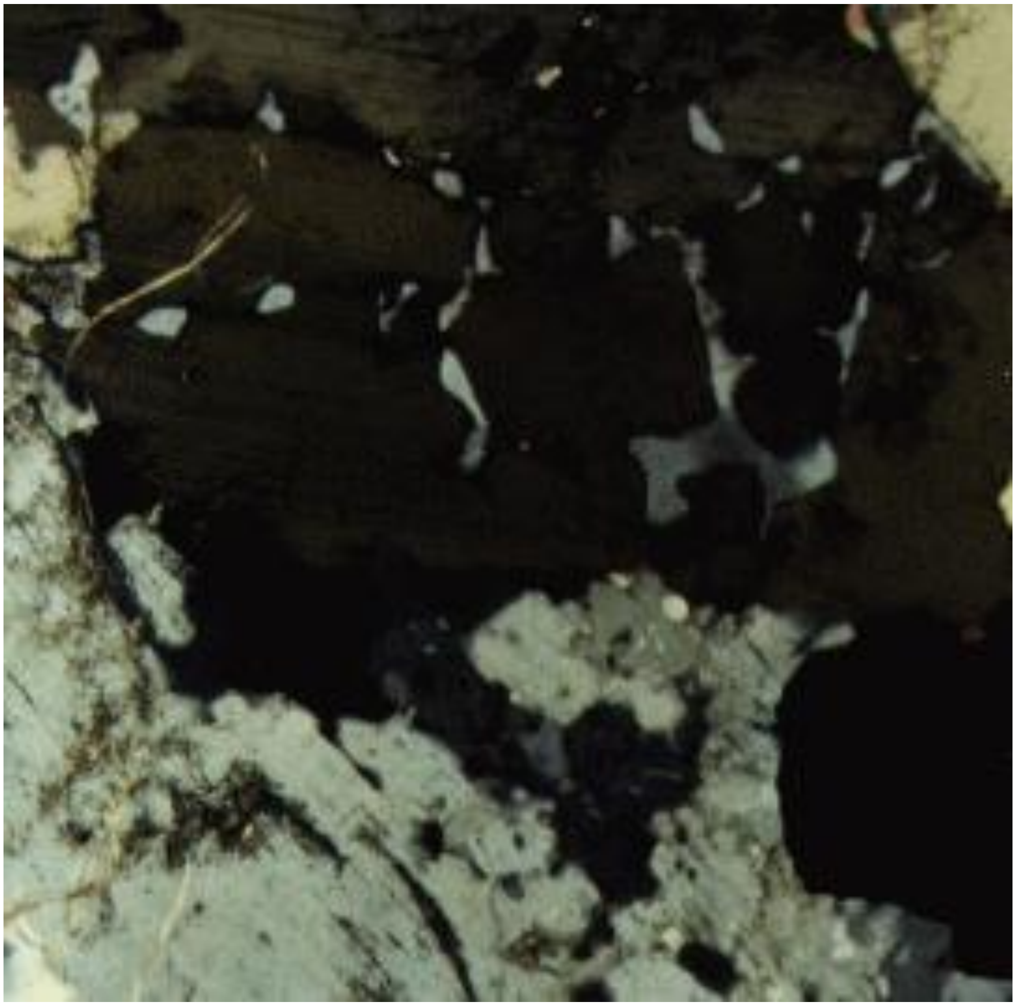

Fig. 10. Albite-twinned plagioclase (top; tan) is penetrated along fractures by K-feldspar (white, gray). Plagioclase (light gray; bottom) is also penetrated by K-feldspar (dark gray) along fractures. Cluanie pluton.

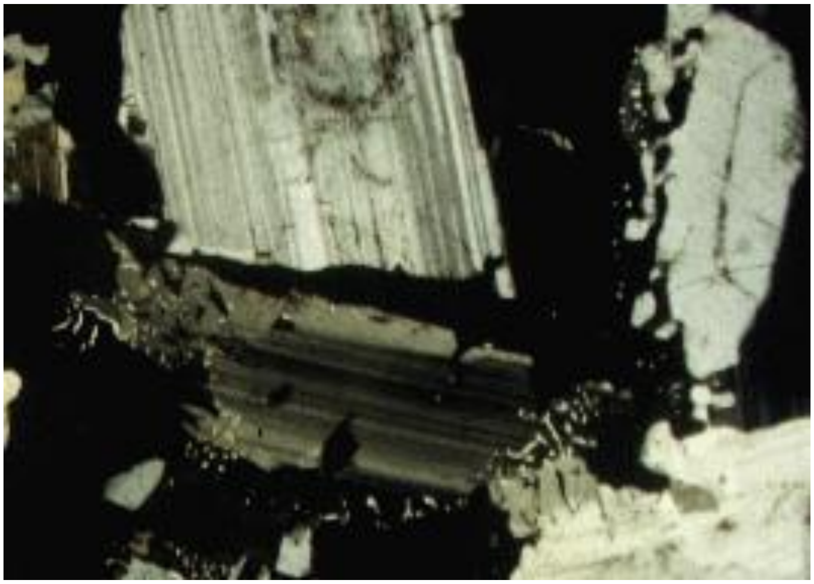

Fig. 11. Fractured, albite-twinned, zoned plagioclase crystals (tan and light gray) surrounded and penetrated by K-feldspar (black) along fractures. Borders of plagioclase against the K-feldspar are myrmekitic in some places. Biotite (brown). Cluanie pluton.

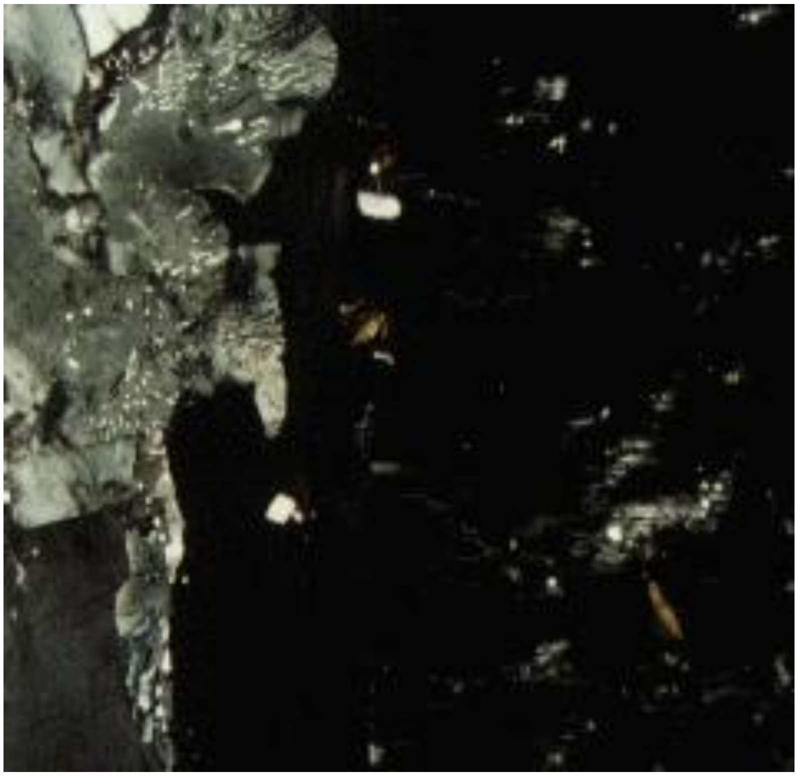

Fig. 12. Myrmekite bordering plagioclase (left side; light gray) against K-feldspar (black). Biotite (brown). Cluanie pluton.

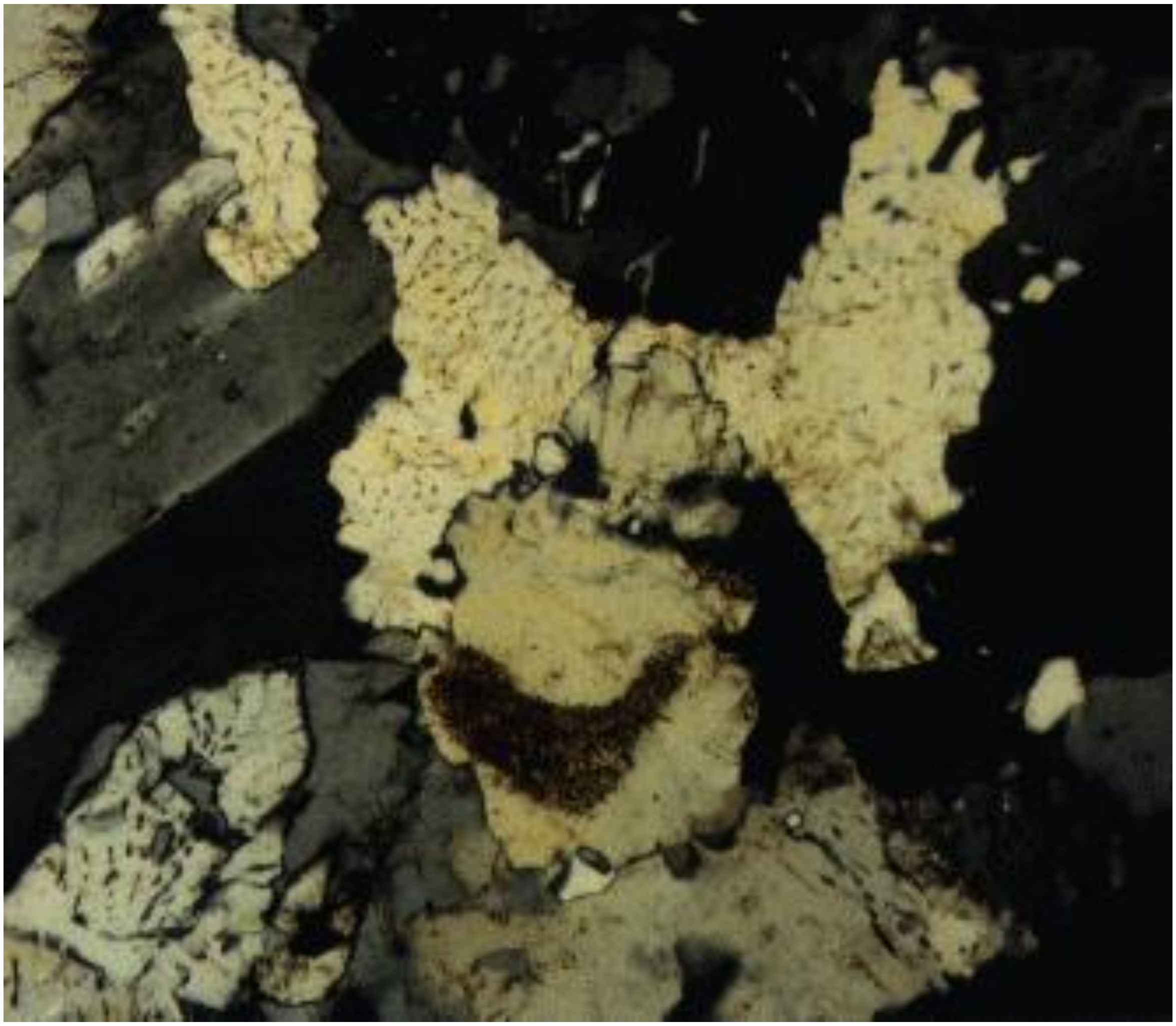

Fig. 13. Myrmekite (top center; cream) replaced by K-feldspar (black; top right). Remnant islands of plagioclase in optical parallel continuity occur in the K-feldspar. K-feldspar (gray; bottom) extend into fractures in myrmekite and occur as interior islands in plagioclase (light tan). Cluanie pluton.

3. Ratagain pluton

The massive pink quartz monzonite at the top of the ridge adjacent to the road near Ratagain (Fig. 14) contains pink perthitic K-feldspar that penetrates fractured, zoned plagioclase (Fig. 15, Fig. 16, and Fig. 17).

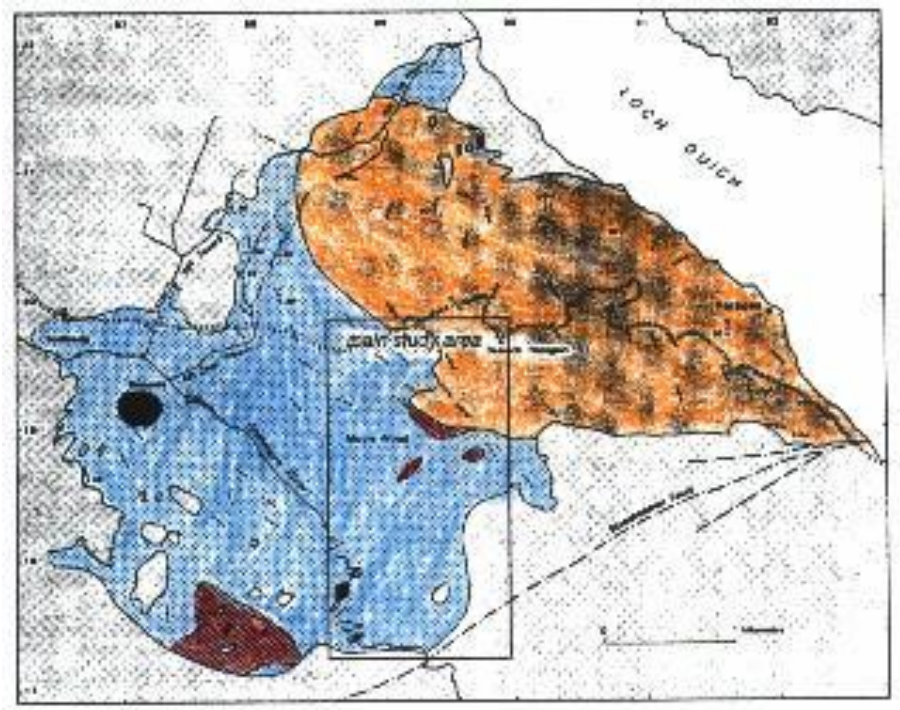

Fig. 14. Map of the Ratagain pluton, showing the main petrological divisions (after Stephens, 1997; taken from Hutton et al, 1993). Quartz monzonite (orange); hornblende diorite, monzodiorite, syenite (blue); appinite (red); pyroxene mica-diorite and olivine gabbro (black).

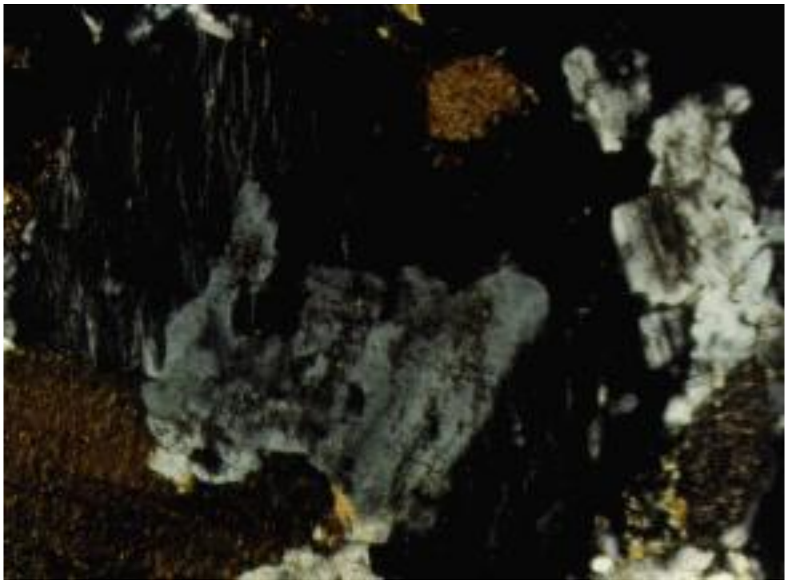

Fig. 15. Perthitic K-feldspar (black) replacing fractured plagioclase (gray; center and right side). Plagioclase lamellae of perthite are optically parallel with large plagioclase crystal (center) . Biotite (brown). Ratagain pluton.

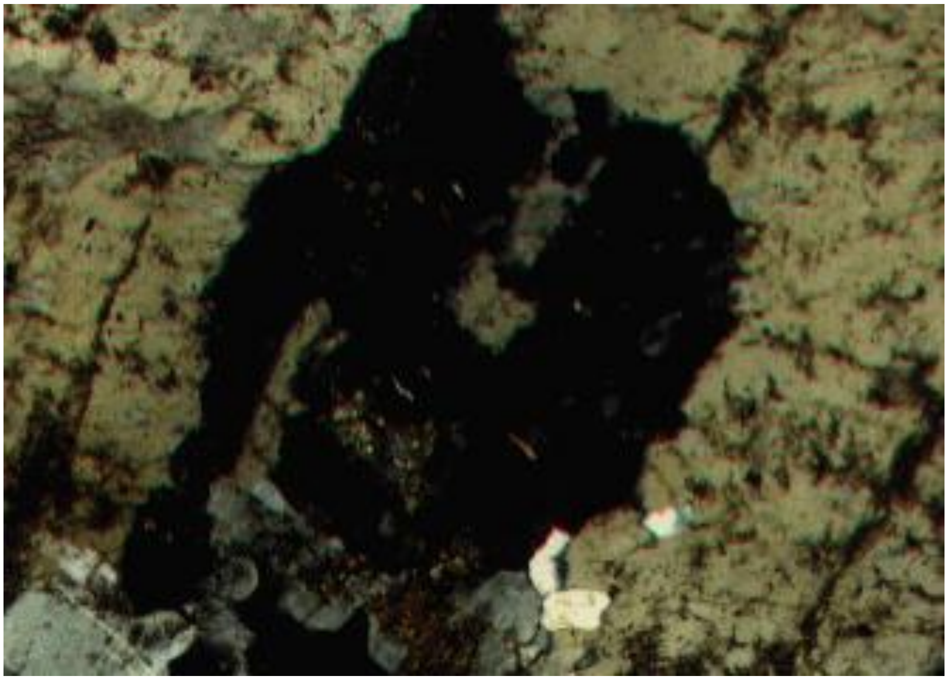

Fig. 16. Large zoned plagioclase crystal (light tan) whose core is almost completely replaced by K-feldspar (black) except for a few island remnants. Ratagain pluton.

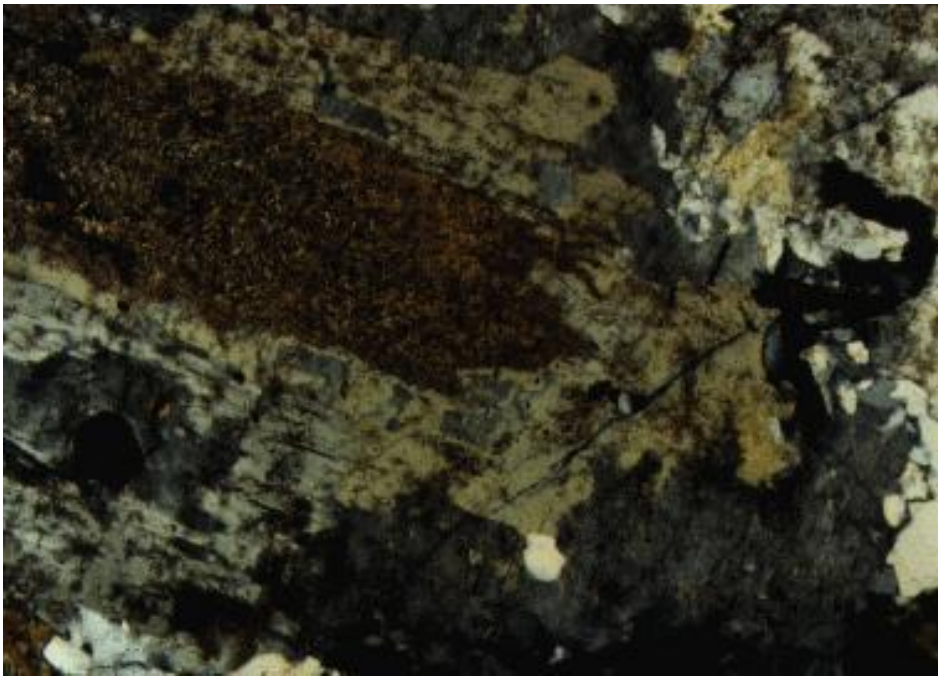

Fig. 17. Large zoned plagioclase with central core (brownish, strongly sericitized). Portions of outer rim of the plagioclase (cream) are replaced by irregular islands of perthitic K-feldspar (gray; lower left quadrant and bottom right). Ratagain pluton.

In many places the plagioclase in the perthitic K-feldspar occurs as irregular patchy islands with either fuzzy or sharp boundaries, and these islands are optically continuous with an adjacent, larger plagioclase crystal either inside or outside the perthitic K-feldspar (Fig. 18 and Fig. 19).

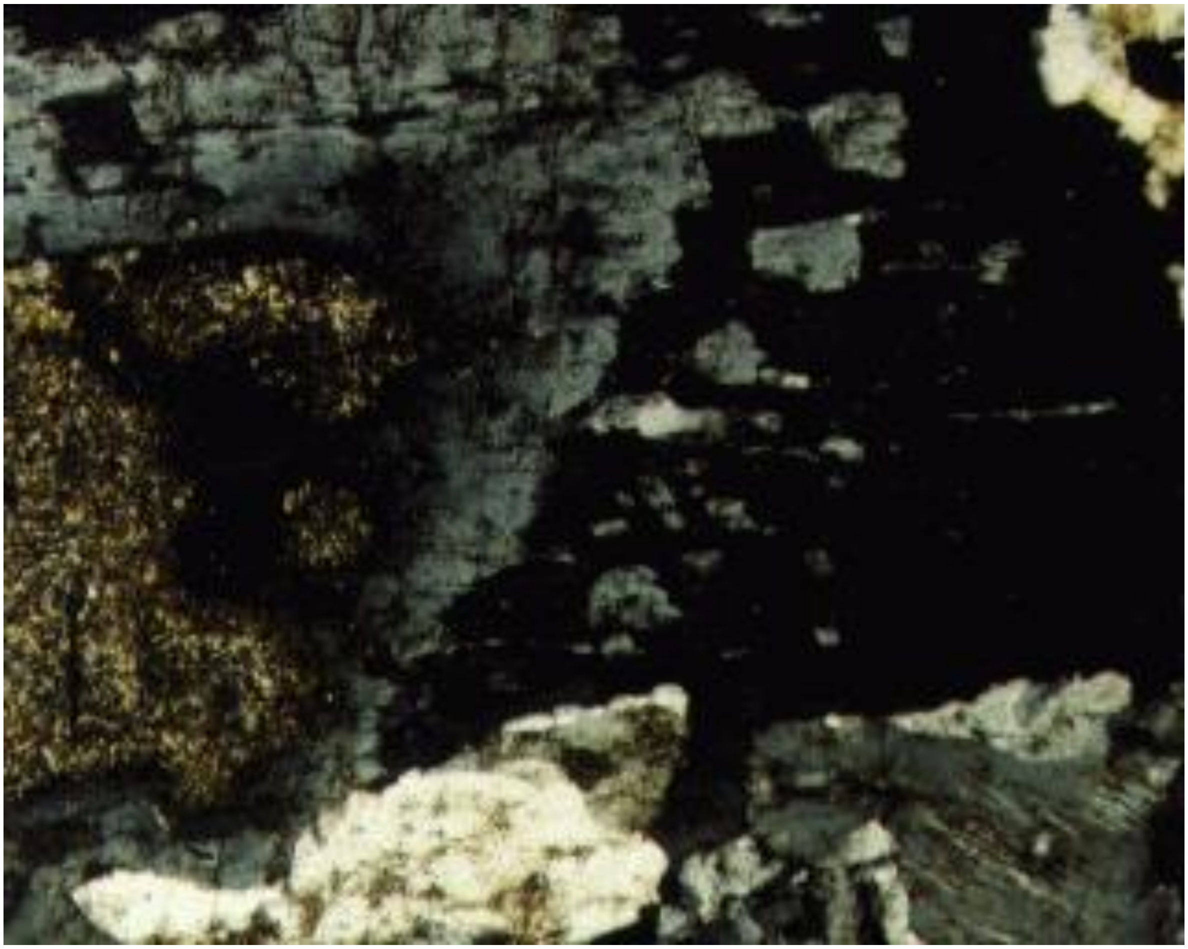

Fig. 18. Large zoned plagioclase (light gray) with sericitized central core (left side; brownish). Outer broad rim of the plagioclase is replaced by perthitic K-feldspar (black). Island remnants of the plagioclase in parallel optic continuity remain in the K-feldspar. Ratagain pluton.

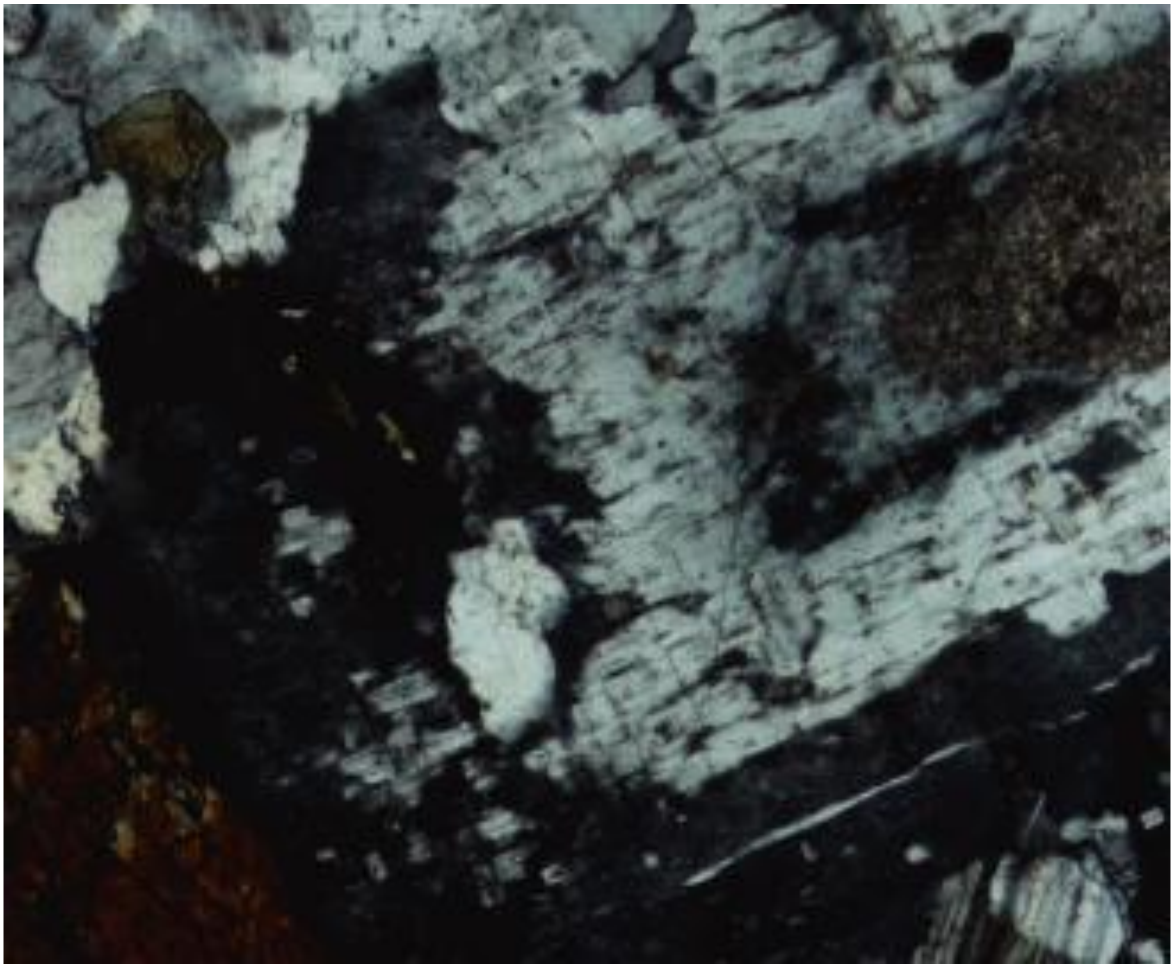

Fig. 19. Large zoned plagioclase (light gray) with sericitized central core (right side, brownish). Island remnants of the outer broad rim of the plagioclase occur in perthitic K-feldspar (black). Elongate oval area (white) enclosed by K-feldspar (left of large plagioclase crystal) is myrmekite; see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

Coexisting with the irregular islands of plagioclase are spindle lamellae, which also are optically continuous with adjacent zoned plagioclase. In some places nearly total replacement of the plagioclase occurs, leaving only plagioclase spindles and/or irregular island remnants that are optically parallel (Fig. 20). These pink perthites are different from magmatic perthites with exsolution spindle lamellae. Exsolved lamellae from high-temperature orthoclase would not be expected to be optically parallel to adjacent larger plagioclase crystals, have irregular distribution, or be variable in shape, abundance, and size from place to place.

Fig. 20. Perthitic microcline (dark gray) with remnant irregular islands of plagioclase and plagioclase lamellae (light gray), both of which are optically continuous. Hornblende (brown). Quartz (white). Ratagain pluton.

The perthitic K-feldspar is also bordered by wartlike myrmekite with tiny quartz vermicules (Fig. 21). The dominant ferromagnesian silicate is hornblende, but some biotite also occurs. if the K-feldspar has formed by replacement of the plagioclase in this rock, what kind of rock, then, was present prior to replacement? The presence of hornblende and biotite suggests that the former rock could have been a hornblende diorite.

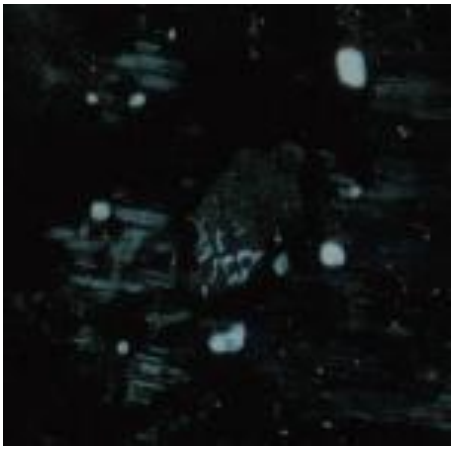

Fig. 21. Myrmekite with tiny quartz vermicules enclosed in microcline (black). Albite-twinned plagioclase (light gray).

Below the ridge top farther to the west, pink quartz monzonite is in contact with a black hornblende diorite (Fig. 14). In some places the contact between the diorite and quartz monzonite is rounded. Participants on the field trip considered the rounded contacts as possible evidence for mingling of magmas. In several other places, however, the diorite is broken and penetrated by a lattice of pink quartz monzonite veins (1 cm wide), which surround angular blocks of black diorite, suggesting introduction of magma into fractured diorite. If the pink K-feldspar of the Ratagain pluton at the top of the ridge is formed by K-replacement of plagioclase (perhaps from a hornblende diorite), it raises the possibility that where the quartz monzonite cuts "brittle" diorite in veins in the contact zone, *pink K-feldspar in these veins may also be the result of K-replacement of plagioclase in the diorite*. The angularity of the diorite fragments certainly suggests that deformation occurred below melting temperatures. No samples were collected, so it was not determined whether this brittle deformation occurs not only megascopically in the diorite but also microscopically in former diorite to form the pink quartz monzonite in the veins. *Without checking thin sections, it is impossible to decide the origin of these veins*.

Rounded contacts between the diorite and quartz monzonite need not represent contacts between two magmas because replacements can occur up to sharp contacts. See the sharp contacts between myrmekite-bearing granitic veins in the more-mafic facies of the Josephine Mountain pluton in California (Fig. 7 in http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf) and between the myrmekite-bearing Cape Ann granite and the Salem diorite in Massachusetts (Fig. 4 in http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf) and between the myrmekite-bearing Woodson Mountain granite and the Bonsall tonalite in California (Collins, 1988ab).

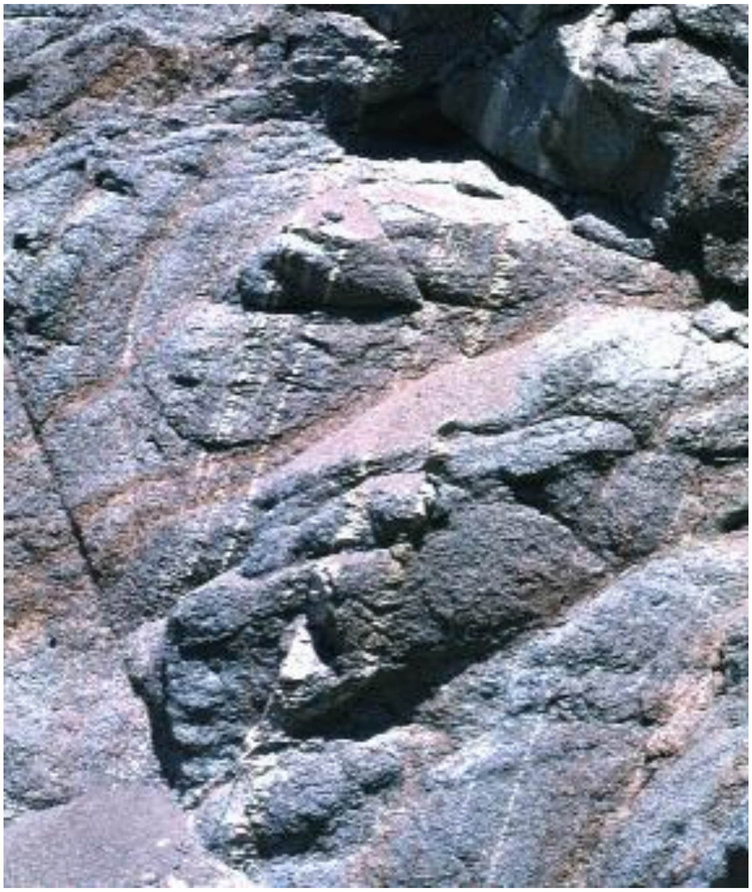

Fig. 7 in Nr3Myrm.pdf. In this photo of a road-cut exposure, a mafic facies of the Josephine Mountain pluton can be seen in the San Gabriel Mountains, north of Pasadena, California (USA).

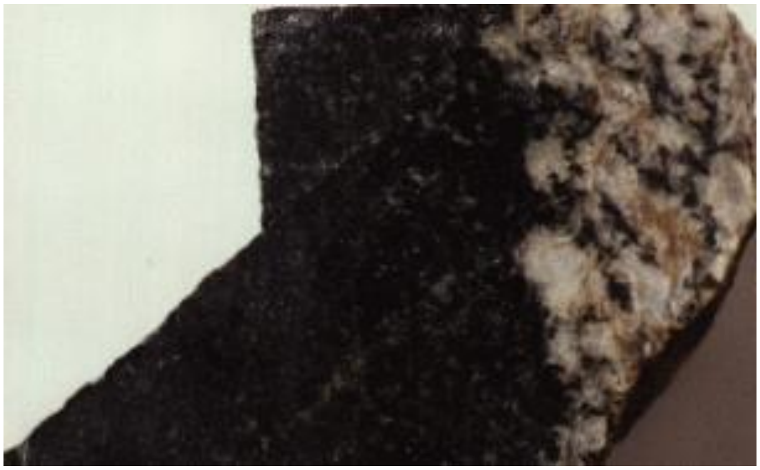

Fig. 4 in Nr3Myrm.pdf. This photo shows a cut and polished drill-core sample from South Hamilton, Massachusetts (USA). (White area is empty space surrounding the core.)

4. Loch Ainort and Dunan granites on Isle of Skye

Excellent examples of granophyric intergrowths of triangular quartz and feldspar (orthoclase) occur in the red granites on the Isle of Skye at Loch Ainort and Dunan (Fig.22). This contrasts with the other plutons in which microcline and myrmekite occur. The granophyric textures, indicating simultaneous crystallization of quartz and feldspar in a melt, are not unexpected because these granites contain fayalite. At any rate, it is clear that these granitic rocks are entirely magmatic in origin and *not affected by younger deformation*.

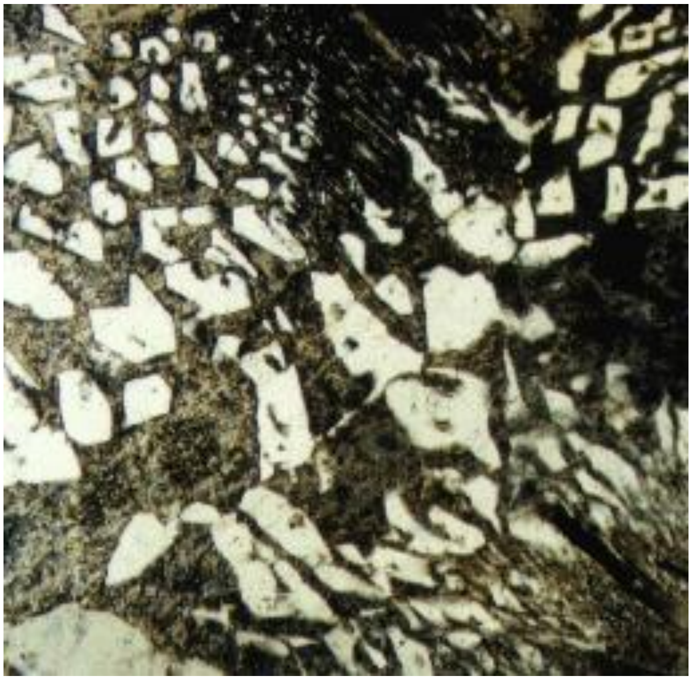

Fig. 22. Granophyric texture in the Dunan granite, Isle of Skye.

5. Garabal Hill pluton

At Garabal Hill there are two facies of granodiorite: a porphyritic megacrystal variety and a non-porphyritic, medium-grained variety (Fig. 23). The non-porphyritic variety examined southeast of the Garabal Fault contains an abundance of zoned plagioclase, augite, amphibole, and biotite. In the samples collected, K-feldspar is not abundant (less than 0.1 vol. %), is interstitial to the other minerals, and is bordered by myrmekite with barely visible tiny quartz vermicules (Fig. 24). In a few places deformed plagioclase crystals with bent albite-twin lamellae occur, but the interstitial K-feldspar crystals are too tiny to enclose fragments and do not show evidence of replacement along fractures. Biotite commonly has a poorly-developed quartz sieve texture (Fig. 25).

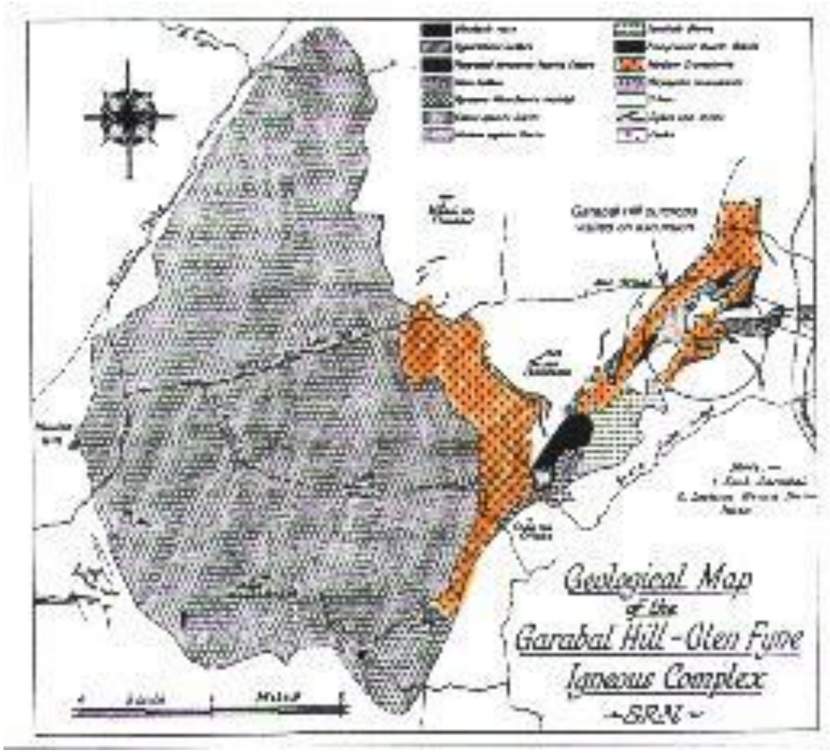

Fig. 23. Petrological map of the Garabal Hill-Glen Fyne complex (after Stephens, 1997; taken from Nockolds, 1941). Medium-grained granodiorite (orange).

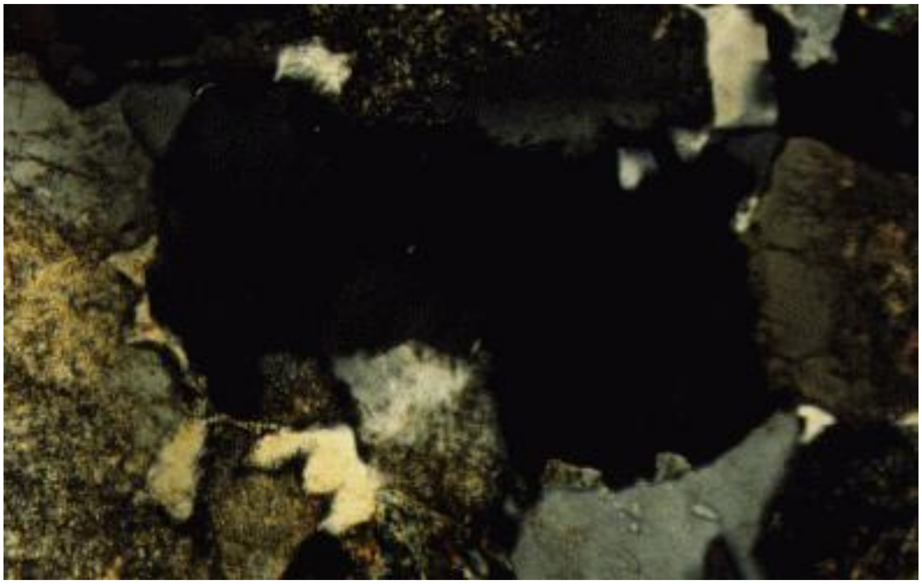

Fig. 24. Interstitial K-feldspar (black), surrounded by sericitized plagioclase (dark gray) and quartz (cream). Projections into the K-feldspar are myrmekitic with barely visible quartz vermicules (lower part of K-feldspar; left center). Garabal pluton.

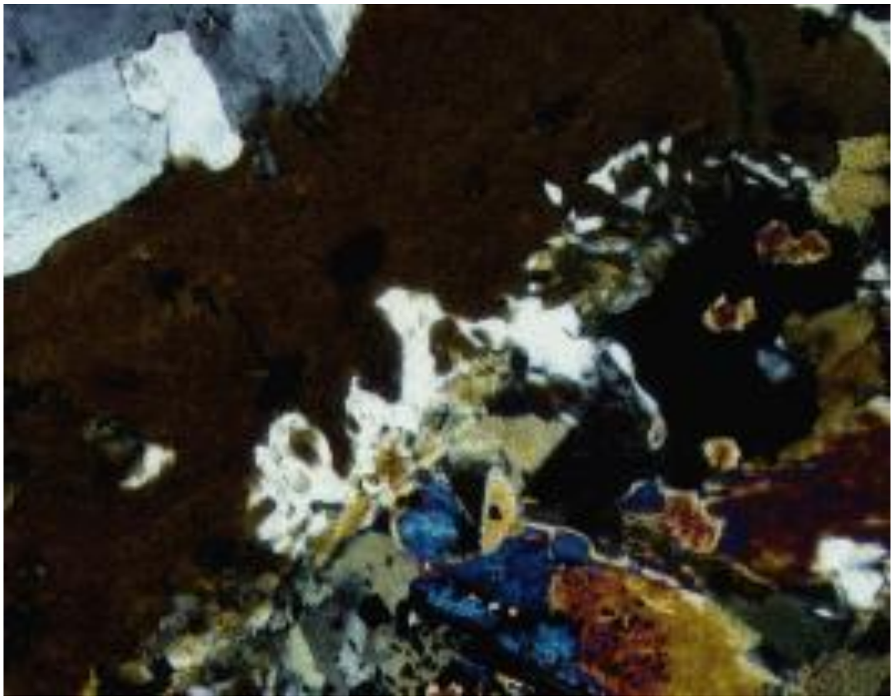

Fig. 25. Biotite (brown) contains quartz (white), forming a quartz sieve texture. Medium-grained granodiorite, Garabal pluton.

Although a liquid line of descent in fractional crystallization (Nockolds, 1941) can explain the compositional changes for most rocks in the Garabal Hill pluton, Stephens (1997) and Mahmood (1986) reported "no simple, closed system, fractionation-model tested is capable of generating the granodiorite compositions." Because the associated rock is a pyroxene-mica diorite, containing plagioclase An_{41} and about 17 % biotite, perhaps deformation and movements of fluids in an open system can account for generating the granodiorite. Because the amount of K-feldspar is so minimal in the thin sections examined, not enough evidence exists to determine whether metasomatism has occurred or not. On that basis, thin sections of the textures in the non-porphyritic granodiorite, where the K-feldspar is more abundant, and in the porphyritic granodiorite, where large megacrysts of K-feldspar occur, should be examined to see if the K-feldspar is formed by replacement of fractured plagioclase crystals; see Addendum.

Criffell zoned pluton

The Criffell pluton contains six different granitic facies, grading from the outer rim, where the most-mafic, clinopyroxene-biotite-hornblende granodiorite facies occurs, to an off-centered core, containing the most felsic, biotite-muscovite granite facies (Fig. 26). A few samples of all the different facies were obtained except for the central biotite-muscovite granite. The following discussion describes various sample areas from the outer rim progressively toward the core, but from different locations that are not directly in line from rim to core.

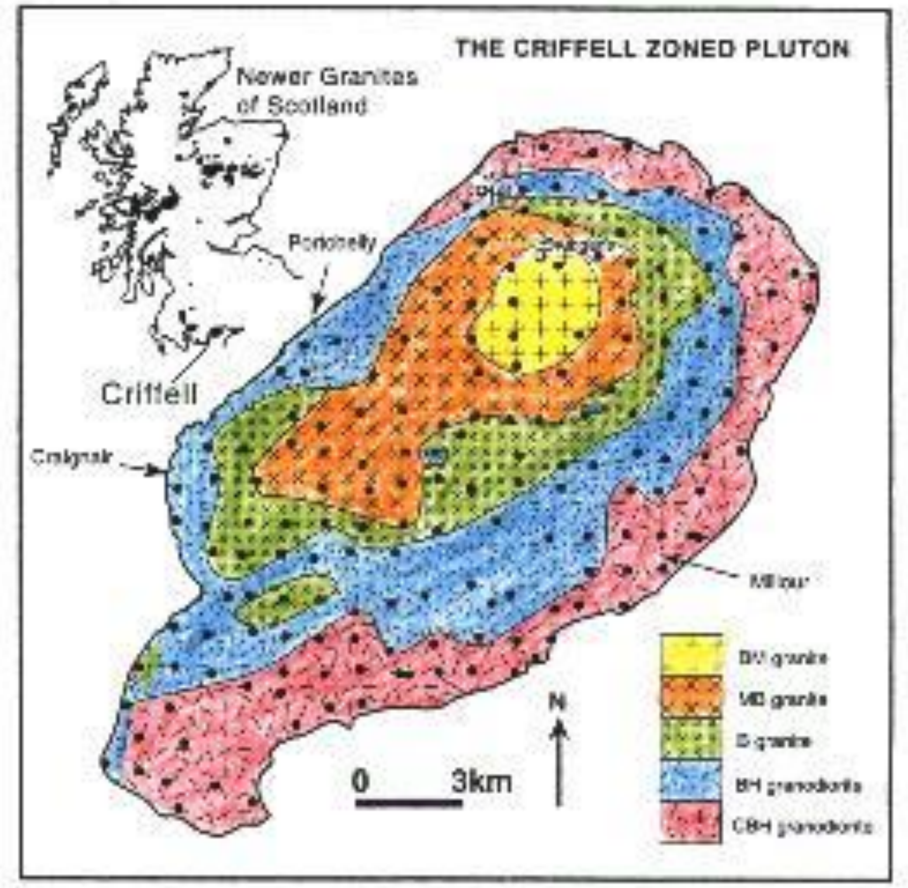

Fig. 26. Petrological map of the Criffell pluton, showing the main zones (after Stephens, 1957, and based on Stephens et al., 1985). Biotite-muscovite granite (yellow); muscovite-biotite granite (orange); biotite granite (green); biotite-hornblende granodiorite (blue); clinopyroxene-biotite-hornblende granodiorite (red).

The outer clinopyroxene-biotite-hornblende granodiorite facies near the contact with the wall rock at Milour (southeastern side of the pluton, Fig. 26), has relatively-abundant, lenticular, mafic, microgranular enclaves that are oriented parallel to the contact with wall rocks. The host granodiorite has a strong foliation, bending of zoned plagioclase crystals, and kinking of biotite (as seen in thin sections). Microcline is seen to replace fractured plagioclase and is bordered by myrmekite with tiny quartz vermicules (Fig. 27). Quartz sieve textures occur in the biotite and hornblende (Fig. 28).

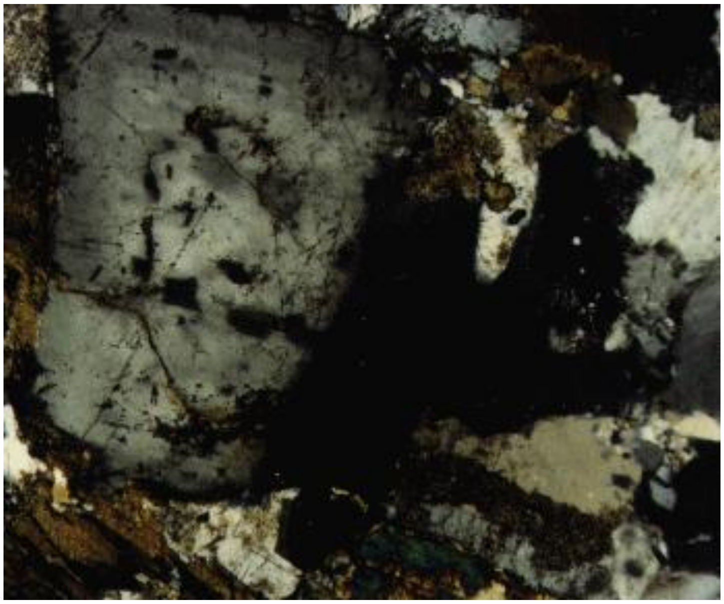

Fig. 27. Zoned plagioclase crystal (light gray, left side; light gray and cream, lower right side) is fractured and penetrated by K-feldspar (black, right side) which also extends into the plagioclase in rectangular islands along a plagioclase zone-band. Myrmekite occurs on right side of K-feldspar but barely visible. Outermost facies, Criffell pluton.

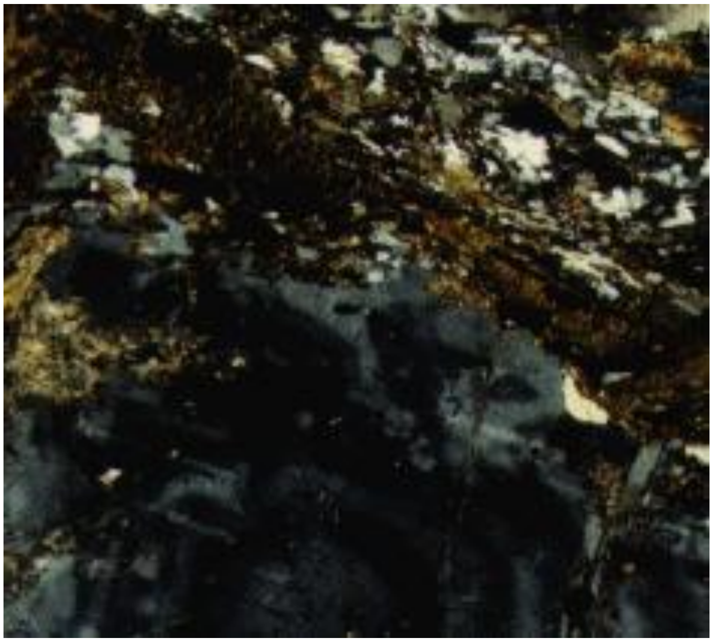

Fig. 28. Zoned plagioclase (gray) and mylonitized biotite (brown) with deformed quartz (white) in former quartz sieve texture. In outer clinopyroxene-biotite-hornblende granodiorite facies of the Criffell pluton.

At the Craignair quarry (southwestern side of the pluton, Fig. 26) the massive, uniform-appearing, biotite-hornblende facies contains zoned and albite-twinned plagioclase crystals. Coexisting hornblende and biotite crystals in some places show quartz sieve textures. Fractured plagioclase are replaced by microcline and bordered by myrmekite (Fig. 29 and Fig. 30).

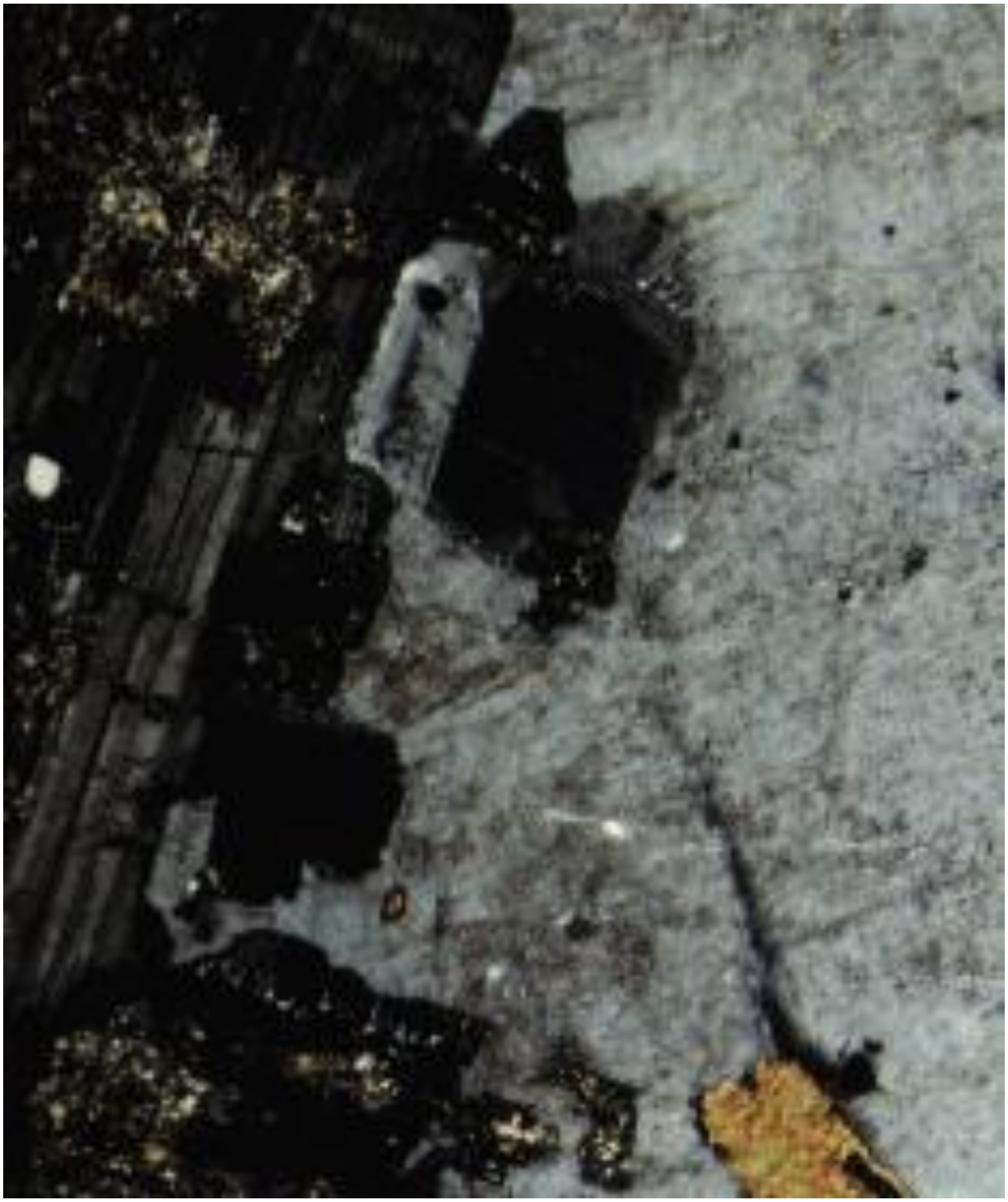

Fig. 29. K-feldspar (gray) penetrating fractured, zoned and albite-twinned plagioclase (black, dark gray). Biotite (brown). From massive biotite-hornblende granodiorite in the Craignair quarry, Criffell pluton.

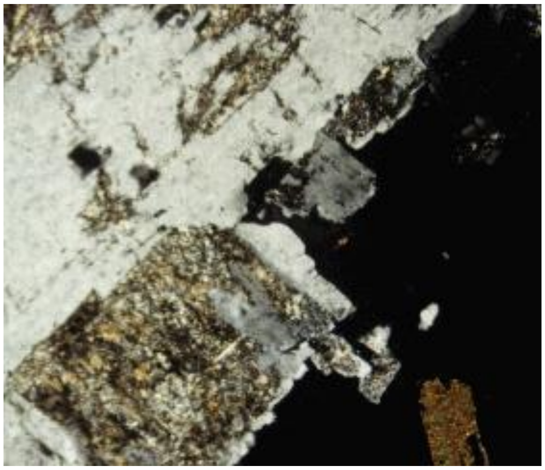

Fig. 30. K-feldspar (black) penetrating fractured, sericitized, zoned, and albite-twinned plagioclase (light gray). Biotite (brown). From massive biotite-hornblende granodiorite in the Craignair quarry, Criffell pluton.

Although the granodiorite is mostly devoid of mafic concentrations in any form, a few mafic angular enclaves (10 cm to 1 m wide) and mafic bands (schlieren, 1 to 5 cm wide and several meters long) locally occur. Thin sections of the enclaves and mafic bands show broken fragments of plagioclase and other ground-mass minerals that are engulfed and partly replaced by K-feldspar. In these relatively mafic rocks the plagioclase fragments maintain parallel optical continuity (Fig. 31, Fig. 32, Fig. 33). Biotite and hornblende in the enclaves also exhibit quartz sieve textures in a few places.

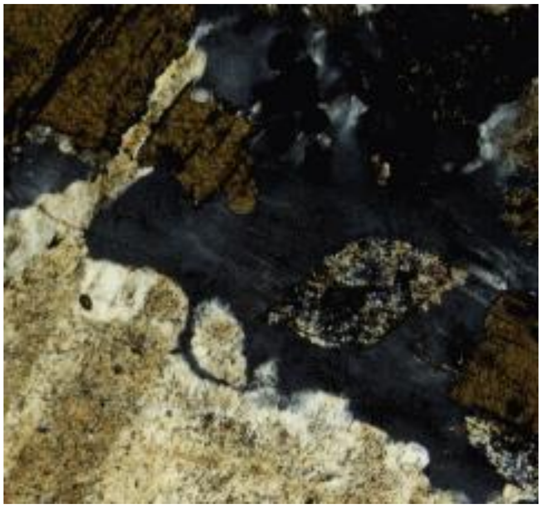

Fig. 31. K-feldspar (gray) penetrating sericitized plagioclase (tan) along fractures. Biotite (brown). Mafic bands in biotite-hornblende granodiorite facies in the Craignair quarry, Criffell pluton.

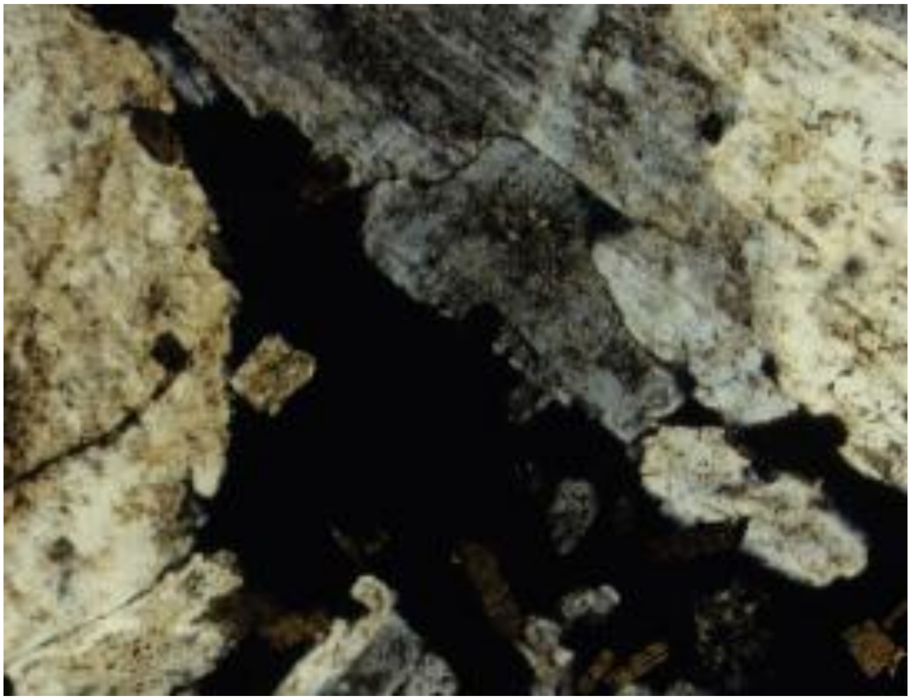

Fig. 32. K-feldspar (black) engulfing fragments of biotite (brown) and plagioclase (gray) and also penetrating plagioclase (tan and light gray) along tiny fractures (top left and right). From mafic enclave in biotite-hornblende granodiorite facies in the Craignair quarry.

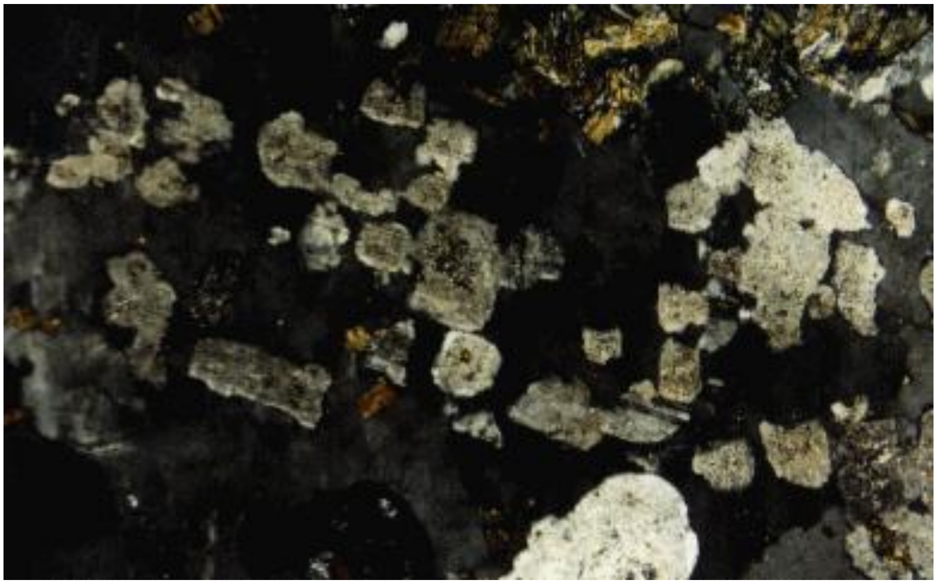

Fig. 33. K-feldspar (dark gray to black) replacing broken plagioclase crystal (light gray) and leaving remnants in parallel optical continuity as islands in the K-feldspar. From mafic enclave in biotite-hornblende granodiorite facies in the Craignair quarry.

Northeast of the Craignair quarry in the biotite granite facies (Fig. 26), a coarse granite with large K-feldspar megacrysts was sampled in a road outcrop. These megacrysts are bordered by wartlike myrmekite with very tiny quartz vermicules (Fig. 34). Islands of plagioclase with parallel optical continuity to adjacent larger plagioclase occur in the megacrysts (Fig. 35).

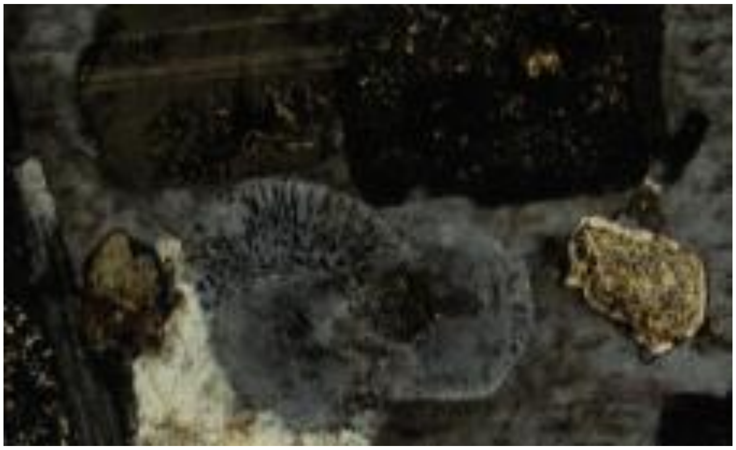

Fig. 34. K-feldspar (light gray; lower right quadrant) surrounding sericitized, albite-twinned plagioclase (tan, gray, cream), one grain of which is bordered by myrmekite (bottom; center) with tiny quartz vermicules (black). Megacrystal granite; Criffell pluton.

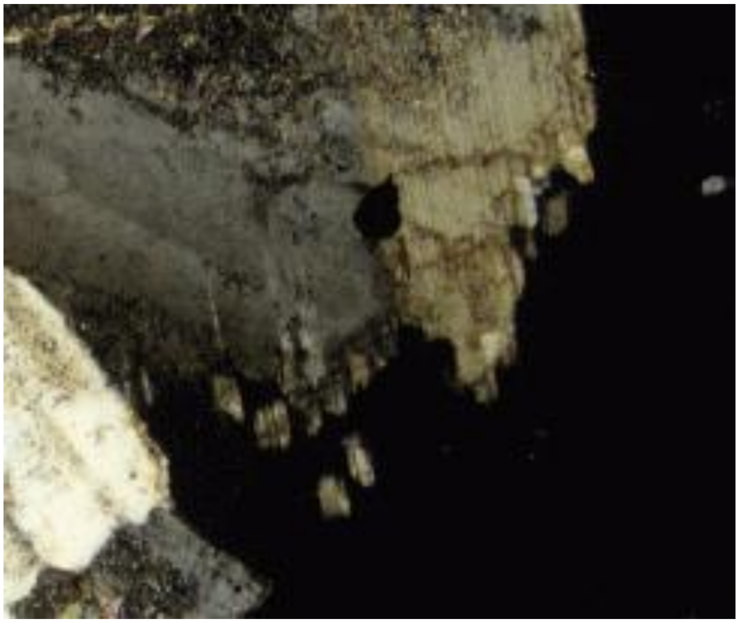

Fig. 35. Portion of large K-feldspar crystal (black) replacing zoned and albite-twinned plagioclase crystal, leaving tiny islands of the plagioclase in the K-feldspar in parallel optical continuity. Megacrystal granite; Criffell pluton.

Finally, a traverse was made in the northwestern part of the pluton at Drungans (Fig. 26) from the north edge of the muscovite-biotite granite facies, near the place where the Rb content of the pluton is highest (Stephens, 1997), and then through the biotite granite facies northwest toward the Lotus Hill quarry in the outermost granodiorite facies. In the biotite granite facies, quartz sieve textures are common (Fig. 36), and coarse K-feldspar crystals occur. In outcrops, a cream-colored rim can be seen on some of the pink K-feldspar megacrysts, giving the appearance of rapakivi K-feldspar (orthoclase) with exsolved albite rims. However the thin sections show that the K-feldspar is *microcline*, and the rims *consist of abundant wartlike myrmekite instead of albite* (Fig. 37).

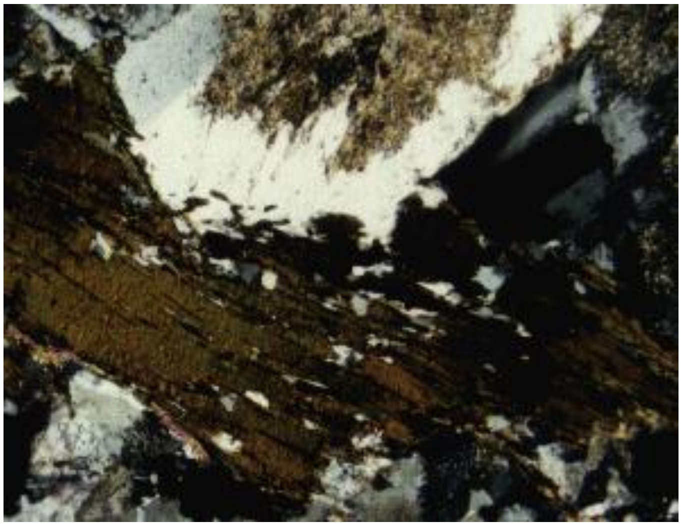

Fig. 36. Quartz sieve texture in biotite (brown). Sericitized, zoned plagioclase (light gray, top). Biotite granite facies; Criffell pluton.

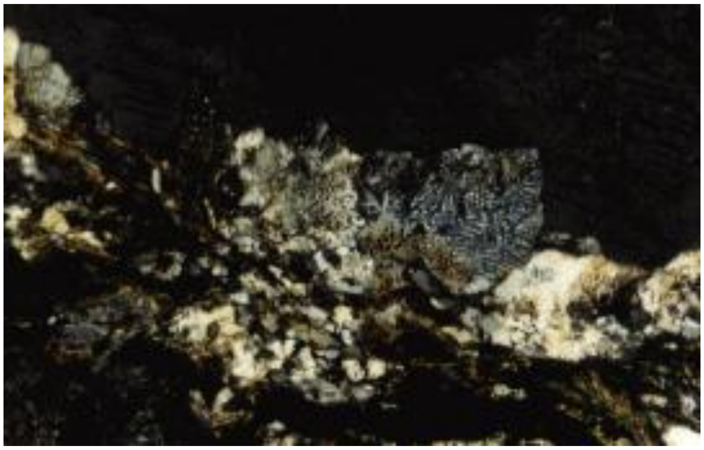

Fig. 37. Myrmekite granules forming the border of a large K-feldspar crystal (black). Quartz (white); biotite (brown). Biotite granite facies; Criffell pluton.

Also in some places along the traverse, the plagioclase crystals exhibit a coarse zoning (wide bands), and in many places the K-feldspar crystals duplicate this coarse zoning. Interior island remnants of plagioclase occur in the larger K-feldspar crystals (Fig. 38), which suggest that the zoning in the K-feldspar is not because of differences in composition of a crystal growing from a melt but because the K-feldspar has inherited the zonation from a former zoned plagioclase crystal.

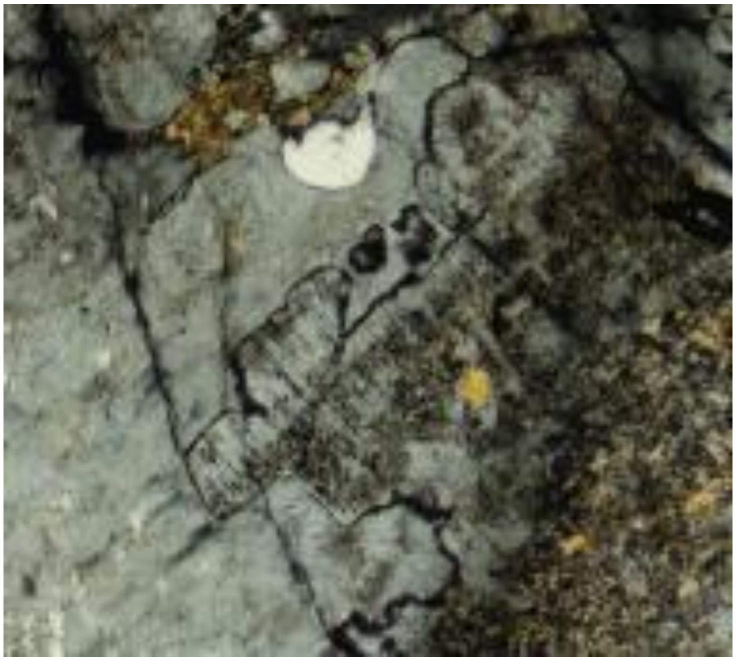

Fig. 38. Perthitic K-feldspar (left side; light gray) penetrating albite-twinned plagioclase (same light gray) along fractures (center). Island remnants of plagioclase (center) remain in the K-feldspar in parallel optical continuity. Biotite granite facies; Criffell pluton.

Thus, the five of the six facies of the Criffell pluton which were sampled all show varying degrees of K- and Si-metasomatism. The replacements in each facies suggest that former more-mafic rocks once occurred there which lacked K-feldspar but which could have been part of a magmatically differentiated mass. That mass would have had more-mafic, clinopyroxene-bearing diorite in the outer portions, instead of the granodiorite that now occurs there, and a more-mafic, biotite-rich tonalite or diorite in the core, instead of the biotite, muscovite-biotite, and biotite-muscovite granites that now occur. An intermediate differentiated zone, where the Craignair quarry now occurs, might have been a biotite-hornblende diorite. The mafic enclaves and bands in this inner differentiated zone, which are now granodiorite, may have once been a biotite-hornblende diorite. That is, initially, a differentiated biotite-hornblende diorite could have been intruded as a magma, which solidified, and then was strongly deformed and partly replaced by K-feldspar and quartz to convert it to a mafic granodiorite. Inner portions of this replaced rock, having greater degrees of replacement and becoming relatively felsic, were re-melted and mobilized to carry remnant fragments (deformed mafic enclaves and bands) to higher levels. After this more-felsic magma solidified with its enclaves, it also was deformed and partly replaced by K-feldspar and quartz to produce the massive, felsic, biotite-hornblende granodiorite, as seen in the quarry. Simultaneously, in the core of the pluton deformation and replacements of the differentiated biotite-rich diorite or tonalite would have been more thorough, eliminating any mafic enclaves. After its melting and re-solidification as a felsic granodiorite or granite, renewed deformation would permit metasomatic fluids to convert these core rocks progressively into even more granitic compositions, the most modified rock being the peraluminous muscovite-rich granite in the innermost part of the core. Recrystallization during the second stage of replacement could eliminate any megascopic evidence of deformation. In order to test this hypothesis, more thin sections of rocks in transitions from felsic granites to more mafic granodiorites from inner to outer zones of the Criffell pluton need to be examined.

Fleet pluton

Both the biotite and biotite-muscovite facies of the Fleet pluton (Fig. 39) contain microcline in strained polycrystalline aggregates. The rocks have a marked fabric with a strongly-developed mortar texture in which strings of granulated quartz and mica develop around large islands of K-feldspar. Myrmekite with tiny quartz vermicules border the K-feldspar in the biotite-muscovite facies in the core of the pluton. The outer biotite granite facies, which is strongly deformed near the contact with sedimentary wall rocks in the quarry near the Clatteringshaw Dam, contains K-feldspar with irregular islands of plagioclase, and the K-feldspar is bordered by aggregate grains of myrmekite (Fig. 40 and Fig. 41). Biotite exhibits quartz sieve textures.

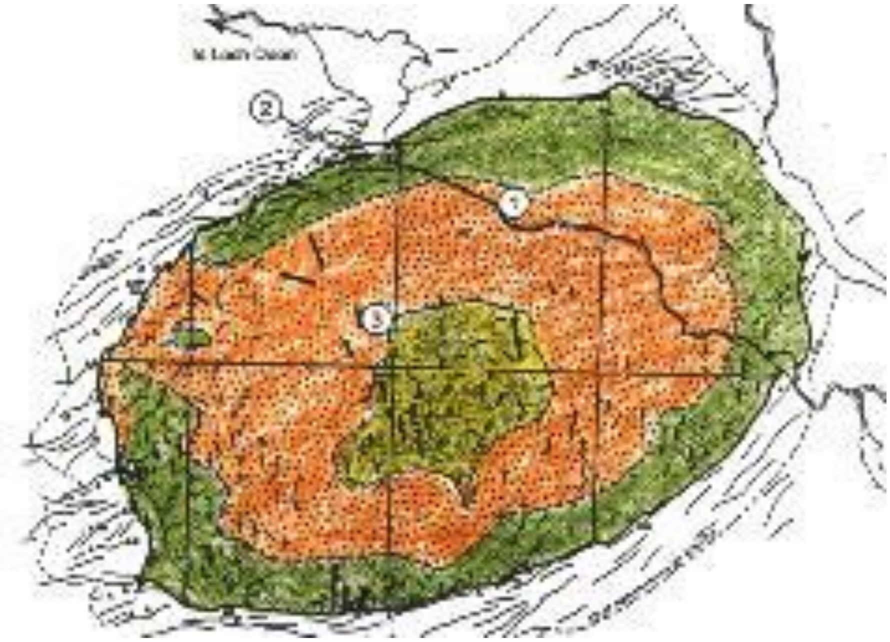

Fig. 39. Petrological map of the Fleet pluton, showing the main zones (after Stephens, 1997; taken from Parslow, 1968). Fine-grained biotite-muscovite granite (yellow); coarse-grained biotite-muscovite granite (orange); coarse-grained biotite granite (green).

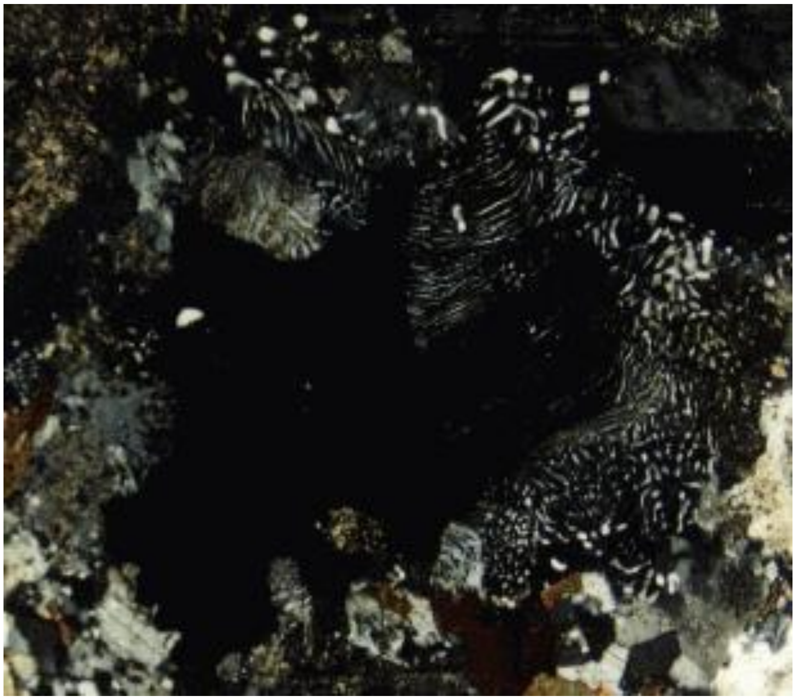

Fig. 40. Myrmekite borders on K-feldspar crystal (black). Zoned plagioclase (light gray). Biotite (brown). Outer biotite granite facies; Doon pluton.

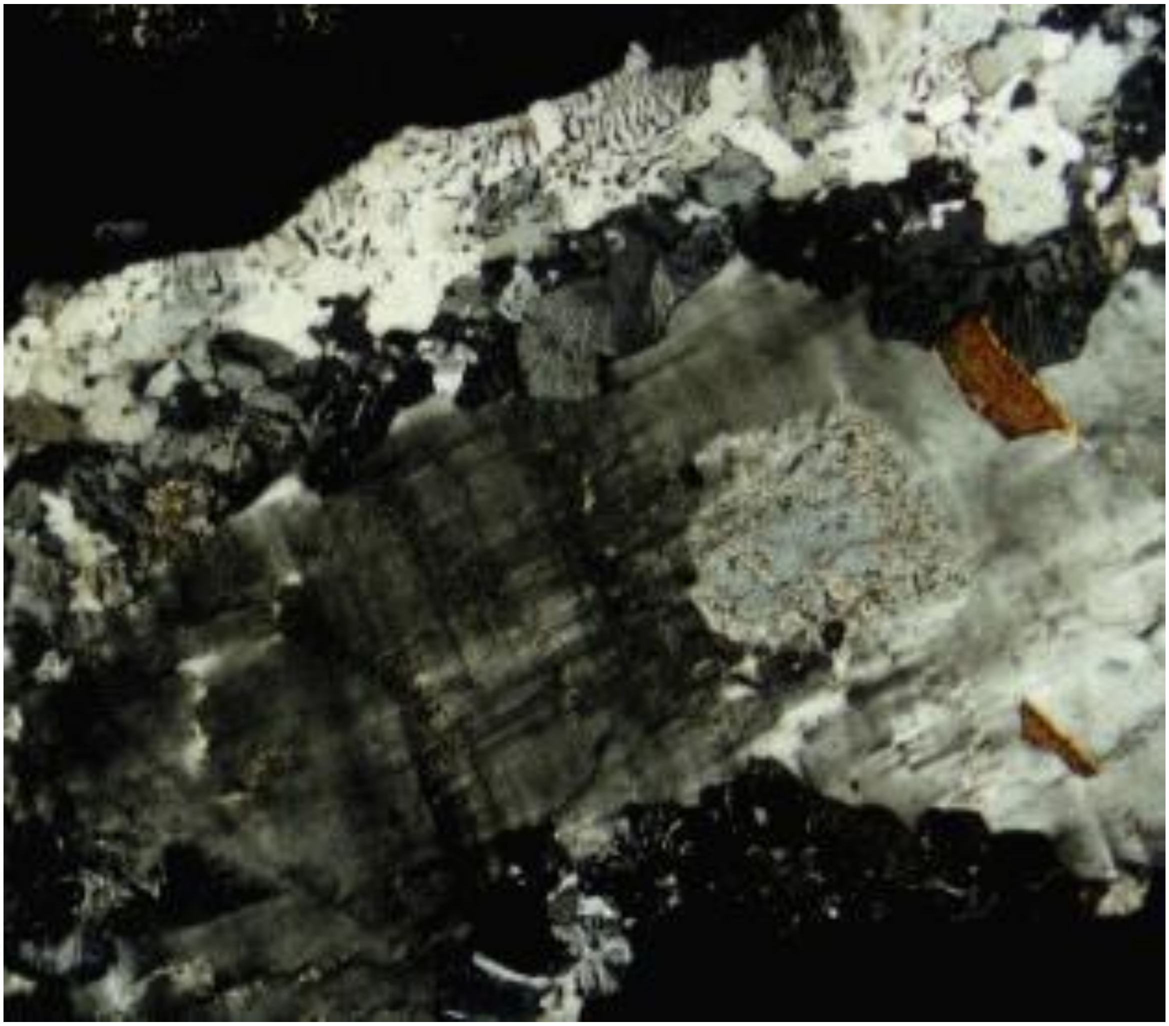

Fig. 41. Myrmekite aggregate borders on K-feldspar (grid-iron twinning, gray center). Remnant of plagioclase is enclosed in the K-feldspar (center, light gray). Biotite (brown). Outer biotite granite facies; Fleet pluton.

Doon pluton

Sampling of the granite core of the Doon pluton (Fig. 42) was not possible during the field trip. However, samples of the norite contain interstitial K-feldspar and myrmekite (Fig. 43) where deformation has locally bent albite-twin lamellae in the plagioclase crystals. Biotite exhibits quartz sieve textures (Fig. 44). Planar deformation in this norite has created openings (veins, 1 cm wide) filled with quartz and K-feldspar bordered by myrmekite (Fig. 45). The adjacent magmatic norite (Fig. 46) lacks K-feldspar and myrmekite. These relationships clearly show that K-feldspar is late, associated with tectonism, and unrelated to the early magmatic processes that crystallized the mafic rocks.

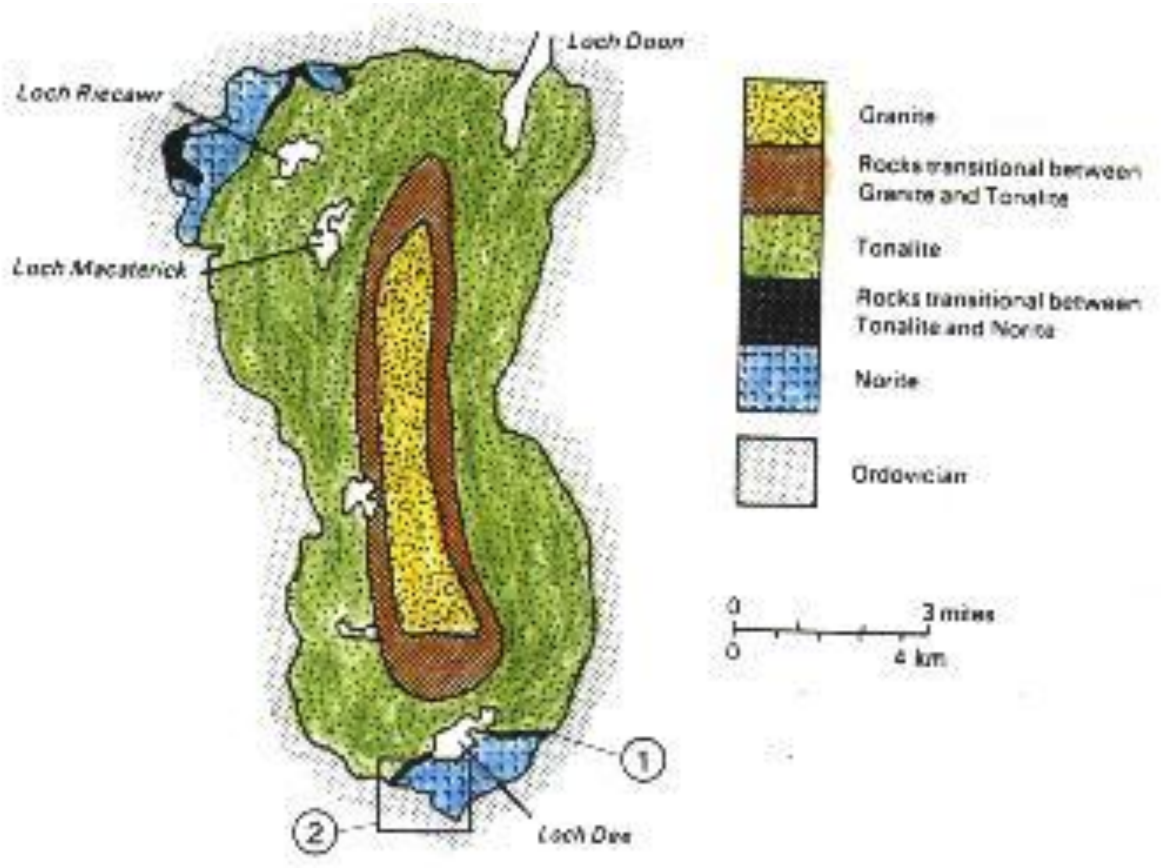

Fig. 42. Petrological map of the Loch Doon pluton, showing the main zones (after Stephens, 1997, and based on map from Gardiner and Reynolds, 1932). Granite (yellow); rocks transitional between granite and tonalite (orange); tonalite (green); rocks transitional between tonalite and norite (black); norite (blue); Ordovician (stippled).

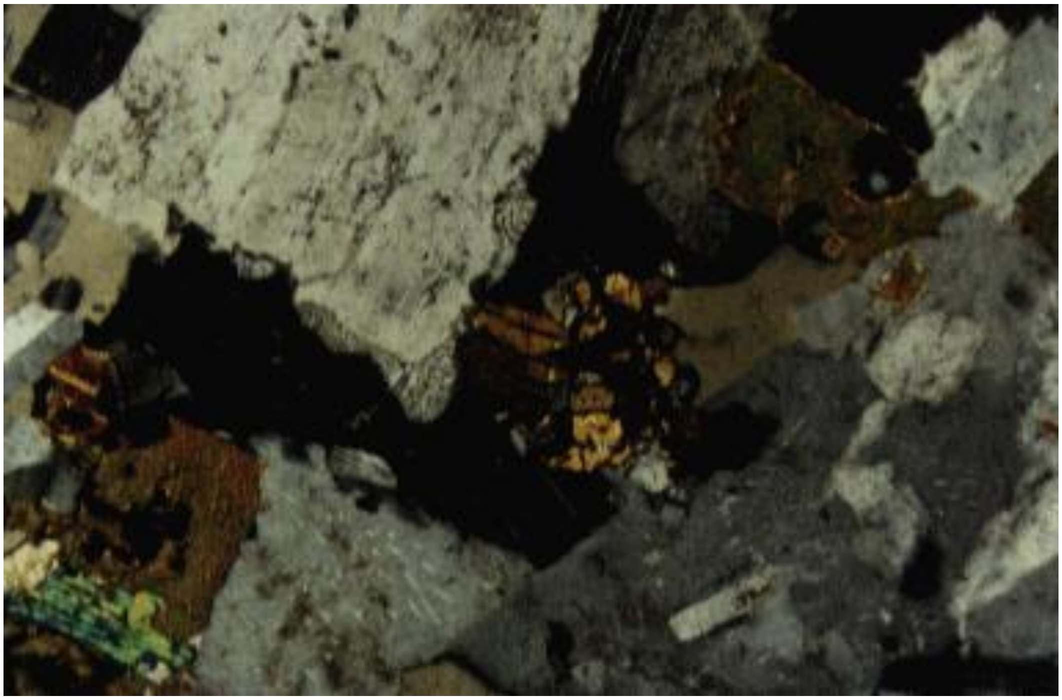

Fig. 43. Perthitic K-feldspar (black, light gray; center and bottom right) penetrating broken plagioclase crystals (lighter gray, top; and bottom right). Borders of plagioclase are myrmekitic (center). Biotite (brown, green). Pyroxene (brown, tan). In norite in the Doon pluton.

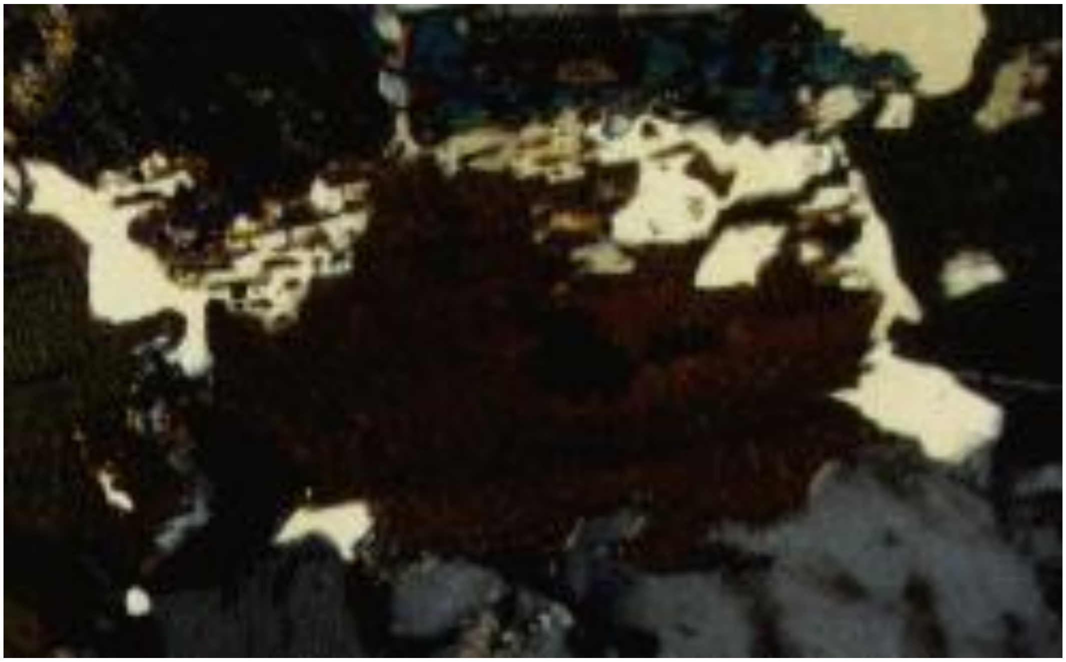

Fig. 44. Biotite (brown) replaced by quartz (white) to form a quartz sieve texture. Pyroxene (green-blue). Plagioclase (dark gray). In norite in the Doon pluton.

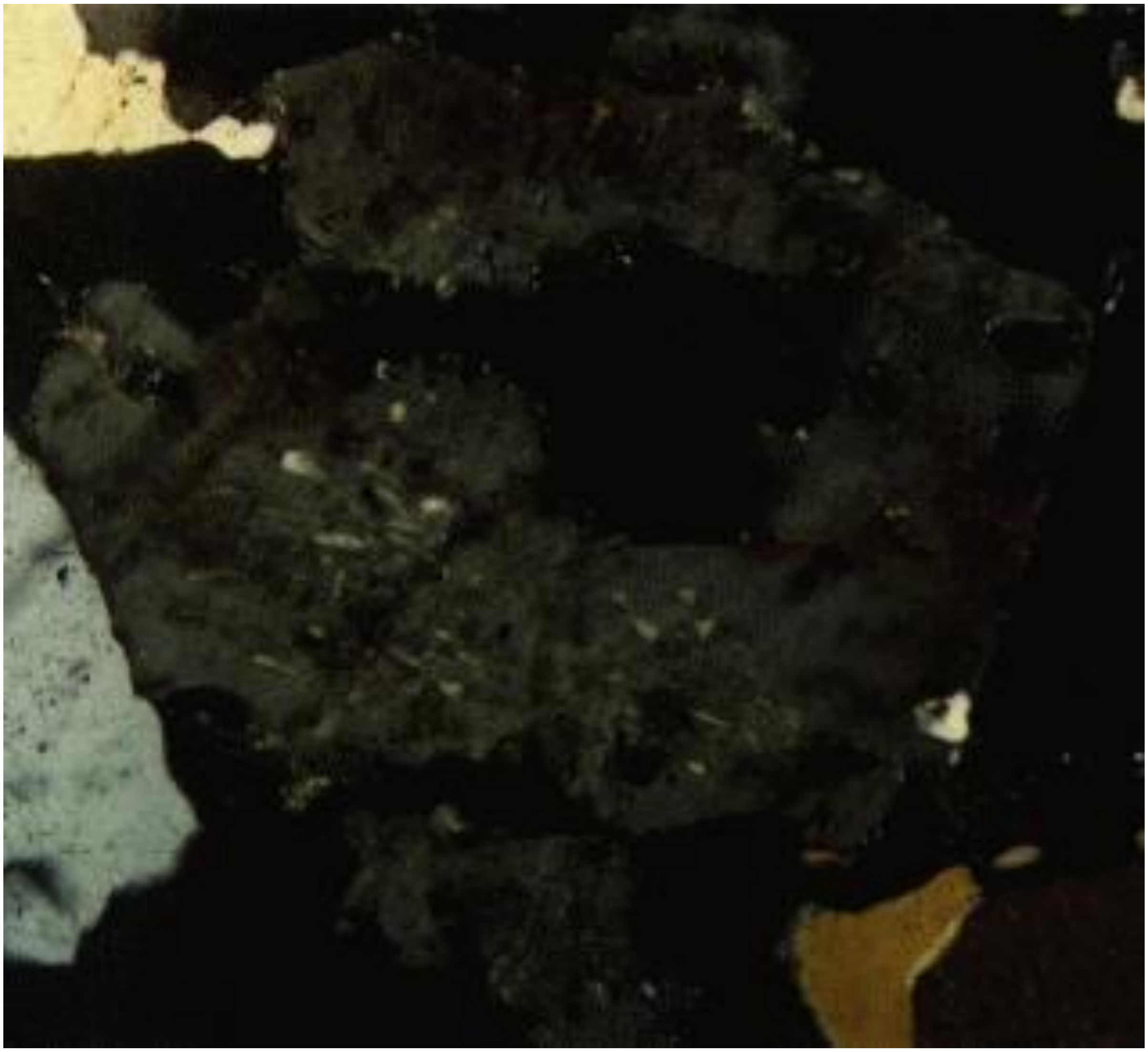

Fig. 45. Perthitic K-feldspar (dark gray) in 1-cm wide vein, surrounding and replacing fractured plagioclase crystal (black, center). Quartz (white, gray, cream). In shear plane cutting norite in the Doon pluton.

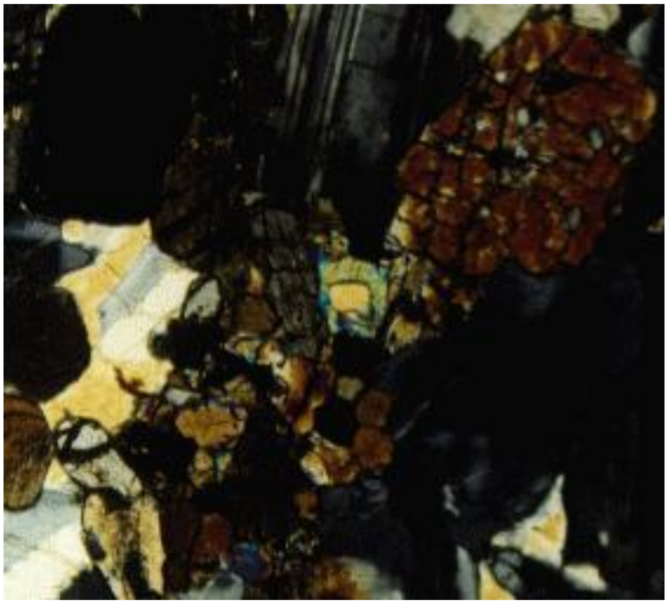

Fig. 46. Norite adjacent to vein (Fig. 41) with albite-twinned plagioclase (gray, black, cream) and orthopyroxene (brown, green). Doon pluton.

The next inner facies of tonalite (Fig. 42), which is exposed along the road leading to a boat ramp along the south shore of Loch Dee, also contains interstitial K-feldspar and myrmekite (Fig. 47). On the basis of secondary K-feldspar in the norite and tonalite, the granite core of this pluton deserves further thin section study; see Addendum.

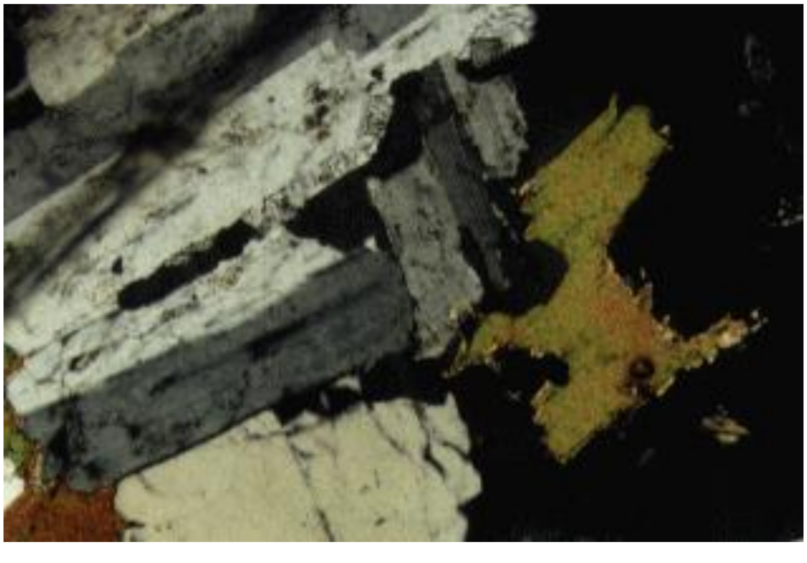

Fig. 47. K-feldspar (black) penetrating and replacing albite-twinned plagioclase (cream, gray, white) along fractures (center, top left) in tonalite. Myrmekite borders the plagioclase adjacent to the K-feldspar. Biotite (brown). Doon pluton.

Discussion

It is clear from the occurrence of zoned plagioclase in all the plutons that the granitic rocks had a primary magmatic origin. Nevertheless, (1) the occurrence of secondary K-feldspar in fractures in broken plagioclase crystals, (2) the enclosures of plagioclase remnants in K-feldspar with parallel optical continuity with adjacent larger plagioclase crystals inside or outside the K-feldspar, (3) the existence of wartlike myrmekite on plagioclase adjacent to the K-feldspar (Collins, 1988a; Hunt et al., 1992), and (4) the presence of quartz sieve textures in hornblende and biotite, suggest that K- and Si-metasomatism likely played a significant role in the history of these plutons after tectonic forces caused these rocks to become an open system in which hydrous fluids could move. Such metasomatism would explain the changes of the initial $^{87}Sr/^{86}Sr$ ratios from low values near 0.705 to higher values near 0.707. During the formation of secondary K-feldspar, K and Rb enrichments would occur which would be simultaneous with the subtraction of Ca and common Sr (Collins, 1988; Hunt et al., 1992). Such differential subtraction and enrichment would create a marked climb in Rb/Sr ratios.

In the conversion to more granitic rocks, the progressive Pb enrichment is logical because the Pb ion is nearly the same size as the K ion and remains behind in the K-feldspar. The depletion in Ce can be explained by the fact that Ce is commonly concentrated in apatite. As the apatite disappears with other Ca-bearing minerals, the Ce content of the rock is reduced. Because the Ba ion is about the same size as the K ion, Ba also tends to remain behind. Because Na tends to recrystallize in some altered plagioclase crystals to form a more sodic species, the Na content of the rocks shows only a slight decrease. The steady losses of Mg, Ca, Al, Fe, and Ni reflect the replacement of the ferromagnesian silicates by quartz. Some of the losses of Ca and Al are explained by the replacement of relatively calcic plagioclase by K-feldspar and more sodic plagioclase.

On the basis of a model of magmatism followed by metasomatism, the continuum of compositions SiO_2 content from about 62 to 72 wt. % for many of the plutons can have the following explanation. Rather than producing this continuum entirely by crystal fractionation, some of this silica enrichment may reflect the progressive replacement of the ferromagnesian silicates by quartz and the conversion of the relatively calcic plagioclase to more sodic plagioclase and K-feldspar.

The K- and Si-metasomatism in the Scottish granitic plutons would likely affect the Rb-Sr systematics on an outcrop scale because the extent to which fluids move through the deformed rocks should be somewhat variable and dependent upon the degree of cataclasis from place to place. This variable of the Rb-Sr data would produce "errorchrons" and the puzzling production of Rb-Sr dates that are older than the fossils in the wall rocks.

The relatively uniform appearance of the metasomatic massive granitic rocks in the Cluanie, Criffell, and Fleet plutons should not be surprising because the original magmatic rocks which were replaced were also likely relatively uniform in composition prior to replacement.

In the Strontian pluton, the changes in epsilon-Nd from values near 0 to values near -7 may reflect differential movements of Sm and Nd during the metasomatic processes. There is little difference in their masses, so the diffusion rates of Sm and Nd should be the same. Nevertheless, this issue of Nd-Sm systematics needs to be re-examined, particularly since the rare-earth elements are concentrated in the ferromagnesian silicates, which are replaced by quartz during the metasomatic processes.

The outer hornblende-bearing zones of the Criffell pluton are undoubtedly I-types, but the inner muscovite-bearing facies is alleged to have "geochemical characteristics rather more like S-type granites, but rather mildly so" (Stephens, 1997). This development of S-type, peraluminous characteristics can more simply be explained by metasomatic processes which enrich the rocks in residual Al as Ca is subtracted, rather than relying on contamination of the core by distant metasedimentary wall rocks.

The strain trajectories, strain gradients, and quartz fabrics that suggest diapirism as a means of emplacement of the Criffell pluton could also provide a reason why the system was open to fluid movement that altered the rocks while the pluton was being emplaced. The diapir need not have risen only while the consisted entirely of magma, but its relatively low density could also have allowed it to rise as a hot plastic to brittle solid. The deformation of the solidified rock would have created fractures through which introduced hydrous fluids could move and recrystallize and replace the rock.

The presence of myrmekite has been noted in this presentation, but it has not been used as evidence of metasomatism, as in other presentations. The Scottish plutons do not have transitional textures that indicated how the myrmekite formed, so it could not be used without dependence on evidence from other localities.

Nevertheless, the K-feldspar show ample evidence of replacing broken and deformed plagioclase crystals.

The scrutiny of a few thin sections suggests that more study of all of these plutons is warranted. More problems were found than solved. If the granitic rocks in the core of a pluton are formed by replacement processes, the possibility still exists that prior to metasomatism, magmatic differentiation of an origin magma produced pyroxene-bearing, relatively-calcic, mafic diorite in the outer rim, intermediate biotite-hornblende compositions in inner zones, and a more potassic, sodic, and biotite-rich tonalite or diorite in the core. If so, why should interiors of the magmatically zoned plutons show greater degrees of metasomatism when outer facies near the wall-rock contacts exhibit the most field evidence for deformation and contain the highest temperature minerals that are the least stable in a metasomatic environment? If brittle deformation occurred in the centers of these plutons following solidification, what mechanism generated this interior deformation in solidified rocks? What is the source of additional Si and K to convert the large volumes in the plutons to more granitic compositions and where did the displaced Mg, Fe, Al, and Ca go? Are the appinite-like bodies the destination of the displaced elements or has all this material been expelled in explosive volcanic ash eruptions, long ago eroded and leaving no trace? Furthermore, why are the quartz vermicules in myrmekite relatively tiny in all facies and NOT correlated with the An content of the plagioclase in the primary rock being replaced (Collins, 1988a; Hunt et al., 1992)? These plutons need further thin section studies.

Addendum, 7/27/98

Garabal Hill pluton.

A thin section of sample GH39 collected from the west side of the megacrystal granodiorite and provided by Ed Stephens shows the following textural and mineralogical relationships. The granodiorite contains megacrysts of orthoclase (1 cm long) surrounded by a groundmass of orthoclase, plagioclase, quartz, chloritized biotite, hornblende, and minor sphene, iron oxides, and apatite. The plagioclase is strongly zoned and albite- and Carlsbad-twinned. The orthoclase megacrysts are Carlsbad twinned, perthitic (containing uniformly-distributed albite lamellae), and zoned, showing alignment of both quartz granules (near the rim) and tiny plagioclase crystals whose faces are parallel to possible faces of the orthoclase. The rock lacks evidence for deformation, and the biotite and hornblende show no indication of Si-metasomatism (quartz replacements). Some tiny plagioclase inclusions in the orthoclase have ragged boundaries and rim myrmekite with tiny, barely-visible quartz vermicules. An occasional, tiny, wartlike myrmekite grain occurs on the orthoclase border and also has barely visible quartz vermicules. If K-metasomatism occurred in this granodiorite to produce the K-feldspar megacrysts, this metasomatism has been obscured by melting and recrystallization. The present texture is typical of magmatic rocks, and any subsequent K-metasomatism that occurred, following crystallization, is insignificant and resulted from late-stage, deuteric alteration, and was nearly isochemical.

Loch Doon pluton.

A thin section made from sample WL10 collected in the central granite core at the south end of the Loch Doon pluton and provided by Ed Stephens shows the following textural and mineralogical relationships. The granite contains normally zoned, albite- and Carlsbad-twinned plagioclase, quartz, orthoclase, hornblende, chloritized biotite, and trace zircon and apatite. An occasional hornblende crystal contains an augite core. The orthoclase is commonly zoned with concentrations of quartz granules in one or two distinct layers in the outer portions which are aligned parallel to possible crystal faces of the orthoclase. The orthoclase is perthitic with tiny albite lamellae which are generally uniformly distributed. Occasional but rare, rim myrmekite with extremely narrow quartz vermicules occur on the zoned plagioclase crystals against the orthoclase. The rock lacks any evidence for deformation, and the biotite and hornblende show no evidence for Si-metasomatism (replacement by quartz). The K-feldspar is primarily magmatic, and any K-metasomatism of plagioclase is insignificant, post-magmatism, and likely the result of deuteric alterations that are nearly isochemical.

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