ISSN 1526-5757

40. Evolution of a layered diorite-gabbro to become a layered quartz monzonite-granodiorite in the Wanup pluton near Sudbury, Canada

Lorence G. Collins

email: lorencecollins@gmail.com

July 12, 2001

Abstract

A horizontally-layered, biotite-rich diorite-gabbro in the Wanup pluton near Sudbury, Canada, is shown to be folded into a tight, nearly isoclinal anticline and then to evolve into a layered quartz monzonite-granodiorite body containing parallel bands of thin amphibolite layers. This evolution occurred during K- and Si-metasomatism that was made possible by strong deformation that accompanied the folding. Myrmekite grains with fine, intermediate, and coarse quartz vermicules occur in the granitic layers, respectively, at the top, middle, and bottom of the former layered diorite-gabbro. Maximum sizes of the vermicules in myrmekite and of quartz blebs in ghost myrmekite in microcline correlate with the plagioclase An-values in the more Na- and K-rich top, in the middle layers, and in the more Ca-, Mg-, and Fe-rich bottom of the Wanup pluton.

The Wanup pluton is an example of the way many Precambrian granitic bodies may have evolved. First, incompatible K in the mantle migrated upward in water-rich magmas that crystallized as biotite-rich tonalites, diorites, and gabbros, lacking orthoclase. Subsequently, deformation in the earth's crust during plate tectonics caused dehydration of the solidified biotite-rich tonalites, diorites, and gabbros. During the dehydration process, K was released from the biotite as some of the deformed biotite and coexisting hornblende were replaced by quartz during Si-metasomatism. The mobilized K moved into deformed and altered, relatively-calcic plagioclase grains to form microcline. Much of the Na in the primary plagioclase, which was displaced by K to form the microcline, replaced other altered plagioclase crystals to form more-sodic recrystallized plagioclase. In all of the aforesaid processes much Ca, Fe, Mg, and Al were lost from the system, perhaps carried upward in hydrous fluids to be crystallized in lamprophyre dikes. The mineralogical conversions in deformed mafic rocks would occur under

subsolidus conditions and change the tonalites, diorites, and gabbros into myrmekite-bearing quartz monzonite or granodiorite and locally into granite. Then, later, re-heating of these rocks above melting temperatures could mobilize them as magmas to form higher-level granitic intrusions.

Introduction

Lumbers (1975) briefly described the Wanup pluton (about 18 km southeast of Sudbury, Ontario, and one kilometer southwest of the village of Wanup, Fig. 1) as a strongly deformed quartz monzonite, but because it represented only 3 square km among the more than 4,000 square km that he mapped, understandably not much attention was paid to it in his report. His small scale map shows a drag fold within the pluton, but no details of the structure or petrography are provided. Tony Davidson from the Canadian Geological Survey called my attention to a megacrystal quartz monzonite in this pluton in dynamited outcrops along Route 69. About 0.5 km west of the junction with Route 537 (Fig. 1), a rounded glaciated surface on the south side of Route 69, shows parallel amphibolite bands, 1-20 cm thick or more in the quartz monzonite (Fig. 2, Fig. 3, and Fig. 4). According to Davidson (oral communication, 2000) these bands have been puzzling geologists for many years. Are they part of a former metasedimentary sequence of alternating felsic and mafic sediments or do they represent former narrow intrusions of basaltic magma into the megacrystal quartz monzonite along parallel fractures? Neither hypothesis seemed logical. These enigmatic amphibolite bands, however, were sufficiently intriguing, suggesting that the pluton warranted further study. Because exposures in the middle third of the pluton are poor and not easily accessible and because the southern third of the pluton does not contain the narrow amphibolite bands, only the northern third was examined in more detail. Hereafter, all discussions are about the northern third even though references are made to the Wanup pluton as if the pluton were being described as a whole.

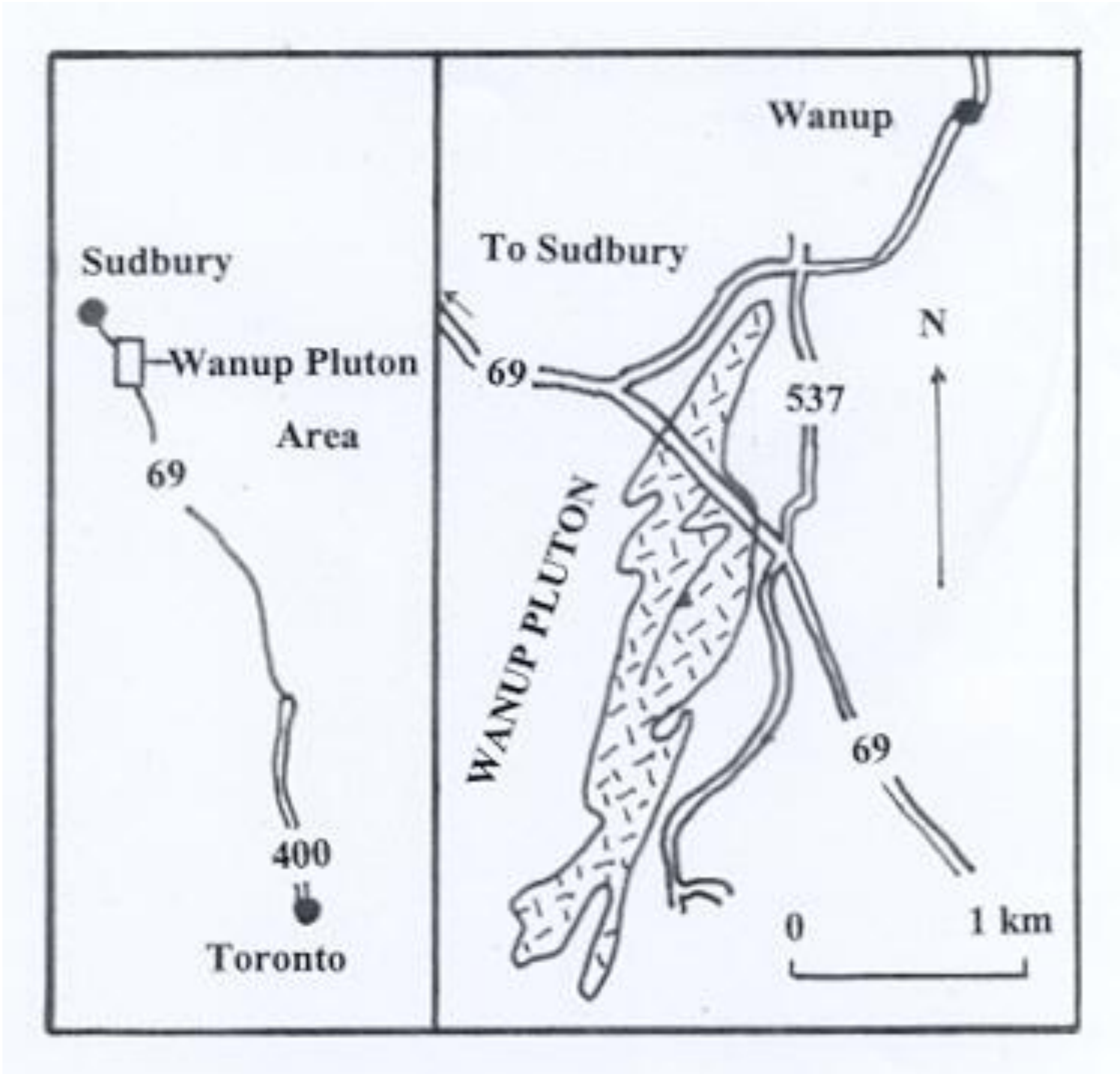

Fig. 1. Geologic map showing the general location of the Wanup pluton, about 18 km southeast of Sudbury, Ontario (modified after Lumbers, 1975).

Fig. 2. Layered megacrystal granitic rock exposed on glaciated surface, west of junctions of Routes 537 and 69 on south side of Route 69. Loose pebbles fill eroded center portion of a thicker amphibolite layer and parts of the layered granitic rock. Some amphibolite layers are broken and disrupted.

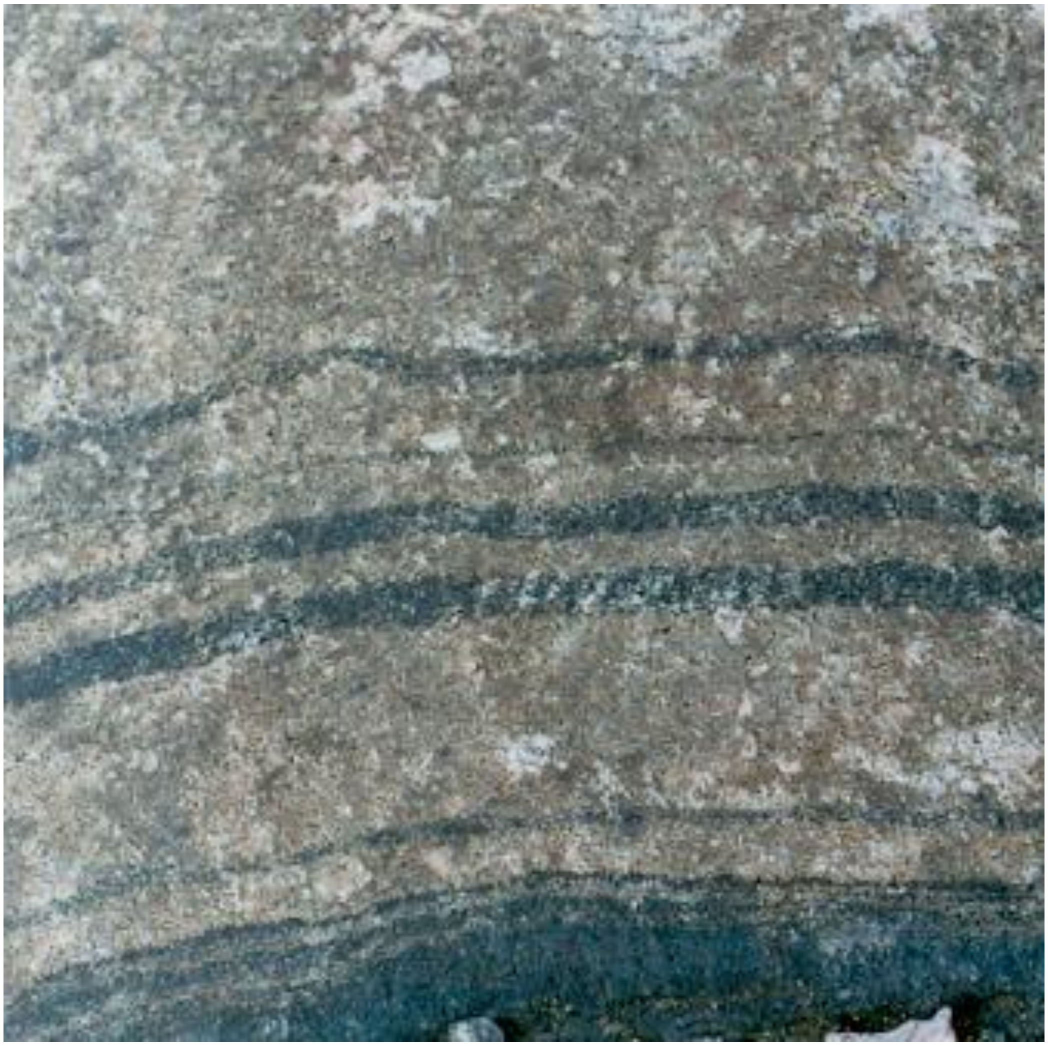

Fig. 3. Layered biotite-hornblende granodiorite-quartz monzonite on south side of Route 69. Dark bands are amphibolite.

Fig. 4. Deformed part of more feldspathic layering has been recrystallized and replaced by microcline megacrysts; south side of Route 69. Some microcline megacrysts intersect or crosscut the amphibolite layering.

Field studies of the pluton showed that structurally it is a steeply plunging, nearly isoclinal anticline with its nose at the northern tip. The middle part of the fold is transected by Route 69, and the broader part, around a central core of thick amphibolite layers, occurs south of Route 69 (Fig. 1). The structural relationships and contact at the base against metasedimentary wall rocks are hidden at the southern margin by glacial till and vegetation.

The petrography and mineralogy of the rocks in the nose, limbs, and core of the anticline are described below and reveal interesting patterns that support the hypothesis that the granitic Wanup pluton is a folded layered intrusion, with relatively more-felsic rocks at the top (Fig. 5 a), intermediate compositions in the middle (Fig. 5 bcdefhi), and more-mafic rocks at the bottom (Fig. 5 g). Textures in thin sections of rocks collected from the various levels (top to bottom) explain the enigmatic relationships in the road outcrop along Route 69 which puzzled other geologists.

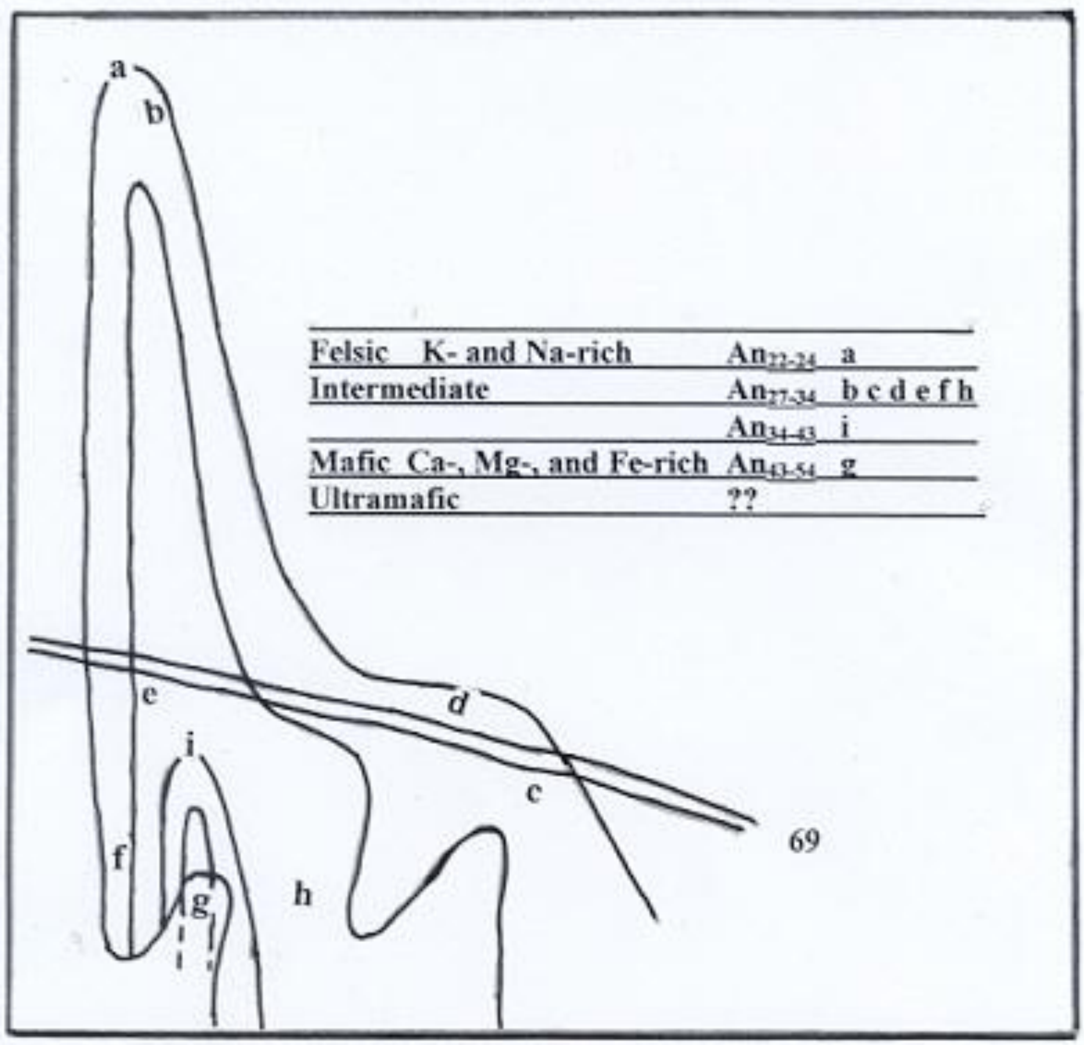

Fig. 5. Cartoon of isoclinal anticline in the layered Wanup pluton, showing locations discussed in the text for felsic (a), intermediate (bcdefhi), mafic (g), and theoretical ultramafic rocks (below g), from top to bottom. Gradual changes in An-content of plagioclase are shown, ranging from An_{22} at the top to An_{54} at the bottom.

Layered rocks at the north end of the Wanup pluton

The nose of the anticline at the north end of the Wanup pluton can be observed one kilometer southwest of the village of Wanup and west of Route 537

(Fig. 1). Surrounding the pluton are wall rocks consisting of hornblende gabbro (plagioclase An_{50}), strongly-deformed, thinly-layered, metasedimentary rocks containing some thin quartzite bands, and younger crosscutting granite pegmatite dikes. The gabbro occurs as sills and dikes in the metasedimentary rocks throughout the area and is unrelated to the pluton (Lumbers, 1975).

The outer (uppermost) layer of the Wanup pluton (Fig. 5 a) is a thick, black, biotite-rich diorite band (10 m wide) that contains 25-30 vol. % biotite. Plagioclase in this layer is the most sodic (An_{22-24}) in the pluton. [An-values for all plagioclase reported in this study were estimated by measuring the maximum extinction angles on the albite twins (Winchell and Winchell, 1951).] Farther south, the thick black biotite diorite changes gradually to alternating layers of thicker biotite-hornblende feldspathic bands and thinner amphibolite bands (Fig. 6 and Fig. 7). The plagioclase of the thicker, feldspathic layers becomes progressively more calcic southward (to lower stratigraphic levels), changing from An_{28} near the biotite-rich diorite to An_{34} at the top of the hill, where further exposures cease because of glacial till and forest cover.

Fig. 6. Layered biotite-hornblende diorite at north end of Wanup pluton, looking north. Early stages of microcline patches (white) occur in some of the bands. Brown autumn leaves cover parts of the rock. Dark bands are amphibolite.

Fig. 7. Layered biotite-hornblende diorite (converting to quartz monzonite) with patches of microcline (white) at the north end of the Wanup pluton, looking north. Dark bands are amphibolite.

Also, progressively south from the outer black diorite, patches of white microcline (1 cm long) begin to appear in the biotite-hornblende-feldspathic layers (Fig. 6) and increase in size (Fig. 7) until at the top of the hill, the layered rocks look similar to those found along Route 69 (e.g., Fig. 3). These microcline patches in the feldspathic layers are not single microcline crystals but aggregates of smaller microcline crystals, the same size as adjacent groundmass plagioclase crystals. As microcline increases in abundance, the feldspathic rock's composition is changed from diorite into quartz monzonite or granodiorite. However, compositions of the interlayered, thin, amphibolite bands remain relatively the same. Accessory minerals in the biotite-hornblende feldspathic layers here and throughout the pluton include apatite, epidote, allanite, zircon, titanite, iron oxides, and rare garnet. Also, the same kinds of younger, biotite-bearing granite pegmatite dikes, as seen in the wall rocks, cut the layers throughout the pluton.

Along the hill ridge, the amphibolite layers (Fig. 6 and Fig. 7) strike northwest-southeast parallel to the outer northern boundary of the Wanup pluton (Fig. 1), but they swing northeast-southwest parallel to the outer contact along the western and eastern sides of the pluton, indicating that the layers are folded into a relatively tight, nearly isoclinal anticline. On the eastern limb, some thin, parallel, amphibolite bands, 20 to 30 meters away from the outer contact, are convoluted into broad folds and are locally broken and disrupted (Fig 5 b). In the disrupted areas (Fig. 8), where deformation is strongest, is the first appearance of microcline megacrysts (1-2 cm long) rather than the aggregate patches of smaller microcline grains.

Fig. 8. Deformed layered biotite-hornblende diorite converted to quartz monzonite with microcline megacrysts (white) on east side of north end of the Wanup pluton. Where layers are deformed the most, the megacrysts are the largest.

Middle part of the Wanup pluton along Route 69

The eastern border of the Wanup pluton along Route 69 contains thick feldspathic bands that alternate with thinner amphibolite bands (Fig 5 c), similar to those at the north end, except that the feldspathic bands are mostly coarser grained with microcline crystals, 1-2 cm long (Fig. 4). These larger megacrysts tend to occur where the layering is strongly disturbed, as was also observed in the eastern limb at the north end of the pluton (Fig. 5 b; Fig. 8). The larger sizes of the microcline crystals here match the larger sizes of some of the coexisting plagioclase crystals, but some microcline crystals are even larger. Moreover, some of the largest microcline megacrysts (up to 2 cm long) cut or extend through some of the thin mafic bands (Fig. 4). These megacrystal rocks in outcrops from southeast to northwest along Route 69 (Fig. 1) vary in composition from quartz monzonite to granodiorite, depending on the relative abundance of microcline and quartz. Plagioclase in these megacrystal rocks also varies in composition but generally falls in the range of An_{27} to An_{34}.

Plagioclase in the coexisting, thin, amphibolite layers in comparison has a greater range in composition. Some layers contain relatively sodic plagioclase (An_{22}); some contain more calcic plagioclase (An_{38-40}); and one thin amphibolite layer at the north end of the pluton has plagioclase as calcic as An_{54}. Some amphibolite layers contain as much as 90 vol. % hornblende while others contain more biotite and lesser quantities of hornblende. Those amphibolite layers with less quantities of hornblende tend to have more sodic plagioclase.

The layered amphibolite bands on the eastern border differ in appearance on the north and south sides of Route 69. On the south side, the bands are consistently parallel although contorted or discontinuous in some places (Fig. 2 and Fig. 5 c). The bands range from 1 to 20 cm or more wide, dip northward steeply 70-80°, but trend east-west at right angles to the north-south border of the Wanup pluton. In a few places they expand to pods 1 m in diameter. The east-west orientation of these bands relative to the north-south trend of the eastern limb of the fold is probably due to a large convolution in layers like that found in an equivalent stratigraphic position in the eastern limb in the nose of the pluton (Fig. 5 b), of which a portion of one convolution is shown in Fig. 8. This hypothesis is supported by the gentle S-bend in the eastern border of the pluton and a large drag fold mapped by Lumbers (1975) here (Fig. 1 and Fig. 5).

In contrast to these relatively undeformed amphibolite layers (Fig. 2, Fig. 3, Fig. 4, and Fig. 5 c), the amphibolite layers on the north side of Route 69 (Fig. 5 d) are strongly deformed with production of drag folds. Where the drag folds are broad (3 m wide, Fig. 9), the amphibolite bands feather out along strike of the layering and disappear into coarse-grained quartz monzonite or granodiorite containing microcline megacrysts (1-3 cm long). Some megacrysts cut thin amphibolite layers (Fig. 9), while in other places biotite wraps around the megacrysts. But where the drag folds are narrow (0.5 m wide) and nearly isoclinal (Fig. 10), the amphibolite bands are narrow and closely spaced, some of which disappear along strike into fine-grained, leucocratic, granite bands, lacking megacrysts. These bands contain dominant microcline grains (65-75 vol. %), quartz (20 vol. %), minor plagioclase, and no mafic minerals.

Fig. 9. Deformed layered quartz monzonite and granodiorite on north side of Route 69, showing a large drag fold. Note megacrysts of microcline in more felsic layers and that some megacrysts cut across the mafic layering.

Fig. 10. Deformed layered quartz monzonite and granodiorite on north side of Route 69 with drag folds shown in the mafic layers. Glacial striae extend across the rock surface from left to right. Note that the more strongly deformed felsic layers have lost their ferromagnesian silicate minerals and have become fine-grained leucocratic granite, unlike that in Fig. 2 on the south side of the road.

The western exposures of the megacrystal granitic rocks along the south side of Route 69 (Fig. 1 and Fig. 5 e) lack the thin parallel layers of amphibolite. Here, the mafic minerals are concentrated in a thick (5 m wide), deformed amphibolite layer (Fig. 11), which is bordered on both sides by thick layers (50-100 m wide) of massive megacrystal quartz monzonite. Farther south 100 m from Route 66, thin amphibolite layers appear again in the quartz monzonite, and the plagioclase composition in the quartz monzonite increases from An_{27-34} at the road to An_{43}, indicating that the calcium content in the Wanup pluton continues to increase southward.

Fig. 11. Deformed, discontinuous, thick, amphibolite layer, offsetting portions of the granitic layers. West side of Wanup pluton on south side of Route 69.

The southern and southwestern part of the Wanup pluton

In the southwest part of the Wanup pluton, near its western border, and several hundred meters south of Route 69, the thin, parallel, amphibolite bands extend N40ºE and are generally parallel to the western border of the Wanup pluton (Fig. 5 f). Unfortunately, glacial till and vegetation cover the western contact of the pluton with the metasedimentary wall rocks and also cover the southern part of the layered Wanup pluton where probable, basal, most mafic layers would have once been in contact with the underlying metasedimentary rocks. However, available outcrops show that from the western side of the pluton eastward along the exposed southern part of the pluton, the thin, parallel, amphibolite bands gradually become more frequent in the granitic rock. Then, in the center of the pluton (core of the anticline, Fig. 5 g), parallel amphibolite bands extend N30ºE and range from 3 to 20 meters thick. Exact thicknesses and contact relationships with adjacent feldspathic bands, however, are difficult to determine because the thick amphibolite layers tend to be more strongly eroded and in swampy depressions, while the interlayered, more feldspar-rich, parallel bands stand out as rounded ridges. Farther east from the anticline core (Fig. 5 h), the reverse pattern occurs. That is, the parallel amphibolite bands generally become less thick and less frequent eastward and strike N10ºE.

These relationships are consistent with a model for a layered biotite-rich diorite-gabbro, which at one time was horizontal with concentrations of mafic- and calcic-rich layers at the bottom (Fig. 5 g), and which later became compressed into a tight, nearly-isoclinal anticline. In that compressive folding process, the bottom mafic- and calcic-rich amphibolite layers were broken and squeezed upward into the core of the tight fold, and the upper, more-sodic, feldspathic, and less mafic layers were wrapped around the core. Thus, from east to west across the pluton near its former bottom, the stratigraphy is repeated in reverse order on opposite limbs (Fig. 5 fgh).

In addition to the thick amphibolite layers, the core of the fold also has interlayered megacrystal quartz monzonite and granodiorite, but here the plagioclase in the quartz monzonite and granodiorite has relatively calcic compositions that range from andesine (An_{45}) to labradorite (An_{54}), and the amphibolite bands contain both hornblende and clinopyroxene, indicating the greater Ca, Mg, and Fe content at the bottom of the pluton.

North of the thick amphibolite bands in the core is an inner nose of the tight anticlinal fold, composed of feldspathic bands and interlayered thin amphibolite bands. Here, the amphibolite layers are compressed and convoluted, showing features of strong deformation (Fig. 5 i, and Fig. 12).

Fig. 12. Portion of inner nose of isoclinal anticline with compressed and contorted amphibolite layers, south of Route 69. Megacrysts of microcline (white) occur in the felsic layers.

Interpretations of textural and mineralogical relationships

Compositional changes.

The compositional changes from the top to the bottom of the folded layered rocks in the Wanup pluton are consistent with changes that are observed in a layered diorite-gabbro intrusion consisting of alternating feldspathic and darker mafic (amphibolite) layers in which more-Na- and K-rich and less-Ca-, Mg-, and Fe-rich rocks occur at the top, intermediate values occur in the middle, and less-Na- and K-rich and more-Ca-, Mg-, and Fe-rich rocks occur at the bottom. However, the Wanup pluton is not completely like a layered diorite-gabbro. Magmatic differentiation processes concentrate K and Na to form orthoclase, biotite, and sodic plagioclase at the top of a layered diorite-gabbro body, but such a crystallization process would not produce orthoclase that could invert to microcline in the middle and certainly not in the bottom layers. Therefore, examination of the textural and mineralogical relationships relative to their K-feldspar content at all levels in the Wanup pluton is important for understanding the origin of this pluton.

Microcline.

Where microcline first appears in the biotite-hornblende feldspathic bands below the uppermost, thick, biotite diorite layer (Fig. 5 a), the microcline is not interstitial or the last feldspar to crystallize, enclosing earlier formed higher temperature minerals, as one might expect if the original K-feldspar were orthoclase that crystallized at the eutectic from a melt. Instead, its first appearance is microscopic and localized in the ***interiors*** of some microfractured plagioclase crystals (Fig. 13 and Fig.14).

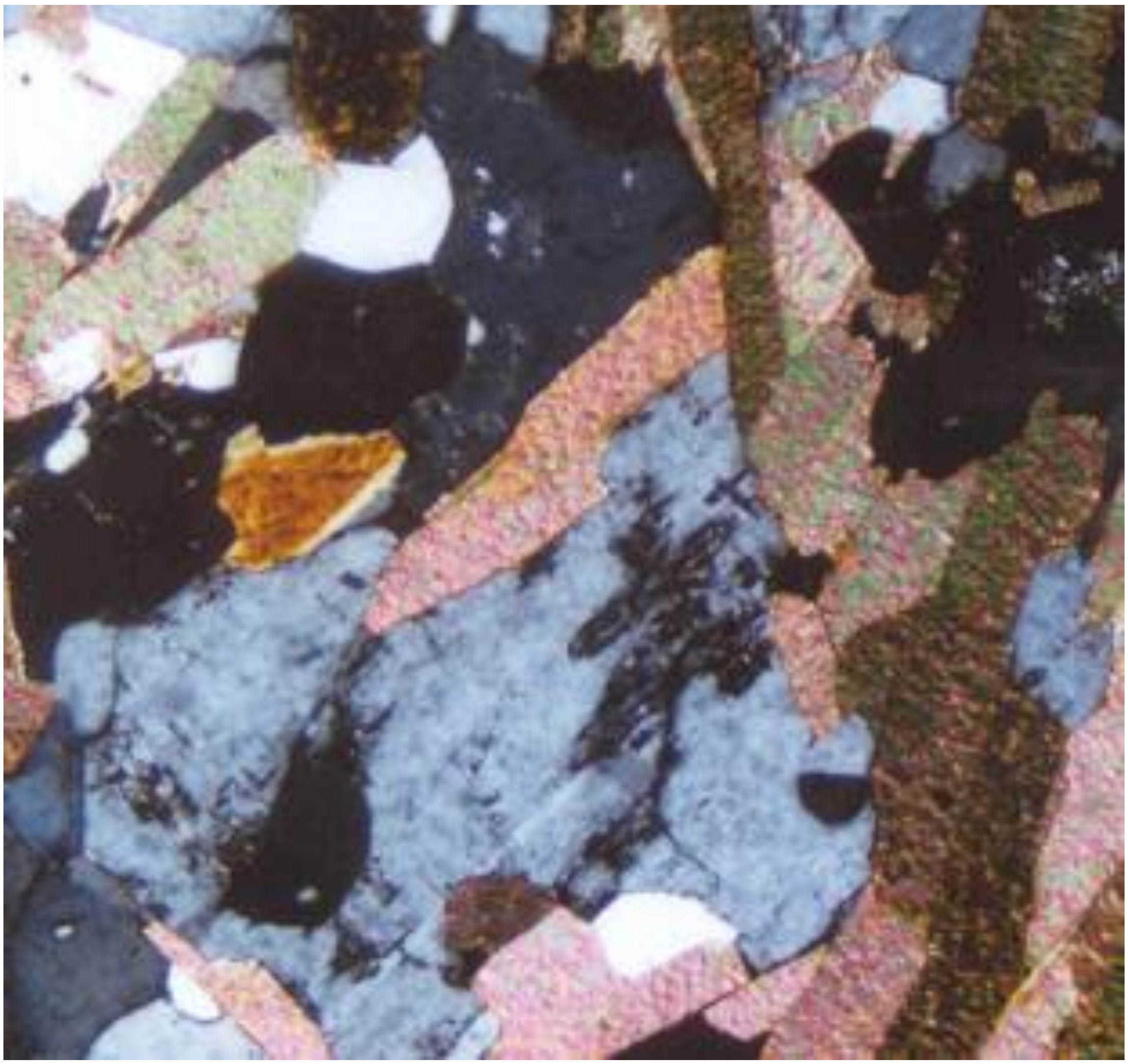

Fig. 13. Interior replacement of plagioclase An_{25} (light gray) by microcline (black). Biotite (shades of brown); quartz (white).

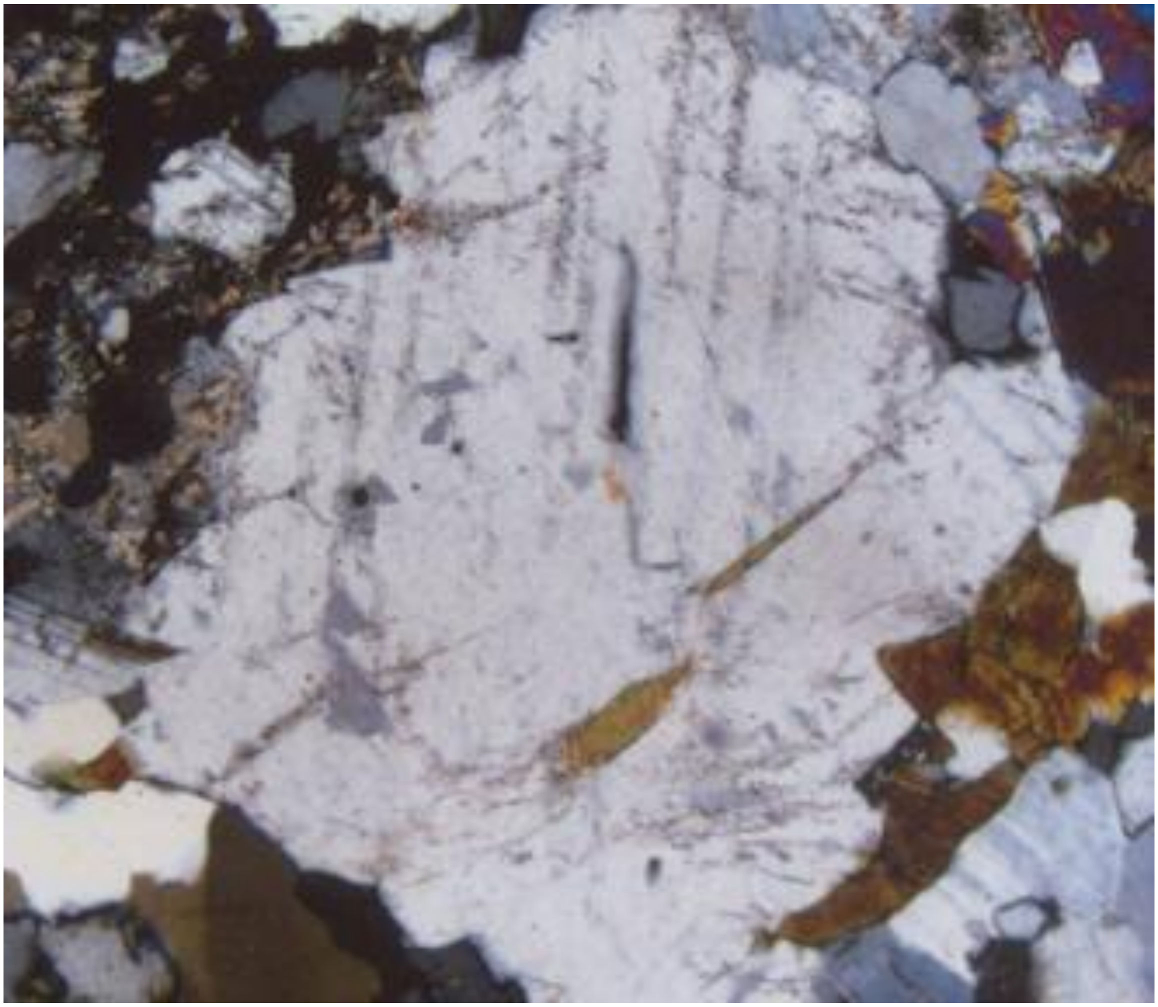

Fig. 14. Interior replacement of plagioclase An_{25} (light gray) by triangular islands of microcline (dark gray; left side of plagioclase). Biotite (brown); quartz (cream white).

Microcline becomes evident megascopically in the feldspathic layers 3-5 meters below the outer (uppermost) biotite diorite layer (Fig. 6 and Fig. 7). The microcline here is bordered by myrmekite with tiny quartz vermicules (Fig. 15). Moreover, at the first megascopic appearance of microcline in the thicker feldspathic layers, the volume of myrmekite ***exceeds the volume of adjacent microcline***. On that basis, it is clear that the myrmekite ***has not formed by exsolution from primary orthoclase*** because sufficient Ca and Na could not have been dissolved in the small volumes of the orthoclase at high temperatures to produce the exsolved volumes of plagioclase and quartz in the adjacent myrmekite. Such relationships support the hypothesis that the myrmekite has been formed during the partial replacement of the primary plagioclase by microcline (Collins, 1988, 1996ab, 1999ab).

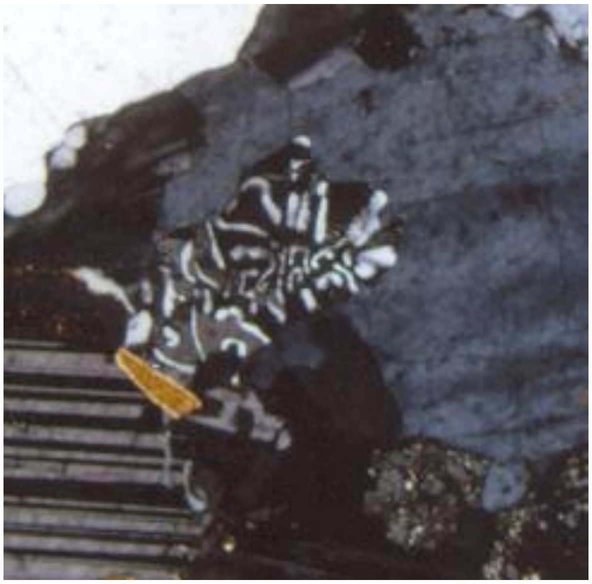

Fig. 15. Myrmekite with tiny quartz vermicules (white) surrounded by microcline (gray). Plagioclase (albite-twinned; black and gray); quartz (white); biotite (brown). Tiny quartz vermicules are typical of myrmekite in north end (top, nose of anticline) of the Wanup pluton and of outermost sodic-granitic layers of eastern and western limbs of the anticline.

As the microcline increases in abundance in these uppermost layers (Fig. 6 and Fig. 7), the microcline crystals occur in isolated aggregates in oblong or oval patches rather than as disseminated single crystals scattered through the rock. The microcline grains in these patches are the same size as the plagioclase grains outside the patches, and the borders of these patches have occasional myrmekite against the plagioclase groundmass. This relationship suggests that the microcline replacements started in a single deformed plagioclase crystal (as in Fig. 13 and Fig. 14) and then moved radial outward, progressively and sequentially, replacing other adjacent deformed plagioclase grains until an aggregate patch of randomly arranged microcline grains is formed. On that basis, the change in composition from feldspathic biotite-hornblende diorite to quartz monzonite in the uppermost layers is ***not*** the result of magmatic differentiation, but the result of K- and Si-metasomatism that allowed some of the primary plagioclase to be replaced by microcline. Furthermore, these same conversions of feldspathic diorite and gabbro layers in the middle and lower parts of the layered body to quartz monzonite and granodiorite must have occurred in the same way.

In the outer layers of the anticline along Route 69 where the microcline megacrysts intersect the mafic layering (Fig. 4 and Fig. 5 c), the low density of microcline, which is 2.56 gm/cc and lower than the densities of all other minerals in the rock, certainly would ***not*** permit primary orthoclase megacrysts (1) ***to settle into a mafic layer*** containing biotite and hornblende whose densities are 3.0 gm/cc or greater, nor (2) ***settle simultaneously with biotite and hornblende crystals*** as they formed a mafic layer. Moreover, late-forming orthoclase megacrysts, crystallizing at the top of the layered body, would not be able to settle through any earlier-deposited, thin, amphibolite layers to collect in the bottom of the layered body where megacrystal quartz monzonite and granodiorite contain calcic plagioclase An_{48-54} with densities of 2.70 gm/cc and are interlayered with pyroxene-bearing amphibolites. In addition, the edges of the microcline megacrysts are not sharp (euhedral) but enclose and penetrate the bordering plagioclase crystals. Therefore, the large microcline megacrysts at the top, middle, and bottom of the layered pluton ***must have formed by later replacement***.

Myrmekite.

Myrmekite associated with the microcline megacrysts has important relationships that need consideration. At the top of the anticline where myrmekite is associated with plagioclase An_{24} in quartz monzonite and granodiorite, the quartz vermicules are tiny (Fig. 15). In the intermediate layers along Route 69 (Fig 5 cdei), where the megacrystal quartz monzonite and granodiorite contain plagioclase An_{34-43}, the myrmekite has quartz vermicules with intermediate maximum thicknesses (Fig. 16 and Fig. 17). In the core (lowest layers) of the anticlinal fold (Fig. 5 g), where the megacrystal quartz monzonite and granodiorite contain plagioclase An_{48-54}, the myrmekite has coarse quartz vermicules (Fig. 18 and Fig. 19).

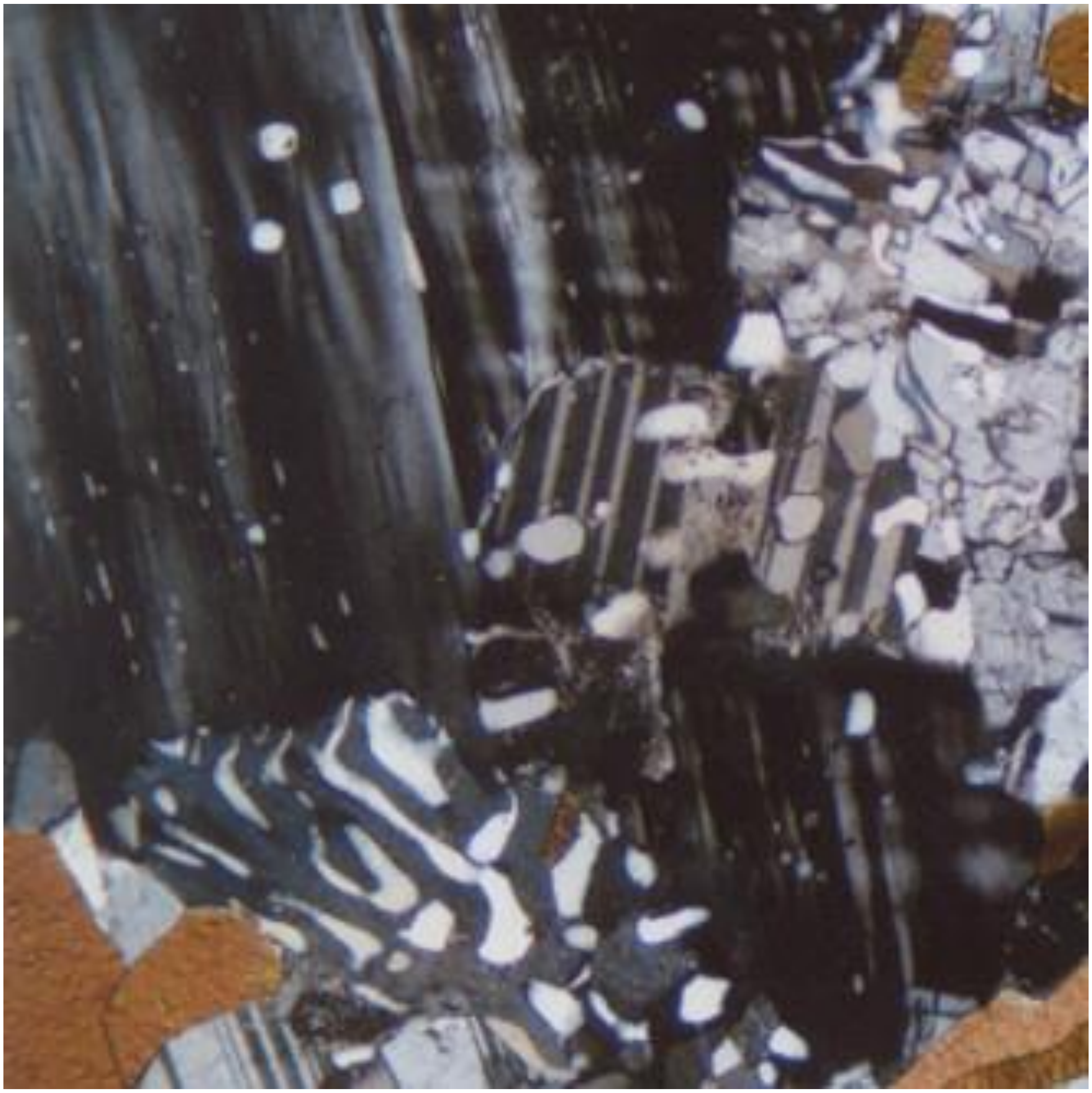

Fig. 16. Myrmekite from a megacrystal granitic layer in the Wanup pluton on the south side of Route 69. Microcline (black, grid pattern) contains large and small quartz blebs of ghost myrmekite. Biotite (brown); plagioclase (albite-twinned; gray and white); quartz (white).

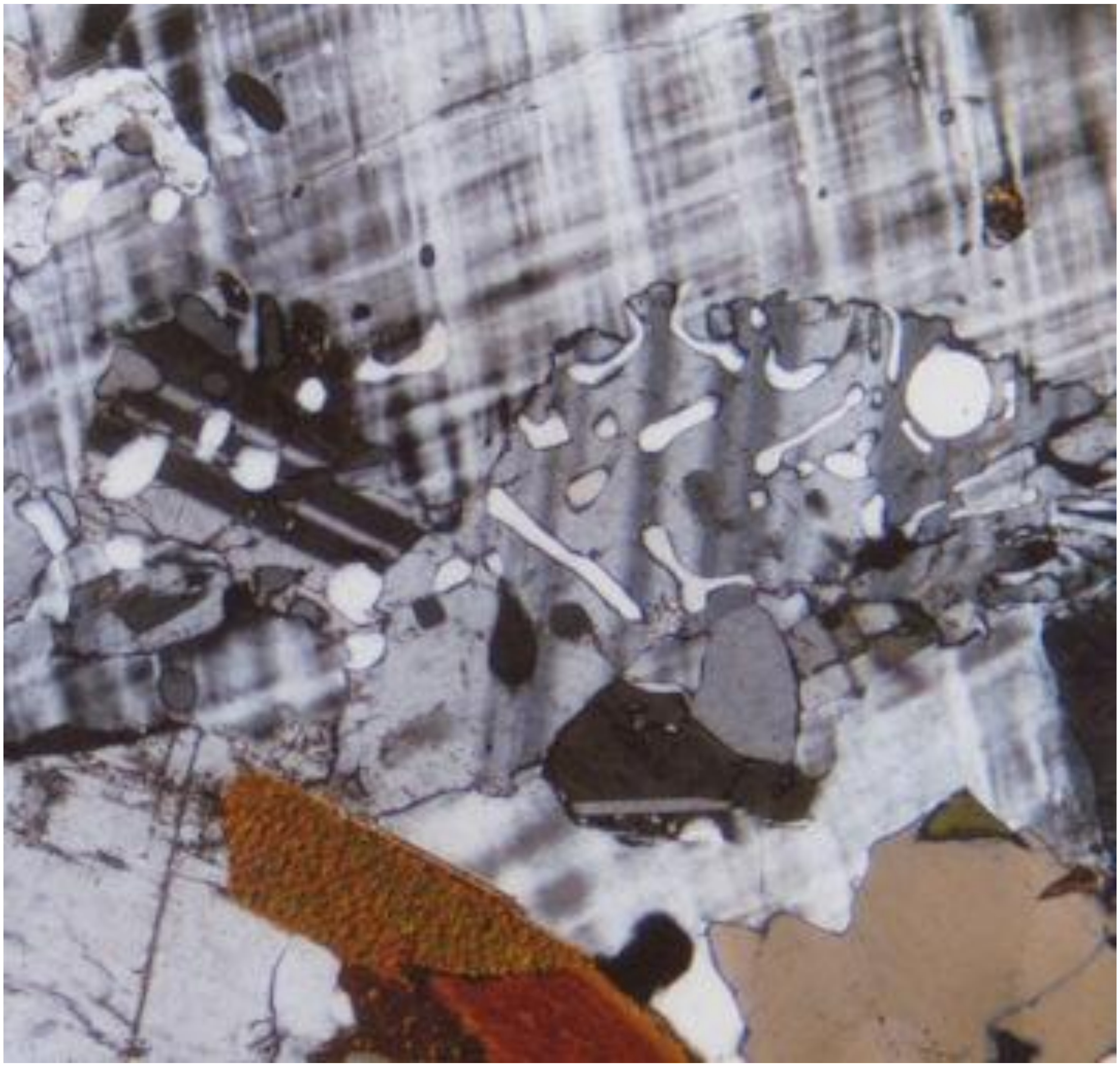

Fig. 17. Myrmekite with intermediate-sized quartz vermicules, typical of quartz monzonite and granodiorite near Route 69 and at intermediate levels between the top and bottom of the layered pluton.

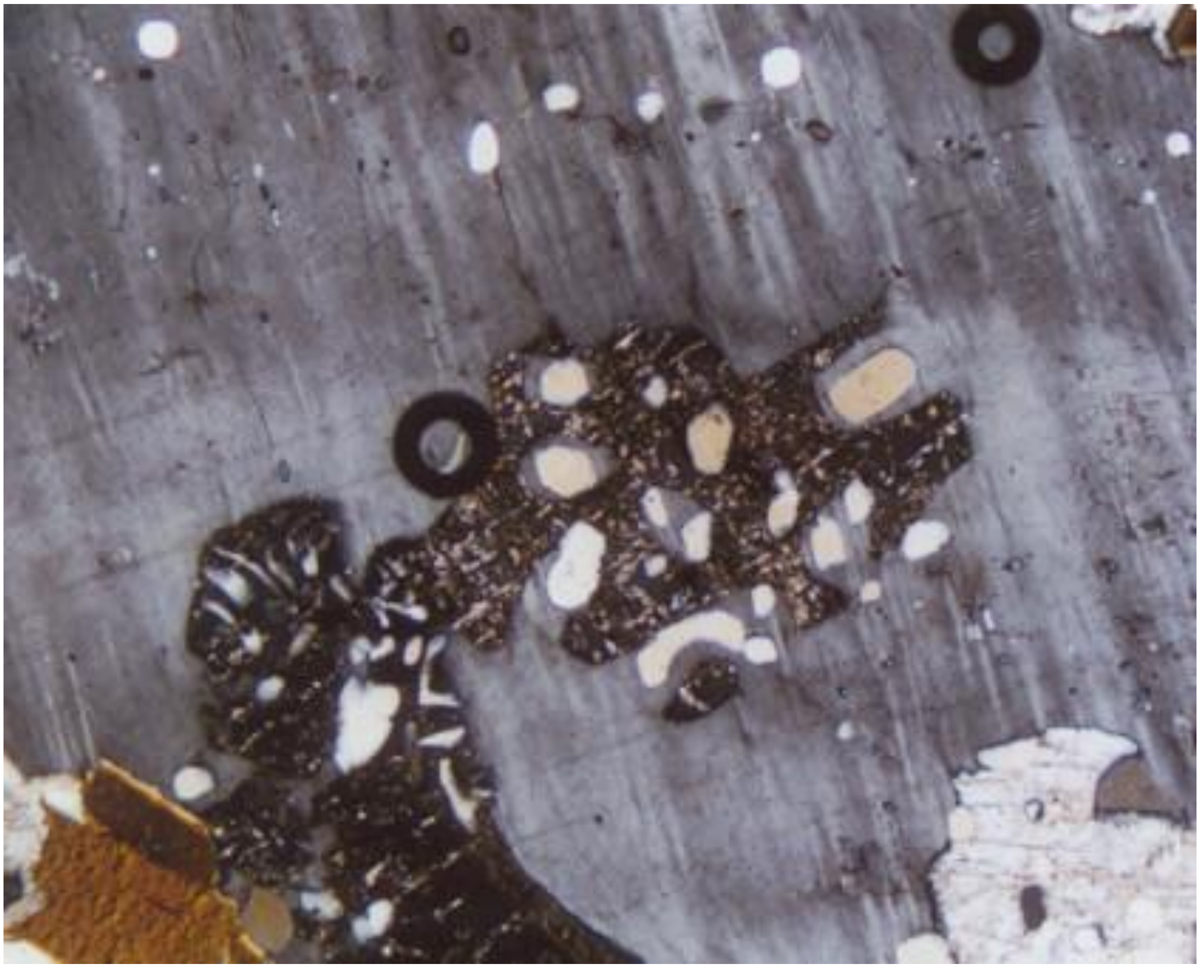

Fig. 18. Myrmekite with coarse quartz vermicules (white and cream), enclosed in microcline (grid pattern, light gray). Plagioclase of myrmekite is speckled brown (sericite alteration). Microcline penetrates the plagioclase along fractures and encloses some of the coarse quartz vermicules. Similar-sized or smaller islands of quartz occur in the microcline (top) as ghost myrmekite.

Fig. 19. Myrmekite with coarse quartz vermicules in megacrystal granitic rock near base of Wanup pluton, south of Route 69. Microcline (black) with scattered quartz blebs (white); some quartz blebs are the same size as those in the myrmekite, and others are tiny in ghost myrmekite. Plagioclase (albite-twinned; light and dark gray); quartz (mottled gray).

Ghost myrmekite.

In addition to myrmekite bordering the microcline, in the lowest megacrystal layers (Fig. 5 g), where the plagioclase has highest An-values, microcline also commonly contains abundant quartz blebs as ghost myrmekite (Fig. 20). These blebs must have resulted from excess silica left over in the lattice when the microcline replaced altered plagioclase grains. The subtraction of Ca and Al from these altered calcic plagioclase grains must have been so extensive that ***insufficient*** Al remained relative to the Si to form microcline in all places where K was introduced. Moreover, the quartz vermicules in myrmekite also occur because insufficient Al remained behind in the altered plagioclase lattice for the remaining Na to utilize all the silica during recrystallization to form the more-sodic plagioclase.

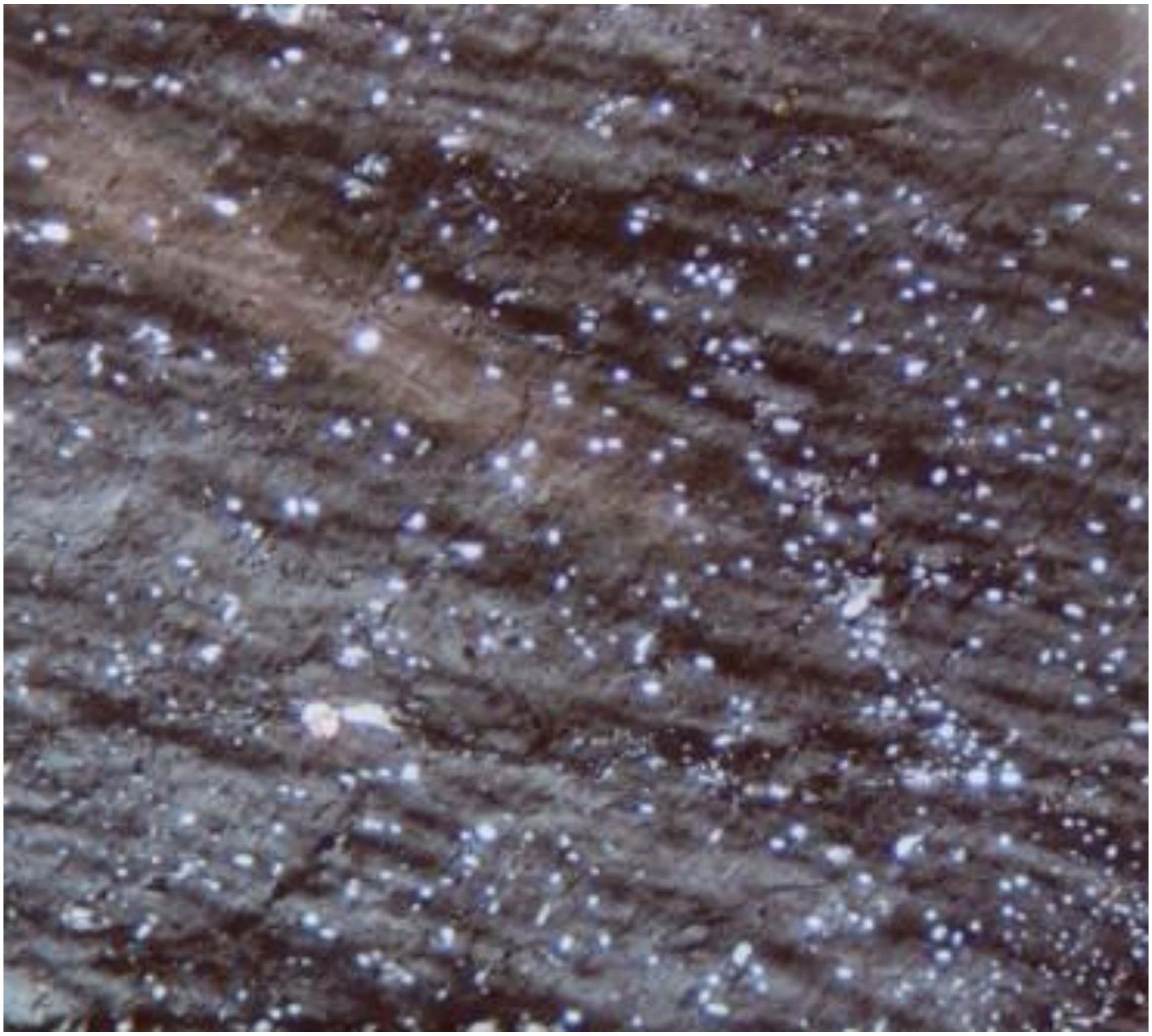

Fig. 20. Ghost myrmekite in microcline (grid-twinned; gray), occurring in megacrystal granitic rock near base of Wanup pluton, south of Route 69.

In some places, microcline is also seen to replace the plagioclase in myrmekite, enclosing large islands of former quartz vermicules (Fig. 18 and Fig. 19). Both kinds of quartz blebs in the microcline regardless of their origin have been referred to as ghost myrmekite (Collins, 1988; Collins, 1996b; Hunt et al., 1992). The presence of ghost myrmekite in the Wanup pluton gives strong support to the metasomatic alteration of a former diorite-gabbro body because such abundant quartz blebs enclosed in microcline (Fig.21) ***do not occur in microcline***

that inverts from orthoclase that crystallized from a magma. Quartz islands can occur in orthoclase when it crystallizes simultaneously with sodic plagioclase (albite) and quartz at the eutectic, but then it forms graphic or micrographic intergrowths with triangular or runic shapes. This is not the case in the Wanup pluton, however, because the coexisting plagioclase is quite calcic, and the quartz is not runic. Ghost myrmekite is found only in granitic rocks resulting from K-metasomatism, and the **coarseness of the enclosed quartz blebs can be correlated with the Ca-content of the former plagioclase** (Collins, 1988). Importantly, the more calcic the original plagioclase, the greater are the diameters of the quartz blebs in the microcline. For example, where the associated plagioclase is An_{48} to An_{54}, the quartz blebs in microcline are readily visible (Fig. 18, Fig. 19, and Fig. 20), but near Route 69 where the coexisting plagioclase is less calcic (An_{34}), ghost myrmekite is also found, but the quartz blebs are barely visible (Fig. 16).

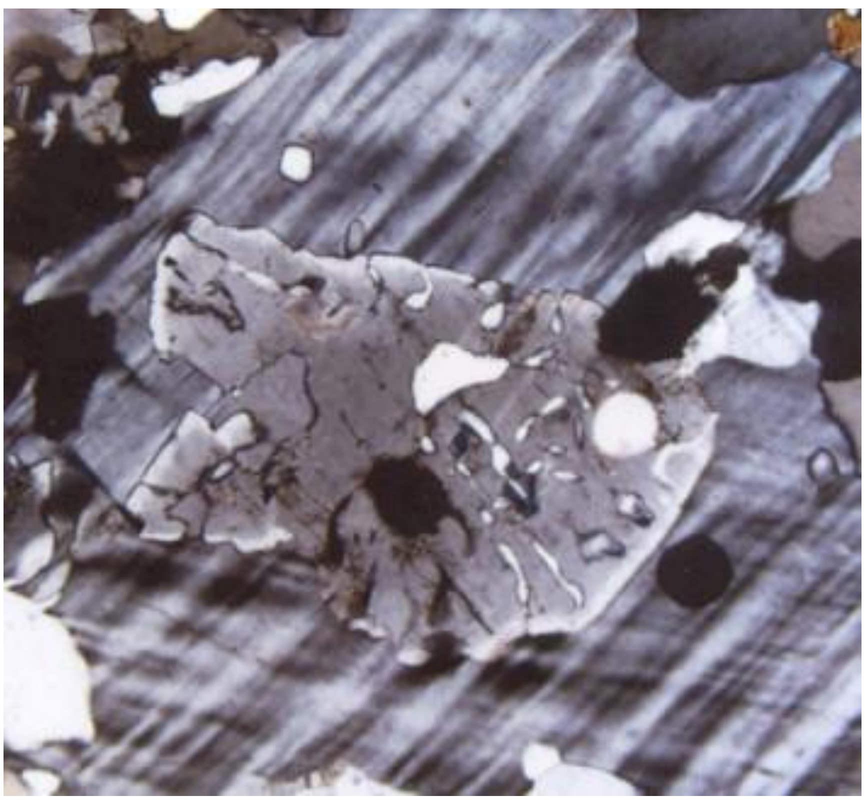

Fig. 21. Myrmekite with albite rims (white) enclosed in microcline (grid-twinned, gray) in leucocratic granite layers in strongly deformed rock on the north side of Route 69 (Fig. 10). Tiny quartz vermicules (white) pinch out into the albite rim. Some remnant thick quartz vermicules remain in the center of the myrmekite of the same size as in the granitic rock on the south side of Route 69 (Fig. 3, Fig. 16, Fig. 17).

More-sodic plagioclase.

On the basis of the above arguments, both myrmekite and ghost myrmekite in the quartz monzonite and granodiorite are indications that microcline replaced more-calcic plagioclase than exists in the present quartz monzonite and granodiorite. Moreover, where microcline replaces altered primary plagioclase grains, K displaces both Ca and Na. Some of this Na moved into other former, deformed, primary, relatively more-calcic plagioclase crystals, which have lost Ca from their lattice, and caused them to recrystallize as secondary, relatively more-sodic plagioclase. This recrystallized plagioclase is now the plagioclase that ranges from An_{24} to An_{54}. In that process evidence of the former deformation of the plagioclase (bent albite-twin lamellae, rotated fragments, and microfractures) and of possible normal zonation was destroyed by the thorough recrystallization, not only where the secondary more-sodic plagioclase was formed, but also where the microcline replaced other deformed plagioclase grains. Consequently, no textural clues exist in thin sections for the presence of a former strong deformation that once occurred in these rocks. But the maximum sizes of the quartz vermicules in myrmekite and of quartz blebs in ghost myrmekite indicate that the present plagioclase is more sodic than what was once there (Collins, 1988; Hunt et al., 1992).

In other terranes where recrystallization is not so thorough and where deformational textures are still preserved, the recrystallized more-sodic plagioclase crystals that coexist with myrmekite-bearing microcline have An-values as low as half that of the original primary plagioclase (Collins, 1988). On that basis, the present An-values in plagioclase in rocks in the layered Wanup pluton could be as low as half that of the original plagioclase of the feldspathic diorite and gabbro layers. For example, plagioclase in rocks exposed along Route 69 would have originally been more calcic than An_{34-43}, probably andesine or labradorite, while plagioclase in former rocks in the core of the anticline would have been more calcic than An_{48-54}, being formerly bytownite or even anorthite.

Movement of Ca and Al.

On the basis that the present plagioclase is less calcic than it once was, both Ca and Al must have left the system in the Wanup pluton. These Ca and Al losses are supported by three bits of evidence. (1) Microcline that replaces plagioclase has less Al in its lattice than in the former plagioclase and almost no residual Ca. (2) Ghost myrmekite in microcline indicates that even greater amounts of Al have been lost from former plagioclase than if microcline without ghost myrmekite had replaced the plagioclase. And (3), secondary, more-sodic plagioclase that replaced some of the primary, relatively calcic plagioclase has less Al in its composition than the more calcic plagioclase, and obviously less Ca. Therefore, if both Ca and Al are so extensively lost from former, relatively calcic plagioclase, other kinds of Ca-bearing minerals that were deformed in these rocks (including hornblende, clinopyroxene, allanite, apatite, titanite, and biotite) would also have been affected by fluids removing Ca and Al, resulting in the elimination of much of these minerals.

Volume changes.

Although replacement of plagioclase by microcline would not cause a volume change, the disappearance of apatite, titanite, allanite, and some biotite and hornblende necessitates a local volume loss which in turn would create strain on adjacent plagioclase, biotite, and hornblende crystals, causing fracturing of the strained crystals. This localized fracturing is important because in order for metasomatism to proceed and continue over long periods of time throughout a whole pluton, openings for fluid movement must be repeatedly created. Otherwise, recrystallization and replacements of crystals would plug the holes or fractures, and no further metasomatism could occur. Thus, the gradual disappearances of biotite and hornblende and other Ca-bearing minerals in a system that is being deformed, create fractures that perpetuate the metasomatism until deformation ceases and recrystallization has eliminated the fractures. The squeezing of rocks into an isoclinal fold favors the loss of Ca, Fe, Mg, and Al in fluids as the system is compressed and volume reduction occurs.

In other terranes, reduction in volume can occur when Ca is lost, but much of the Al, Fe, and Mg remain and is deposited in minerals of higher density, such as garnet, sillimanite, or magnetite (Collins, 1988, 1997). The Wanup pluton contains only trace amounts of garnet and magnetite and no sillimanite. The absence of dense and/or aluminous minerals is likely caused by large volumes of fluids moving through the rocks, removing displaced Ca, Al, Fe, and Mg. Breakdown of the abundant biotite may have supplied much of the fluids, but even greater volumes of fluids could also have come from outside the system because the Wanup pluton lies within the broad shear zone of the Grenville Front which has many deeply extending faults (Davidson, 2001).

Because the amphibolite bands interlayered with the feldspathic bands in the Wanup pluton show little to no recrystallization and replacement in most places, most of the above volume losses in the Wanup pluton must have occurred in the interlayered feldspathic bands. These losses are further suggested by the convolutions of the amphibolite bands (e.g., Fig. 12) which could have been crumpled as the interleaved feldspathic bands were locally differentially or unequally thinned across their width and shortened along their length as their volumes decreased.

Interpretation of the strongly deformed rocks on the north side of Route 69.

The strongly-deformed layered rocks that are part of the drag folds (Fig. 9 and Fig. 10) on the north side of Route 69 (Fig. 5 d) have some different features that are not shown in the less-deformed layered rocks on the south side of the road (Fig. 3). For example, thick amphibolite layers in the wide drag fold feather out and disappear into coarse granitic rocks with microcline megacrysts (top to center of Fig. 9) or into fine-grained leucogranite without microcline megacrysts (bottom right of Fig. 9). In the nose of the anticline (Fig. 5 b), microcline megacrysts first form in the Wanup pluton in areas of strong deformation (Fig. 8). Here, the system was opened to fluid movement, and nearly all the biotite and hornblende were removed, leaving a residue of mostly quartz, microcline, and secondary more-sodic plagioclase. This same process occurs in the wide drag fold where the removal of biotite and hornblende and formation of microcline megacrysts clearly results in a reduction in volume (see cartoon, Fig. 22 ab).

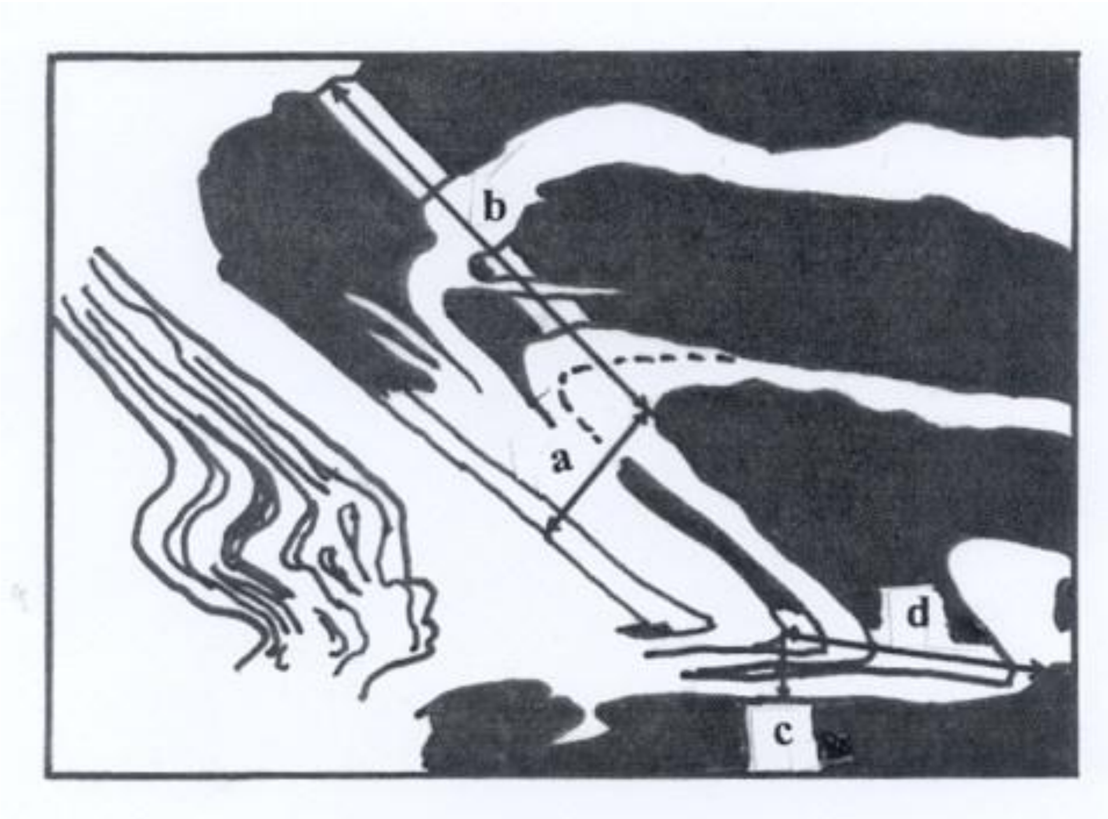

Fig. 22. Cartoon of the large drag fold shown in Fig. 9. In the center, the thickness of the megacrystal granitic rock (a) is about one-third of the combined thicknesses of two amphibolite and two granitic layers (b) in the equivalent position in the upper limb. In the lower right, the thickness of the leucocratic granite bands (c, vertical line) is about one-fourth the combined thicknesses of two amphibolite and two granitic layers (d) in the equivalent position in the lower limb.

Where deformation is more intense, adjacent to narrow isoclinal drag folds (Fig. 10), thin amphibolite layers disappear laterally into leucocratic granite without megacrysts. Amphibolite layers also disappear into leucogranite at the bottom right of Fig. 9 (see cartoon, Fig. 22 cd). In both places, even greater degrees of removal of biotite and hornblende occur, and lateral sliding in planar shear zones cause cataclasis, reduction in grain size, and stretching of amphibolite bands to make them thinner. This sliding and repeated deformation prevents the formation of large microcline megacrysts. Nevertheless, much microcline is formed (65-75 vol. %), because the plagioclase crystals are repeatedly fractured and granulated, enabling more replacements, but now forming small microcline crystals. In addition, release of Na from the replaced plagioclase would have caused some of the plagioclase to be recrystallized as more sodic plagioclase An_{20}. The end product of the extreme cataclasis and replacements is a fine-grained leucocratic granite band that resembles a former magmatic aplite dike or a former arkosic sediment.

The evidence in these leucocratic bands for replacements, however, is mostly gone because recrystallization removes the former cataclastic textures and because replacements eliminate what minerals were once there. Nevertheless, coexisting myrmekite (Fig. 21) in the leucocratic granite band, which is not normally found in granite aplite dikes of magmatic origin or in arkoses, is a clue, not only to this cataclasis (Collins, 1988), but also the earlier presence of a biotite-hornblende feldspathic diorite band where the leucocratic granite bands now occur. This myrmekite differs in some respects from the myrmekite in the megacrystal granitic rocks on the south side of Route 69 (Fig. 16 and Fig. 17). It contains relatively coarse quartz blebs in its core like that in myrmekite south of the road (Fig. 17), but these coarse vermicules do not taper and extend to the microcline. Instead, tiny quartz vermicules, unconnected to the central coarse quartz blebs, extend outward toward the microcline and pinch out into an albite rim (Fig. 21). This rim is probably caused by the increased Na, resulting from a later K-replacement of plagioclase during repeated episodes of deformation. Formation of sodic plagioclase consumes silica; therefore, quartz vermicules will be thin and taper toward the albite rim. The thicker quartz blebs (vermicules) in the core (Fig. 21), on the other hand, suggest that the former rock once had more calcic plagioclase than is indicated now by the tiny quartz vermicules near the rim (Collins, 1988). Therefore, the rock must have undergone more than one cycle of K-metasomatism during the repeated episodes of cataclasis. During these episodes, additional Na, released from the K-replacement of plagioclase, replaced the relatively more-calcic plagioclase of a former myrmekite grain, thereby producing the disconnected, thin, quartz vermicules and albite rim. As a result, the present myrmekite is a modified remnant of a previous myrmekite, like that in the megacrystal granitic rocks on the south side of Route 69 (Fig. 16 and Fig. 17). Thus, myrmekite can be used as a clue to the origin of the rocks.

In a magmatic model, the megacrystal granitic rock in the wide drag fold (Fig. 9) might be interpreted as the result of anatexis in which felsic components in the rock melted and migrated to produce migmatite in a low pressure site where the partial melts crystallized as quartz, microcline, and oligoclase. But if that were true, then the migration of such felsic melts should leave behind a residue enriched in mafic or aluminous minerals (a restite), and that is not the case. The mafic minerals are not concentrated near where the amphibolite bands feather and disappear into the megacrystal granitic areas. Instead, hornblende and biotite decrease in abundance without any enrichment; residual plagioclase does not become more calcic; and no sillimanite, kyanite, and/or cordierite are formed from the breakdown of biotite. Moreover, if the megacrystal granitic rock and leucocratic granite bands represent the products of partial melting of the adjacent more mafic rocks, then such melts would not crystallize to form myrmekite. If the myrmekite were there prior to melting, such melting would have destroyed it, particularly if the myrmekite went through two cycles of K-metasomatism, as in the leucocratic granite bands (Fig. 21). Furthermore, myrmekite has never been produced experimentally from melts. Therefore, anatexis and migration of partial melts can be ruled out as an explanation for the origin of these granitic rocks.

Evolution of the Wanup pluton

An evolutionary history of the Wanup pluton could be reconstructed as follows. An initial, very wet, relatively mafic, K-rich magma was intruded into older Precambrian sediments. As this magma cooled, relatively Ca-rich minerals (hornblende, clinopyroxene, and calcic plagioclase) began to crystallize and settle to the bottom to form amphibolite layers. During this process the residual magma at higher levels was progressively enriched in Na and K and depleted in Ca, Mg, and Fe. This, in turn, allowed biotite, hornblende, and relatively more-sodic plagioclase to crystallize to form more-feldspathic layers until the overlying magma became saturated in Ca, Mg, and Fe again. The cycle was then repeated again and again, upward, to form alternating layers of amphibolite and layers of biotite-hornblende feldspathic rocks (first gabbro and then higher up, diorite). In the last stage of crystallization when the residual magma was most K- and Na-rich at the top of the pluton, the final layer that was formed was the biotite-rich diorite containing oligoclase. No layers from top to bottom contained any K-feldspar. The layers at or closest to the bottom likely contained plagioclase of the highest An-content in gabbro, but these rocks are glacially eroded and covered by till and forest, and their more mafic and calcic compositions cannot be verified.

After final crystallization and at some later time, this layered diorite-gabbro body was intensely folded into a tight, nearly-isoclinal anticline (Fig. 5). Because the layered rocks were so strongly compressed, essentially most of the solidified pluton (except for the very nose at the north end) was subjected to cracking of mineral grains, replacements, and recrystallization. The slippage of rock layers in the limbs of the anticline, adjusting to the lateral displacements during the compression, would have caused extensive crystal deformation in the feldspathic rocks containing abundant biotite. The amphibolite layers, containing mostly hornblende and little biotite, would have been more competent, unaffected, and rafted along, but locally broken in boudins and convoluted.

Additional cracking and rotation of mineral grains must have also occurred during foreshortening of the biotite-bearing feldspathic layers at and near the base of the pluton as these layers were shoved toward each other from opposite sides. This foreshortening is indicated by the convolutions in the more-competent mafic layers (Fig 12). Because of the strong deformation that occurred, the rocks were open to fluid movement and release of water as biotite and hornblende were replaced by quartz. Calcium would have been removed from deformed plagioclase crystals which were replaced by microcline. Displaced sodium would have moved into some of the broken plagioclase grains. Thus, the recrystallization and replacements of the biotite-hornblende diorite and gabbro layers in between the amphibolite layers changed their compositions to quartz monzonite, granodiorite, or granite and destroyed the evidence for their former more-calcic compositions while eliminating the cataclastic textures.

Furthermore, the replacement of plagioclase by microcline displaced, not only Ca and Na, but also some Al. Some of this Al would have precipitated in epidote, a common coexisting accessory mineral. In other places, some Al was precipitated in garnet or rare scapolite. Obviously, much Fe, Mg, Al, Ca, and Na must have left the system as the residual rocks were relatively enriched in K, Na, and Si during metasomatic processes. Relative movements of elements in an aqueous open system below melting temperatures ***is opposite from what occurs during anatexis in magmatic processes***. First to move in a melt are K, Na, and Si, which then leave behind Fe, Mg, Al, and Ca in more mafic minerals.

The existence of a former layered diorite-gabbro in the Wanup pluton suggests the possibility that hidden under the glacial till and forest cover at the southern boundary could be a chromite or platinum deposit that commonly forms as the lowest layer in a layered diorite-gabbro body. This hypothesis has not been checked.

The evolution of the Wanup pluton also suggests the possibility that zircon crystals in the recrystallized rocks might record two different isotopic U-Pb ages. An older age could exist in the cores of zircons that formed when the original layered diorite-gabbro was emplaced, and a younger age might be found in overgrowths on these cores when the diorite-gabbro layers were modified to form quartz monzonite and granodiorite. This possibility has not been tested.

Furthermore, the evolution of the Wanup pluton suggests that many Precambrian granitic bodies evolved in the same way. If so, the stages of evolution would begin with the upward migration of incompatible K from the mantle in water-rich magmas that crystallized as biotite-rich tonalites, diorites, and gabbros, lacking orthoclase. Subsequently, these mafic rocks would have been deformed during plate tectonics and modified by K- and Si-metasomatism to form more granitic compositions. Then, later, re-heating of these rocks above melting temperatures could mobilize them as magmas to form higher level granitic intrusions. Those bodies in which myrmekite is found give clues to this evolution prior to melting.

Similarity of layered granitic rocks in Greenland with the layered Wanup pluton

Finch et al. (1990) described rapakivi granite in southwestern Greenland, which is interlayered with thin (2-4 cm wide) hornblende- and pyroxene-rich mafic layers, containing minor biotite. This biotite was suggested to have formed by K-metasomatism of the hornblende and pyroxene when these mafic layers were deformed parallel to the layering. The assumption was made that the thicker, interleaved, rapakivi granite layers were primary and undeformed and that the parallel hornblende-pyroxene mafic layers formed by crystal settling in a granitic magma. Abundant fluorine in the rocks was suggested to permit a granite magma to become less viscous, thereby allowing the heavy hornblende and pyroxene crystals to settle. However, the K-feldspar in the rapakivi granite is microcline, rather than orthoclase (Collins, 1999ab), and the microcline crystals are bordered by myrmekite with relatively coarse quartz vermicules (similar to Fig. 18 and Fig. 19). Their coarseness supports the hypothesis that relatively calcic plagioclase was formerly present in feldspathic, biotite- and orthopyroxene-bearing diorite or gabbro (norite) bands that were interlayered with the hornblende-pyroxene layers (Collins, 1988). That is, the rapakivi granite layers are not primary, as suggested by Finch et al. (1990), but resulted from K- and Si-metasomatism of former deformed feldspathic norite bands.

If Finch et al. (1990) were correct that deformation allowed K to enter and replace hornblende and pyroxene in the mafic layers to form biotite, it is logical that this same deformation also affected the adjacent feldspathic norite layers. In that way, K could enter and replace deformed primary plagioclase in the norite to form microcline megacrysts, thereby changing the norite bands into a more granitic rock (Collins, 1998). More likely, the K did not come from an outside source but came from the breakdown of abundant biotite that was once present in the feldspathic norite bands. Its presence would have facilitated the deformation because biotite has a hardness of 3 and planar cleavage, whereas the mafic bands, containing mostly hornblende and pyroxene with hardnesses of 6 and no planar cleavage, would remain relatively undeformed and unreplaced. The absence now of the former abundant biotite in these feldspathic bands is because the biotite would have been replaced by abundant quartz (during Si-metasomatism), and this quartz along with the abundant microcline make the granitic rock a rapakivi granite. The myrmekite is part of the narrow plagioclase rim on the microcline megacrysts. At any rate, the similarity of these layered rocks and of myrmekite to that found in the Wanup pluton suggests that this Greenland site (Finch et al., 1990; Brown et al., 1992; Harrison et al., 1990) is another example of a layered, biotite-rich, mafic rock that was converted to a layered granitic rock by K- and Si-metasomatism.

Conclusions

An outcrop in the Wanup pluton along Route 69, showing interlayered amphibolite and megacrystal granitic rocks was found to be puzzling to other geologists because their models did not explain how such compositional interlayers could logically form. During my initial visit to this outcrop with Tony Davidson, I collected a single sample from which a thin section was made. Myrmekite with coarse quartz vermicules was found in this thin section (Fig 16). Previous studies of myrmekite (Collins, 1988) indicated a direct correlation between such coarse quartz vermicules and the former presence of a calcic diorite or gabbro. On that basis, a prediction was made that the megacrystal granitic rocks were once plagioclase-rich diorite or gabbro lacking K-feldspar, and because this plagioclase-rich rock was interlayered with parallel amphibolite bands, then the megacrystal rock might have been a former layered diorite or gabbro. If that were true, then a top should be found consisting of K- and Na-rich and Ca-, Mg-, and Fe-poor layers, a middle zone with intermediate compositions, and a bottom consisting of K- and Na-poor and Ca-, Mg, and Fe-rich layers, which are typical of a layered diorite-gabbro. This was exactly what was found.

An equally important observation is that if a layered diorite-gabbro body that now is a layered quartz monzonite and granodiorite "pseudomorph" had not been strongly deformed, it would still be a horizontally layered diorite-gabbro. It was the strong cataclasis caused by folding, the subsequent openness of the system for fluid movement in solids at temperatures below melting conditions, and the availability of K in abundant biotite that allowed the conversion of these mafic rocks to become the megacrystal layered granitic Wanup pluton.

Acknowledgments

I wish to acknowledge the help of Tony Davidson for calling my attention to the outcrop of layered rocks in the Wanup pluton along highway 69, southeast of Sudbury, and Adrian Finch for the gift of two thin sections of rapikivi granite from the layered rocks in Greenland. I thank my wife, Barbara, for many, many, excellent editorial suggestions, and David Liggett for assistance with placing the article on the website for Internet access.

References

Brown, P. E., Dempster, T. J., Harrison, T. N., and Hutton, D. H. W., 1992, The rapakivi granites of S Greenland --- crustal melting in response to extensional tectonics and magmatic underplating; in Brown, P. E., and Chappell, R. W., (eds.), The Second Hutton Symposium on the Origin of Granites and Related Rocks, Geological Society of America Special Paper 272, p. 95-106.

Collins, L. G., 1988, *Hydrothermal differentiation and myrmekite - A clue to many geological puzzles*: Athens, Theophrastus Publications, 387 p.

Collins, L. G., 1996a, Replacement of primary plagioclase by secondary K-feldspar and myrmekite: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 2, http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf.

Collins, L. G., 1996b, Microscopic and megascopic relationships for myrmekite-bearing granitic rocks formed by K-metasomatism: Myrmekite, ISSN 1526-757, electronic Internet publication, no. 3, http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf.

Collins, L. G., 1997, Myrmekite in garnet-sillimanite-cordierite gneisses and Al-Ti-Zr trends, Gold Butte, Nevada: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 11, http://www.csun.edu/~vcgeo005/Nr11Gold.pdf.

Collins, L. G., 1998, Contrasting characteristics of magmatic and metasomatic granites and the myth that granite plutons can be only magmatic: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 19, http://www.csun.edu/~vcgeo005/Nr19Myth.pdf.

Collins, L. G., 1999a, Experimental studies demonstrating metasomatic processes and their application to natural granitic environments: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 36, http://www.csun.edu/~vcgeo005/Nr36Experimental.pdf.

Collins, L. G., 1999b, Overlooked experimental evidence for K-replacements of plagioclase and origin of microcline in granite plutons: Myrmekite, ISSN 1526-5757, electronic Internet publication, no. 37, http://www.csun.edu/~vcgeo005/NrOverlooked.pdf.

Davidson, A., 2001, The Chief Lake complex, revisited, and the problem of correlation across the Grenville Front south of Sudbury, Ontario: Precambrian Research, v. 107, p. 5-29.

Finch, A. A., Reavy, R. J., Harrison, T. N., and Brown, P. E., 1990, Rapakivi granites, south Greenland: hydrothermal alteration of igneous layering: Journal of the Geological Society of London, v. 147, p. 739-742.

Harrison, T. N., Reavy, R. J., and Brown, P. E., 1990, Co-existing mafic and felsic magmas in the early Proterozoic rapakivi granite suite of southern Greenland: Bulletin of the Geological Society of Denmark, v. 38, p. 53-58.

Hunt, C. W., Collins, L. G., and Skobelin, E. A., 1992, *Expanding Geospheres, Energy And Mass Transfers From Earth's Interior*: Calgary, Polar Publishing Company, 421 p. Order from: http://polarpublishing.com.

Lumbers, S. B., 1975, Geology of the Burwash area, Districts of Nipissing, Parry Sound, and Sudbury: Ontario Division of Mines, Geological Report 116, 158 p.

Winchell, A. N., and Winchell, H., 1951, Elements of Optical Mineralogy, An Introduction to Microscopic Petrography, fourth edition, Part II, Description of Minerals: John Wiley & Sons, Inc., New York, 551 p.