33. Origin of the augen granite gneiss in the Bill Williams Mountains, Arizona, USA; A prediction confirmed

Lorence G. Collins

email: **lorencecollins@gmail.com**

December 9, 1998

Introduction

In only a few places in the world is myrmekite found with very coarse vermicules. In each of these places the myrmekite occurs in granites, augen gneisses, or garnet-sillimanite gneisses that are transitional through zones of strong deformation into undeformed gabbro having abundant biotite (as much as 30 vol. %) and plagioclase with high Ca-content, An_{80-100}. These places include biotite gabbroic gneisses in the Broken Hill area of Australia, a biotite-orthopyroxene gabbroic layer in the Dover magnetite district in New Jersey, and a biotite-rich gabbroic layer in the Central City area of Colorado (Collins, 1988). In comparison, granite containing myrmekite with intermediate or tiny vermicules in many places is found to grade through zones of strong deformation into undeformed diorite bodies rather than gabbro. The sizes of the vermicules depend upon the Ca-content of the primary plagioclase. The less Ca in the original plagioclase, the narrower are the quartz vermicules in the myrmekite.

During an examination of a thin section collection that Eric Bender had acquired for his Ph.D thesis study of the geochemistry of Precambrian granites in southwestern United States (Bender, 1994), I noted three places in which augen granites contained myrmekite with very coarse quartz vermicules. One was in the Orocopia Mountains south of Chiraco Summit in southeastern California east of Indio. The second was in the Eagle Mountains north of Chiraco Summit, and the third was in the Bill Williams Mountains southeast of Lake Havasu City, Arizona (Fig. 1). Subsequently, I went to look for augen granite coexisting with gabbro in the Orocopia and Eagle Mountains. Although I easily found the augen granites in road or stream cuts, there was no remnant gabbro. Thin sections of the granite samples, however, revealed myrmekite with very coarse quartz vermicules. Because possibly finding gabbro in these places would require extensive

reconnaissance in remote areas, I decided to wait to do further exploration until the augen granite in the Bill Williams Mountains had also been examined.

The samples from which the thin sections of the augen granite in the Bill Williams Mountains (Fig. 1) were made were obtained by Sue Orrell, Keith Howard, and Lawford Anderson. At the time of the sampling, Sue was doing a master's thesis under the guidance of Lawford Anderson on augen granite in the Whipple Mountains on the west side of Lake Havasu in California (Orrell, 1988). Lawford had suggested that she compare her rocks with the augen granite in the Bill Williams Mountains. The three of them flew by helicopter to collect samples in a canyon below a water fall in the central part of the augen granite (Fig. 2). The surrounding desert landscape above the (dry) water fall is rugged, but rock outcrops are abundantly exposed because of the sparse desert vegetation. In the ridges and slopes the augen granite is generally weathered, but fresh rock occurs along scoured walls of dry stream beds.
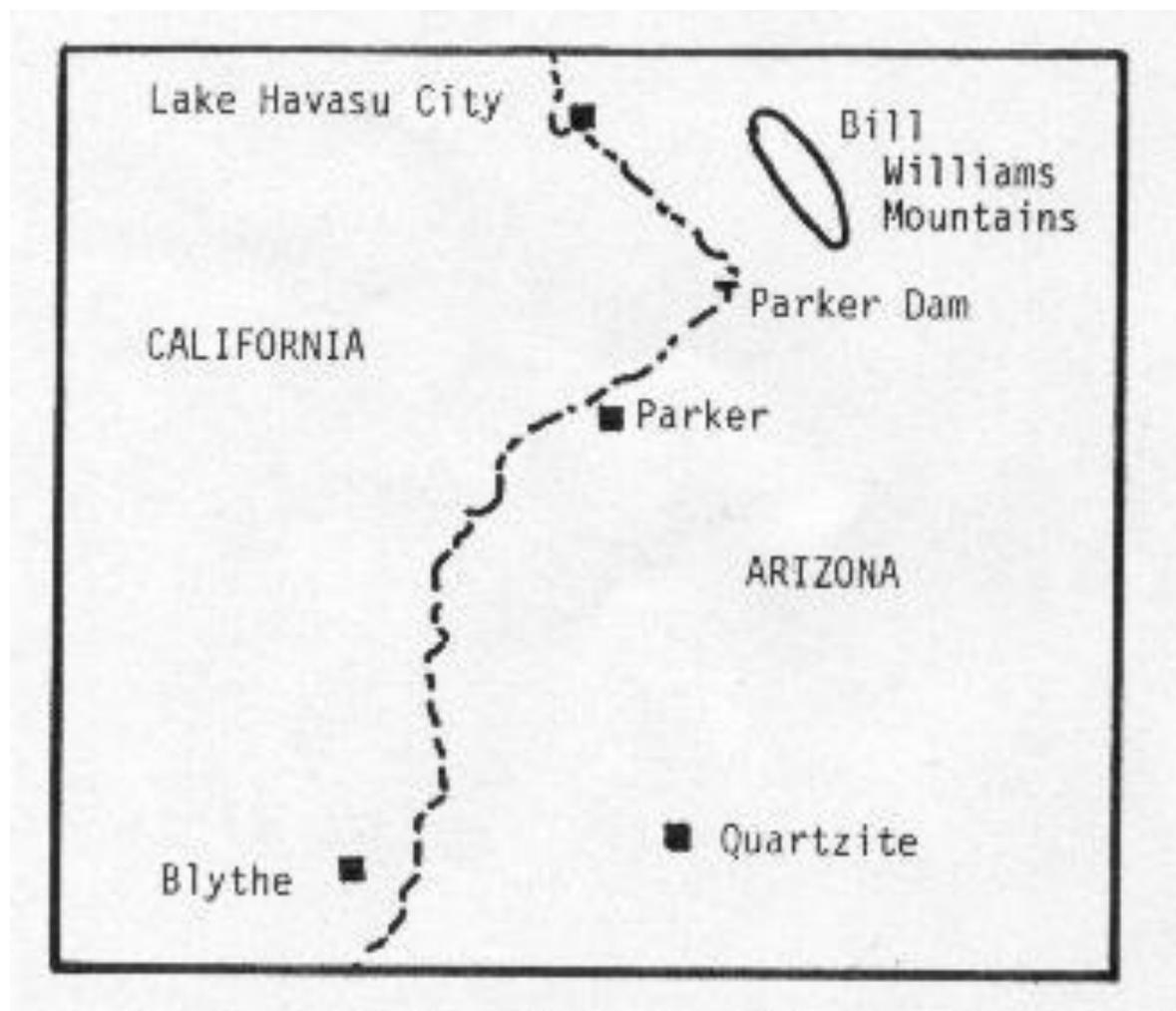
Fig. 1. Sketch map, showing location of Bill Williams Mountains, southeast of Lake Havasu City, Arizona, and northeast of Parker Dam.
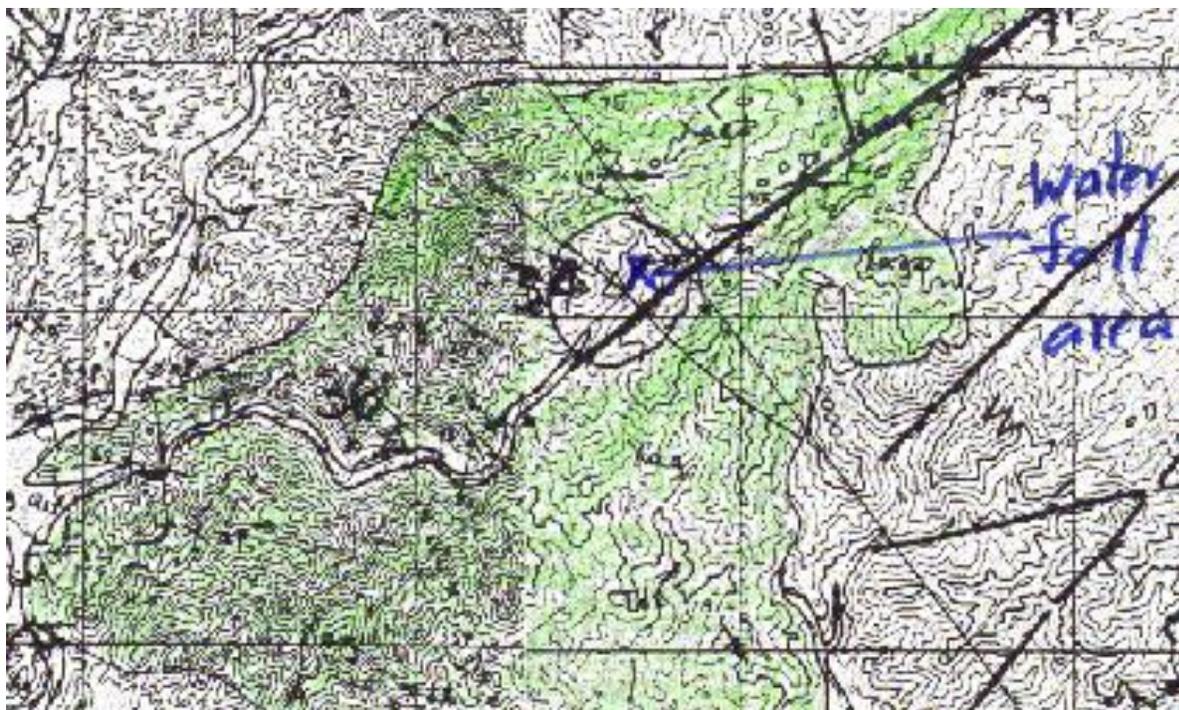
Fig. 2. Portion of geologic map of the augen granite gneiss in the Bill Williams Mountains; from Howard *et al*., (1990).

After obtaining information from Keith Howard as to where these samples were collected, David Liggett and I went there to see if gabbro was indeed present, and, if so, could transition stages be found showing conversion of the gabbro to augen granite? Or, is the augen granite entirely magmatic in origin?

The augen granite in the map area (Fig. 2) is in the upper plate of a low-angle detachment fault of Miocene age in a metamorphic core complex that extends into the Whipple Mountains in California and farther west (Anderson *et al*., 1979; Davis *et al*., 1980; Howard *et al*., 1982; see also Anderson (1983), Anderson *et al*. (1988), Anderson and Bender (1989), and Wooden and Miller (1990). This augen granite is divided by Howard *et al*. (1990) into three facies. The relatively narrow Xap unit is felsic and lies in the southwestern part of the body. Northeast from here is a thicker, more mafic unit Xag, and farther northeast is the Xagd unit which is the most mafic. All facies are biotite-bearing, and in some places also hornblende-bearing. K-feldspar augen are generally slightly less than 1 cm long (Fig. 3), but in some places, augen are 2-3 cm long. Mafic biotite-hornblende-rich amphibolite layers are occasionally found. Younger volcanic rocks of several types also cut the body. In some places the augen granite gneiss is strongly mylonitized, but otherwise the granite generally gives a massive appearance of a relatively uniform, medium-grained, magmatic rock. Locally,

felsic garnet-bearing dikes cut the Xag unit (Fig. 3), and these dikes have the appearance of crystallizing from an intrusive magma because of the sharp contacts and contrasting mineralogy.

Fig. 3. Felsic garnet-bearing dike in augen granite (Xag), in Bill Williams Mountains. Dike is mostly perthitic microcline and quartz, with occasional clots of garnet. Myrmekite occurs on borders of microcline against uncommon plagioclase.

Before going to the area, however, I examined a suite of 25 thin sections of the three different augen granite facies in the Bill Williams Mountains (a loan from Keith Howard), and these thin sections revealed a large variability in composition. Many rock types were relatively mafic and hornblende-bearing while others were felsic. All were biotite-bearing. Some contained garnet, and some were myrmekite-bearing. In those that were myrmekite-bearing, the maximum sizes of quartz

vermicules ranged from tiny to intermediate (Fig. 4) to very coarse (Fig. 5), including a thin section of a sample collected at the same time and location that Sue collected her samples. Keith Howard had not seen any gabbro in the area, and in his suite of 25 thin sections, those that contained myrmekite did not show any evidence that the K-feldspar had replaced plagioclase or that myrmekite had formed by K-metasomatism. The various augen granite facies appeared as if all were formed entirely by magmatic processes.
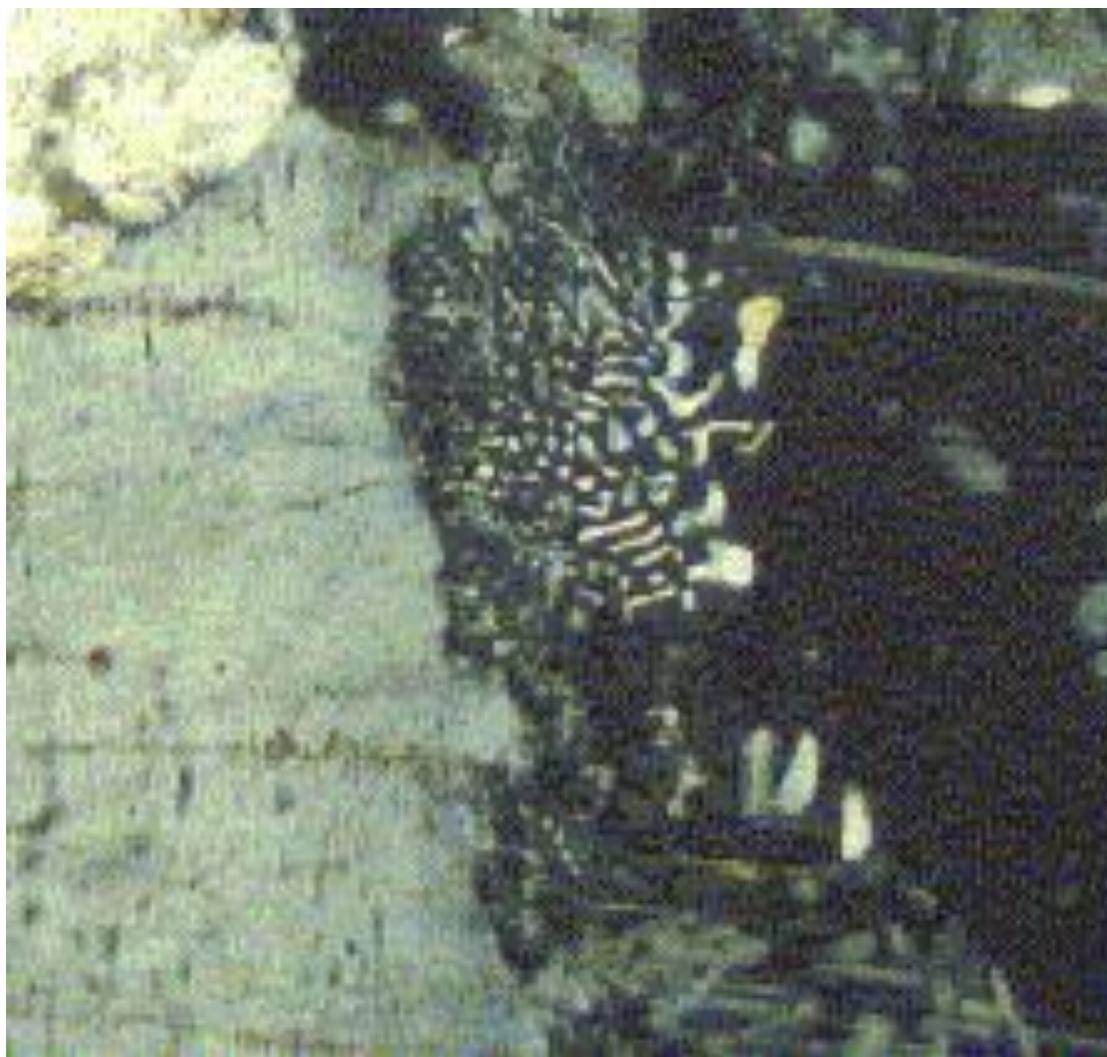

Fig. 4. Myrmekite in augen granite gneiss (Xag) with tiny to intermediate-sized quartz vermicules..
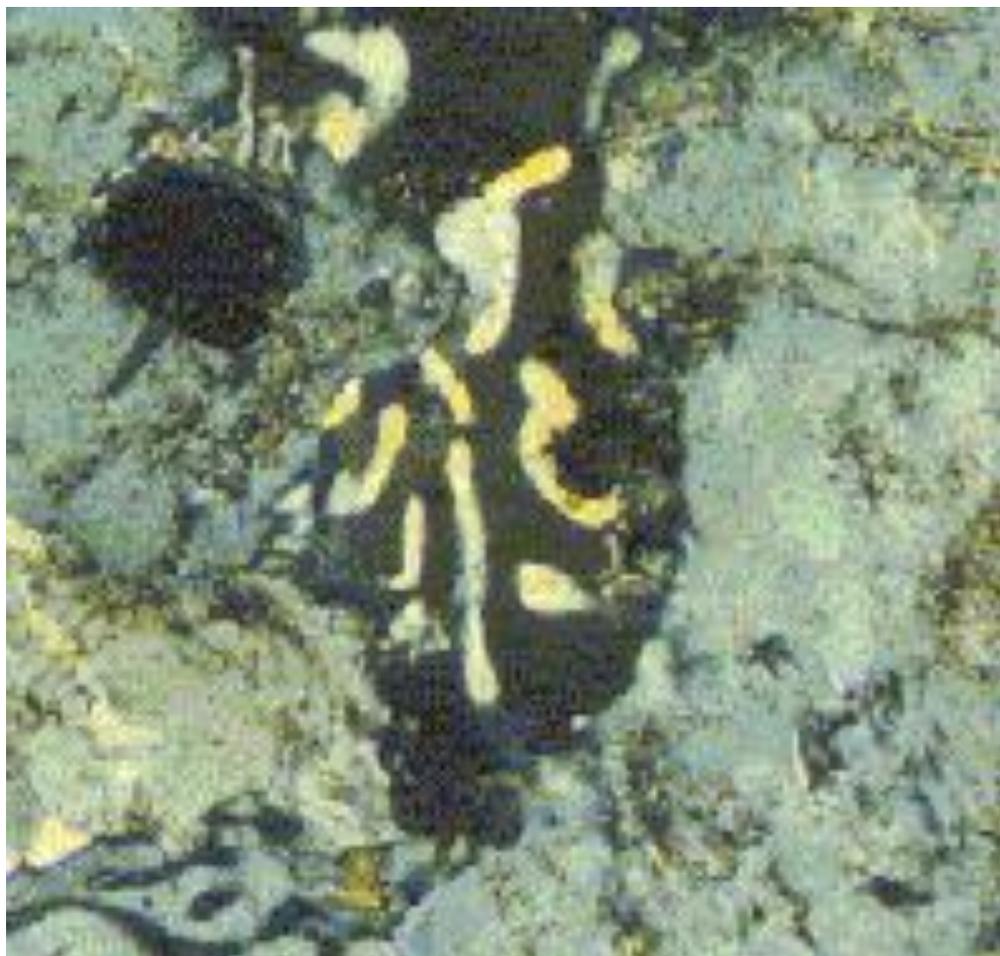
Fig. 5. Myrmekite with coarse quartz vermicules enclosed in microcline or bordering it (lower edge; center). Microcline is slightly perthitic.

Results of investigation

When David Liggett and I hiked up the canyon toward the water fall area (Fig. 2), we found that the bed rock was massive augen granite like that shown in Fig. 3. About 300 m down-valley from the water fall, however, the massive augen granite is deformed and becomes progressively more gneissic toward the water fall. Through this distance of 300 m, most of the biotite in gneissic bands can be seen to convert to garnet along strike. At the water fall the granite is completely changed into quartz-rich garnet gneiss, giving the appearance of a leucocratic metapelite. No gabbro is exposed along the canyon floor, but about 300 m down-stream from the water fall on the east side of the canyon floor is a large boulder about 3 m long containing two layers of gabbro (15 to 30 cm wide) alternating with augen granite. The original outcrop from which the boulder was eroded must have come from the adjacent valley slopes or farther upstream. The coexistence of the

augen granite and the two gabbro layers, however, ***confirmed my prediction*** that gabbro would occur in the area of the water fall where the myrmekite with coarse quartz vermicules was found. Thin section analyses of the coexisting augen granite revealed the presence of myrmekite with very coarse quartz vermicules (Fig. 5). In the two gabbro layers the clinopyroxene-orthopyroxene gabbro (Fig. 6) contains calcic plagioclase An_{80}, and the biotite-orthopyroxene gabbro contains plagioclase An_{50} (Fig. 7).
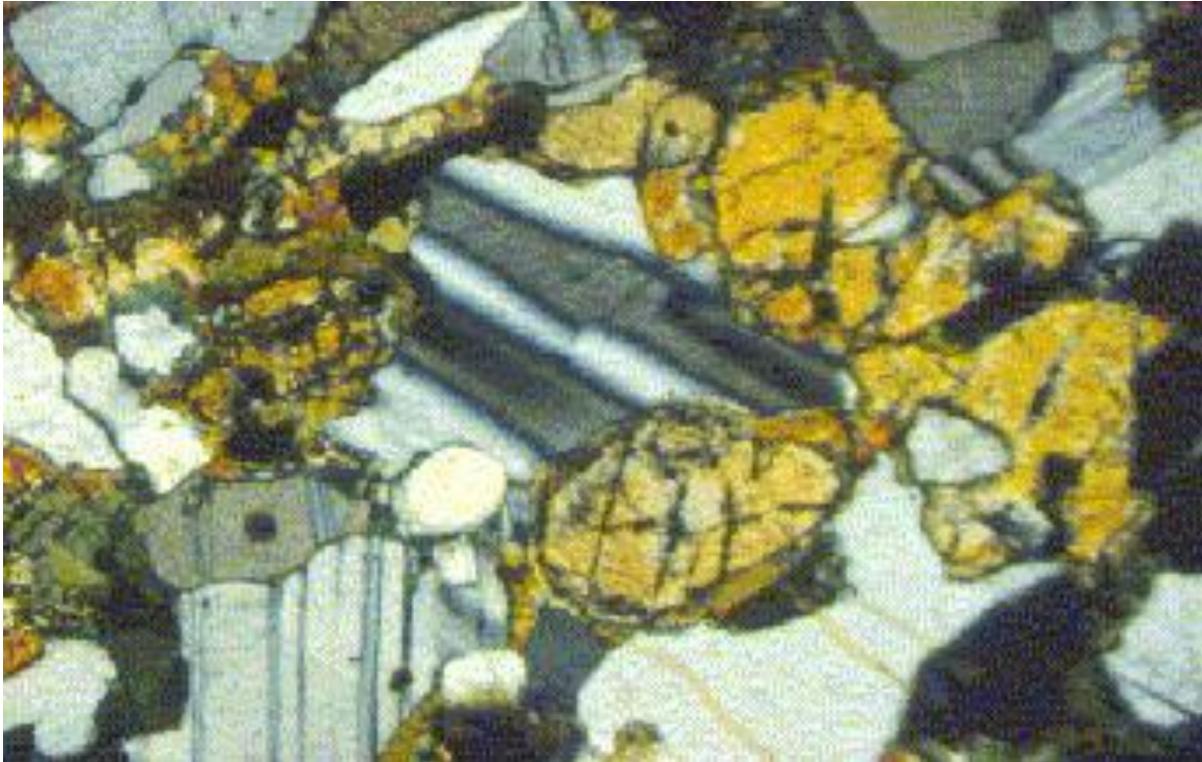

Fig. 6. Fine-grained clinopyroxene-orthopyroxene gabbro. Plagioclase is calcic, An_{80}. Orthopyroxene (tan). Occasional hornblende forms narrow rims on the pyroxenes.
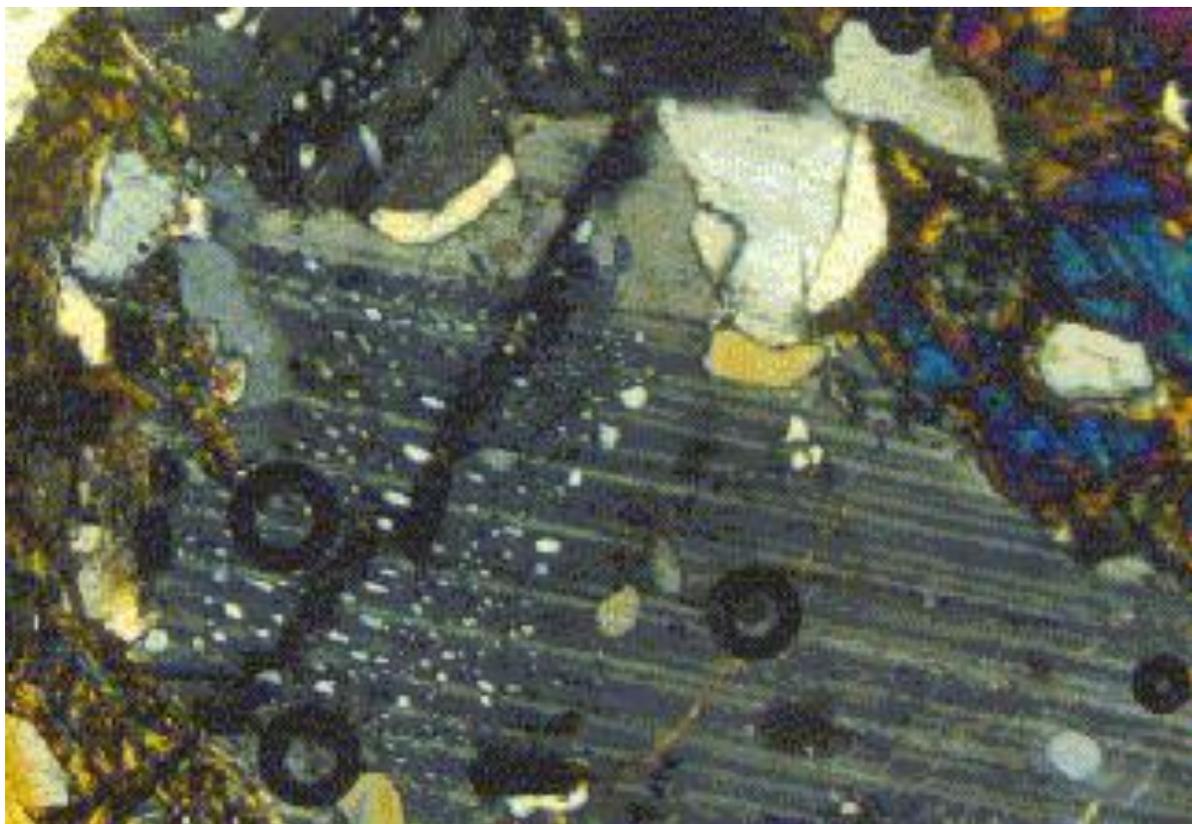
Fig. 7. Medium-grained biotite-orthopyroxene gabbro. Plagioclase is An_{50}. Orthopyroxene (tan and blue); quartz (yellow, white). Albite-twinned plagioclase has tiny quartz blebs. Plagioclase in both gabbros locally have circular blebs of quartz that may have crystallized simultaneously during late stages, or this quartz may represent later hydrothermal alteration associated with metasomatism.

I then wondered whether a transition zone would be present between the gabbro layers and the augen granite? A thin section in the granite adjacent to the biotite-orthopyroxene gabbro (Fig.7) shows three different kinds of plagioclase coexisting within a few millimeters of each other: (1) plagioclase lacking any inclusions, (2) plagioclase having islands of microcline, and (3) plagioclase containing islands of myrmekite. The first kind, lacking any inclusions (Fig. 8), is interpreted to be primary plagioclase of the original biotite-bearing gabbro that was relatively undeformed and unaffected by any later alteration.
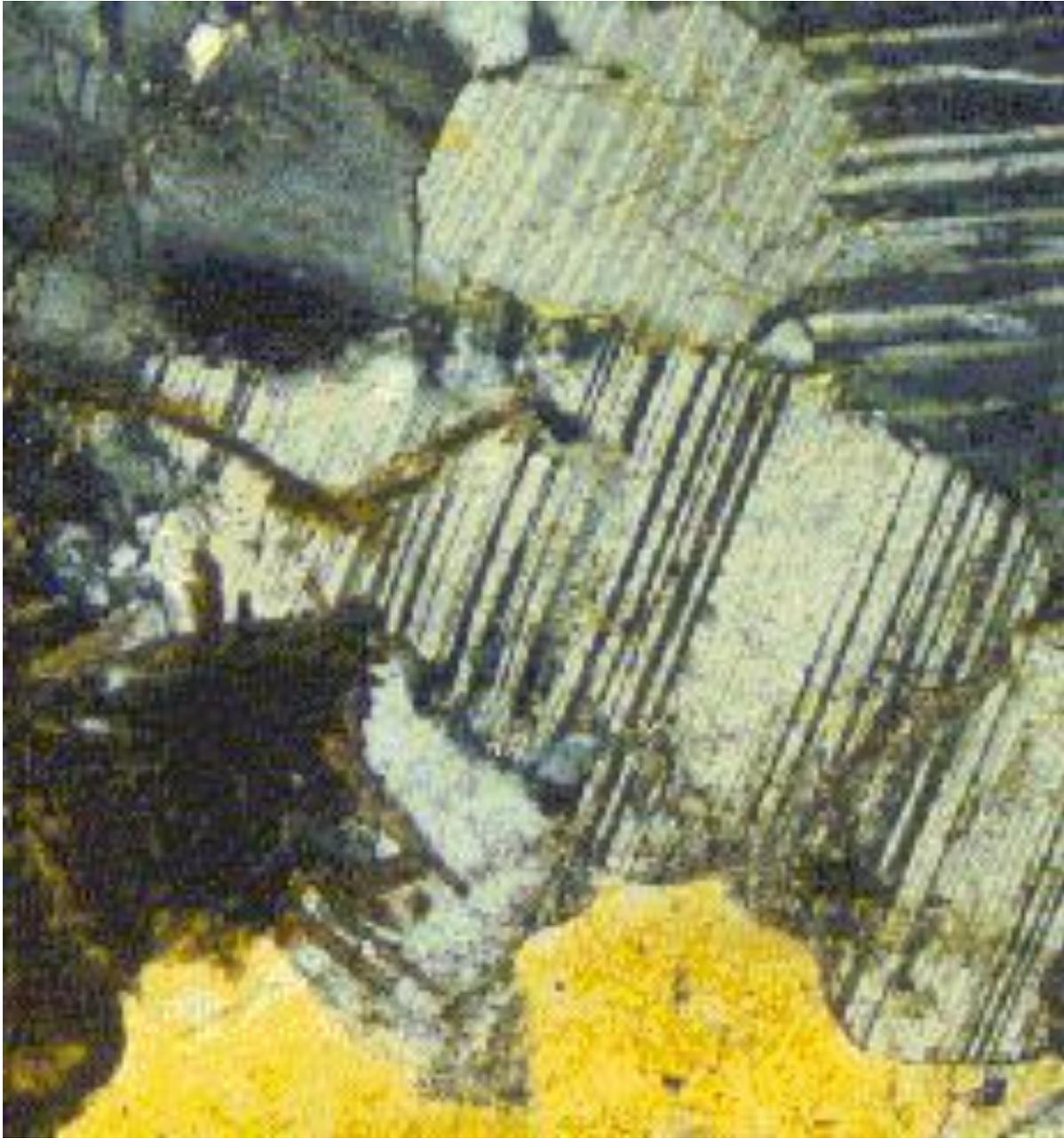
Fig. 8. Primary, albite-twinned plagioclase lacks any inclusions and is undeformed. Microcline (dark gray; upper left side). Quartz (yellow); biotite (dark brown). Figs. 8-14 are from the same thin section.

In the second kind of plagioclase, which contains islands of microcline, in some grains the islands are uniformly distributed and give the appearance of being antiperthite crystallized from magma (Fig. 9; lower left corner). But in other plagioclase grains (Fig. 9 and Fig. 10) the microcline islands are not uniformly distributed and are irregular in shape. Many are somewhat rectangular and have

edges parallel to albite-twin planes. In still other plagioclase grains, microcline occurs in veins penetrating former fractures in the plagioclase (Fig. 11 and Fig. 12) or replacing the edges of a plagioclase crystal (Fig. 9; right of center). These microcline-filled plagioclase grains are often adjacent to myrmekite with coarse quartz vermicules against perthitic microcline crystals.

Fig. 9. Plagioclase (light gray) replaced by microcline (dark gray), extending in from top right edge of crystal and in interior as blebs primarily parallel to albite-twin planes. Quartz (mottled gray, dark gray, cream yellow) occurs in upper and right side. Plagioclase with regular K-feldspar islands in lower left.
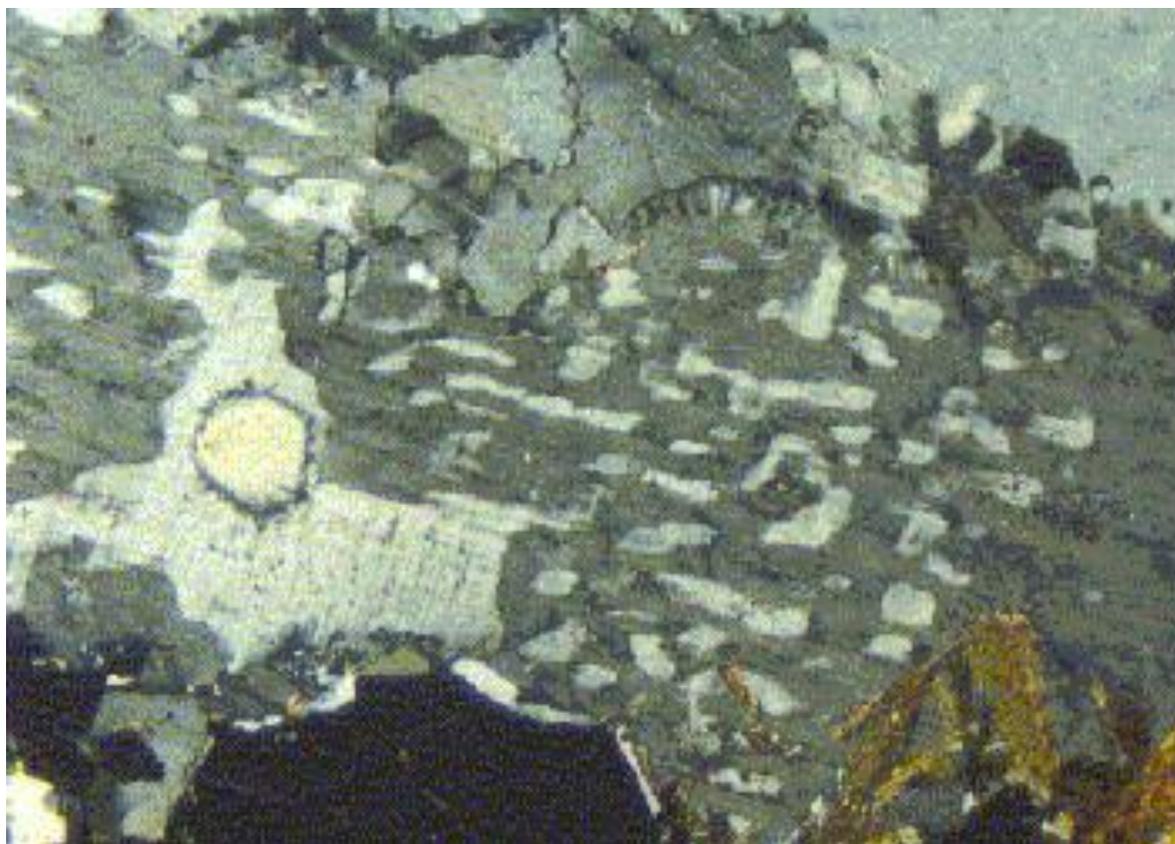
Fig. 10. Plagioclase (light tannish gray) replaced by irregular islands of microcline (lighter gray) and in veins extending into the plagioclase. Top border has rim myrmekite against slightly perthitic K-feldspar. Bottom is garnet (black) and biotite (brown). Quartz is cream.

If the rock in the transition zone had crystallized from a melt, it would be illogical that two kinds of plagioclase crystals would coexist --- those with islands of microcline and those without. The melt composition should not be different within a few millimeters to cause those two different kinds of plagioclase. Moreover, where *magmatically* derived antiperthitic plagioclase is found in other terranes, the K-feldspar islands occur in all plagioclase crystals, and the islands are uniformly distributed. In contrast, in the Bill Williams transition rock, the relatively large islands of microcline in some of the plagioclase grains (Fig. 11 and Fig. 12) have volumes too large to be exsolved from adjacent parts of a high-temperature plagioclase lattice. Exsolution of K-feldspar also does not make sense when some larger microcline areas in the plagioclase occur at crystal edges (Fig. 9) or along former fractures (veins) in the plagioclase (Fig. 10, Fig. 11, and Fig. 12). K-metasomatism of deformed plagioclase crystals is more logical as an explanation of the microcline islands than exsolution.
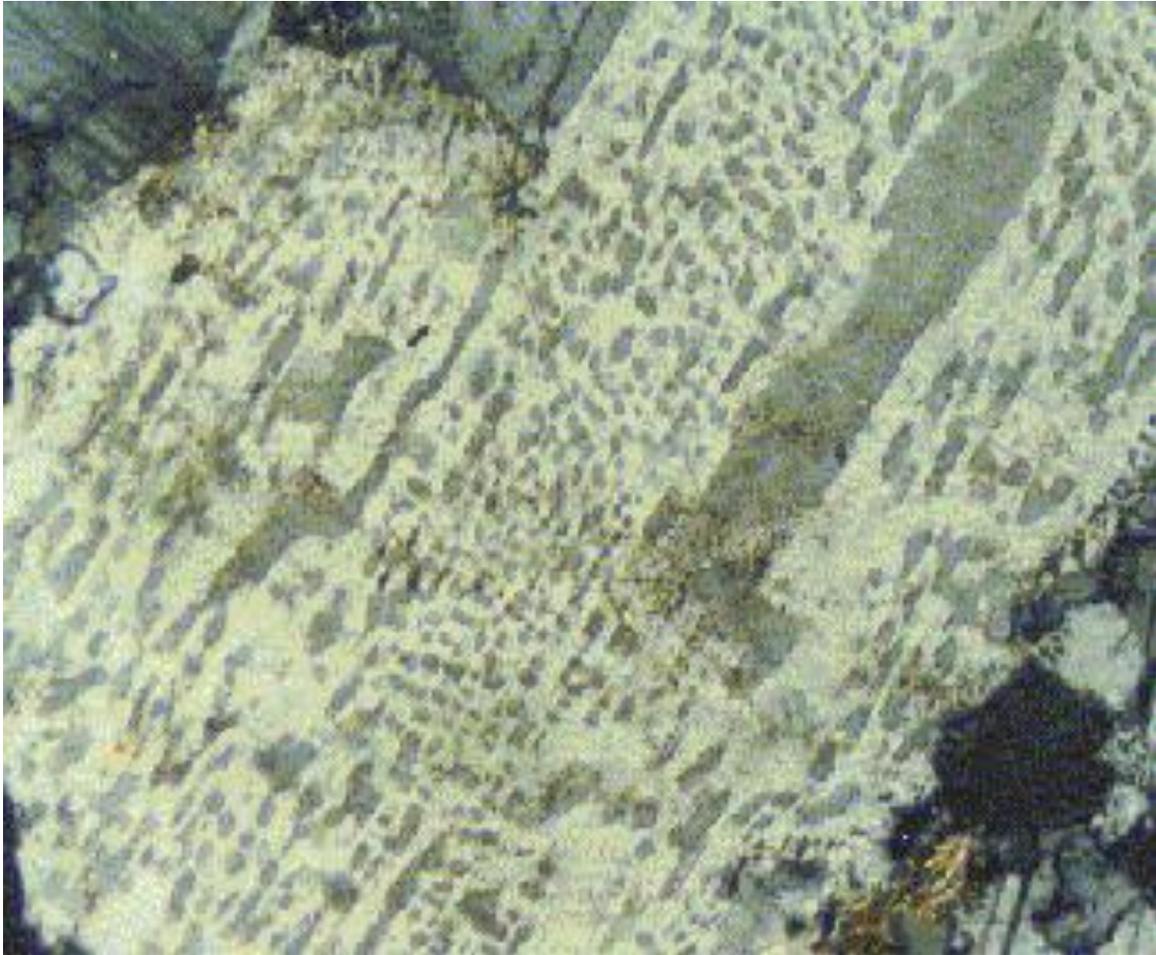
Fig. 11. Same thin section as in Fig. 8. Plagioclase light tannish gray) replaced by irregular islands of microcline (darker gray) and by veins extending into the plagioclase. Lower right and upper left is albite-twinned plagioclase lacking any microcline islands.

Fig. 12. Large albite-twinned plagioclase (light gray), penetrated by thick vein of microcline that replaces plagioclase along fracture. Islands of microcline replace plagioclase in blebs generally parallel to twin planes.

As further support for a metasomatic model for the augen granite gneiss is the fact that a third type of plagioclase coexists with the other two types in the same thin section of the transition zone. This third type consists of plagioclase with islands of myrmekite that have tiny quartz vermicules (Fig. 13).
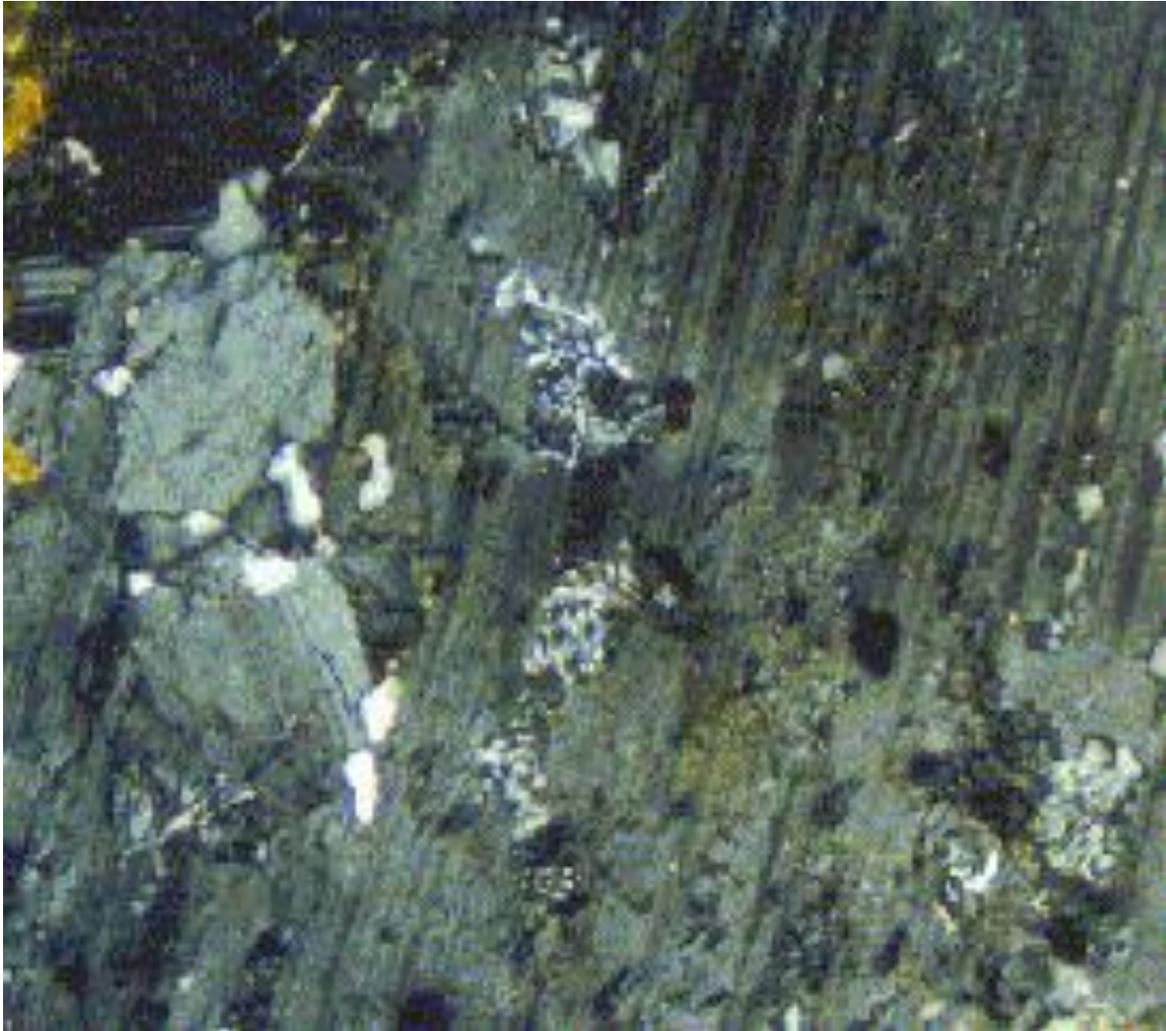
Fig. 13. Same thin section. Albite-twinned plagioclase with interior islands of myrmekite with tiny quartz vermicules.

Myrmekite with tiny quartz vermicules, occurring as islands inside plagioclase, is logically formed only by Ca-metasomatism. Such Ca-metasomatism is known to occur in deformed anorthosite bodies where relatively sodic plagioclase in the anorthosite has been replaced by more calcic plagioclase to produce myrmekite along the crystal borders (Wager and Brown, 1967; De Waard *et al*., 1977; Schiffries and Dymek, 1985). Ca-metasomatism also occurs in deformed primary K-feldspar megacrysts in Finland, producing many interior islands of myrmekite (http://www.csun.edu/~vcgeo005/Nr4CaMyrm.pdf). In some places this Ca-replacement was so thorough that whole former K-feldspar crystals (1 to 2 cm long) were filled with myrmekite. On that basis, where some deformed plagioclase crystals in the transition zone (in the boulder) are replaced in their interiors by microcline, as in Figs. 9-12, some Ca displaced by introduced K

moved into other deformed plagioclase crystals and replaced the relatively more sodic (but calcic) plagioclase by still more calcic plagioclase. In that process, silica is left over to create tiny quartz vermicules in myrmekite. Significantly, in some places the plagioclase containing myrmekite in islands is replaced by microcline so that the microcline encloses these myrmekite islands with tiny vermicules.

In this same thin section in the transition to the augen granite, biotite is replaced by garnet and quartz. Alternating leaves of biotite and quartz are formed (Fig. 14). In some places only tiny shreds of biotite remain in the quartz where the replacement is nearly complete.

Fig. 14. Biotite (brown) interleaved with quartz (gray, white, yellow). Large quartz crystal (yellow) on left side.

Beyond the transition zone with the three different kinds of plagioclase into the adjacent augen granite, such islands of either microcline or calcic myrmekite in the plagioclase crystals are absent. There, the myrmekite with coarse quartz vermicules is found (Fig. 15), and the feldspars are either totally perthitic microcline or albite-twinned plagioclase with no microcline islands. The totally perthitic microcline grains are presumed to result from the coalescing of the

microcline islands during complete replacements of interiors of former plagioclase grains. On that basis, the augen granite faces (Xag and Xagd) are interpreted to be derived either from gabbro having plagioclase with high An-content (An_{80}) where the augen granite has myrmekite with very coarse quartz vermicules or from gabbro or diorite having plagioclase compositions near An_{50} where the augen granite facies contains myrmekite with quartz vermicules of intermediate to coarse size.

Fig. 15. From granitic layer between two gabbro layers. Microcline (light gray) surrounding myrmekite with coarse quartz vermicules. Quartz (cream white; light gray).

The replacements of biotite by quartz and plagioclase by microcline in the transition zone (Figs. 9-12 and Fig. 14) provide the clues as to how the main bulk of augen granite is formed. The replacement of biotite by quartz during Si-metasomatism would release K to cause the K-metasomatism. Mg, Fe, and Al released from the biotite and some Al displaced from the plagioclase by K, where microcline is formed, would be incorporated in the garnet. The Ca leaves the system, but much of the Na displaced by the K either stays behind in albite lamellae or moves into other altered plagioclase grains to cause them to recrystallize as more sodic species. In the final stages of replacement, complete interior replacements of most plagioclase crystals by K have occurred to produce perthitic microcline crystals. In some places if too much Al is extracted from localized places in the plagioclase so that not enough remains to combine with residual Si and introduced K to produce K-feldspar, then quartz blebs remain in the K-feldspar. I have called such quartz-bleb clusters: ghost myrmekite (Fig. 16).
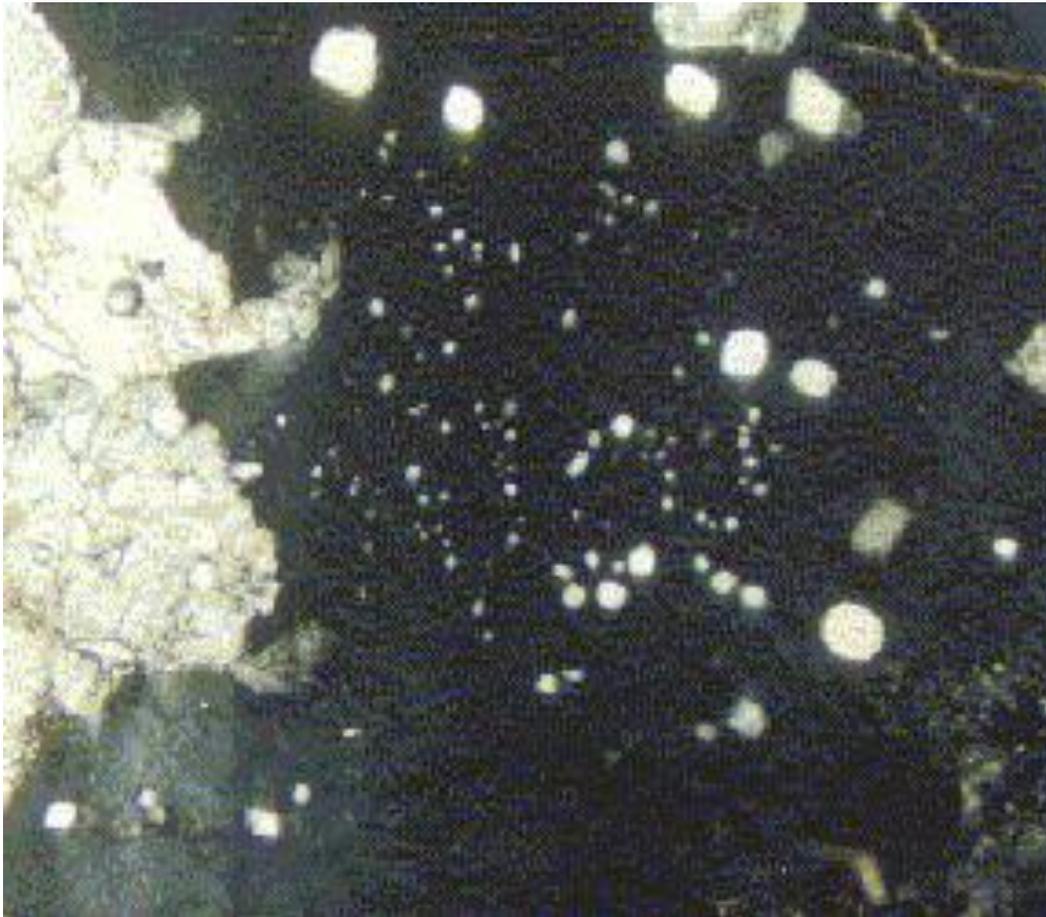

Fig. 16. Microcline (black, at extinction position), showing islands of quartz blebs (ghost myrmekite). Myrmekite with coarse quartz vermicules (faint ovals) is at left of the black microcline.

Because the K-replacements are from the interiors of plagioclase crystals outward, the displacement of Ca by K is generally unrestricted, and most plagioclase grains become entirely perthitic microcline. But where some Ca is prevented from escaping for some reason, perhaps being trapped between two centers of K-replacement or against a sealed grain boundary, then myrmekite is formed (Fig. 17).

Fig. 17. Myrmekite with relatively coarse quartz vermicules surrounded by slightly perthitic microcline (whitish, light, medium, and dark gray) in augen granite gneiss (Xag).

In typical augen granite gneiss (Xag) in the southwestern part of the body (Fig. 2) much, if not most, of the plagioclase in a former parent diorite or gabbro has been replaced by perthitic microcline to convert the diorite or gabbro into augen granite. Myrmekite in rocks in this area then becomes the clue to the former

existence of a diorite or gabbro. Because the myrmekite is found almost everywhere, the replacement has occurred on a plutonic scale. The augen granite now has the physical appearance of granite crystallized from magma, but the granite has inherited its magmatic texture and structure from the original intrusive biotite-rich diorite or gabbro that once filled this space.

Plagioclase crystals in the former gabbro (Fig. 6 and Fig. 7) lack Carlsbad twinning. Correspondingly, the microcline crystals in the adjacent augen granite lack Carlsbad twinning. In other terranes where Carlsbad twinning occurs in the primary plagioclase, the microcline inherits this twinning during replacement.

Because garnet holds less silica per unit volume than biotite of the same volume, much quartz is formed as the biotite breaks down and garnet is formed. Therefore, progressive replacements of biotite and the simultaneous formation of garnet near the water fall produce quartz-rich gneiss that looks like a metamorphosed sandy pelite.

On the premise that the augen granite is formed by K-metasomatism of former biotite-rich diorite and gabbro, how can the felsic, garnet-bearing dike (Fig. 3) that cross-cuts the augen granite (Xag) be explained by K-metasomatism? Is not its physical appearance that of a pegmatite or aplite dike that is intrusive as former magma into a crack in the darker granite? A thin section of the dike, however, shows that it consists dominantly of slightly-perthitic microcline and quartz. Only very minor amounts of plagioclase occur. Moreover, no micrographic intergrowths of quartz and feldspar occur in the plagioclase and/or K-feldspar; and, instead, wartlike myrmekite locally is found on microcline borders adjacent to plagioclase. In other terranes in which garnet-bearing magmatic pegmatitic dikes occur, the composition is that of a eutectic granite consisting of about 1/3 K-feldspar, 1/3 albite, and 1/3 quartz; micrographic intergrowth of quartz and feldspar are present; and no myrmekite is found.

The absence of a eutectic composition and micrographic intergrowths and the occurrence of myrmekite in the garnet-bearing dike (Fig. 3) strongly suggest that the dike is metasomatic in origin. Such metasomatism is supported by the fact that in the Sierra Nevada near Lake Isabella, similar felsic, myrmekite- and garnet-bearing aplite dikes can be walked out continuously for several km into places where the dikes can be seen to have a gradual transition to granulated hornblende granodiorite of the same width as the felsic dike. Increasing degrees of shearing and crushing of the original granodiorite in a linear band allowed progressive replacements of the ferromagnesian silicates by quartz and of deformed plagioclase

grains by K-feldspar and myrmekite. The final product is a garnet-bearing felsic dike with sharp contacts. The sharp contacts result because replacements occurred in the linear band of strong cataclasis up to a sharp transition into relatively undeformed wall rock where fluids could not penetrate to replace the undeformed rock. Recrystallization and replacements eliminate the evidence for this former strong cataclasis.

Acknowledgments

I wish to thank Lawford Anderson for permitting me to see several master's theses in his office and for copying maps. Eric Bender took time from his busy teaching schedule to let me see his thin section collection and gave me a copy of his Ph.D thesis. Sue Orrell directed me to Keith Howard for locating the collecting area in the Bill Williams Mountains, and Keith then provided me with a reference, geologic map, a more precise location, and a loan of 25 thin sections. David Liggett helped me in my first visit to the field location, giving me extra eyes for spotting rock types, including the boulder containing the gabbro layers. Finally, much thanks are given to my wife, Barbara, who spent many hours doing editorial work to make this article (and others) grammatically correct and improving its readability and clarity.

References

Anderson, J. L., 1983, Proterozoic anorogenic granite plutonism of North America: *in* Medaris, L. G., Jr., Byers, C. W., Mickelson, D. M., and Shanks, W. C., eds., *Proterozoic Geology; Selected Papers from an International Proterozoic Symposium*: Geological Society of America Memoir 161, p. 133-154.

Anderson, J. L., and Bender, E. E., 1989, Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America: Lithos, v. 23, p. 19-52

Anderson, J. L., Barth, A. P., and Young, E. D., 1988, Mid-crustal roots of Cordilleran metamorphic core complexes: Geology, v. 16, p. 366-369.

Anderson, J. L., Davis, G. A., and Frost, E. G., 1979, Field guide to regional Miocene detachment faulting and early Tertiary (?) mylonitization, Whipple-Buckskin-Rawhide Mountains, southeastern California and western Arizona; *in* Abbott, P. L., ed., *Geologic Excursions in the Southern California Area, San Diego, California, San Diego State University*, p. 109-133.

Bender, E. E., 1994, Petrology of early Proterozoic granitoids from the southwestern United States: Implications for genesis and tectonics of the

Mojave crustal province: Ph.D thesis, University of Southern California, 322 p.

Collins, L. G., 1988, *Hydrothermal Differentiation And Myrmekite - A Clue To Many Geological Puzzles*: Athens, Theophrastus Publications, 387 p.

Davis, G. A., Anderson, J. L., Frost, E. G., and Shackelford, T. J., 1980, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona; *in* Crittenden, M. D., Jr., and others, eds*., Cordilleran Metamorphic Core Complexes*: Geological Society of America Memoir 153, p. 79-129.

De Waard, D., Hancock, S. A., and Robinson, J. E., 1977, Mineral variation in anorthositic rocks of eastern Paul Island, Nain complex, Labrador: Nederlandse Akademie van Wetenschappen, Afdeeling Natuurkunde, Proceedings, Ser. B, v. 80, no. 4, p. 322-335.

Howard, K. A., Goodge, J. W., and John, B. E., 1982, Detached crystalline rocks of the Mohave, Buck, and Bill Williams Mountains, western Arizona; *in*

Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: San Diego, Cordilleran Publishers, p. 377-390.

Howard, K. A., Nielson, J. E., Wilshire, H. G., Nakata, J. K., Goodge, J. W., Reneau, S. L., John, B. E., and Hansen, V. L., 1990, Preliminary map of the Mohave Mountains area, Mohave County, Western Arizona: U. S. Geological Survey Open-File Report 90-684, 56 p.

Orrell, S. E., 1988, Petrologic studies in the basement of the upper plate of the Whipple detachment fault, Whipple Mountains, southeastern California: Master's thesis, University of Southern California, 418 p.

Schiffries, C. M., and Dymek, R. F., 1985, Calcic myrmekite in anorthositic and gabbroic rocks: Geological Society of America Abstracts with Programs, 98th Annual Meeting, October 28-31, 1985, Orlando, Florida, v. 17, p. 709.

Wager, L. R., and Brown, G. M., 1967, *Layered Igneous Rocks*: San Francisco, Freeman and Company, 588 p.

Wooden, J. L., and Miller, D. M., 1990, Chronologic and isotopic framework for Early Proterozoic crustal evolution in the eastern Mojave Desert region, SE California: Journal of Geophysical Research, v. 95, p. 20133-20146.