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28. Primary microcline and myrmekite formed during progressive metamorphism and K-metasomatism of the Popple Hill gneiss, Grenville Lowlands, northwest New York, USA

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Introduction

Detailed petrographic and chemical studies of rocks in the Grenville Lowlands along the northwestern flank of the Adirondack massif of New York (Fig. 1) show that thick biotite-oligoclase-quartz gneiss (the Popple Hill gneiss) has been subjected to increasing degrees of metamorphism (Engel and Engel, 1953ab, 1958, 1960; Buddington and Leonard, 1962; Bohlen *et al.*, 1985; Carl, 1988). In many places the gneiss contains less than one volume percent K-feldspar. In the transition across 56 km between Emeryville and Colton (Fig. 1), trace muscovite disappears, biotite diminishes, microcline and garnet are formed, and the plagioclase increases in abundance to form garnet-biotite-plagioclase-quartz gneiss. Some facies also contain sillimanite; others contain hornblende. Orthopyroxene is formed in some facies near Colton (Bohlen *et al.*, 1985).

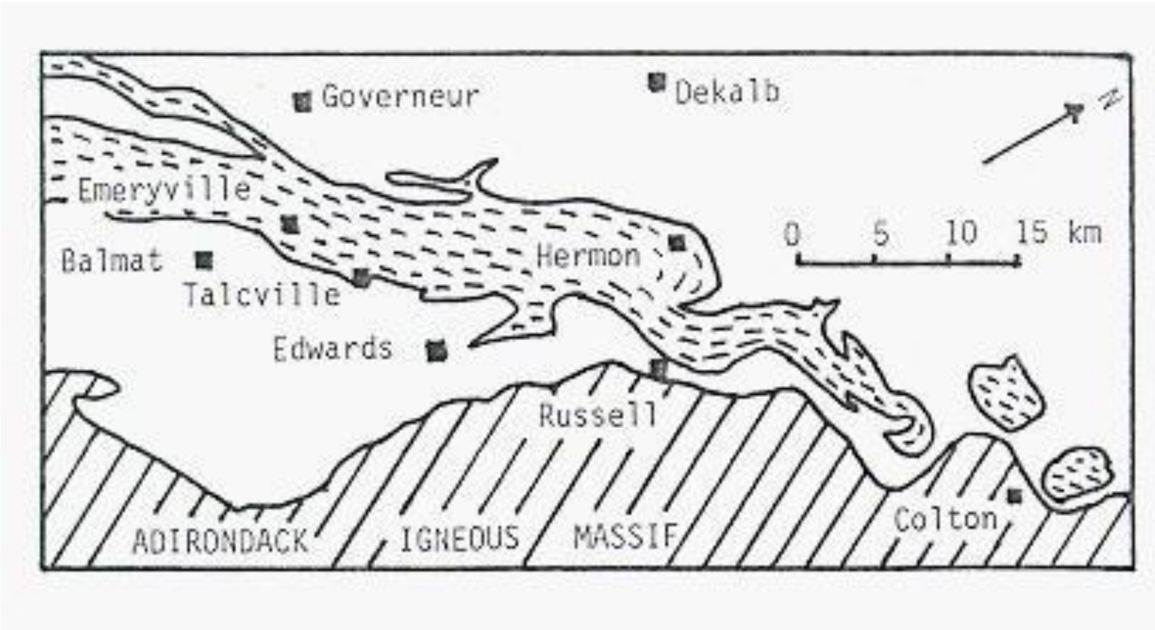

Fig. 1. Geologic map showing location of the Popple Hill gneiss. The map is modified and simplified from plate 1 of Engel and Engel (1958), eliminating locations of granite, amphibolite, marble and other lithologic units in order to emphasize that part of the Popple Hill gneiss from which samples in the central zone were collected.

On the basis of five different geothermometers, Engel and Engle (1958) suggested that temperatures ranged from about 500º C, 16 km from the Adirondack massif near Emeryville, to about 600º C, about 1 km from the massif-contact near Colton (Fig. 1). However, using other geothermometry methods, Bohlen *et al.* (1985) found that across this distance, temperatures increased from about 650º C at Emeryville to 700-750º C at Colton. Engel and Engel (1958) proposed that during this progressive thermal-metamorphism, the Popple Hill gneiss lost K and Si and gained Ca, Mg, Fe, and Al. In other places, however, the gneisses gained K and Si while losing Ca, Mg, Fe, and Al. In these places Engel and Engel found that *microcline progressively replaced plagioclase*, causing the gneiss to be granitized, forming veins (leucosomes), inequigranular granite gneisses, augen gneisses, and alaskites. On that basis, Engel and Engel (1958) proposed that the K was introduced from outside sources to produce the granitized rocks.

For gneisses containing leucosomes, the interpretation of progressive granitization, however, was based on chemical analyses of only the gneisses (mesosomes) and not the associated leucosomes. In contrast, Carl (1988) analyzed both mesosomes and leucosomes from many different places, averaged their compositions proportional to their volumes, and then compared averaged chemical analyses across the 56-km interval. He found a positive correlation between trace element abundances (*e.g.*, Ba, Sr, and Rb) in the leucosomes and mesosomes. Although element abundances varied from outcrop to outcrop, where a trace element was relatively abundant in the K-feldspar-rich leucosomes, it was also abundant in the mesosomes. Therefore, Carl (1988) reasoned that the K in the leucosomes was derived *in situ* from the breakdown of nearby biotite and muscovite instead of introduction of K from an outside source. Moreover, Carl (1988) found that the chemical variation in the rocks between Emeryville and Colton was very slight, and, therefore, he proposed that this variation reflected primary compositions instead of progressive chemical changes across a T-P gradient, as postulated by Engel and Engel (1960).

Engel and Engel (1958, 1960) suggested that at higher grades of metamorphism the plagioclase became slightly more calcic, changing from about An_{27} to An_{34}, but Engel and Engel also reported that plagioclase compositions in the Emeryville area (the least metamorphosed rocks) range from An_{12} to An_{62}, while plagioclase compositions in the Colton area (the most metamorphosed rocks) range from An_{26} to An_{54}. On the basis of the wide range of An-compositions and their overlap in the two areas, Carl (1988) is probably correct that the variations are mostly primary. Nevertheless, Engel and Engel (1958, 1960) observed progressive increases in Mg-content in biotite and garnet, of Ca-content in plagioclase lamellae in perthites, and in the average An-content of groundmass plagioclase across the interval from Emeryville to Colton, and, therefore, slight changes in Ca-content in plagioclase to higher An-values may also occur and reflect the effects of increasing temperature.

Carl (1988) disagrees with interpretations of others that the gneisses are metamorphosed clastic sediments (Engel and Engel, 1958, 1960; Wiener *et al.*, 1984). Instead, he suggests that the Popple Hill gneiss is composed of meta-dacitic volcanic ash-flow tuffs. This interpretation is based on the average chemical composition (which differs from that in shales and graywackes but is like dacitic volcanic rocks), the high total alkali, Na_2O, and SiO_2 contents, a slightly peraluminous composition, and low index of chemical alteration.

In spite of the high temperatures of metamorphism reported by Bohlen *et al.* (1985) for the Popple Hill gneiss, Carl (1988) suggests that the K-feldspar in the leucosomes of the Popple Hill gneiss was formed by metamorphic differentiation instead of anatexis. The evidence for the lack of melting includes the facts that (1) the leucosomes in many places are pure K-feldspar instead of having eutectic composition, (2) the rocks are too dry for melting to occur under the T-P conditions that caused the metamorphism (Seal, 1986; Bohlen *et al.*, 1985), and (3) a restite does not appear to be produced. Seal (1986) calculated that temperatures of 900º C would be required for partial melting.

In the rocks between Emeryville and Colton, the *in situ* metamorphic differentiation converted the Popple Hill gneiss into banded gneiss with four different types of leucosomes. Carl (1988) classified these four types by texture and shape. One type is gradational to the mesosomes. In some outcrops, narrow selvages of biotite occur adjacent to relatively narrow leucosomes; but thicker leucosomes lack such selvages. At any rate, for the leucosomes the metamorphic differentiation is a kind of localized K-metasomatism that occurs below melting conditions.

In more advanced stages of the K-metasomatism that produces increasing amounts of *microcline by replacement of plagioclase* throughout the deformed rocks, as reported by Engel and Engel (1958), the dacitic gneiss was converted to inequigranular granite gneiss, augen gneiss, and alaskite granite. Locally, amphibolites are also affected by this kind of advanced K-metasomatism. In these places, the progressive greater abundance of microcline suggests that some migration of K from outside sources must also occur although that source is likely from deeper levels of the Popple Hill gneiss. In the granitizing process, the plagioclase compositions changed from the former higher An values (An_{27-62}) in the dacitic gneiss to An_{10} or less in the alaskites.

Significant for this web-site article is that Engel and Engel (1958, 1960) reported that microcline occurs in the Popple Hill gneiss from Emeryville to Russell, but in the higher temperature rocks (700-750º C) near Colton, the microcline loses its grid-twinning and presumably recrystallized to form orthoclase. On that basis, a thin section study of 45 samples collected from the dacitic gneisses across the 56-km interval (Fig. 1) was made in order to answer the following three questions.

(1) *Where microcline replaced the plagioclase in each of the gneiss types, as reported by Engel and Engel (1958), is myrmekite formed as an indicator of this replacement?*

(2) *If present, does myrmekite have coarser quartz vermicules where microcline replaced plagioclase with higher An-content than where it replaced plagioclase of lower An-content?*

(3) *Where sillimanite forms, is the original rock former aluminous sediment, such as a pelite, or is it some kind of volcanic rock whose composition differs from dacite?*

Observations of thin sections

Thin sections of leucosomes and of least altered and metamorphosed dacitic gneiss show that myrmekite borders microcline in both leucosomes and host mesosomes as well as in inequigranular granite gneiss and augen gneiss. The alaskites lack myrmekite. In many leucosomes the quartz vermicules in the myrmekite are very tiny, almost invisible, correlating with the more sodic composition of the groundmass plagioclase (Collins, 1988); see Fig. 2, Fig. 3, and Fig. 4).

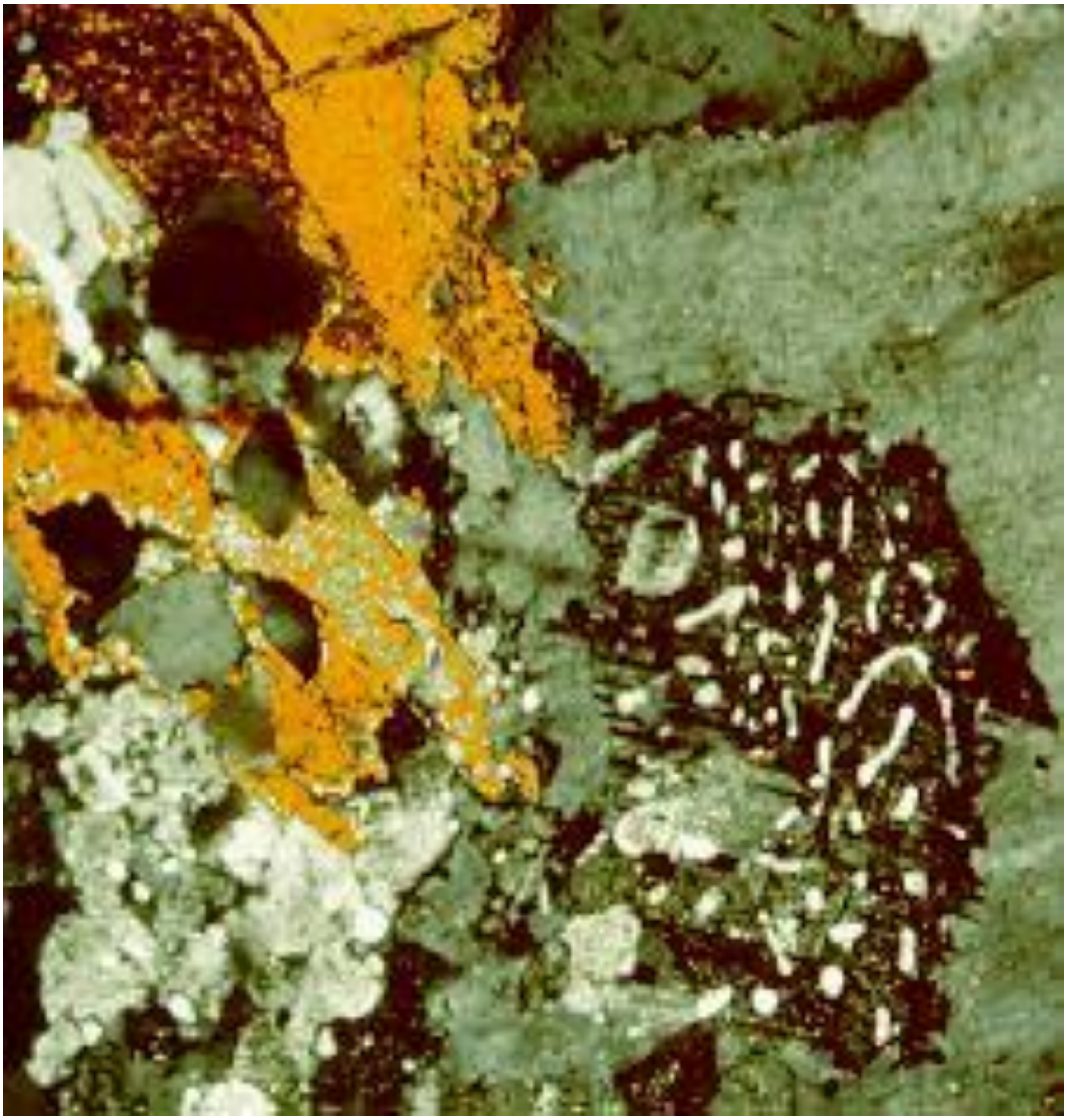

Fig. 2. Myrmekite (black) with relatively tiny quartz vermicules (white) in a leucosome vein about 7 km west of Emeryville. Microcline (light gray); biotite (brown).

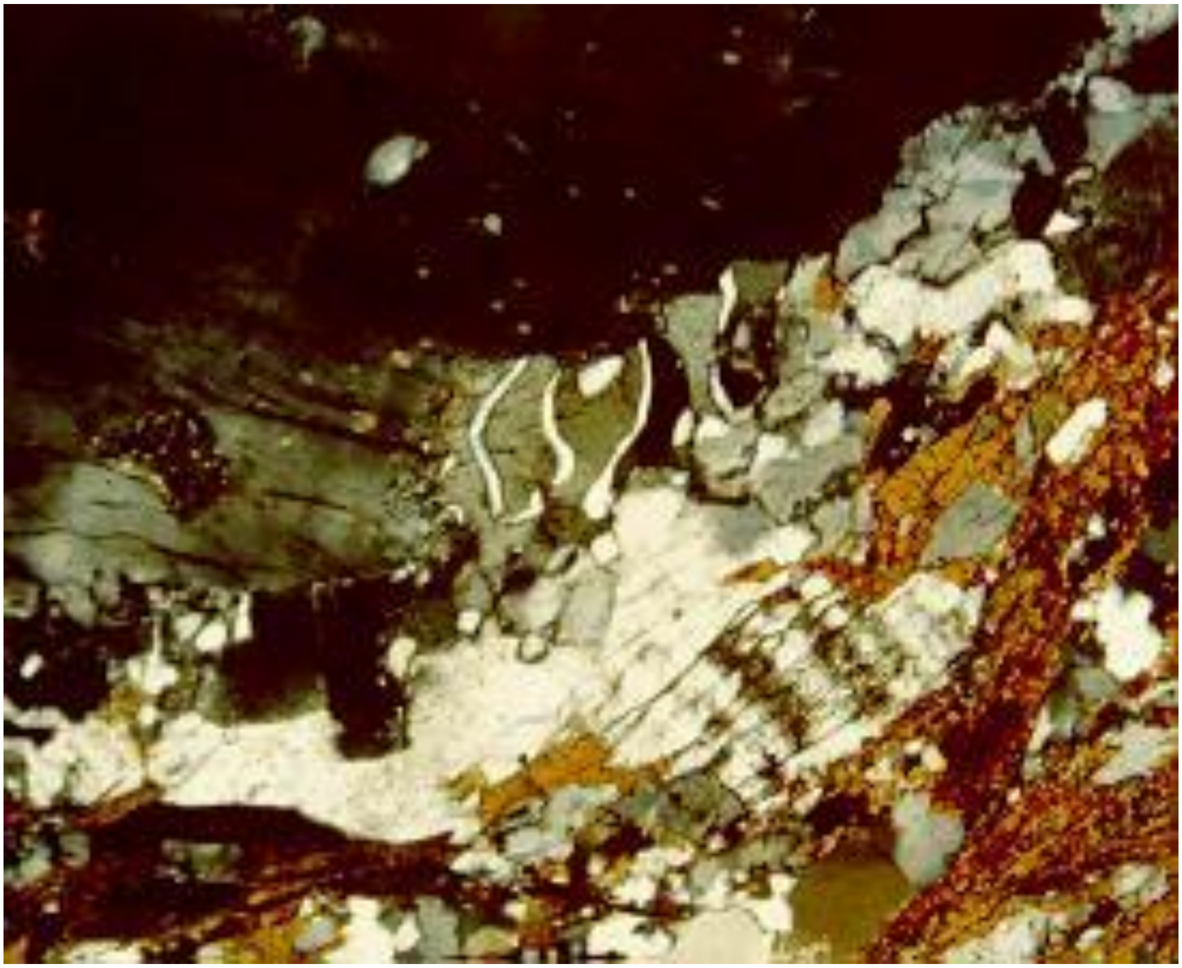

Fig. 3. Myrmekite with relatively tiny quartz vermicules (white) in Popple Hill gneiss mesosome; about 5 km southeast of Hermon along Highway 87. Microcline (black, white, gray; grid-twinning); biotite (brown); plagioclase (tan).

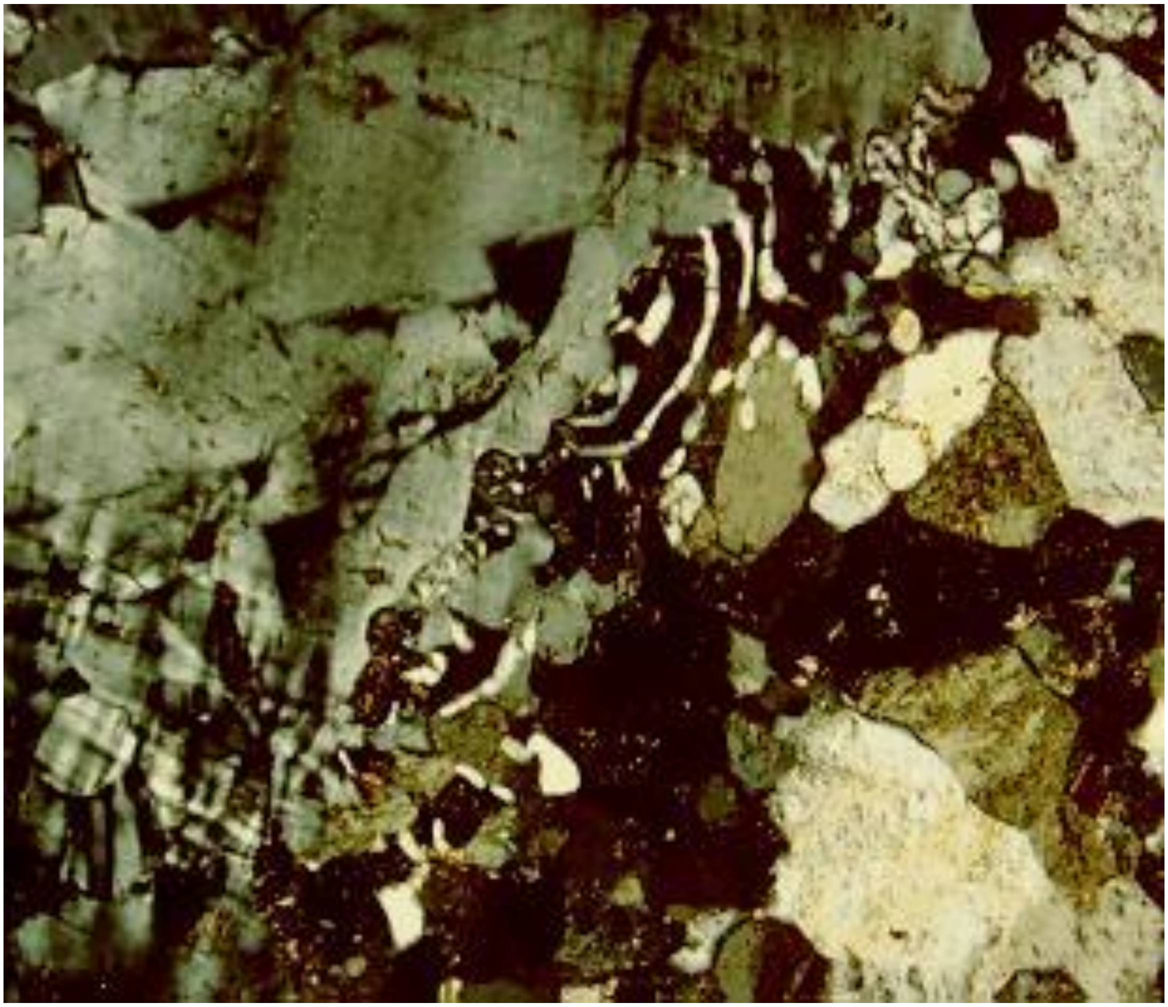

Fig. 4. Myrmekite with intermediate-sized quartz vermicules (white) in augen gneiss mesosome near the south tip of Trout Lake north of Edwards. Microcline (black, gray; grid-twinning); plagioclase (tan, light gray).

The tiny sizes of the quartz vermicules and the small abundances of the myrmekite (less than 0.5 vol. %) probably explain why many other investigators have not bothered to report the myrmekite in petrographic descriptions of the Popple Hill gneiss or the leucosomes. Myrmekite in mesosomes generally has coarser quartz vermicules than in leucosomes, although the quartz vermicules are still relatively tiny.

In the Colton area, perthitic orthoclase in the higher-grade metamorphosed Popple Hill gneiss encloses remnant biotite and quartz grains. Locally, myrmekite with intermediate-sized quartz vermicules is also enclosed in the orthoclase (Fig. 5).

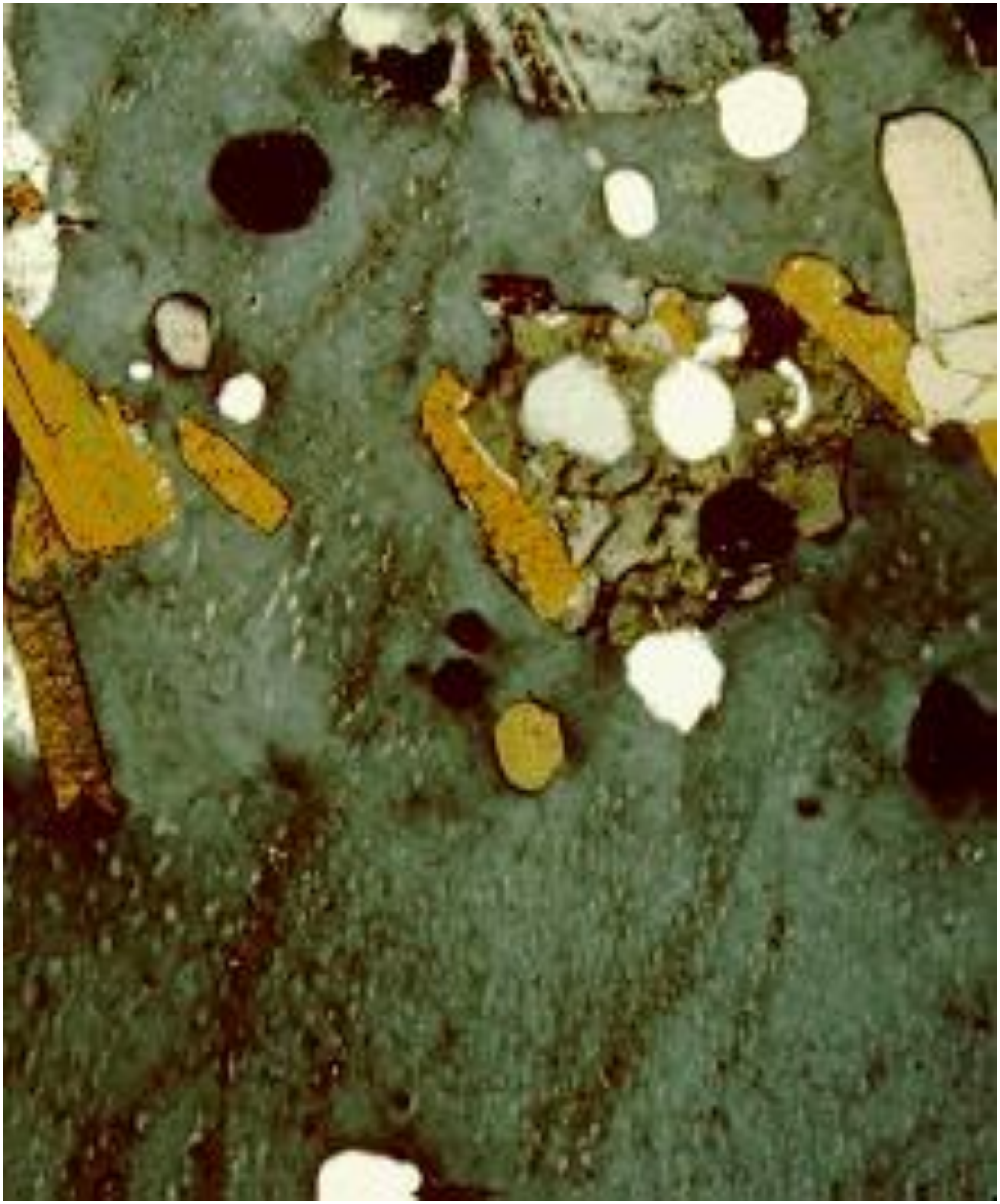

Fig. 5. Perthitic orthoclase (dark gray) enclosing remnant biotite (brown) and rounded quartz grains (white) as well as myrmekite (light gray; right of top center) with intermediate-sized quartz vermicules (black and white). Rounded quartz blebs are also enclosed in the myrmekite.

Where amphibolite is deformed, penetrated, and replaced by granitic rocks near Talcville (Fig. 1; Fig. 6), microcline is bordered by myrmekite with relatively coarse quartz vermicules (Fig. 7), correlating with the more calcic composition of the plagioclase in the amphibolite (Collins, 1988; Hunt *et al.*, 1992).

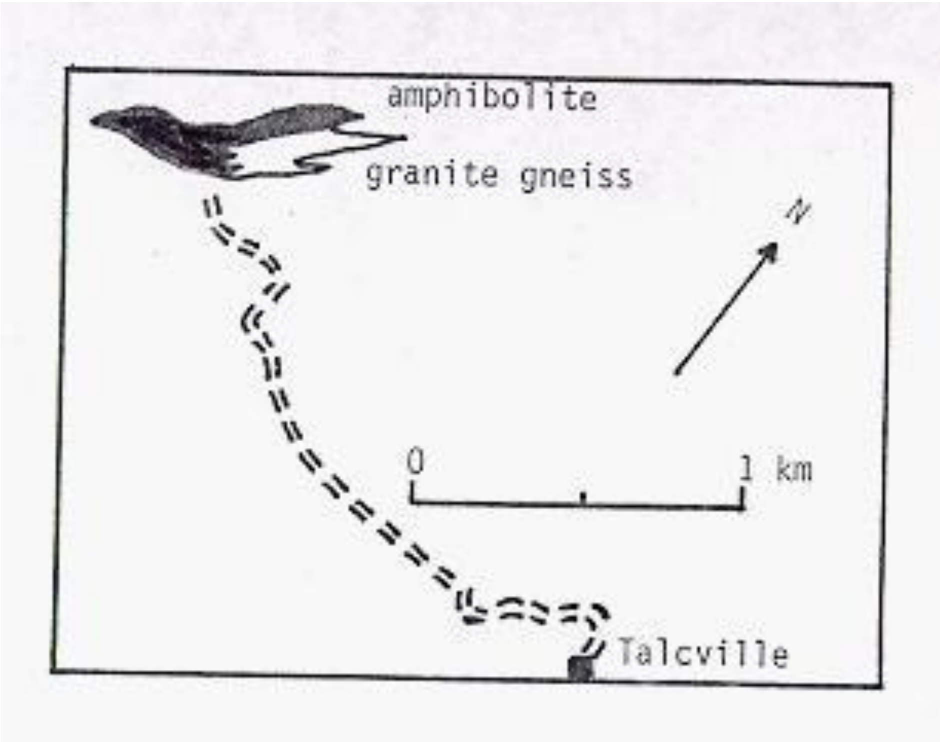

Fig. 6. Geologic map showing location of granitized amphibolite near Talcville. Modified and simplified from plate 4 of Engel and Engel (1958).

Fig. 7. Sericitized myrmekite with quartz vermicules (white) surrounded by microcline (black) in granitized amphibolite at contact with granitic gneiss near Talcville; see Fig. 6.

Carl (1988) and Engel and Engel (1958) report that the Popple Hill gneiss near its lower and upper contact with marble locally contains sillimanite. A sample of sillimanite-bearing gneiss was collected in a road-cut southeast of Hermon and northwest of Russell on Highway 87 at Devil's Elbow near the marble contact. It contains sillimanite, garnet, and chloritized cordierite pseudomorphs as well as myrmekite with intermediate-sized quartz vermicules (Fig. 8).

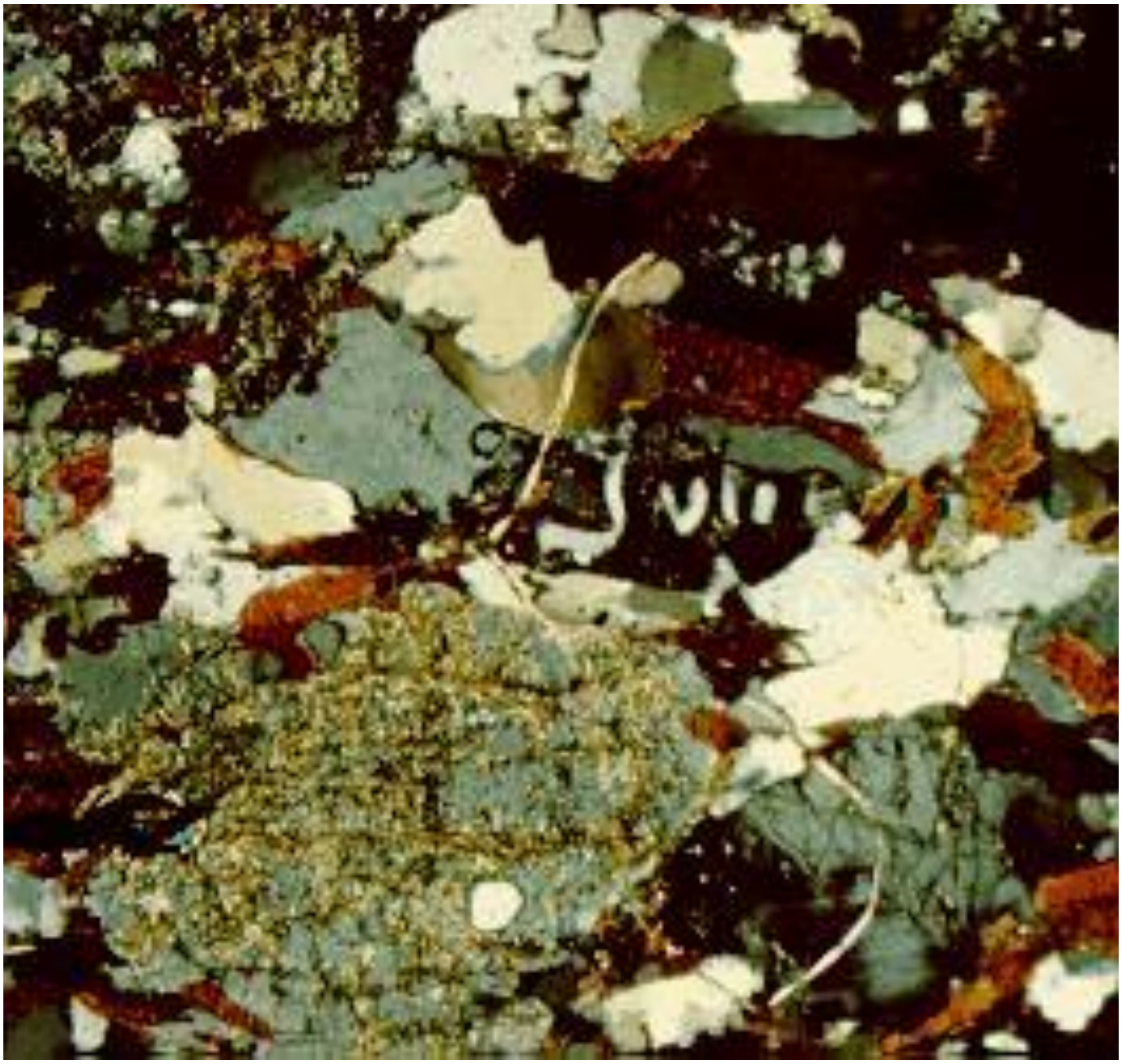

Fig. 8. Myrmekite (center, with white quartz vermicules) in sillimanite-garnet-cordierite gneiss. Biotite (brown); quartz (cream, white); plagioclase (sericitized, speckled gray).

Discussion

The presence of *myrmekite adjacent to microcline* in the Popple Hill gneiss as well as in inequigranular granite gneiss and augen gneiss from Emeryville to Russell (Fig. 1) is consistent with the progressive conversion of the Popple Hill gneiss to more granitic compositions by K-metasomatism at temperatures below melting conditions; see web-site articles: http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf; and http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf. The absence of myrmekite in the alaskites, however, should be expected because plagioclase compositions of An_{10} or less are too sodic for myrmekite to form (Collins, 1988; Hunt *et al.*, 1992). Although the maximum thicknesses of quartz vermicules in the myrmekite vary from very tiny to intermediate, in every place the maximum thickness corresponds to the An-content of the plagioclase in the host rocks, being thickest where the An-content is highest (Collins, 1988; Hunt *et al.*, 1992).

Evidence that metamorphic differentiation occurs at temperatures below melting conditions is provided by the following two relationships: (1) Microcline replaces interiors of deformed plagioclase crystals (Fig. 9 and Fig. 10) and (2) it penetrates broken plagioclase crystals along veins, leaving islands of remnant plagioclase in the microcline in parallel optical continuity with the adjacent larger plagioclase grain. Both of these observations are in agreement with the statement by Engel and Engel (1958) that plagioclase in the Popple Hill gneiss is replaced by K-feldspar.

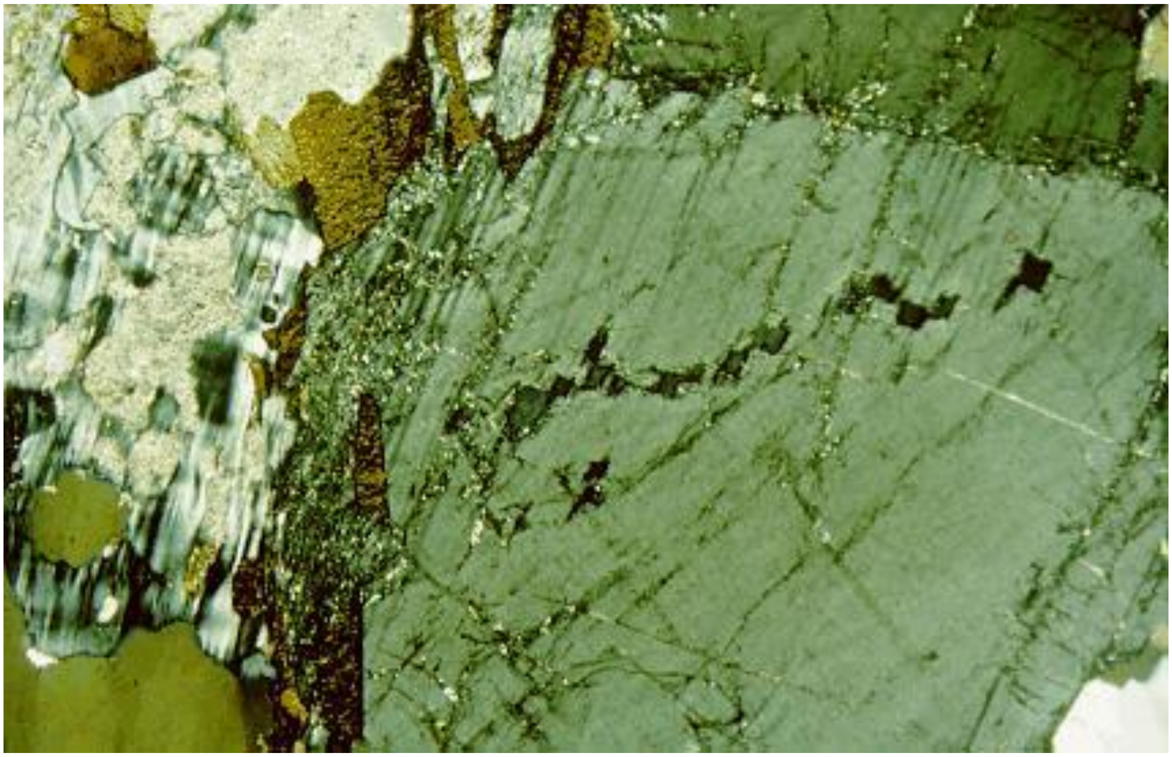

Fig. 9. Right side shows interior replacement of albite-twinned plagioclase crystals (light gray) by microcline (black) in a discontinuous vein of rectangular islands. On left side, microcline (black, white; grid-twinning) replaces plagioclase (speckled tan). Biotite (brown); quartz (tan). From sample of Popple Hill gneiss west of Emeryville.

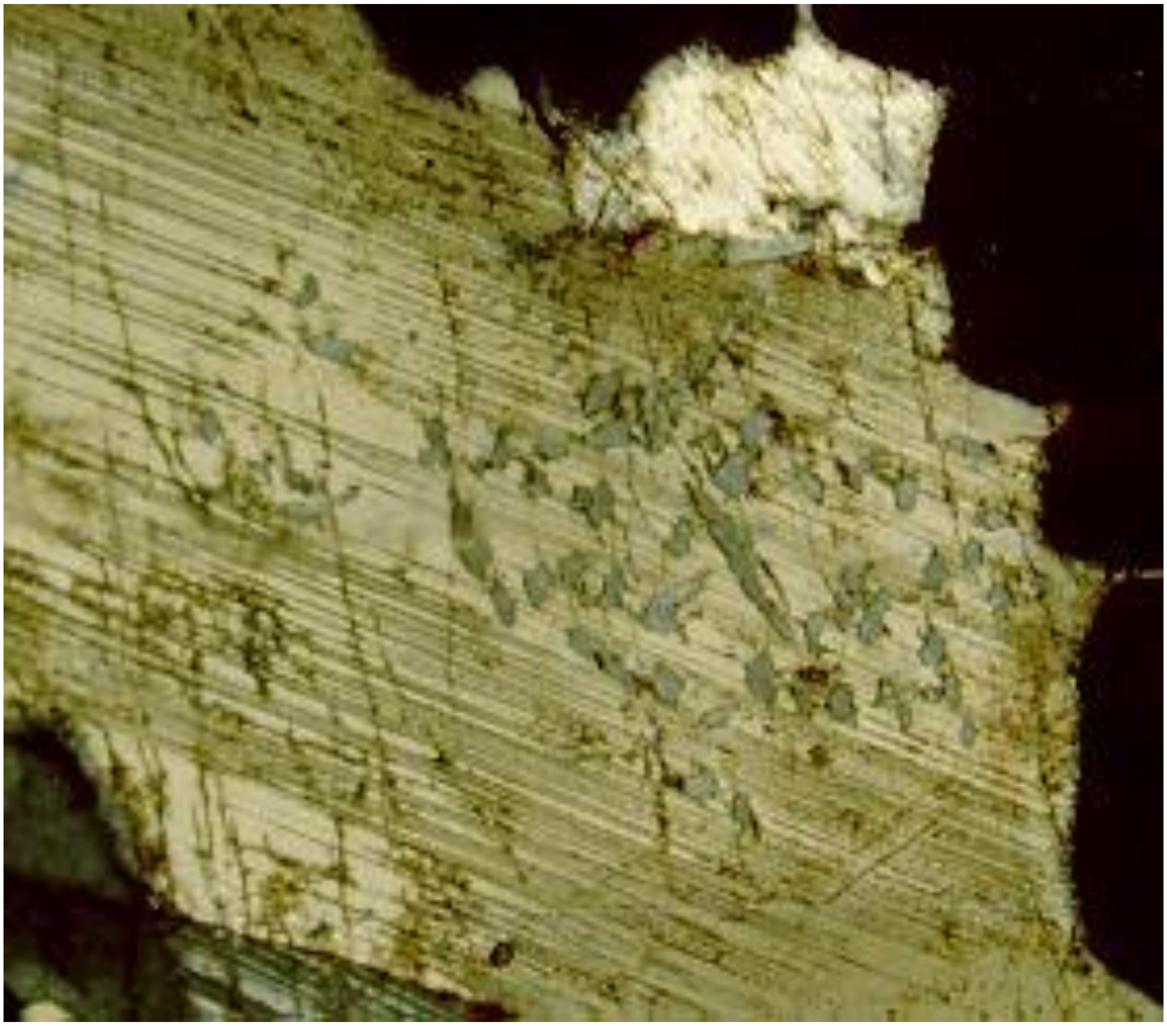

Fig. 10. Albite-twinned plagioclase (tan) showing interior replacement by irregular islands of K-feldspar (gray; orthoclase that was formerly microcline ?). The K-feldspar cross-cuts the albite twinning. Such replacement occurs only rarely in the thin section and, thus, is atypical of antiperthite in granitic rocks crystallized from a melt in which the majority of the plagioclase grains would have K-feldspar islands. From Popple Hill gneiss near Colton.

The proposed origin of the Popple Hill gneiss by Carl (1988) as metamorphosed dacitic ash-flow tuffs seems reasonable. If the original rock was dacitic, tiny crystals of primary K-feldspar (orthoclase) might have been formed in the ash, but the large crystals of K-feldspar which occur in the leucosomes, inequigranular granite gneiss, and augen gneisses could not have been formed at that time. Therefore, there could not have been large primary orthoclase crystals in the Popple Hill gneiss which could have inverted to the microcline in the manner that Laves (1950) indicated as a requirement for the formation of microcline. The increasing abundance of microcline in deformed rocks and the evidence that the microcline has formed by replacement of plagioclase in the more granitic facies of the Popple Hill gneiss indicate that the microcline is *totally unrelated to any possible magmatic K-feldspar in the former dacitic volcanic rocks*. On that basis the microcline is likely primary and inherits its triclinicity from the altered plagioclase crystals during interior replacements; see http://www.csun.edu/~vcgeo005/primary.htm.

Because myrmekite is associated with the microcline in the Popple Hill gneiss at the lower temperatures (500º C ? to 650º C) near Emeryville, the enclosure of remnant myrmekite in orthoclase near Colton at 700-750º C further supports the assertion that the orthoclase has been derived by conversion of the primary microcline. The logic for this conclusion is two-fold: (1) The higher pressure and low water activity (Bohlen *et al.*, 1985; Seal, 1986) would have prevented melting; and (2), if melting had occurred, the enclosed remnant myrmekite would have been destroyed. That is, the quartz vermicules would have melted and recrystallized as a single quartz grain that could not be intergrown as vermicules in the plagioclase.

Because the sillimanite-garnet-cordierite gneiss is gradational to Popple Hill gneisses that have dacitic compositions, it is possible that this gneiss is either a metapelite or a more-aluminous volcanic rock of some type. Metapelites should have relatively sodic plagioclase (low An-content) and abundant muscovite as the source of extra aluminum. By contrast, a more aluminous, possibly-mafic, volcanic rock might not contain muscovite but could contain a plagioclase with high An-content and, therefore, high-aluminum content. The occurrence of myrmekite with intermediate-sized quartz vermicules in the sillimanite gneisses and the coexisting garnet and cordierite suggest that the former source rock was a relatively mafic rock that once contained plagioclase with high An-content. On that basis, this sillimanite-garnet-cordierite gneiss needs further investigation to see if remnants of a rock containing plagioclase of high An-content can be found along strike; see Collins (1988) and http://www.csun.edu/~vcgeo005/gold.htm, describing the Gold Butte area, for other examples.

The occurrence of biotite selvages bordering narrow leucosomes and the positive correlation of relative abundances of trace elements in both leucosomes and mesosomes support the hypothesis of Carl (1988) that metamorphic differentiation occurs. In that case, the K would have been derived locally in nearly a closed system for a given outcrop. Nevertheless, the absence of biotite selvages in wider leucosomes and gradations of leucosomes to mesosomes as well as the transitions of the Popple Hill gneiss to inequigranular granite gneiss, augen gneiss, and alaskite support the hypothesis of Engel and Engel (1958, 1960) that some of the K has been introduced from an outside source. The losses of Ca, Mg, Fe, and Al with increasing K also point to an open system instead of a closed system. Progressive compositional changes would be expected, depending upon the extent of deformation of the rocks and the resultant increasing degrees of openness of the system for fluids to move through the rocks.

Conclusions

The following four conclusions can be reached from the observations and data presented in this article.

(1) Under the pressure, temperature, and relatively dry conditions in which the Popple Hill gneiss was formed, the microcline and myrmekite in this gneiss must have been formed at temperatures below melting.

(2) The microcline must have been primary, grew during increasing grades of thermometamorphism to produce megacrysts or augen, and formed by replacement of primary plagioclase instead of by conversion of primary orthoclase, crystallized from a melt.

(3) Myrmekite in both gneiss and granitized amphibolite has quartz vermicules whose maximum thicknesses are proportional to the An-content of the associated plagioclase (Collins, 1988; http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf; http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf; http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf).

(4) Further study is needed to assess the significance of myrmekite in the sillimanite-bearing gneisses.

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