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17. THE MOBILITY OF IRON, CALCIUM, MAGNESIUM, AND ALUMINUM DURING K- AND Si- METASOMATISM

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Introduction

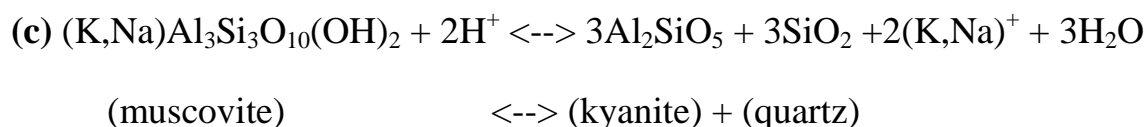
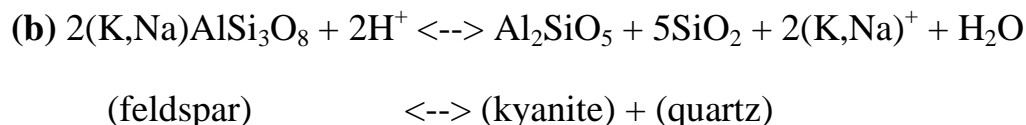
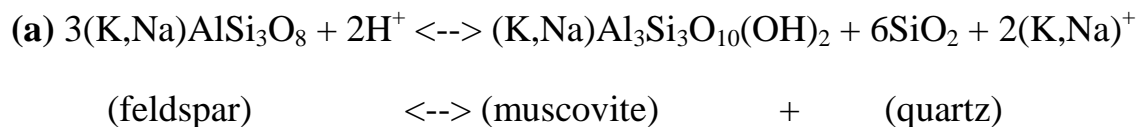
A common perception among petrologists is that Al is immobile in most geologic processes, and, therefore, the conversion of gabbro with high Al-content (16-18 wt. % Al_2O_3) to granitic rocks with lesser Al-content (12-13 wt. % Al_2O_3) by K- and Si-metasomatism is not possible. The mobility of Ca, Mg, and Fe is not doubted in hydrothermal fluids, but Al is thought not to be mobile. Two different terranes are selected in this presentation where myrmekite-bearing granitic rocks occur and in which the mobility of Ca, Mg, Fe, and Al can be demonstrated. Mg and Ca in these terranes are more mobile than Al and Fe, but Al is much more mobile than what might be expected. These terranes involve the concentration of Fe in magnetite and of Al in kyanite, muscovite, and epidote or in sillimanite and garnet.

Aluminum Concentrated In Kyanite And Muscovite

Hodder and Owens (1994) expressed belief that aluminosilicate mineral assemblages (kyanite and muscovite) and associated nearby gold-quartz veins were formed during large-scale pervasive metasomatism of granitic rocks in the Cargo Muchacho Mountains in southeastern California (Henshaw, 1942). These investigators suggested that during this metasomatic process biotite, hornblende, plagioclase, and microcline in the granitic rocks were destroyed by cation leaching. Their hypothesis of cation leaching is logical but does not seem to go far enough regarding the mobility of Al for the following three reasons.

(1) A Central Quartzite Zone.

Hodder and Owens described three gradational superimposed zones (from outer to inner), consisting of feldspar (in granite), muscovite, and kyanite, and explained the mineral relationships in these zones by using the following three mass-for-mass balanced equations:



Hodder and Owens (1994), however, did not mention a fourth central non-aluminous zone (inside the kyanite zone), which would have also been formed by cation leaching. It consists of pure granular quartzite and represents the most intense stage of leaching (Fig. 1C). The aforesaid balanced mass-for-mass equations do not account for this pure quartzite layer, which is 10 to 30 m thick. These equations, involving simple hydrolysis, indicate the kinds of reactions that are possible, but they do not completely apply to the actual situation because of the existence of the quartzite layer. Hodder and Owen's hypothesis also does not take into account the existence of cation leaching (metasomatism) that occurred in the adjacent wall rocks where former, relatively-mafic igneous rocks were converted to myrmekite-bearing granite (Collins, 1988).

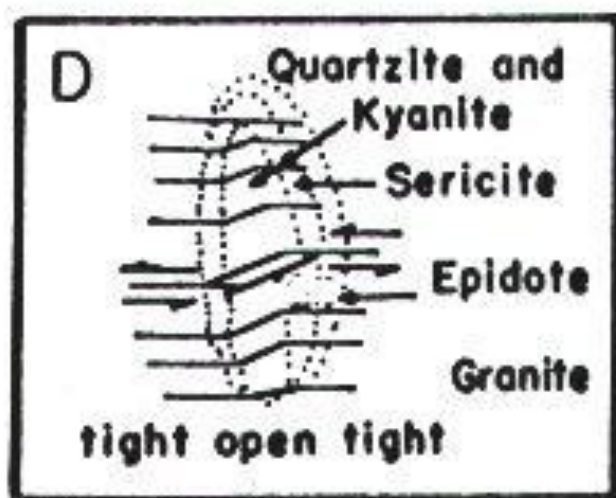
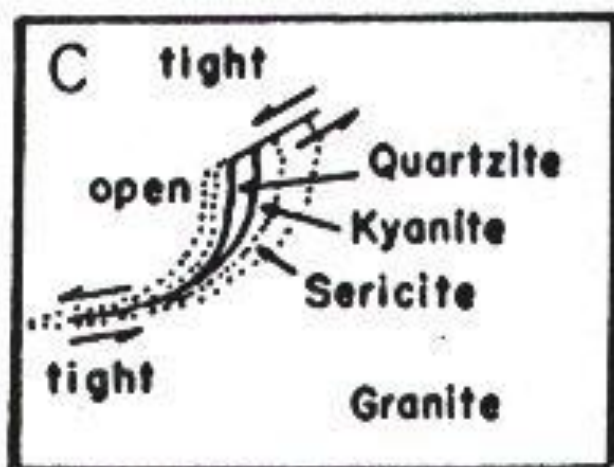


Fig. 1. Schematic drawings of (C) quartzite, kyanite, sericite, and feldspar zones in one locality in the Cargo Muchacho Mountains and of (D) quartzite, kyanite, sericite, epidote, and feldspar zones in another locality; see Collins (1988) for expanded descriptions.

(2) Mobility Of Aluminum.

Hodder and Owens implied by using the aforesaid equations that no Al was introduced or subtracted, and, therefore, the Al was an immobile residue. Four kinds of evidence exist to show that the Al was quite mobile in these rocks, and much Al had to be introduced in some places and subtracted in others.

(a) The absence of aluminosilicate minerals in the quartzite layers shows that Al as well as other cations was entirely subtracted from former igneous rocks during cation leaching.

(b) Microcline is replaced volume-for-volume to produce muscovite (sericite) pseudomorphs in the transition from the feldspar zone (granitic rocks) to the kyanite zone (Collins, 1988). Because muscovite has more than twice the Al per unit volume than occurs in the same volume of microcline, Al must be introduced in order for muscovite to replace the microcline (Fig. 2). The same arguments can be used for replacement of plagioclase by muscovite (sericite). Therefore, both kinds of feldspar replacements by muscovite indicate the mobility of Al.

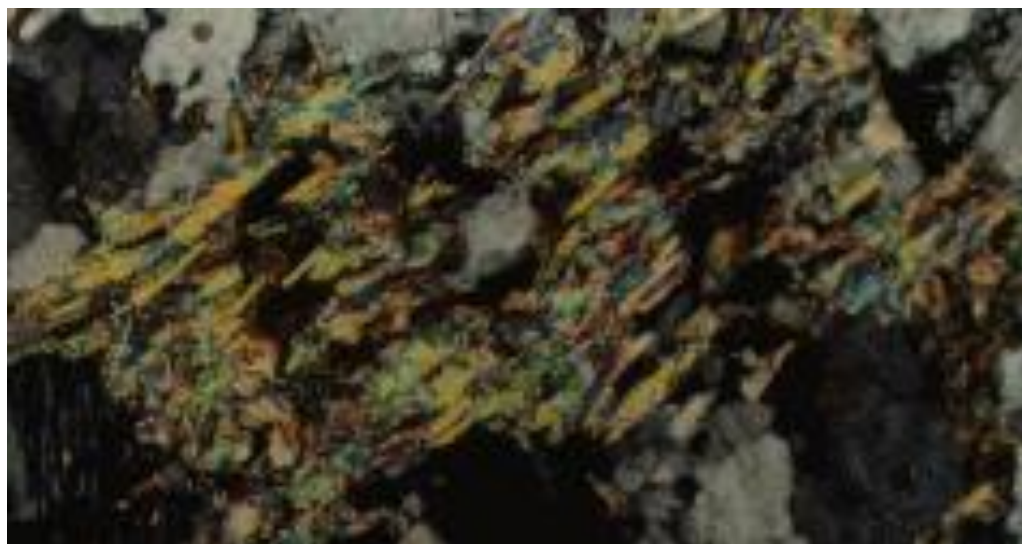


Fig. 2. Sericite replacement of feldspars.

(c) The occurrence of epidote concentrations is a third indication of Al mobility. In many terranes epidote is commonly thought to be a hydrous alteration product of some Ca- and Al-bearing mineral, such as plagioclase or hornblende. In rocks where primary Ca-bearing minerals do not exist but in which secondary epidote is found, Ca is suggested to be introduced in hydrous fluids and to react with Al in the altered mineral to produce the epidote. An example is the epidotization of K-feldspar. In either case, Al is supposed to be residual (non-mobile). Nevertheless, in many places in the Cargo Muchacho Mountains, rocks consisting entirely of microcline and quartz are cut by epidote veins, 1-4 cm wide, and the assemblage of these veins occupies up to 40 vol. % of the rock across several meters. The amounts of Al in microcline in the host rock would be inadequate to account for all Al in these veins.

Moreover, in some places between the aforesaid feldspar and muscovite zones, a pale-green to white epidote (zoisite ?) zone (10 to 30 m wide) occurs (Fig. 1D). This zone contains more than 40 vol. % interstitial epidote. On that basis, the replacement of relatively-calcic plagioclase by K-feldspar, myrmekite, and more-sodic plagioclase in the igneous wall rocks (Collins, 1988) would have mobilized both Ca and Al that could have moved to this epidote zone or into the aforesaid epidote veins.

(d) Replacement of biotite by muscovite is a fourth indication of the mobility of Al. Chemical data presented by Hodder and Owens (1994) show a progressive enrichment of biotite in Mg and Al as released Fe is recrystallized in magnetite. Remnant biotite occurs in some muscovite crystals (Figs. 3, 4, and 5). Perhaps, the aforesaid enrichment of Al in the biotite results because of shrinkage in the volume of biotite, but the thin section evidence suggests that replacement of biotite by muscovite occurs and is at constant volume.



Fig. 3. Early stage of replacement of biotite by muscovite in relatively undeformed biotite granite.

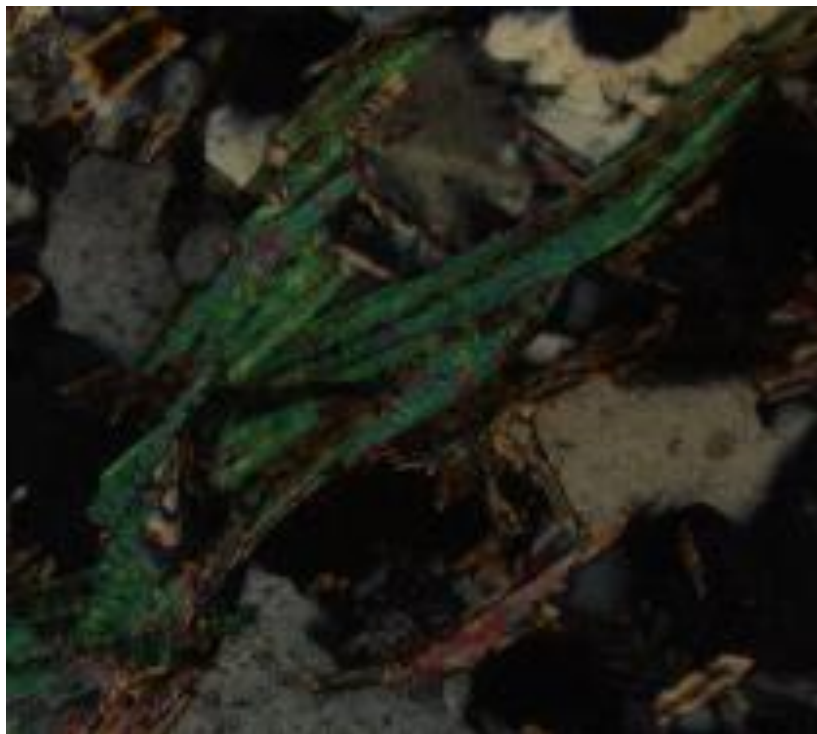


Fig. 4. More-advanced stage of replacement of biotite by muscovite in deformed granite.

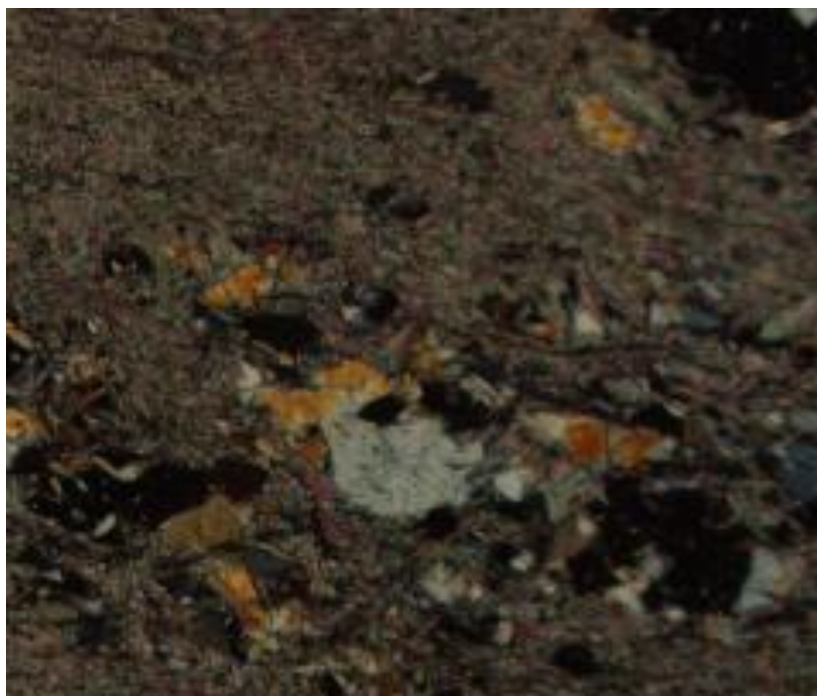


Fig. 5. Strongly deformed and mylonitized granite which has been converted to a sericite-muscovite schist.

(3) *Lack of Volume Losses.*

The three aforesaid balanced mass-for-mass equations show that water (H^+) is introduced and that water (H_2O) plus cations (K, Na^+) are subtracted. On that basis, volume losses should occur because the products of either (1) kyanite plus quartz or (2) muscovite plus quartz occupy smaller volumes than the original feldspars. Additional volume losses would occur if balanced mass-for-mass equations had been written for the conversion of hornblende (or pyroxenes) to magnetite plus quartz. However, there is no evidence in the field that the former relatively-mafic igneous rocks that became myrmekite-bearing granitic rocks shrank in volume during the cation leaching and replacement except for the quartzite zone. Vugs in the innermost quartzite zone, containing kyanite crystals projecting into the cavities show that some volume losses occurred where cation leaching was very intense.

Most wall rocks near the kyanite concentrations are biotite tonalites or granite, but in some places the wall rocks were biotite-hornblende tonalites and diorites. Where these rocks are replaced by K-feldspar and myrmekite (Fig. 6 and Fig. 7 [Fig. 4 in presentation 1], the hornblende exhibits quartz sieve textures (Fig. 8), which show that the quartz interior replacements of the hornblende crystals are also at constant volume. On that basis, although abundant leached cations are leaving the system, Si must have come into the rocks during the metasomatism to maintain constant or nearly constant volume, and additional Al must have come in to convert the feldspars to muscovite.



Fig. 6. Myrmekite with intermediate-sized quartz vermicules in deformed granitic rocks in the Cargo Muchacho Mountains.

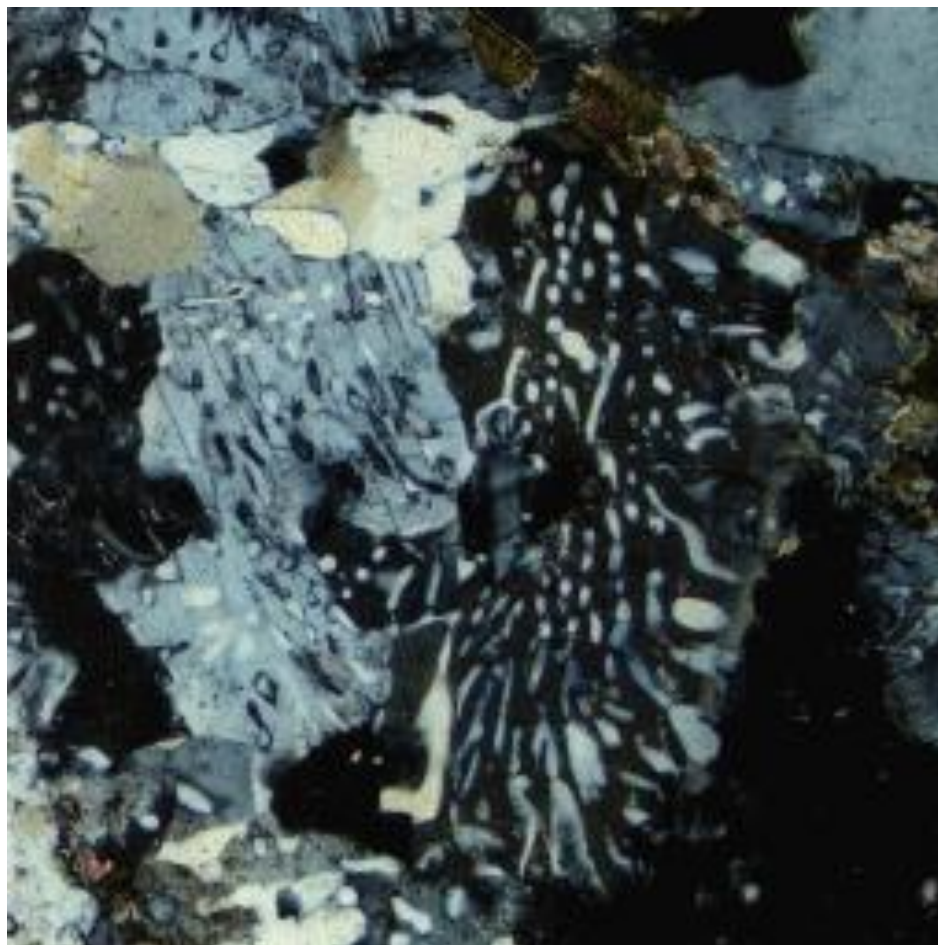


Fig. 7. Myrmekite with intermediate to coarse vermicules in deformed granitic rocks in the Cargo Muchacho Mountains.

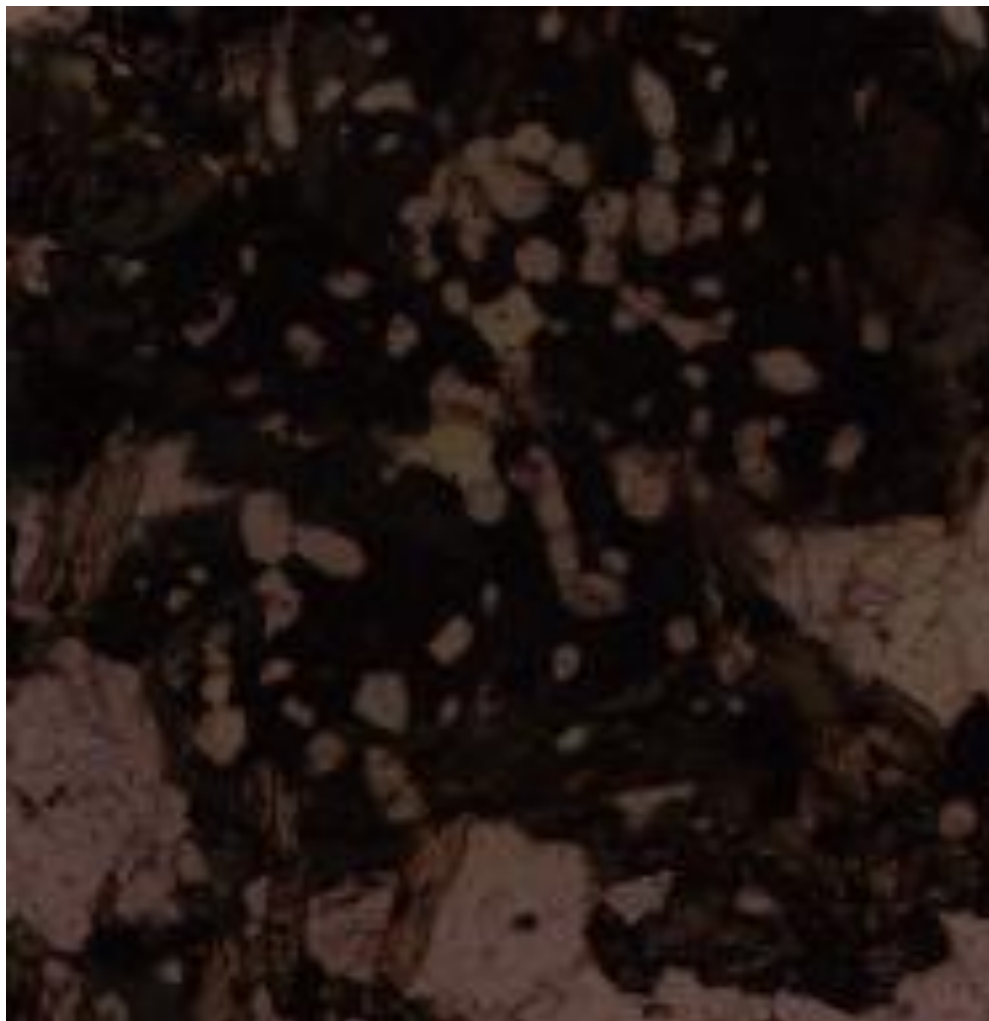


Fig. 8. Quartz sieve textures in hornblende in deformed and replaced diorite.

Similar replacement relationships, cation leaching, and mobility of Al must have also occurred in the Skidoo muscovite-granite pluton in southeastern California where muscovite (sericite) has replaced the feldspars as well as biotite. See <http://www.csun.edu/~vcgeo005/Nr16Skidoo.pdf>.

Iron Concentrated In Magnetite Ore Zones

The iron mines in the Dover magnetite district of New Jersey occur on the limbs of the Precambrian Split Rock Pond anticline --- a tight, nearly isoclinal fold (Sims, 1958). In the nose of the fold the rocks are relatively undeformed, but in the limbs strong deformation, because of sliding of layers to compensate for the tight folding, has sheared the rocks and allowed hydrothermal fluids to enter. These fluids have altered the mineralogical and chemical composition of the rocks. For example, a gabbroic gneiss layer (30 m wide) in the nose of the fold contains

plagioclase with high An-content (An_{80}), iron-rich hypersthene (containing 80% ferrosilite, $FeSiO_3$), and iron-rich biotite. Progressively into the deformed limbs, the hypersthene in this layer gradually disappears, biotite becomes magnesium rich and decreases in modal abundance, plagioclase gradually recrystallizes to become more sodic (An_{40}), and quartz, K-feldspar, microcline, garnet, and sillimanite appear and increase in abundance. Locally, in zones of strongest deformation but which are most open for fluid migration, concentrations of magnetite (10 to 15 m wide) occur in magnesium-rich biotite skarns. The adjacent garnet-sillimanite gneisses contain wartlike and isolated myrmekite with coarse quartz vermicules ([Fig. 9](#)).

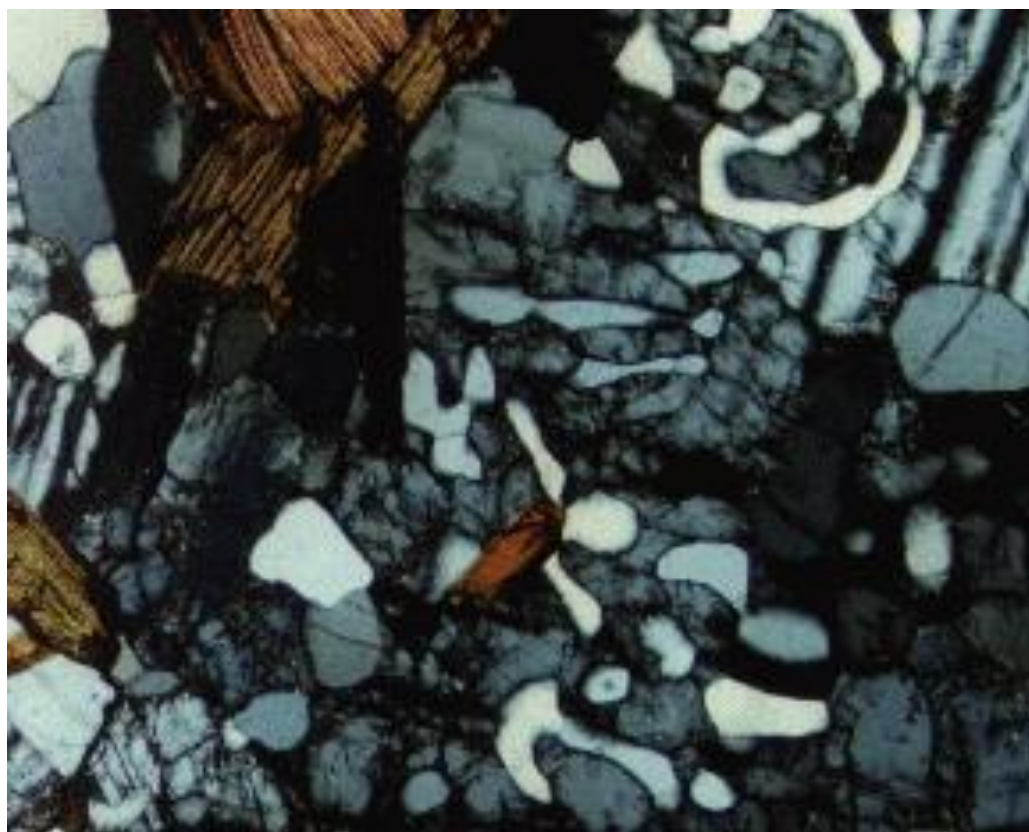


Fig. 9. This photomicrograph is from a deformed biotite-orthopyroxene gabbro layer (30-50 m wide and 20 km long) near Split Rock Pond northeast of Dover, New Jersey (USA). The gabbro gradationally becomes sillimanite-garnet-muscovite-biotite gneiss along strike where planar deformation of the former gabbro is greatest. Reddish titaniferous biotite occurs in the photo. Plagioclase composition in the gabbro is An_{80} , but in the sillimanite gneiss is An_{40} . Maximum sizes of quartz vermicules in myrmekite shown in this transition rock are thick where K-feldspar is absent and less thick in the sillimanite gneiss where K-feldspar is present, but still quite thick.

The maximum coarseness of the vermicules correlates with the high An-content of the plagioclase along strike in the nose of the fold (Collins, 1988). The amounts of iron in the iron-rich hypersthene and biotite are greater than that found in the volumes of garnet and the magnetite concentrations in the skarns, and, therefore, it is logical to assume that the former undeformed gabbroic gneiss contained more than an adequate source of iron to produce the magnetite concentrations. The source of aluminum in the garnet and sillimanite is explained by the high-aluminum content of the former calcic plagioclase that recrystallized as more sodic plagioclase, containing less aluminum.

Other magnetite concentrations also occur in hornblende-clinopyroxene skarns in the deformed limbs of the fold, and these concentrations occur along strike with undeformed, iron-rich hornblende-orthopyroxene, magnetite-bearing amphibolites in the nose of the fold. Gradationally toward the magnetite concentrations and with increasing degrees of deformation, the iron-rich hornblende and orthopyroxene are recrystallized as magnesium-rich hornblende and clinopyroxene, and the magnetite percentages decrease to zero (Collins, 1969). Coexisting plagioclase in the undeformed amphibolites in the nose of the fold is andesine (An₄₀), but progressively toward the magnetite concentrations and with increasing deformation, the plagioclase is gradually recrystallized as oligoclase and finally albite (An_{0.5}) in the gneisses adjacent to the magnetite concentrations in the skarns (Collins, 1969). Where the deformation is strongest, but most open to fluid migration, magnetite concentrations compose 50-100 vol. % of the hornblende-diopside skarns. Because of these gradual mineralogical and structural relationships from the nose to the limbs of the fold, it is logical that the iron in the magnetite concentrations has come from the deformed and recrystallized wall rocks rather than being introduced from an outside source.

The recrystallized gneisses in the limbs that are derived from the amphibolites generally lack K-feldspar and myrmekite, and their absence occurs because the amphibolites contain only minor amounts of biotite (a potential source of K). Therefore, little to no K was released to form K-feldspar and its associated myrmekite (Collins, 1969).

Calculations show that the amount of iron in the primary magnetite and ferromagnesian silicates in the original amphibolites are more than four times the amount of iron in the magnetite concentrations and the ferromagnesian silicates in the adjacent recrystallized gneisses. Therefore, much of the released iron must have been carried out of the system by escaping fluids. Some of the progressive losses of Ca and Al from plagioclase during the recrystallization would have been

precipitated in the Mg-rich hornblende and newly-formed clinopyroxene as the orthopyroxene disappeared, but the volumes of hornblende and clinopyroxene in the recrystallized gneisses are insufficient to account for all of the released Ca and Al. Therefore, some Ca and Al must have also left the system.

Sphalerite (ZnS) And Galena (PbS) Concentrations

On the basis of the aforesaid relationships for the mobility of Fe and Al in the formation of magnetite and kyanite concentrations, it is possible to speculate about other kinds of elemental concentrations that might be associated with terranes containing wartlike myrmekite. For example, wartlike myrmekite with coarse quartz vermicules (Fig. 10) occurs abundantly in the Potosi Gneiss that contains the zinc, silver, and lead ore zones in the Broken Hill mining district of Australia (Phillips and Ransom, 1970; Phillips et al., 1972; Vernon, 1969).



Fig. 10. Myrmekite with very coarse quartz vermicules in isolated myrmekite in transition to biotite skarns in garnet-sillimanite gneisses containing magnetite concentrations.

Away from the ore zones are myrmekite-free layers containing biotite and plagioclase in which the An-content is as much as An₈₀ and higher. The coarseness of the quartz vermicules gives strong evidence that the K-feldspar has replaced primary plagioclase with relatively high An-content (Collins, 1988). The occurrence of ghost myrmekite (Fig. 11) in the K-feldspar in the Potosi Gneiss also provides support that the K-feldspar results from replacement of deformed plagioclase. The Al in both garnet and sillimanite likely was derived from the former calcic plagioclase as it was replaced by K-feldspar, myrmekite, and more sodic plagioclase.



Fig. 11. Ghost myrmekite with tiny quartz blebs (white) in microcline (black).

Because the gneiss contains abundant trace metals (averaging 158 parts per million [ppm] Zn, 113 ppm Pb, and 31 ppm Cu; Drake, 1974), the replacement of the gneiss to form myrmekite-bearing rocks could have released the metallic elements to the sphalerite and silver-bearing galena ore zones in the Broken Hill mining district. This possibility warrants further study.

Conclusion

The above examples illustrate the possible correlation between myrmekite-bearing granitic rocks and nearby concentrations of Al and Fe. Although some of the Al and Fe can be accounted for in these terranes, the problem still remains where most of the Ca and Mg and the remainder of the released Al and Fe have gone. Perhaps, lamprophyre dikes that overlie myrmekite-bearing granites and which show evidence of abundant water content may be the depository for these elements. More research is obviously needed.

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