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16. SERICITIZATION IN THE SKIDOO PLUTON, CALIFORNIA: A POSSIBLE END-STAGE OF LARGE-SCALE K-METASOMATISM

Lorence G. Collins

email: lorencecollins@gmail.com

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Introduction

It is well known that in shear zones, which cut through granitoid rocks or granitic gneisses, introduced fluids bring in additional water, K, and Na as Fe, Ca, and Mg are subtracted (Beach, 1976; Dipple and Ferry, 1992). Such hydrothermal fluids commonly cause sericitization of plagioclase and may result in local concentrations of gold. The exchanges of K and Na for Ca in the feldspars are supported by the experimental work of Orville (1963). Such interrelationships of fluid transport and deformation are well illustrated in the Skidoo pluton in the northern Panamint Range of southeastern California (Figs. 1 and 2) where biotite-muscovite granodiorite and muscovite granite have been strongly deformed and hydrothermally altered in broad shear zones that are associated with thrust faulting of adjacent Precambrian metasedimentary rocks. These sheared rocks also contain additional quartz and locally gold concentrations, which were mined in the early 1900s (Hunt and Mabey, 1966).

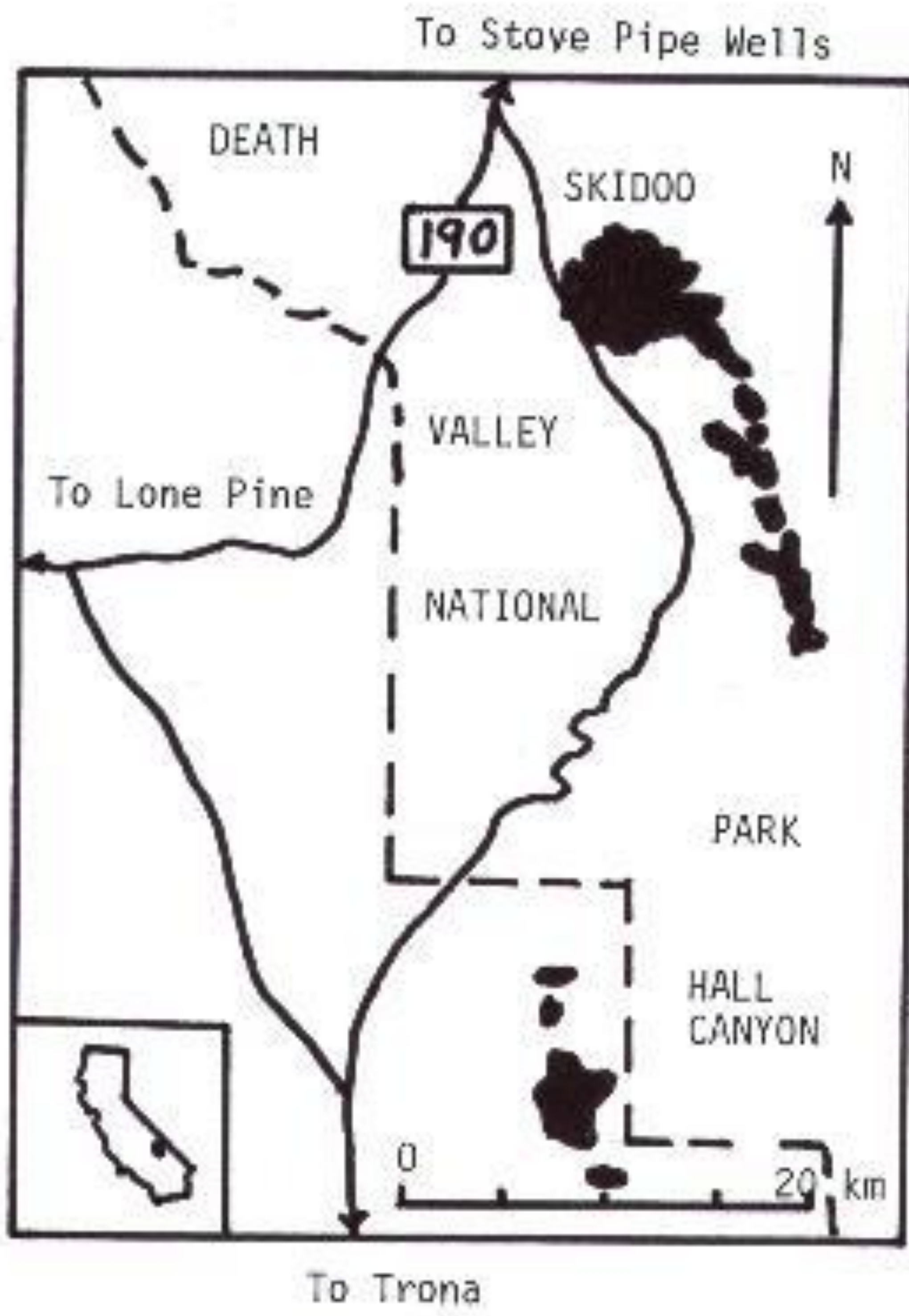

Fig. 1. Location map of Skidoo and Hall Canyon plutons in and near the Death Valley National Park area. For the topography in and around the Skidoo pluton, see the Emigrant Canyon 15 Minute Quadrangle Map or the Emigrant Canyon, Tuck Wash, and Wildrose 7 1/2 Minute Quadrangle Maps, California.

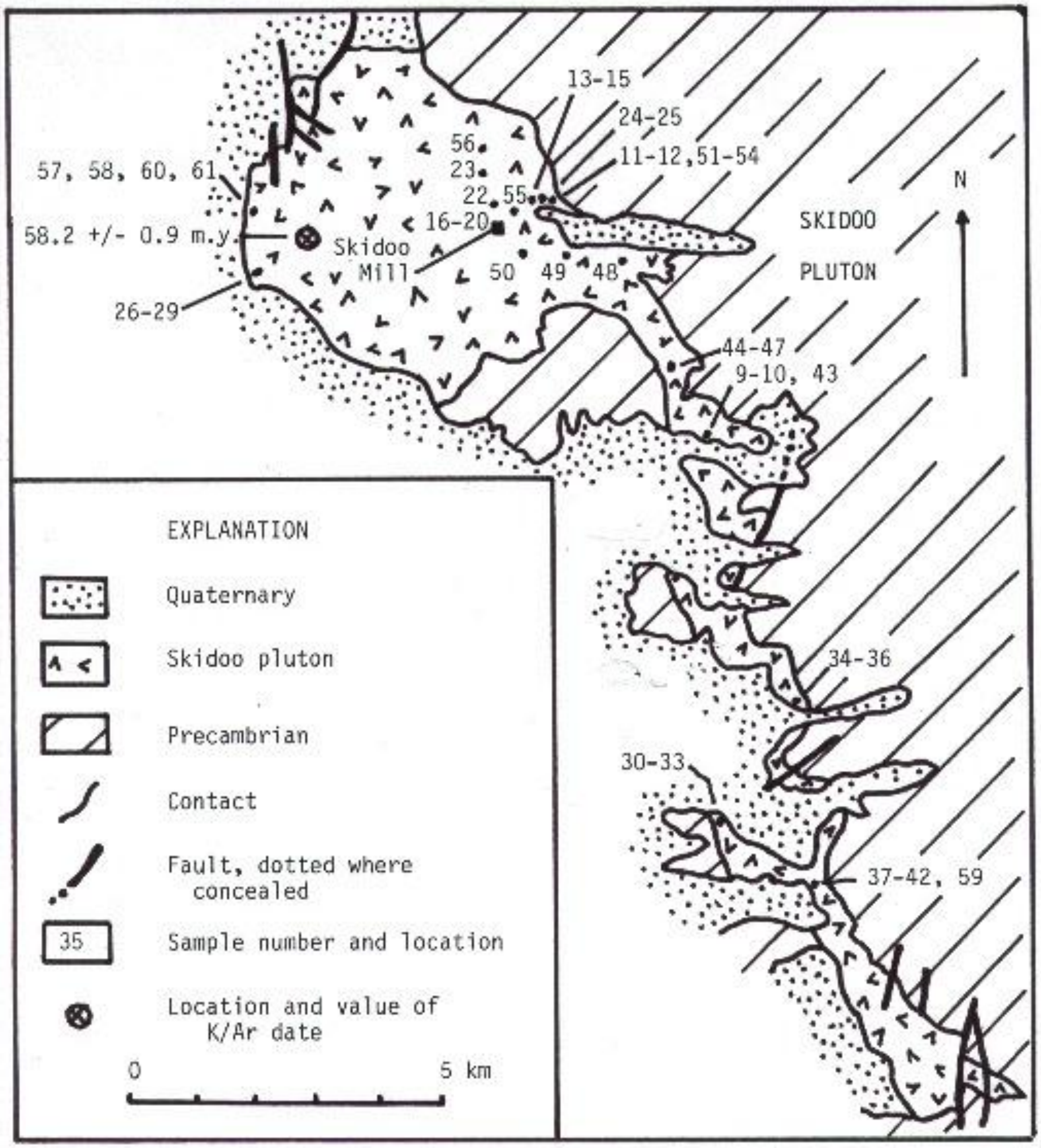

Fig. 2. Generalized geologic map of the Skidoo pluton showing sample sites and location of the radiometric date from Armstrong and Suppe (1973).

In the hydrothermal alteration process biotite and feldspars (particularly plagioclase) throughout the Skidoo pluton were strongly sericitized in and near the shear zones. The process of sericitization in the Skidoo granitic rocks is a large-scale metasomatic process that affects the whole pluton. In order to replace a relatively sodic plagioclase by sericite, additional K and Al must be added, and to change K-feldspar into sericite, additional Al must be added. In this presentation, this kind of large-scale K- and Al-metasomatism at relatively low-grade conditions is suggested to be a possible end-stage process of ongoing large-scale K-metasomatism that also occurred earlier in the pluton's history at higher-temperature, amphibolite-grade metamorphism.

General geology of the Skidoo pluton

The Skidoo pluton crops out in the Panamint Range of Death Valley National Park between 1,150 and 1,850 meters elevation (Fig. 2). The granitic rocks are poorly exposed, heavily weathered, extensively sheared by thrust faulting, and locally strongly altered by hydrothermal fluids. Hunt and Mabey (1966) briefly described the Skidoo pluton as a laccolithic body that was intruded into Precambrian carbonates, argillites, and quartzites with mostly concordant contacts. Surface exposures of the pluton extend for 30 km^2. Armstrong and Suppe (1973) obtained a K-Ar age date of 58.2 +/- 0.9 m.y. from muscovite in the pluton. A Rb/Sr age date of 100.6 +/- 7.6 m.y. has been determined for this pluton (Hodges et al., 1990), which is similar to the ages of 81 and 83 m.y. that have been estimated from Rb/Sr and K/Ar methods for the Hall Canyon pluton south of the Skidoo pluton (Lanphere and Dalrymple, 1967; Dalrymple and Lanphere, 1971; Fig. 1).

Four facies of granitic rock with poorly-defined contacts occur in the Skidoo pluton: (1) a muscovite-biotite granodiorite, (2) a non-porphyritic muscovite-biotite granite, (3) a porphyritic biotite-muscovite to muscovite granite, and (4) an alaskite. The granodiorite and non-porphyritic granite are more commonly found near the wall rocks but are intermingled *gradationally* with the porphyritic granite throughout the pluton. The freshest samples of the granodiorite occur in a mine dump between two roads where the main Skidoo road splits in a narrow fork (the southern branch extends to the old Skidoo mill structure). Other readily-accessible exposures of the granodiorite occur in stream-cuts along the main highway from Stove Pipe Wells to Trona (Fig. 1). Examples of the porphyritic granite facies, containing phenocrysts of K-feldspar, 2 cm long, occur in both the northern and southern parts of the pluton and can be seen in road cuts on the aforesaid road to the old Skidoo mill structure. The alaskite occurs in the north-central part of the pluton core in the second ridge north of the old Skidoo mill structure.

In the field, the granites are white to light gray; the granodiorite is a darker gray; and the alaskite is pinkish and generally lacks any dark minerals. Locally, younger basaltic dikes cut the granitic rocks.

Petrography

1. ***Muscovite-biotite Granodiorite*.**

The muscovite-biotite granodiorite is fine- to medium-grained (1 to 4 mm) and hypidiomorphic seriate granular (Wood, 1981). It consists primarily of plagioclase (35-40 vol. %), quartz (23-28 vol. %), K-feldspar (5-25 vol. %), biotite (7-15 vol. %), and muscovite (3-5 vol. %). Accessories include magnetite, apatite, and zircon and rare traces of sphene. Where the rock is strongly sheared, epidote is relatively abundant (1 vol. %), biotite is altered to chlorite containing rutile and opaque oxides, the feldspars (particularly plagioclase) are strongly sericitized, and tiny cubes of pyrite crystals occur in fracture zones. Plagioclase (An_{11-18}) is normally zoned with relatively calcic cores and shows both albite- and Carlsbad-twinning. The K-feldspar (microcline) is interstitial or poikilitic where larger crystals enclose groundmass minerals. Locally, the microcline is slightly perthitic with tiny, irregularly-distributed albite lamellae. Knots (2 to 10 mm across) of biotite, muscovite, epidote, and apatite may occur.

2. ***Muscovite-biotite Granite*.**

The muscovite-biotite granodiorite is gradational to muscovite-biotite granite where the interstitial and poikilitic anhedral microcline locally increases in abundance greater than modal plagioclase. Where the rock becomes granite, muscovite increasingly is interleaved with biotite (Figs. 3, 4, and 5) and commonly contains opaque iron oxides (Fig. 6).

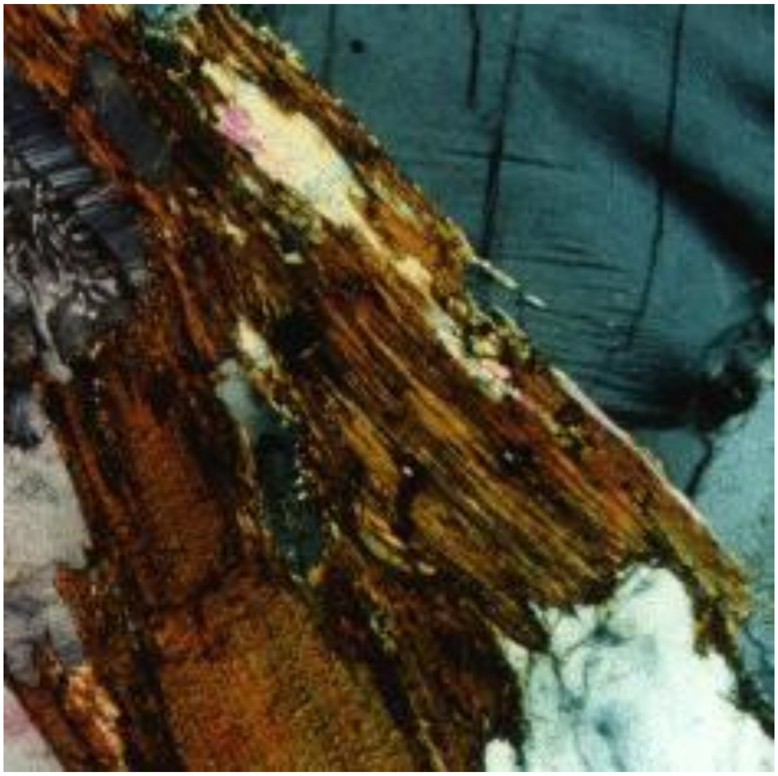

Fig. 3. Biotite (brown) in possible early stages of replacement by muscovite (white, yellow, pink). Myrmekite is enclosed by microcline (dark gray).

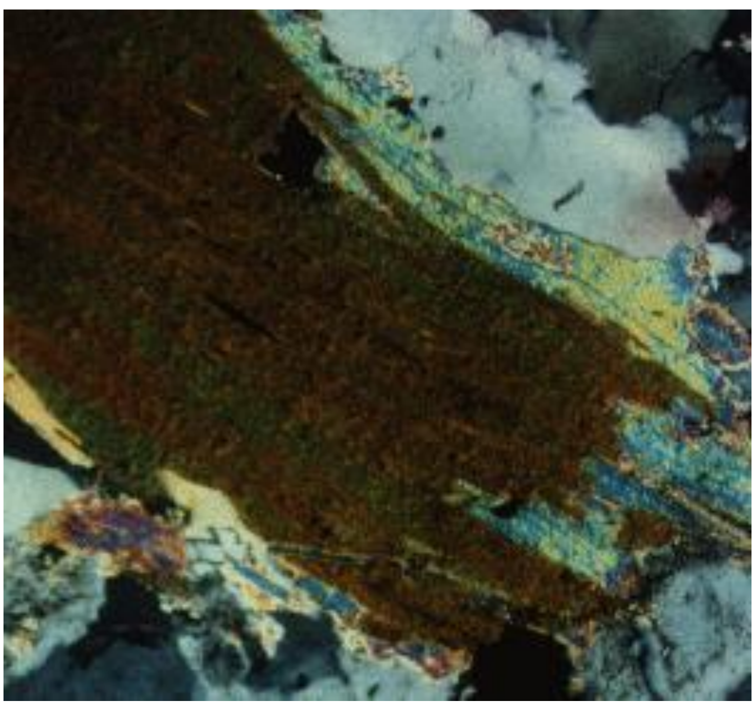

Fig. 4. Biotite (brown) in early stages of replacement by muscovite (bright colors).

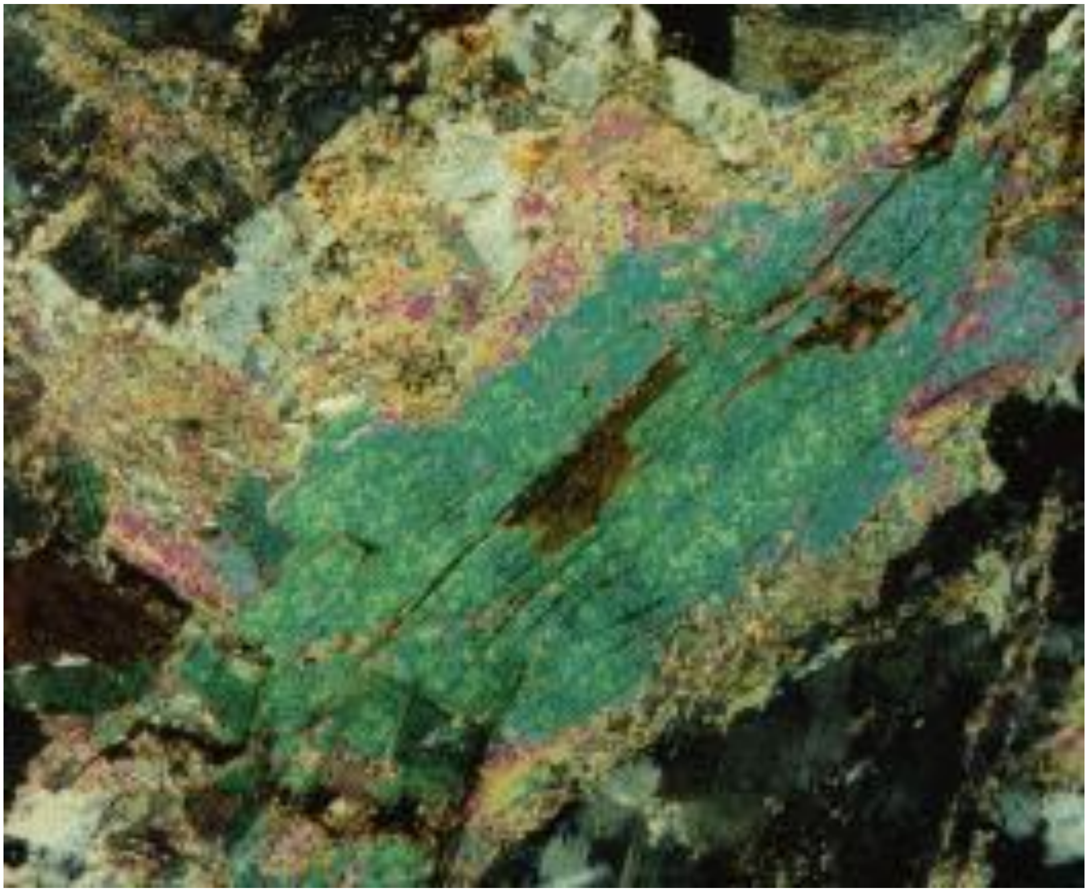

Fig. 5. Muscovite (green, blue-green, pink) in advanced stage of replacement of biotite. Plagioclase grains (light gray) are strongly sericitized (tan, pink).

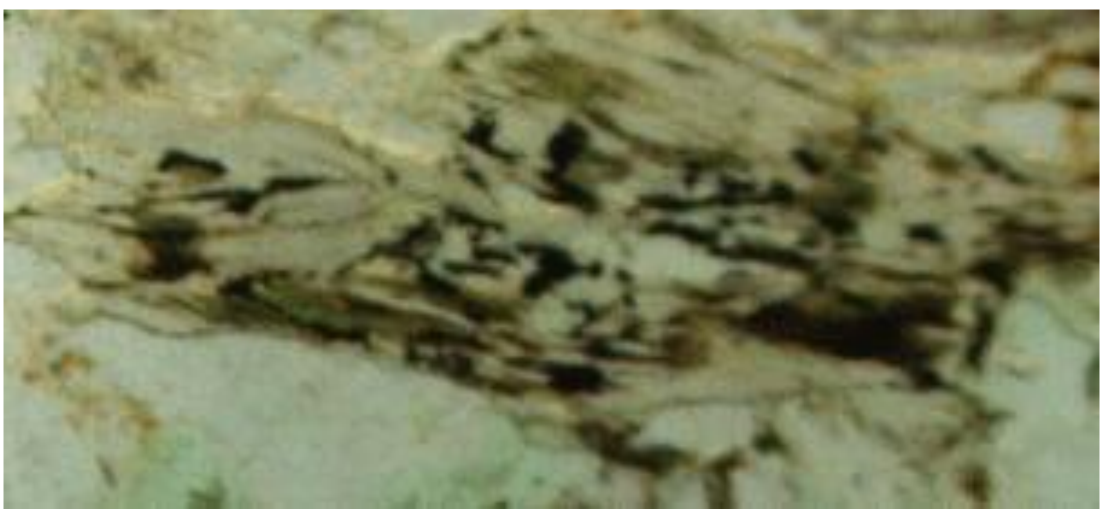

Fig. 6. Muscovite crystal in unpolarized light showing inclusions of opaque iron oxides with remnant biotite (brown).

3. *Porphyritic Granites*.

The porphyritic biotite-muscovite and muscovite granites are gradational to each other and contain the same mineralogy and alterations as the non-porphyritic granodiorite and granite facies but with different modal abundances of the minerals, containing more K-feldspar (25-40 vol. %), quartz (30-39 vol. %), and muscovite (4-8 vol. %) and less biotite (0-4 vol. %) and plagioclase (30-35 vol. %). The primary differences in the porphyritic granites from the non-porphyritic facies are: (1) the K-feldspar occurs as zoned, subhedral to euhedral orthoclase crystals (instead of microcline), (2) myrmekite is absent, and (3) muscovite crystals are clean (devoid of opaque iron oxides, Fig. 7). Most orthoclase crystals are 1 to 2 cm long, but in a few places they are as much as 5 cm long. The zoning of the orthoclase can be seen in hand specimen and thin section and consists of concentrically-arranged inclusions of tiny plagioclase and muscovite crystals whose faces are parallel to former faces of the growing orthoclase crystals (Fig. 8). The orthoclase is slightly perthitic and partly inverted to microcline.

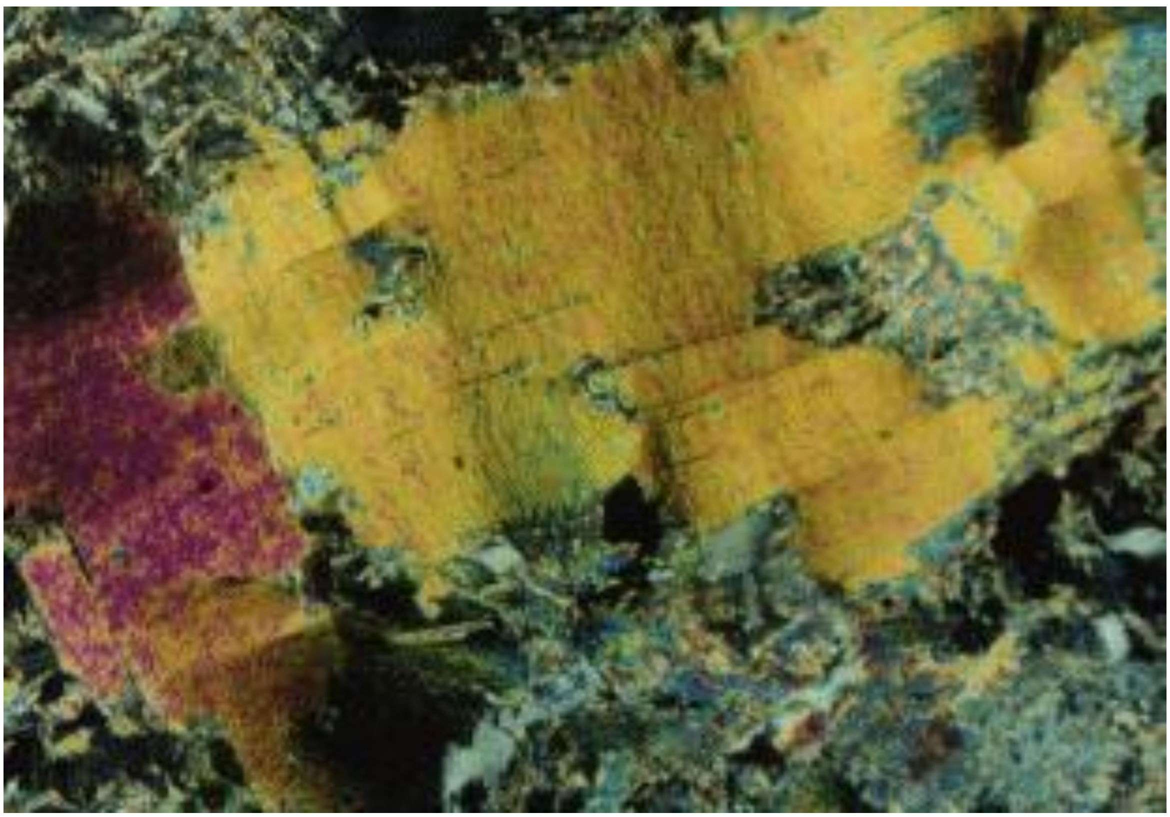

Fig. 7. Clean muscovite crystal (yellow, red-pink) in magmatic muscovite granite which lacks inclusions of opaque iron oxides. Adjacent plagioclase crystals (gray) are strongly sericitized (speckled bright colors)

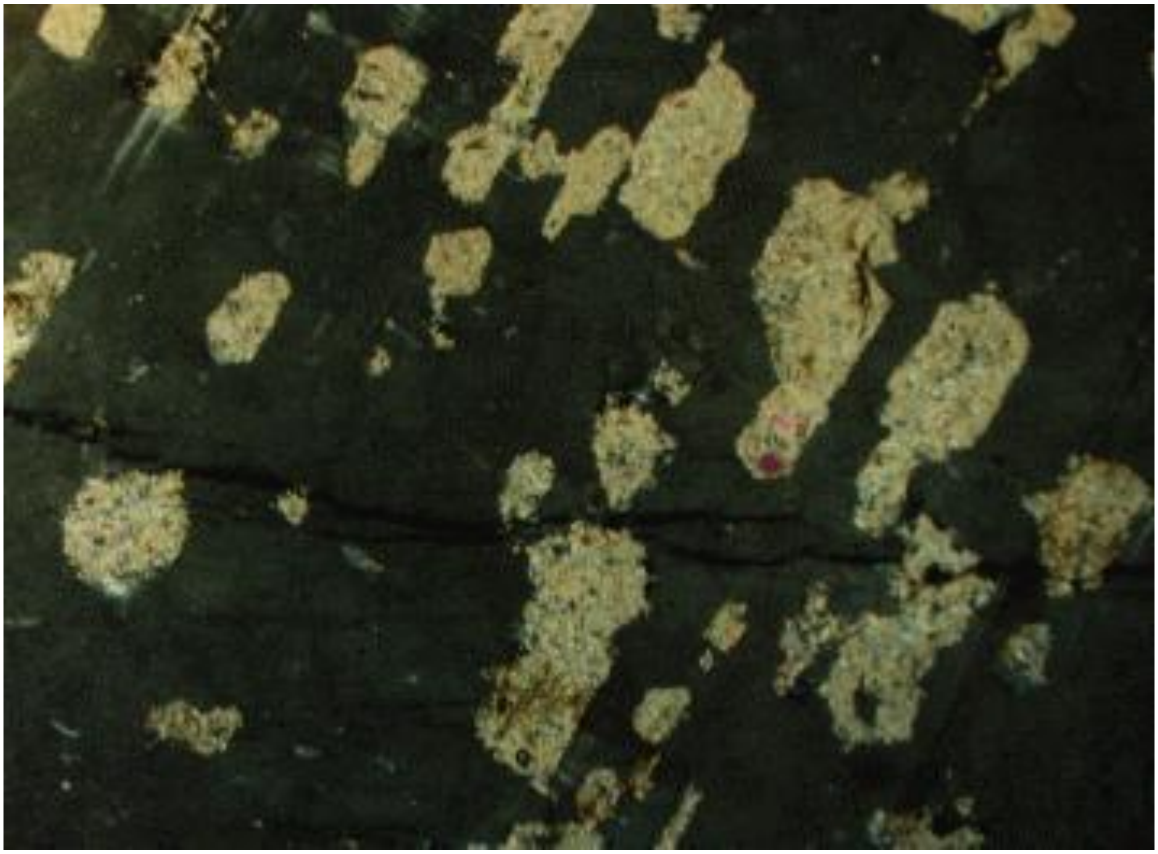

Fig. 8. Portion of orthoclase phenocryst (gray) containing oriented inclusions of tiny plagioclase crystals that are strongly sericitized.

4. *Alaskite*.

The alaskite consists mostly of pink K-feldspar (orthoclase) partly inverted to microcline) and quartz with minor amounts of plagioclase (albite) and traces of muscovite. In the field this rock looks like a sugary aplite or a pinkish quartzite. It is a minor component of the Skidoo pluton but extends for several hundred meters on the second ridge north of the old Skidoo mill structure in the northern core of the pluton.

5. *Hydrothermally Altered Facies*.

All four of the aforesaid facies are variously altered by hydrothermal fluids that came into broad shear zones (described in the introduction) that extend through the Skidoo pluton. Amounts of hydrothermal alteration vary greatly from place to place and are dependent upon the degree of cataclasis and shearing. Throughout the pluton deformation and hydrothermal alteration have caused sericitization of biotite and the feldspars, and quartz grains are highly strained or have a mortar texture. Sericitization of the calcic cores of plagioclase is particularly common, if not universal in many places (Figs. 9 and 10). The micas are commonly bent or kinked, and biotite is converted to chlorite.

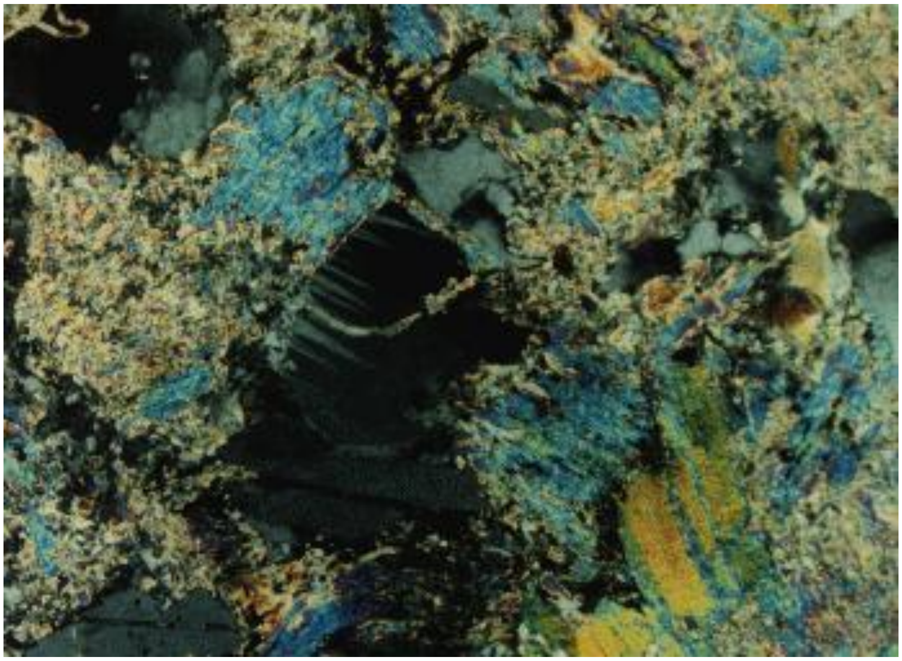

Fig. 9. Strongly sericitized muscovite granite.

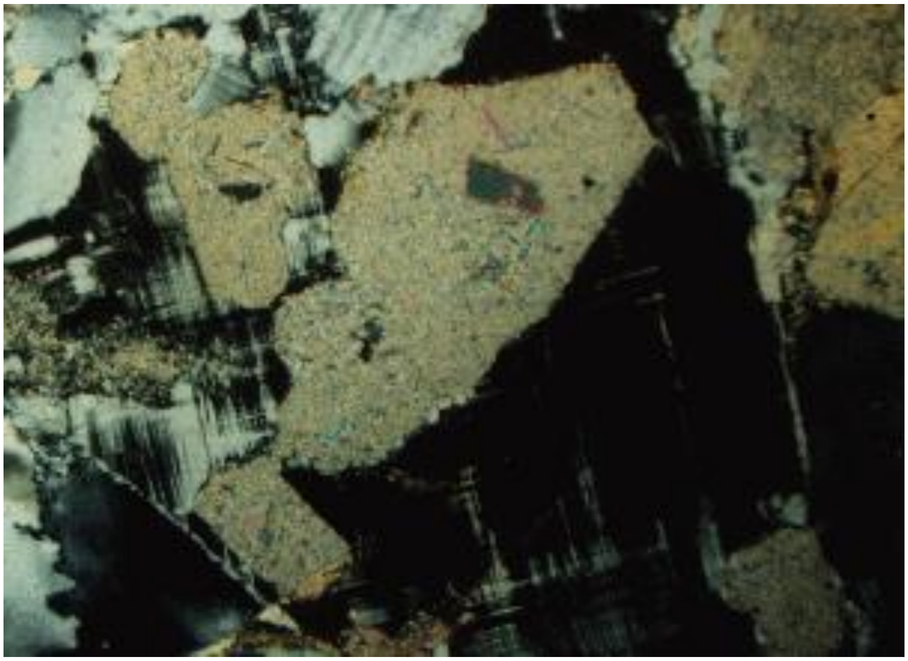

Fig. 10. Strongly sericitized plagioclase crystals enclosed in microcline (black and gray, cross-hatch pattern).

Chemistry

Chemical analyses of the porphyritic muscovite granite and the muscovite-biotite granodiorite, obtained by Wood (1981), show the high silica, alumina, sodium, and potassium contents of these peraluminous rocks.

The leucocratic porphyritic granite contains the following amounts of oxides: SiO_2 74.42%; TiO_2 0.07%; Al_2O_3 13.56%; FeO (total iron) 0.67%; MnO 0.02%; MgO 0.14%; CaO 1.04%; Na_2O 3.22%, and K_2O 5.46%.

The more mafic granodiorite contains the following amounts of oxides: SiO_2 69.68%; TiO_2 0.27%; Al_2O_3 15.41%; FeO (total iron) 2.66%, MnO 0.05%; MgO 0.64%; CaO 3.30%; Na_2O 3.39%; and K_2O 3.64%.

Discussion and interpretations

Throughout the Skidoo pluton much of the plagioclase has been sericitized (Figs. 7, 8, 9, and 10). Long after the granodiorite was formed and the porphyritic granite was solidified and cooled, thrust faulting caused shearing and deformation. This shearing enabled hydrothermal fluids to be introduced, carrying K, Al, and Si, which caused the sericitization of the feldspars. Much of the biotite was altered to chlorite, releasing K, and some of this released K likely also helped to form the sericite. Because of the greater volumes of sericite than the volumes of the original primary biotite and because of the relatively small amounts of Al per unit volume in the feldspar than in sericite, additional K and Al must have been introduced into the sheared rocks. If additional K, Si, and Al were introduced on a large scale during thrust faulting, it does not seem unreasonable to hypothesize that similar fluids were introduced earlier in the history of the rocks to cause modifications during similar periods of deformation. Evidence for such an occurrence can be seen in the thin sections. This evidence includes penetration of primary zoned plagioclase by K-feldspar along fractures (Figs. 11 and 12), island remnants of broken plagioclase in K-feldspar in optical continuity with an adjacent larger plagioclase crystal (Fig. 13), development of myrmekite with tiny quartz vermicules (Figs 13, 14, and 15) where portions of plagioclase are surrounded by K-feldspar, and penetration of biotite by muscovite as indicated by remnant opaque iron oxides in the muscovite which could have been derived from Fe in the former biotite (Figs. 3, 4, 5, and 6). This evidence suggests the following sequential history.

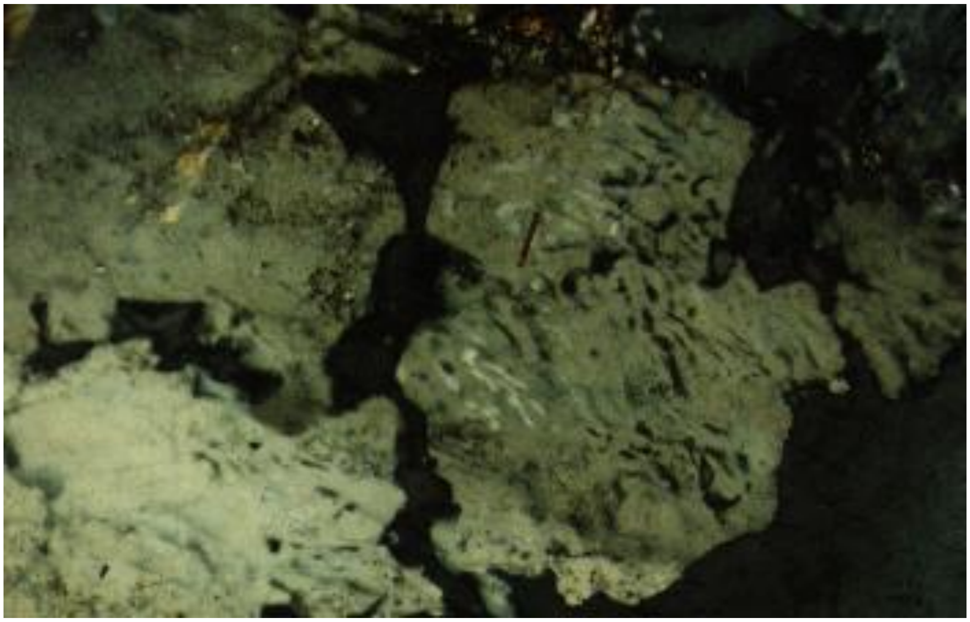

Fig. 11. Microcline (dark gray) penetrating fractured plagioclase (light tan) that has been partly converted to myrmekite.

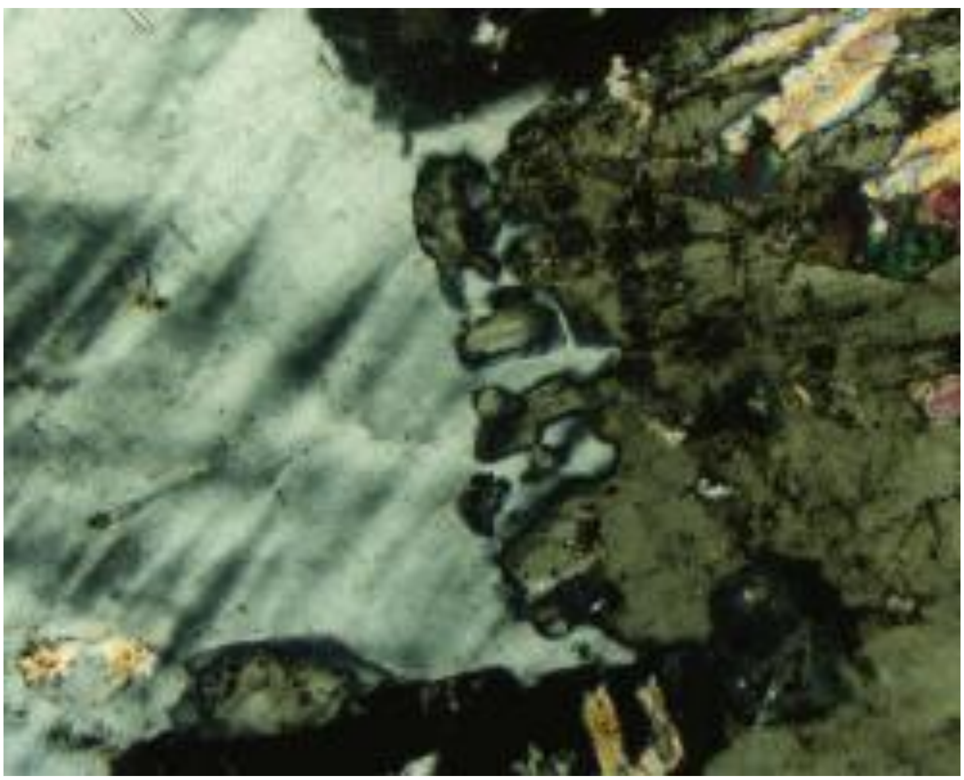

Fig. 12. Microcline (left side, light gray, cross-hatch pattern) penetrating and replacing broken end of plagioclase crystal (tan). Plagioclase contains muscovite crystals (bright colors).

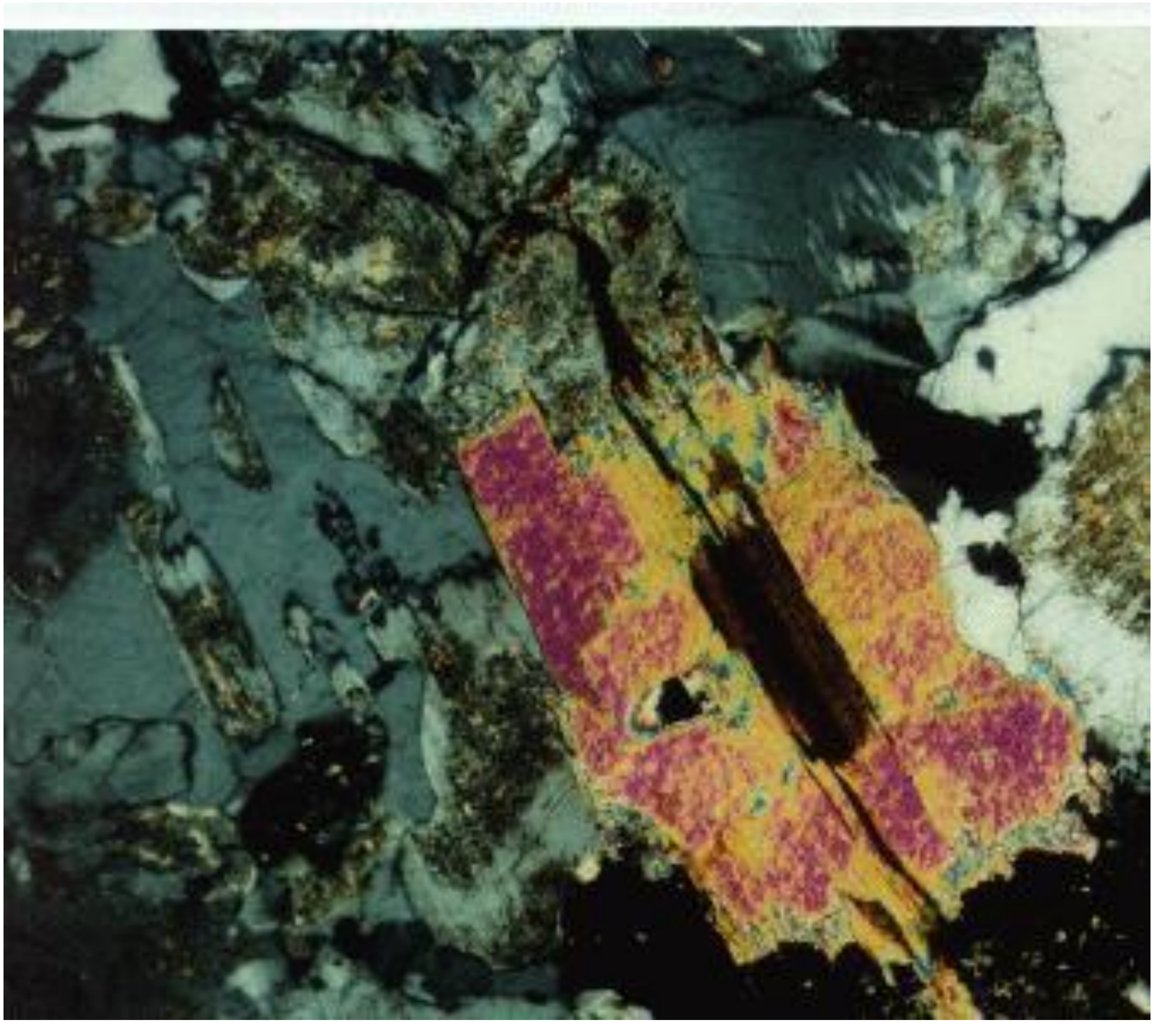

Fig. 13. Muscovite-biotite granodiorite showing possible muscovite (bright colored crystal) replacement of biotite (brown stringers and patches). To the left of the muscovite is an area in which microcline (dark gray) has replaced portions of a large plagioclase crystal which extends above the muscovite-biotite crystal. Remnant islands of plagioclase in the microcline are optically parallel to the larger plagioclase crystal. The plagioclase has been partly altered to sericite and clay. A portion of a zoned plagioclase crystal (right side, white) has a sericitized core (tan).

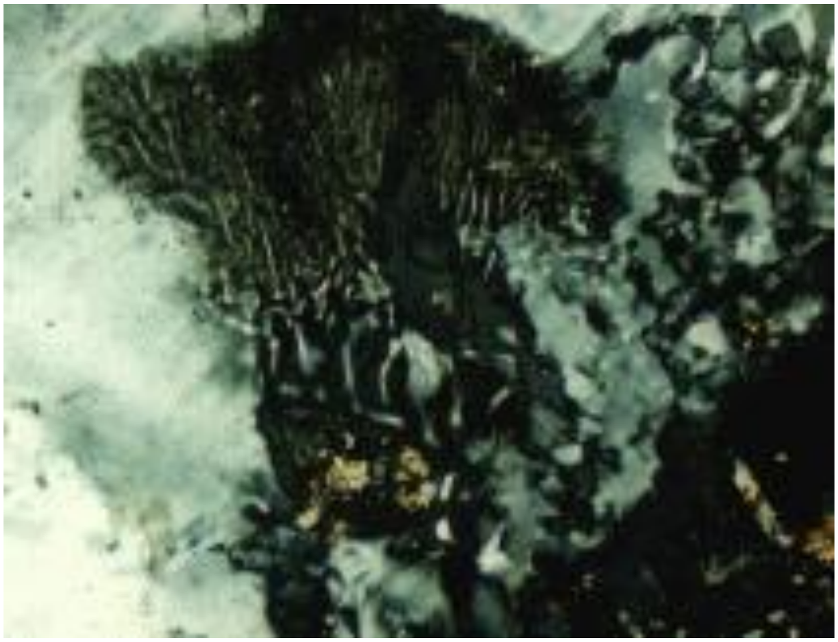

Fig. 14. Myrmekite with intermediate and finely-branched quartz vermicules enclosed in microcline (light gray). Branched vermicules are so tiny in the top part of the myrmekite that they are barely visible.

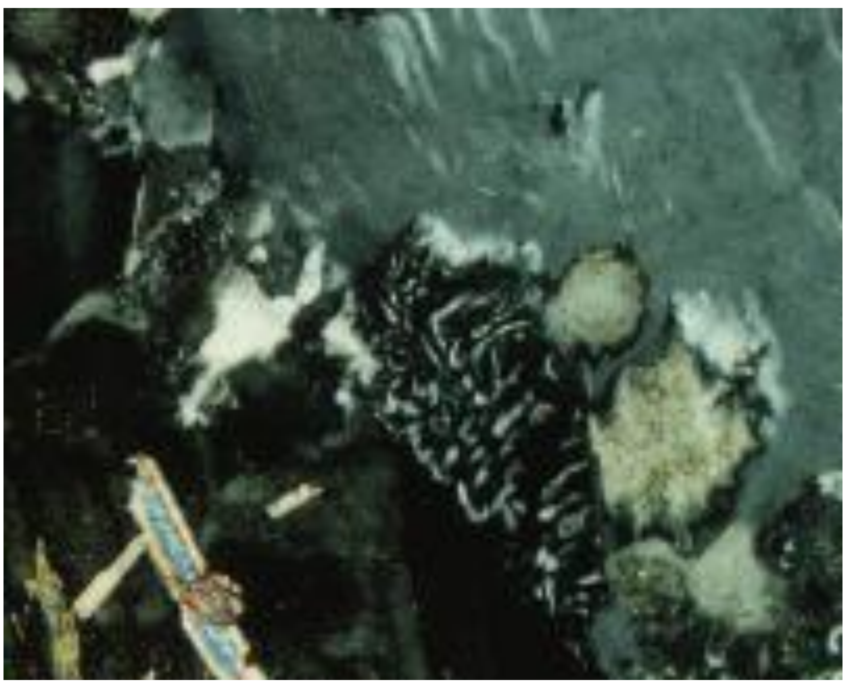

Fig. 15. Myrmekite bordering slightly perthitic K-feldspar (light gray) in muscovite-biotite granodiorite. Muscovite is light blue or pink. Albite-twinned plagioclase (dark) is continuous with plagioclase in the myrmekite and encloses or is adjacent to the muscovite.

The biotite-muscovite granodiorite is the oldest facies presently exposed in the Skidoo pluton. Remnants of biotite in muscovite and K-feldspar replacing primary plagioclase suggest that originally was once an intrusive biotite tonalite in which the potassium was concentrated in biotite rather than in K-feldspar and/or muscovite. The tonalite must have started as hot magma, which did not penetrate far before it solidified. Rapid cooling, because of contact with the adjacent colder wall rocks, created zoned plagioclase crystals with relatively calcic cores (Fig. 13), an indication of the rock's early magmatic history. Following crystallization the pluton continued to rise as a hot plastic to brittle mass of tonalite. This upward movement would have broken grain-boundary seals and fractured crystals. Hydrothermal fluids then could move through the solid, fractured, deformed rock, causing the break-down of biotite and release of K, Al, and Si. The K migrated upward in these fluids to replace some of the broken plagioclase crystals Figs. 11, 12, and 13) and form K-feldspar (microcline). Where replacements were incomplete, myrmekite was also created with tiny, branched quartz vermicules (Collins, 1988; Hunt et al.., 1992; Figs. 13, 14, and 15). Some of the released and transported Al also replaced Fe and Mg in the biotite to form muscovite, interleaved with the biotite (Figs. 3, 4, 5, and 6). In that process some of the displaced Fe was precipitated as opaque iron oxide granules in the muscovite (Fig. 6), giving evidence that biotite once was present there. Not all muscovite crystals contain iron oxide granules in the granodiorite, however, so it is uncertain whether all muscovite was formed by replacement of biotite or whether some could be primary and simultaneously crystallized with the biotite in the original tonalite. Some of the Ca displaced from the plagioclase by K may have precipitated with introduced (or released) Al in epidote; other quantities of Ca must have been carried away with displaced Na in escaping fluids. The sum of all these replacement processes and resulting mineralogical changes gradually converted the rising, solid, but deformed tonalite into the composition of the presently exposed muscovite-biotite granodiorite.

Because replacement of tonalite to produce granodiorite occurred at temperatures below the melting interval of the tonalite (less than 600º C), the contact of the rising, cooler, solid plutonic mass, as it moved upward into the overlying metasediments, created little to no thermal metamorphism of the wall rocks. Thus, the lack of any detectable metamorphism of the adjacent wall rock carbonates or argillites adjacent to a large plutonic mass becomes understandable.

With continued deformation and replacement of plagioclase by K-feldspar and of some biotite by muscovite, the compositions of some portions of the granodiorite were converted to granite. Where this occurred and where temperatures locally became hot enough, this granite partly or completely melted. Subsequently, this melt recrystallized as a *magmatic porphyritic biotite-muscovite or muscovite granite*, containing zoned phenocrysts of *orthoclase lacking myrmekite borders*. In some places the melt crystallized as an alaskite. The places where melting occurred are irregularly distributed in the pluton. Likely their locations are functions of the degree of deformation and replacements to more granitic compositions prior to melting. Significantly, the magmatic granites are gradational to unmelted, myrmekite-bearing granodiorite containing microcline and lacking orthoclase phenocrysts, and, therefore, there are no separate intrusions of magmas of different compositions. Instead, *all the various granitic rocks represent recrystallization, replacements, and melting of the theoretical original tonalite*. The melting also occurred primarily in the interior of the pluton, so that the heat from the rock was not sufficient to cause any significant thermal metamorphism of the nearby Precambrian metasedimentary rocks. The temperatures for melting would have been near 600º C, the eutectic minimum, which would also explain why little thermal metamorphism of the wall rocks occurred.

Conclusion

Sericitization of plagioclase has occurred on a large scale in the Skidoo pluton at low temperature-pressure conditions as a result of introduction of hydrothermal fluids bringing in additional water, K, Al, and Si. If such large-scale sericitization processes produce sericite at low temperature-pressure conditions, *why cannot a similar metasomatic process occur at slightly higher temperatures and produce K-feldspar on a large scale instead of sericite?* Although most igneous petrologists consider all plutonic granites to be magmatic in origin, evidence in the Skidoo pluton suggests otherwise. In the evolution of the granitic rocks in the Skidoo pluton, there was an early episode of magmatism (an intrusion of tonalite magma) and a later local re-melting (?) of some portions of the intruded rocks or introduction of hydrothermal K-feldspar. The hydrothermal K-feldspar probably formed at moderate temperatures (450-550º C), as in copper porphyry granite systems. Because the hydrothermal system cools more rapidly, and less Na is dissolved in the K-feldspar, it has only minor exsolution of albite lamellae (E. J. Essene, e-mail communication, 1997). Also see http://www.csun.edu/~vcgeo005/Nr7K-differentiation.pdf. Each period of magmatism (melting) was followed by complete solidification, deformation, and metasomatism of solid but broken rocks. (1) The subsolidus replacements of plagioclase and biotite by K, Al, and Si to form K-feldspar, muscovite, and myrmekite in the early metasomatic stage to form granodiorite and (2) the sericitization of the feldspars by K, Al, and Si in the late metasomatic stage both occurred on a plutonic scale.

Because of the deformation and openness of the system for movements of hydrothermal fluids during the formation of the muscovite-biotite granodiorite and porphyritic muscovite granite, the relatively high initial $^{87}Sr/^{86}Sr$ ratio of 0.7128 (Hodges et al., 1990) may be explained. Although radiogenic strontium is likely transported away from the system by escaping fluids, the addition of Rb coming in with introduced K would increase the amounts of ^{87}Rb relative to residual ^{86}Sr. The greater amounts of ^{87}Sr generated by the large amounts of ^{87}Rb would raise the initial $^{87}Sr/^{86}Sr$ ratio. See also other discussions of this possibility (Collins, 1997; presentation 14 and 15 on this web site: http://www.csun.edu/~vcgeo005).

The Skidoo pluton is similar to the Hall Canyon pluton (Mahood, et al., 1996; http://www.csun.edu/~vcgeo005/Nr15Hall.pdf) in that both plutons consist of muscovite-biotite granodiorite and muscovite granite, but the lack of separation of an upper muscovite granite from a lower muscovite-biotite granodiorite in the Skidoo pluton, as occurs in the Hall Canyon pluton, makes an origin of the muscovite granite in the Skidoo pluton entirely by magmatic differentiation improbable. The metasomatic relationships in the Skidoo pluton give more reason to doubt that the myrmekite-bearing granitic rocks in the Hall Canyon pluton have been entirely formed by magmatic processes. In fact, the pattern of K-, Al-, and Si-replacements in the Skidoo and the Hall Canyon plutons is likely typical of the muscovite-bearing granitic rocks in the Mojave Desert (Collins, 1997; Miller et al., 1996, 1997; http://www.csun.edu/~vcgeo005/Nr14Mojave.pdf) and in other myrmekite- and muscovite-bearing granitoids in western United States (Miller and Bradfish, 1980; Miller and Barton, 1990). Probably, in all these places, early magmatic intrusions of biotite-rich diorite or tonalite were followed by deformation and K-, Al-, and Si-metasomatism to create myrmekite-bearing rocks of more granitic composition. Such processes would represent continuations of upward migration of K from the mantle since Precambrian time; see: http://www.csun.edu/~vcgeo005/Nr7K-differentiation.pdf.

The processes observed in the Skidoo pluton have application to granitic plutons in the Sierra Nevada and in many other places in the world. That is, in late stages following solidification of the plutons crystallizing from magma, renewed upward movements of the hot but solid plutons (or even later lateral shearing during tectonic transpressive shearing) can break grain-boundary seals and fracture the primary crystals. Migration of hydrothermal fluids through the cataclastically broken rocks could cause the breakdown of biotite, releasing K, Al, and Si to be carried in the fluids. The K could replace plagioclase to produce interstitial K-feldspar (microcline). The Al could precipitate in epidote, and the Si in quartz. As part of that process, rim myrmekite forms on zoned plagioclase crystals adjacent to the microcline.

In most plutons in the Sierra Nevada batholith amounts of K-feldspar that are produced are quite small, and the changes in the rocks are almost isochemical. Replacements in the rocks, however, occur on a plutonic scale, and the mineralogical and chemical changes are commonly referred to as deuteric alteration or autometamorphism during late-stage magmatism. In reality, the replacements are below melting conditions and need not occur immediately following magmatism but occur at any time that deformation allows opening for fluids to move through the rocks. *It is time to recognize that all degrees of K-metasomatism occur on a plutonic scale. In some places the K-metasomatism is very minor, but in other places, where much K is available, the K-metasomatism results in major changes and conversions of original diorite or tonalite into metasomatic myrmekite-bearing granodiorite or granite, which could then potentially re-melt and become a magmatic granodiorite or granite, lacking myrmekite.*

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