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Myrmekite and muscovite developed by retrograde metamorphism at Broken Hill, New South Wales

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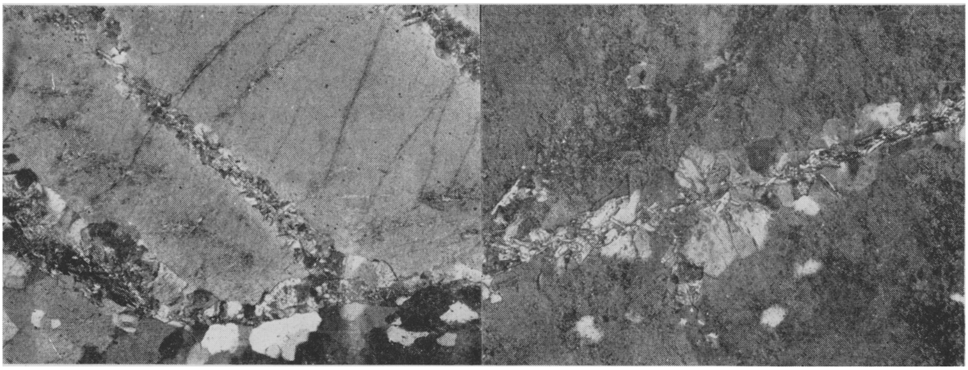
SUMMARY. Retrograde metamorphism of gneisses and pegmatites leads in part to the destruction of feldspar and its replacement by late-stage lobate myrmekite and muscovite. Reactions promoted by retrogression suggest a range in volume of quartz production that may supplement that developed by exsolution and lead to deviations from the strict proportionality relationship suggested by previous workers. There is no need, however, to propose that quartz in myrmekite originates by constriction of pre-existing quartz within exsolved albite.

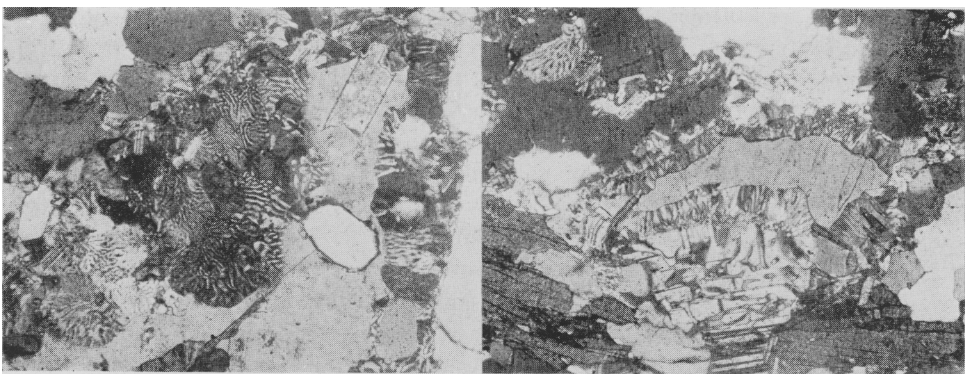
RECENT papers by Phillips and Ransom (1970) and Shelley (1970, pp. 679–80) have drawn attention to the co-existence of muscovite and myrmekite in certain metamorphic rocks. Concomitant with this association in some gneisses is the apparent paucity of potash feldspar. This stands in contrast to many other occurrences, particularly in igneous rocks, where rim and intergranular myrmekite, usually without muscovite but commonly with secondary albite, are associated with well-developed perthite (e.g. Phillips, 1964).

Preliminary petrographic investigations of the Potosi gneiss at Broken Hill revealed the development of a lobate myrmekite associated with fine-grained muscovite and a corresponding low potash feldspar content (Phillips and Ransom, 1970, p. 729). It was suggested that such an association was connected with retrograde metamorphism affecting some of the Broken Hill gneisses (Hobbs *et al.*, 1968, p. 296; Vernon, 1969; Vernon and Ransom, 1971). Additional work has shown that a similar myrmekite–muscovite association occurs in some deformed pegmatites of the Broken Hill region. This paper presents descriptions of the myrmekite–muscovite intergrowths occurring in both the pegmatites and the gneisses and discusses their mode of origin.

Myrmekite and muscovite in the pegmatites. Coarse-grained pegmatites occur in many of the high-grade metamorphic rocks of the Broken Hill area (Vernon, 1969, pp. 33–4). Where intersected by retrograde schist-zones they have been extensively deformed and partly recrystallized. Deformed pegmatites have been examined in detail in the area



FIGS. 1 and 2: FIG. 1 (left). A large potash feldspar from a pegmatite with marginal myrmekite and muscovite and subparallel zones of similar phases crossing its interior. The anhedral quartz at the bottom of the photograph grades into a larger crystal with undulatory extinction. $\times 20$. FIG. 2 (right). Detail of an interior zone of lobate myrmekite developed about a matted trail of muscovite. Potash feldspar on either side of the intergrowth has the same optical orientation. $\times 45$.



FIGS. 3 and 4: FIG. 3 (left). A dense mat of myrmekite and muscovite apparently replacing potash feldspar in the Potosi gneiss. The quartz content of this myrmekite appears to be high. The total volume of myrmekite in comparison with the associated potash feldspar is in excess of any amount expected by the simple exsolution theory. $\times 40$. FIG. 4 (right). Relict lenticular potash feldspar of the Potosi gneiss partially replaced by myrmekite. The coarser myrmekite (showing twinning) to the bottom-centre of the photograph is believed to belong to a different generation of myrmekite formation. $\times 40$.

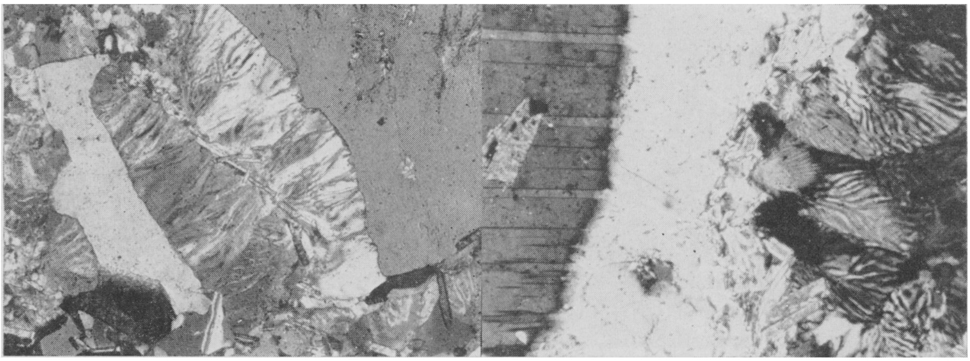
elsewhere (Phillips and Ransom, 1970). This myrmekite type is believed to belong to an early generation of myrmekite formation and it is not discussed further here.

The Potosi gneiss is one of the main rock types of the Broken Hill region (Binns, 1964, p. 309; Hobbs *et al.*, 1968, p. 297; Vernon, 1969, p. 30). It is an even-grained moderately dark coloured quartz–plagioclase–(orthoclase)–garnet–biotite gneiss that forms elongate separated masses especially along the footwall of the Broken Hill orebody. Chemically it does not conform to any common igneous rock group, and its origin is enigmatic. Retrograde schist-zones cut the Potosi gneiss and it is from processes leading to retrograde schist development that lobate myrmekite and muscovite appear to be formed. These changes may be readily observed in the Eyre Street quarries at South Broken Hill (Vernon, 1969, p. 40). The progressive microstructural changes occurring in the Potosi gneiss as retrograde metamorphism proceeds are briefly outlined as follows:

Unaltered Potosi gneiss. Virtually unaltered Potosi gneiss (e.g. Binns, 1964, p. 315) is a coarse-grained, generally massive grey rock containing xenoblastic quartz, plagioclase, orthoclase, garnet, and biotite and accessory myrmekite, ilmenite, and apatite. Some chemical analyses are listed in Binns (1964, p. 310) and Phillips and Ransom (1970, p. 730). In thin-section all the quartz grains (up to 5 mm in diameter) exhibit a slight undulatory extinction defined by small misoriented subgrains within the crystal. Grain boundaries are markedly cuspate. The potash feldspar (perthite with rods and strings of plagioclase) is orthoclase (Binns, 1964) and is finer-grained than quartz but is similar in morphology. It is usually penetrated by relatively coarse myrmekite colonies (e.g. fig. 4). Plagioclase is finer-grained than the perthite and its composition ranges from An_{34} to An_{42}. Myrmekite considered to be unrelated to retrograde processes is present at the contact of many grains with potash feldspar. Microprobe and optical measurements have shown the myrmekitic plagioclase of such intergrowths to be very similar compositionally to non-myrmekitic plagioclase (Phillips and Ransom, 1970). Garnet (commonly cut by subparallel sets of cracks containing micas), biotite, ilmenite, and apatite comprise the rest of this rock. Varying stages of alteration of this rock type have been recognized.

Incipient alteration. This affects mainly the garnet (commonly partially altered to biotite) and biotite so it is not particularly relevant to this discussion. However, white mica appears in the grain boundaries of contiguous biotite and orthoclase and may also occur included in plagioclase.

Pseudomorphous alteration. Between the retrograde schists proper and high-grade gneiss, pseudomorphous retrograde rocks are developed. These have the appearance of the high-grade gneisses in hand-specimen but are extensively altered in thin-section. Some of the high-grade phases retain their old habits and are gradually replaced *in situ* by new phases. The quartz grain size is reduced and quartz grain boundaries become variable in morphology, some retaining the original cuspate shapes of the unaltered gneiss, others becoming highly sutured and irregular. Lobate myrmekite with muscovite is well developed. Potash feldspar may exhibit undulatory extinction and its volume appears to decrease gradually as the amount of myrmekite increases, leaving in some rocks only small relics in a mat of myrmekite and muscovite (e.g. fig. 4; cf. Shelley, 1970, p. 679, and his figs. 5 and 6). Certain sections show a particularly dense, intricate quartz–plagioclase intergrowth with quartz apparently in high proportion. In such sections potash feldspar appears to be almost totally replaced and muscovite is present as fine flakes (fig. 3). Myrmekite fringes locally project outwards from a middle trail of muscovite flakes as in the pegmatites. In this intergrowth, however, the adjacent potash feldspar need not be part of the same crystal (fig. 5).



FIGS. 5 and 6: FIG. 5 (left). Large lobes of myrmekite advancing into two adjacent potash feldspar crystals whose original interface appears to be outlined by the middle trail of muscovite flakes (Potosi gneiss). ×50. FIG. 6 (right). Lobate myrmekite associated with plagioclase. A dense mat of muscovite is developed between the twinned plagioclase and the myrmekite (Potosi gneiss). ×70.

Dense fan-shaped lobes also appear to have grown out from plagioclase. Here muscovite may be well developed between the plagioclase and the myrmekite (fig. 6). Plagioclase remains as relics or has been altered pseudomorphously to oligoclase (An_{20}) antiperthite and this may indicate approximately the composition of the plagioclase in the lobate myrmekite as measurements here are difficult to make. Twinning has not been seen in any of the plagioclase in the lobate myrmekite.

Microstructural reorganization close to the retrograde schist-zones. Rocks in this category are visibly strained in outcrop, and in thin-section show major microstructural reconstruction. Polygonal aggregates of new grains are common and the number of recognizable old grains is diminished. The feldspars are further altered and potash feldspar has been almost completely replaced by fine-grained myrmekite and muscovite.

The retrograde schist. Myrmekite is rare in the retrograde schist-zones and its place is taken by fine-grained quartz–feldspar–mica zones set parallel to the schistosity. These retrograde schists are described in detail elsewhere (Vernon and Ransom, 1971).

Discussion

Much of the discussion of myrmekite formation today is based on the exsolution (unmixing) theory of Schwantke (1909), which proposes that myrmekite is exsolved as quartz–plagioclase phases from (high temperature) alkali feldspar holding Ca^{++} and 'excess' silica. We may write an approximate equation thus:

$$\left.\begin{cases} x\ KAlSi_3O_8 \\ y\ NaAlSi_3O_8 \\ z\ Ca\square(AlSi_3O_8)_2 \end{cases}\right\} \rightarrow \underset{\text{orthoclase}}{x\ KAlSi_3O_8} + \underbrace{\underset{\text{plagioclase}}{y\ NaAlSi_3O_8.z\ CaAl_2Si_2O_8} + \underset{\text{quartz}}{4zSiO_2}}_{\text{myrmekite}} \qquad (1)$$

alkali feldspar where
$\square$ stands for vacant cation sites,
and $x > y \gg z$.

This vacancy theory, first proposed by Phillips (1964), has found increasing support in recent years, e.g. Barth (1969, pp. v, 14, 28), Carman and Tuttle (1963, 1967), Carstens (1967), Hubbard (1966, 1967*a*, 1967*b*, 1969), Mehnert (1968, p. 199), Perry (1968, p. 216), Phillips and Ransom (1968, 1970), Ransom and Phillips (1969), Sturt (1970), Widenfalk (1969), and Wyart and Sabatier (1965).

On the other hand Shelley (1964, 1966, 1967, 1969, 1970) believes that myrmekite forms as the result of the constriction of pre-existing quartz within albite exsolved in rim and intergranular positions (see also Garg, 1967). He further maintains that there is no definite ratio between the amount of quartz present in myrmekite and the composition of the allied plagioclase, a relationship the exsolution theory demands. A deficiency of Shelley's theory is that it fails to explain the origin of quartz-bearing perthite (e.g. Spencer, 1945). It also fails to rationalize the volume change produced by the movement of albite into a region previously occupied by quartz. The alkali feldspar supplying the albite must, under the circumstances proposed by Shelley, suffer a reduction in size and we have seen no evidence of this. Further, we have as yet not seen an example of any relict strained groundmass of quartz positioned between potash feldspar and plagioclase as is proposed by Shelley (e.g. fig. 2, p. 678, Shelley, 1970).

Two main points stand out in the present work on the Broken Hill rocks: retrogressive metamorphism appears to be connected with some myrmekite formation, and in such cases muscovite is an important accompanying mineral.

The idea that a variety of myrmekite could be associated with strained rocks was presented some 56 years ago by Sederholm (1916, pp. 127, 135) in his description of 'myrmekite in granites showing signs of mechanical metamorphism'. Sederholm does not mention the presence of muscovite in this setting but some of the plates in his paper are remarkably similar to the figures in this present paper. Shelley (1970, p. 679), whilst not implying retrograde metamorphism, says in his discussion of myrmekite not associated with potash feldspar that the Constant Gneiss has 'suffered a complex history of plutonism and flattening'. He notes that the absence of potash feldspar is an unusual feature stating that 'it is conceivable that K-feldspar was present but has been removed in some way'. He records a different morphology for this myrmekite as opposed to typical plug-like myrmekites that are elsewhere associated with potash feldspar, and the myrmekite illustrated in his figs. 5 and 6 is 'typically clustered together in irregular mosaics with muscovite grains'. Many of the figures in his 1964 paper also suggest the presence of myrmekite (and muscovite?, see fig. 4) in deformed rocks, and he makes special mention of mortar textures (p. 42).

Turning to our second point we believe that an obvious source for the muscovite illustrated in this present paper is the potash feldspar. In particular the trails of muscovite running through the large potash feldspar grains of the pegmatites could have a local origin. Destruction of potash feldspar under retrograde conditions may proceed along at least two lines as shown by the approximate equations:

$$\underset{\text{alkali feldspar}}{\begin{Bmatrix} 3KAlSi_3O_8 \\ NaAlSi_3O_8 \end{Bmatrix}} + \underset{\text{calcic plagioclase}}{\begin{Bmatrix} CaAl_2Si_2O_8 \\ NaAlSi_3O_8 \end{Bmatrix}} + \underset{\text{water}}{H_2O} \rightarrow \underbrace{\underset{\text{more sodic plagioclase}}{\begin{Bmatrix} CaAl_2Si_2O_8 \\ 2NaAlSi_3O_8 \end{Bmatrix}}}_{\text{myrmekite}} + \underset{\text{quartz}}{6SiO_2} + \underset{\text{muscovite}}{KAl_2(Al,Si_3)O_{10}(OH)_2} + K_2O \quad (2)$$

or, more simply:

$$\underset{\text{orthoclase}}{3KAlSi_3O_8} + \underset{\text{water}}{H_2O} \rightarrow \underset{\text{muscovite}}{KAl_2(Al,Si_3)O_{10}(OH)_2} + \underset{\text{quartz}}{6SiO_2} + K_2O. \quad (3)$$

(The K_2O could, for example, go towards the retrograde development of biotite replacing garnet, or be used in the sericitization of associated plagioclase.)

Thus by using equations 1, 2, and 3 to suggest *approximate* reactions under retrograde conditions the possibilities for myrmekite genesis have been broadened. We believe that the basic drive is still one of exsolution leading to a quartz–plagioclase intergrowth. Equations 2 and 3, however, may be considered as supplementary reactions that, under certain conditions, allow for a much greater flexibility in the amount and proportions of the resultant products. Such reactions suggest a mechanism for the formation of late-generation myrmekite. For example, a combination of equations 1 and 3 leads to a reaction of the type:

$$\underset{\text{alkali feldspar}}{\begin{Bmatrix} 3xKAlSi_3O_8 \\ yNaAlSi_3O_8 \\ zCa\square(AlSi_3O_8)_2 \end{Bmatrix}} + \underset{\text{water}}{xH_2O} \rightarrow \underset{\text{muscovite}}{xKAl_2(Al,Si_3)O_{10}(OH)_2} + \underbrace{\underset{\text{plagioclase}}{\begin{Bmatrix} yNaAlSi_3O_8 \\ zCaAl_2Si_2O_8 \end{Bmatrix}} + \underset{\text{quartz}}{(6x+4z)SiO_2}}_{\text{myrmekite}} + xK_2O \quad (4)$$

The quartz in this kind of reaction is derived in part from exsolution and in part from the destruction of orthoclase. Equation 4 need not, of course, go to completion and it is highly likely that in many reactions relict alkali feldspar will remain. In these reactions the amounts of muscovite and quartz are indeterminate but would be less than is shown in equation 4. Actual amounts of reaction products are impossible to estimate without having an accurate measurement of the volumes occupied by muscovite and myrmekite in a given volume of (former) alkali feldspar, a good estimate of the quartz: plagioclase ratio in the myrmekite, measurement of the An content of the myrmekite and, ideally, the Ca content of the alkali feldspar. However, the equation suggests that such a reaction, with total destruction of alkali feldspar, could produce more quartz than simple exsolution. Here we see the possibility of a breakdown in the proportionality relationship that appears to hold for unsupplemented exsolution (Phillips and Ransom, 1968). A reaction similar to equation 4 may explain the apparently high quartz content for the myrmekite illustrated in fig. 3. Equation 2 indicates interesting possibilities where retrograde metamorphism causes reaction between co-existing feldspars. Thus the simple proportionality relationship implied by equation 1 may not pertain, and Shelley's (1969) objections are probably justified for particular types of myrmekite. (Further discussion on the proportionality of quartz is given by Barker (1970, p. 3344).)

The process envisaged here does not require that pre-existing quartz be situated in just the right position to be constricted within exsolving albite as suggested by Shelley (1964, 1970). The reactions listed above provide an ample local and internal source of quartz, which could readily be incorporated in blastic plagioclase developing essentially by exsolution and promoted to a large degree by strain. They could equally apply to hydrothermally altered rocks or to rocks affected by contact metamorphism. It is relevant that in the pegmatites large deformed quartz crystals at their junctions with potash feldspar have recrystallized into polygonal aggregates. On the other side of the junction, perhaps developed in a similar attempt to relieve strain, prominent marginal myrmekite is formed. No evidence exists, however, to indicate that any of this recrystallized quartz has been incorporated into the myrmekite.

The morphology of myrmekite, a factor emphasized by Shelley (e.g. 1964, 1970), appears to be simply the result of a simultaneous crystallization of quartz and plagioclase (essentially by growth in the solid state regardless of the origin of the quartz). Undoubtedly the occurrence of quartz in rods is an attempt to reduce interfacial area and this could happen even if the quartz was not present earlier, but was formed along with plagioclase as the result of the same chemical reaction. It appears that myrmekite is just an example of two phases without enough structural anisotropy to form planar interfaces growing together from a single point of nucleation. Considering the simultaneous crystallization of quartz and plagioclase Hubbard (1966, p. 773) suggests the morphology of the myrmekite 'may be interpreted as reflecting the decreasing degree of suitability of growth foundation found by the exsolving phases at these interfacial types, i.e., increasing lattice dissimilarity between the nucleating plagioclase and the available growth foundation'. Further detailed considerations of this problem are beyond the scope of this paper.

None of the above discussion has changed our belief that the underlying cause for the development of myrmekite is exsolution from an alkali feldspar solid solution and that commonly (as in unstrained igneous rocks) exsolution is the sole method for myrmekite production. However, the simple exsolution theory proposed previously by us and other workers cannot adequately explain some of the myrmekite formed in the metamorphic rocks described here. The fairly clear relationship between myrmekite development and retrogressive metamorphism at Broken Hill has led us to the theory proposed in this paper, and we have little doubt that myrmekite is polygenetic. Although the ideas expressed here are of a preliminary and speculative nature, they are put forward in the hope that they will stimulate further the expanding interest in the microstructure called myrmekite.

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REFERENCES

BARKER (D. S.), 1970. *Bull. Geol. Soc. Amer.* **81,** 3339.
BARTH (T. F. W.), 1969. *Feldspars.* New York (Wiley-Interscience).
BINNS (R. A.), 1964. *Journ. Geol. Soc. Aust.* **11,** 284.
CARMAN (J. H.) and TUTTLE (O. F.), 1963. *Progr. Abstr. Geol. Soc. Amer. Ann. Meeting,* 29A.
—— —— 1967. Ibid. 33.
CARSTENS (H.), 1967. *Contr. Min. Petr.* **14,** 316.
GARG (N. K.), 1967. *Amer. Min.* **52,** 918.
HOBBS (B. E.), RANSOM (D. M.), VERNON (R. H.), and WILLIAMS (P. F.), 1968. *Min. Depos.* **3,** 293.
HUBBARD (F. H.), 1966. *Amer. Min.* **51,** 762.
—— 1967*a*. Ibid. **52,** 920.
—— 1967*b*. *Geol. Fören. Förh.* **89,** 410.
—— 1969. *Amer. Min.* **54,** 988.
MEHNERT (K. R.), 1968. *Migmatites and the origin of granitic rocks.* Amsterdam (Elsevier).
PERRY (K.), 1968. *Lithos,* **1,** 201.
PHILLIPS (E. R.), 1964. *Journ. Geol. Soc. Aust.* **11,** 49.
—— and RANSOM (D. M.), 1968. *Amer. Min.* **53,** 1411.
—— —— 1970. *Min. Mag.* **37,** 729.
RAMBERG (H.), 1962. *Neues Jahrb. Min. Abh.* **98,** 14.
RANSOM (D. M.) and PHILLIPS (E. R.), 1969. *Amer. Min.* **54,** 984.
SCHWANTKE (A.), 1909. *Centr. Min.* 311.
SEDERHOLM (J. J.), 1916. *Bull. Comm. Géol. Finlande,* no. 48.
SHELLEY (D.), 1964. *Amer. Min.* **49,** 41.
—— 1966. *Min. Mag.* **35,** 678.
—— 1967. Ibid. **36,** 491.
—— 1969. *Amer. Min.* **54,** 982.
—— 1970. *Min. Mag.* **37,** 674.
SPENCER (E.), 1945. Ibid. **27,** 79.
STURT (B. A.), 1970. Ibid. **37,** 815.
VERNON (R. H.), 1969. *Journ. Geol. Soc. Aust.* **16,** 20.
—— and RANSOM (D. M.), 1971. Ibid. **18,** 267.
WIDENFALK (L.), 1969. *Lithos,* **2,** 295.
WYART (J.) and SABATIER (G.), 1965. *Compt. Rend. Acad. Sci. Paris,* **260,** 1681.

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