Journal of Structural Geology, Vol 13 No 9, pp 979 to 985, 1991
Printed in Great Britain

0191-8141/91 $03 00 + 0 00

Questions about myrmekite in deformed rocks

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(*Received 28 March 1990, accepted in revised form 18 April 1991*)

Abstract—Several questions about the development of myrmekite in deformed felsic and metapelitic rocks remain unanswered Although a general relationship between deformation and myrmekite appears to be well established, the fact that myrmekite grows into relatively non deformed K feldspar, while being simultaneously deformed and recrystallized at the rear of the growing lobes, suggests that strain energy may not be a major contributor to the advance of the growth interface of the myrmekite colony Furthermore, because myrmekite typically nucleates on existing plagioclase, rather than in K feldspar, strain energy may not contribute directly to nucleation of myrmekite either, at least in many instances However, strain energy probably contributes indirectly by facilitating access of fluids to growth sites, thereby altering the local chemical environment and so promoting development of myrmekite Because myrmekite recrystallizes readily in deformed felsic rocks, it is one of the main contributors to the development of folia

INTRODUCTION

THIS NOTE asks some questions about processes responsible for the development of myrmekite in deformed felsic and metapelitic rocks This is a long standing, complex problem, reviewed by Simpson & Wintsch (1989), and definitive answers to many of the questions are not available Though confident interpretations are unwarranted at this stage, judicious questions, even if somewhat speculative, may help to guide future research The main questions are concerned with (1) whether myrmekite grows in the solid state, rather than by crystallization from a melt, and (2) whether strain energy is a dominant contributing factor to either the growth or the nucleation of myrmekite, or whether deformation contributes indirectly by promoting access of fluids.

Myrmekite is best known in mesoscopically non deformed granitoids, for which Simpson & Wintsch (1989, p. 273) suggested that myrmekite may form in response to local stress differences on K feldspar grain boundaries during subsolidus cooling. Myrmekitic intergrowths in several deformed granitoids have also been described (e g. Binns 1966, Phillips *et al.* 1972, Vernon *et al.* 1983, Simpson 1985, Simpson & Wintsch 1989 and references therein), and my observations suggest that it is very common in such rocks. This note is concerned mainly with these occurrences, though some reference is also made to mesoscopically non deformed granitoids Myrmekite also occurs in metapelitic gneisses (e.g. Vernon 1978, 1979, Nold 1984, Vernon *et al.* 1990).

Most commonly, the myrmekite occurs as lobes or colonies projecting into porphyroclasts of K feldspar (typically microcline) from the margins of the clast, which may show marginal internal recrystallization and neocrystallization to fine-grained aggregates (Fig. 1). In places, myrmekite also occurs as fringes along former fractures in K-feldspar (Figs. 2a & b). Generally the development of myrmekite in these rocks is attributed to solid state replacement processes accompanying deformation, and many people have postulated that myrmekite grows at sites of locally high stress, see Simpson & Wintsch (1989, p 261) for references However, Hibbard (1987) suggested that myrmekite crystallizes from melt during deformation of incompletely crystallized granite. This proposition will be examined first, after which various questions about solid state growth of myrmekite will be discussed

DOES MYRMEKITE CRYSTALLIZE FROM A MELT?

Hibbard (1979) inferred that myrmekite in mesoscopically non deformed granitoids is due to crystallization from a water saturated, pressure quenched melt, as opposed to more conventional hypotheses involving replacement of K feldspar in the solid state (e.g. Phillips 1974, 1980) Hibbard (1987) also suggested that myrmekite in deformed granitoid rocks is due to crystallization of small amounts of water saturated magma in a largely crystallized rock, in response to 'micro pressure quenching' during deformation. Hibbard's hypothesis is based on his observation of crystal faces and zoning in the plagioclase of some myrmekitic aggregates (Hibbard 1979, fig 5), as well as on his general model of late magmatic crystallization in granitoids (Hibbard 1979) Referring to Jahns & Burnham (1969), he suggested that K is partitioned strongly into an aqueous phase, which ends coprecipitation of K feldspar with plagioclase and quartz, allows crystallization of myrmekite from the remaining melt during pressure quenching, and eventually promotes precipitation around the myrmekite of K feldspar from the K-rich aqueous phase However, more recent experimental work has shown that the K/Na ratio in the aqueous phase is never greater than in the coexisting silicate melt, unless the melt is also in equilibrium with a K-poor, Na rich mineral, such as hornblende or tourmaline (Burnham 1982, Burnham & Nekvasil 1986) Even if conditions are suitable for partitioning of K into the melt, how can the aqueous phase precipitate late K feldspar after it is lost from the system during pressure quenching? Furthermore, the partitioning probably would not be strong enough to prevent K-feldspar from precipitating from the silicate melt (Burnham 1982) Therefore, some K feldspar should crystallize, along with quartz and sodic plagioclase, right to the solidus, rather than K feldspar following plagioclase and quartz, as in Hibbard's model.

In support of his hypothesis, Hibbard (1979) stated that myrmekite is abundant in aplites, which he contended are formed by crystallization of pressure quenched, water saturated magma This interpretation of the origin of aplites may well be correct, but myrmekite is not especially common in undeformed aplites, as indicated by extensive reviews of igneous petrography (e g. Johannsen 1932, pp. 91-93), implying that this is not an effective argument. Myrmekite in aplites may still be interpreted as being replacive, on the available evidence

Many myrmekitic aggregates are lobate, without obvious crystal faces (Figs 1b & c) However, the observations of Hibbard (1979) and Simpson (1985) that the plagioclase component of some myrmekitic aggregates locally has straight boundaries that may be crystal faces (Fig. 1b) can be explained by the presence of fluid along the advancing interface between the myrmekite and K-feldspar, and need not imply crystallization from a melt. In fact, fluid films generally may be involved in the development of crystal faces in minerals in metamorphic rocks, although this is still speculative (e g. Vernon 1976). The complex diffusion of components necessary for the aggregate to grow (Mongkoltip & Ashworth 1983) may necessitate the presence of fluid along the boundary between myrmekite and K feldspar, the access of such a fluid being favoured by an approximately 10% reduction in volume accompanying the replacement of K feldspar by myrmekite (Simpson & Wintsch 1989, p. 271) Furthermore, if myrmekite crystallizes from a melt, why doesn't its plagioclase component always develop crystal faces, as feldspar invariably does during free growth in a melt?

With regard to partly molten granitoids undergoing deformation, Hibbard (1987, p. 1059) suggested that this deformation would enhance 'micro pressure-quenching', so that myrmekite could precipitate from the remaining melt. This idea is opposed by the arguments against Hibbard's general hypothesis presented above, as well as by the occurrence of myrmekite as replacive fringes along former fractures in K feldspar (Figs. 2a & b). In any event, whether or not pressure quenching would occur in deforming granitoids relatively deep in the crust is arguable. Moreover, as pointed out by Simpson & Wintsch (1989), the presence of melt is out of the question for granitoids undergoing subsolidus deformation millions of years after they have crystallized For example, in retrograde zones at Broken Hill, Australia, myrmekite was formed in felsic rocks at lower amphibolite facies conditions, following peak granulite facies metamorphism (Phillips *et al* 1972) Myrmekite is also common in felsic gneisses and mylonites produced in shear zones in the Anmatjira Range, central Australia, during the mid Palaeozoic 'Alice Springs Orogeny' (Collins & Teyssier 1989). The mylonitic rocks were formed by the deformation of granitoids that had been metamorphosed at granulite facies conditions some 1400 Ma previously, and the temperatures during the mylonitic deformation were too low to permit remelting

With regard to deforming granitoids, Hibbard (1987, pp 546–547) stated that myrmekite occurs mainly in 'pressure-shadow' (strain shadow?) areas, rather than in zones normal to the local direction of maximum shortening, suggesting migration of magma to low-strain or low-pressure zones. However, observations of Vernon *et al* (1983, fig 6), Simpson (1985) and La Tour (1987) indicate that, on the contrary, myrmekite occurs most commonly in zones parallel to the foliation, normal to local zones of maximum shortening Moreover, in deformed granitoids from the Papoose Flat pluton, California, which was used as a prime example by Hibbard (1987), myrmekite occurs very commonly as replacive lobes concentrated along zones perpendicular to the inferred local direction of maximum shortening or even completely surrounds K feldspar porphyroclasts (Fig. 1c).

Therefore, a replacive, rather than a magmatic, origin for myrmekite is preferable, judging from the available evidence

WHAT ARE THE ROLES OF STRESS, STRAIN AND FLUID COMPOSITION?

Simpson & Wintsch (1989) inferred that local increases in both stress and strain localize the development of myrmekite. They suggested that temperature, pressure and chemical activities control the occurrence of myrmekite, but that strain energy localizes the reaction at sites of high normal stress These sites occur along boundaries of K feldspar porphyroclasts that are parallel to folia in the deforming rock This interpretation is particularly strong where K feldspar boundaries fringed with myrmekite are parallel to *S* surfaces at 45° to the plane of shear in *S*-*C* gneisses, as these surfaces develop normal to the direction of maximum local compressive stress (e g. Simpson 1985, Simpson & Wintsch 1989) However, myrmekite may also occur in sites where the inference of former high compressive stresses cannot be defended (Fig. 1a). Moreover, with advancing growth, myrmekite may completely fringe K feldspar porphyroclasts (Fig 1c), although this myrmekite growth could be fostered by locally high normal compressive stress that changes its orientation with progressive deformation. However, it would be difficult to exclude the possible effects of shear stress in all these situations. Furthermore, myrmekite also occurs along fractures (Figs. 2a & b), not only those oriented in such a way that high compressive stress could occur across them, but

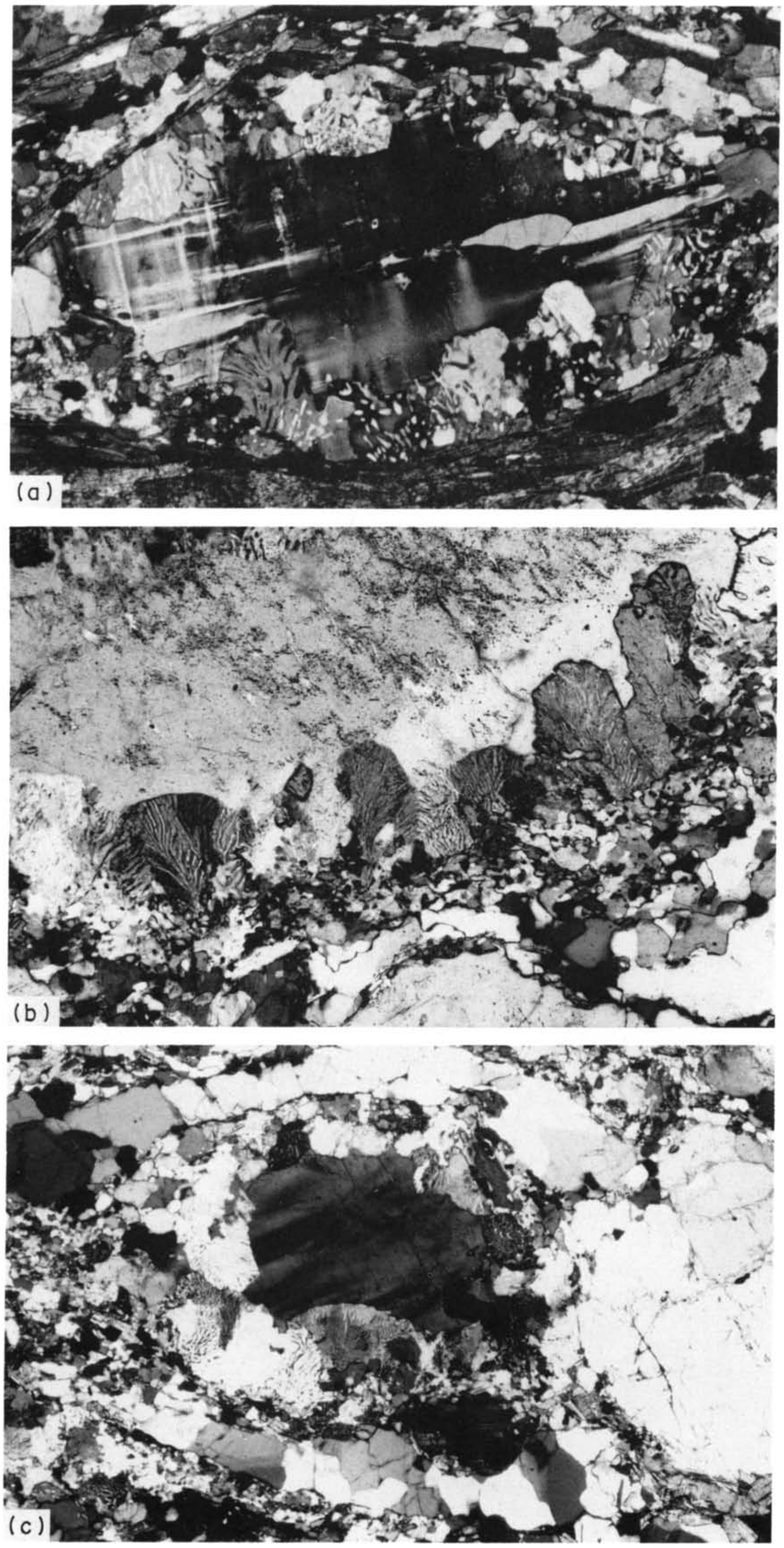

Fig. 1. (a) Augen gneiss from the Lake Maggiore area, Italy, showing microcline microperthite porphyroclast that has been locally replaced by lobes of myrmekite. Crossed polars, base of photograph 4.4 mm. (b) Myrmekite lobes fringing a porphyroclast of K feldspar in the Papoose Flat pluton, California. The myrmekite has sharp, generally rounded boundaries against the K feldspar, but locally the boundaries are straight and possibly crystallographic. The myrmekite passes into fine grained, recrystallized aggregates of quartz and plagioclase (some with residual quartz blebs from the former myrmekite) in the matrix. Crossed polars, base of photograph 1.3 mm. (c) Small relic of K feldspar completely surrounded by lobate myrmekite. Papoose Flat pluton, California. Crossed polars, base of photograph 2.7 mm.

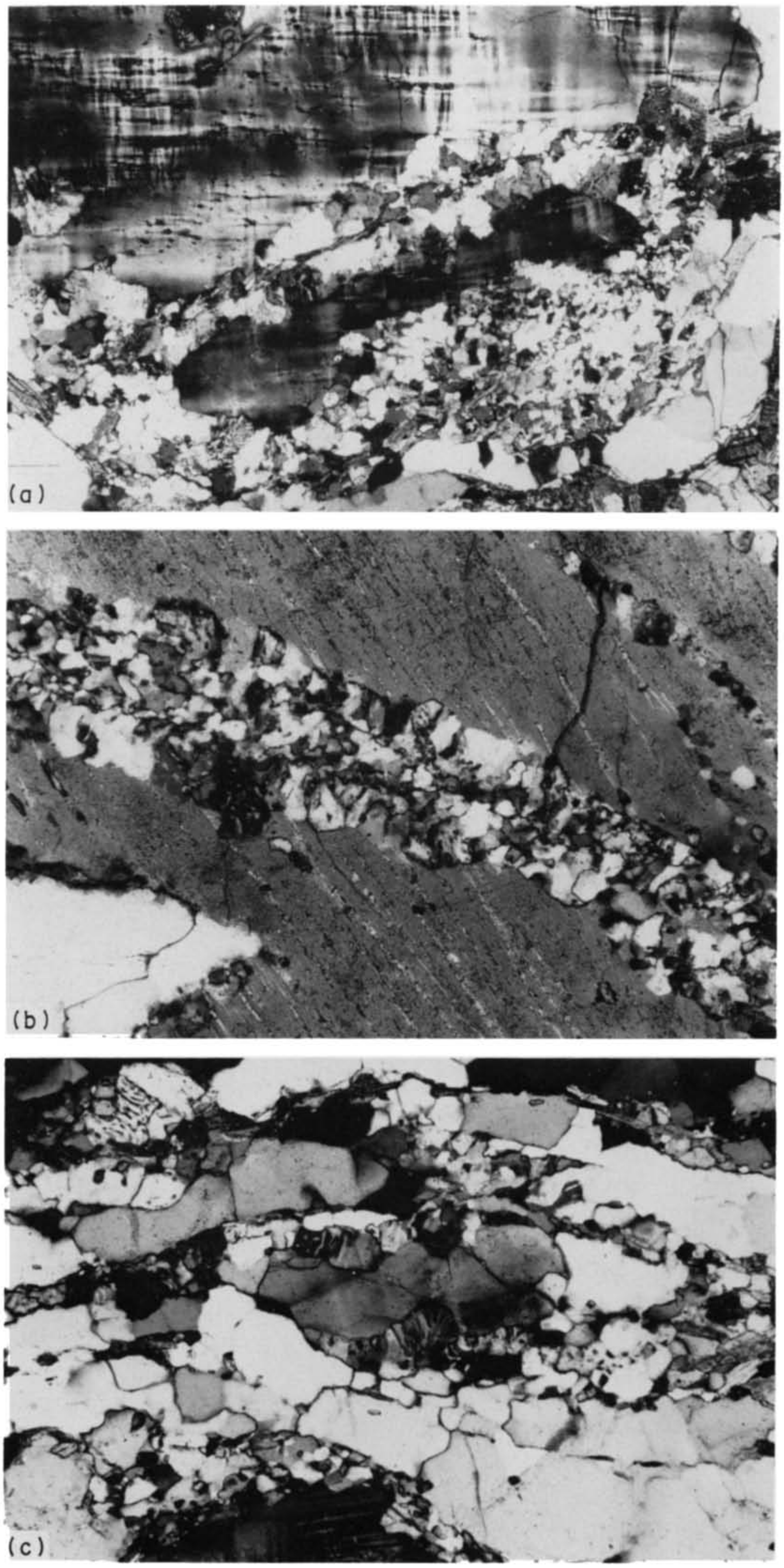

Fig. 2. (a) Replacive fringe of myrmekite along a former fracture in microcline. Papoose Flat pluton, California. Some muscovite also occurs along the fracture, and so the local myrmekite-forming reaction may have involved the production of muscovite (Ashworth 1972; Phillips *et al.* 1972). Crossed polars, base of photograph 2.7 mm. (b) Small lobes of myrmekite fringing a zone of recrystallization along a former fracture in microperthitic K-feldspar, late Jurassic pluton, Foothills terrane, California. Exsolved lamellae of albite in the K-feldspar continue right up to the myrmekite, suggesting that the myrmekite is not of simple exsolution origin. However, muscovite is absent. The central part of the vein is occupied by former myrmekite that has been recrystallized to granoblastic plagioclase and quartz in response to movement along the vein. Crossed polars, base of photograph 1.3 mm. (c) Very small relic of K-feldspar fringed by myrmekite, Papoose Flat pluton, California. Fine-grained folia of recrystallized and partly recrystallized myrmekite lead away into the matrix. Crossed polars, base of photograph 1.3 mm.

also in situations where high compressive stress would be unlikely. Therefore, a question may be asked as to whether strain and consequent recrystallization may prove to be more important than compressive stress in promoting the development of myrmekite. If the published evidence indicating a connection between deformation and the development of myrmekite is accepted, the following three questions are relevant.

IS STRAIN ENERGY A DIRECT, MAJOR CAUSE OF MYRMEKITE GROWTH?

Is strain energy in the form of high concentrations of tangled dislocations (Simpson & Wintsch 1989, p. 271) the main, direct contributing factor to the development of myrmekite or is chemical environment the more direct cause, deformation assisting by promoting access of fluids? Simpson & Wintsch (1989, pp. 269–271) suggested that local increases in strain energy would cause replacement of K feldspar by plagioclase and quartz, via components in a fluid. However, Hanmer (1982) suggested that delicate vermicular intergrowths could not survive much strain, and consequently inferred that myrmekite is post-deformational. For myrmekite fringing K feldspar porphyroclasts, microstructural evidence shows that progressive deformation and neocrystallization destroys myrmekitic intergrowths, converting them to polygonal aggregates of quartz and plagioclase in fine grained folia (Vernon *et al.* 1983, Simpson 1985, Moore 1987), as shown in Figs. 1(b) & (c) and 2(b) & (c). This, combined with other evidence (e.g. Vernon *et al.* 1983, Simpson & Wintsch 1989), suggests that myrmekite in deformed rocks is a product of reactions accompanying deformation and so is syndeformational, not post deformational. However, it also indicates that myrmekite lobes cannot exist (and hence cannot grow) in the high strain environments that occur at the margins of K feldspar porphyroclasts. Instead, they appear to grow by replacement of K feldspar in an environment protected from deformation, the growth occurring at the front of the lobes, where the strain should be minimal, and away from the deforming, recrystallizing edge of the porphyroclast (Figs. 1b & c). In other words, the growth front moves ahead of an advancing front of deformation and recrystallization–neocrystallization that simultaneously destroys the myrmekite behind the advancing lobe, so that the proportion of myrmekite to residual K feldspar tends to increase with progressive deformation (Figs. 1c and 2c). In extreme examples, myrmekite fringes advancing from opposite sides of a K-feldspar porphyroclast may meet, resulting in an aggregate of myrmekite enclosed by matrix folia.

This implies that strain energy is not a direct cause of the *growth* of myrmekite, unless strain energy associated with transformation twins in microcline and/or lamellae of exsolved albite is effective, which possibility is discussed in the next section. Regardless of the foregoing uncertainties, deformation may well be a major *indirect* contributing factor to the growth of myrmekite, by facilitating access of fluids to the growth front, thereby altering the local chemical environment and promoting development of the myrmekite (e.g. Simpson & Wintsch 1989, p. 271), with or without a notable contribution from strain energy. At this stage, the nature of the chemical changes, as well as sources and sinks for chemical components, are matters for modelling (e.g. Simpson & Wintsch 1989), clear evidence being difficult to obtain.

Similar reasoning applies to myrmekite occurring as fringes replacing K feldspar along former fractures in K feldspar (Phillips *et al.* 1972, Vernon *et al.* 1983, pp. 134–135, fig. 6D), as shown in Figs. 2(a) & (b). Some of the myrmekitic lobes are curved, suggesting growth and possible ductile deformation of the aggregates during movement along the fracture. Continued movement along the fracture or former fracture induces deformation and recrystallization of the myrmekite closest to the site of the fracture, the recrystallized aggregates being partly fringed with myrmekite advancing into the undeformed K feldspar (Fig. 2b). Therefore, as for myrmekite fringing porphyroclasts, the growth face of the colony progresses away from the fracture into relatively weakly deformed K feldspar. Indeed, concentration of tangled dislocations in K feldspar adjacent to a fracture is less likely than in K feldspar adjacent to an active folium involving plastic deformation of the margin of the K feldspar in a mylonite or augen gneiss. Again, the inference is that the growth of the myrmekite is not controlled directly by strain energy in K feldspar, though the fracture presumably provided access for fluids that supplied nutrient components for the myrmekite and removed excess components.

The foregoing discussion refers to *growth* of myrmekite. The question of the possible contribution of strain energy to *nucleation* of myrmekite is discussed in the next section.

DOES STRAIN ENERGY ASSIST NUCLEATION OF MYRMEKITE OR DOES HETEROGENEOUS NUCLEATION PREDOMINATE?

Conceivably, strain energy could assist nucleation of the myrmekite, in as much as the aggregates tend to be concentrated adjacent to high-strain zones in felsic mylonitic rocks, as discussed previously. For example, Simpson & Wintsch (1989, p. 271) suggested that high concentrations of tangled dislocations in K-feldspar along boundaries subjected to high normal stress destroy the K-feldspar–plagioclase–quartz equilibrium that pertains elsewhere in the rock and so induce replacement. Though no evidence of the dislocations is available, this mechanism may apply to some or all myrmekite bearing rocks. However, in most myrmekite bearing, mesoscopically non-deformed granitoids, the plagioclase of myrmekitic aggregates is optically continuous with primary plagioclase, implying that the plagioclase component nucleated heterogeneously on existing plagioclase. This also applies to deformed felsic and metapelitic rocks in which myrmekite is in contact with plagioclase. However, can it apply to myrmekite on K-feldspar–K-feldspar grain boundaries or along intragranular fractures in K-feldspar? Sodic plagioclase (locally myrmekitic) in 'swapped rims' along K-feldspar–K-feldspar boundaries, with the same crystallographic orientation as exsolved albite lamellae in the opposite K-feldspar grain, implies that heterogeneous nucleation on plagioclase (in this instance exsolved plagioclase, rather than primary plagioclase) initiated growth of the rim plagioclase. This mechanism could also apply to myrmekite occurring along fractures in microperthitic K-feldspar (e.g. Vernon *et al.* 1983), although recrystallization and growth of muscovite commonly obscure the relationships. In fact, microstructural evidence of the nucleation substrate for myrmekite in deformed rocks is commonly obscured by increasing deformation-recrystallization and/or replacement, and so the question of the contribution of strain energy to nucleation of myrmekite remains unanswered. Observations of optical continuity between myrmekitic and primary quartz in some rocks (Stel & Breedveld 1990) suggest that nucleation on quartz may initiate the growth of some myrmekitic colonies.

In myrmekite-bearing, mesoscopically non-deformed granitoids, the K-feldspar commonly has strain energy at the boundaries of (1) deformation twins caused by the transformation of orthoclase to microcline and (2) semicoherent lamellae of exsolved albite. However, this strain energy in the K-feldspar is inadequate to promote nucleation of myrmekite, because it nucleates at grain or fracture boundaries, rather than inside microperthitic microcline grains.

In summary, a contribution from strain energy may not be necessary for the nucleation of myrmekite in many rocks, in which heterogeneous nucleation on existing primary plagioclase (less commonly quartz) or exsolved plagioclase may be effective.

HOW DOES MYRMEKITE DEFORM AND CONTRIBUTE TO FOLIATION DEVELOPMENT?

In deformed granitoids, myrmekite lobes commonly pass continuously into areas of polygonal (recrystallized) plagioclase and quartz (Fig. 2c), via intermediate stages in which some of the quartz remains as blebs (Vernon *et al.* 1983), owing to progressive recrystallization of myrmekite (Vernon *et al.* 1983, Simpson 1985, Moore 1987). The aggregates pass laterally into fine-grained folia (shear bands) in augen gneisses and mylonitic rocks (Vernon *et al.* 1983, p. 135), as shown in Fig. 2(c). In places, the aggregates curve into the folia, suggesting displacement along the folia during the recrystallization and continued growth of myrmekite (Vernon *et al.* 1983, p. 135, Simpson 1985, Simpson & Wintsch 1989, p. 264). In some rocks, the myrmekite recrystallizes more readily than most of the other minerals and is one of the main contributors to the development of folia (Vernon *et al.* 1983). The questions may be asked, is this ability connected with its fine grain size, and, if so, does the large interfacial area of the myrmekitic intergrowth allow fluids to penetrate and promote boundary movement during recrystallization?

CONCLUSIONS

Several somewhat controversial questions relevant to the development of myrmekite in deformed felsic and metapelitic rocks remain unanswered. Though a relationship between myrmekite and deformation has been established and an ingenious model relating strain and chemical reaction has been proposed (Simpson & Wintsch 1989), it is not yet clear that these relationships extend to myrmekite in mesoscopically non-deformed granitoids, although it is a possibility. In addition, the exact nature and degree of the contribution of lattice strain energy to the nucleation and growth of myrmekite remains to be clarified. The fact that myrmekite grows into relatively non-deformed K-feldspar, while being simultaneously deformed and recrystallized at the rear of the growing lobes, suggests the possibility that strain energy may not be a major contributor to the advance of the growth interface of the myrmekite colony. Furthermore, the fact that myrmekite typically nucleates on existing plagioclase (primary or exsolved), rather than inside K-feldspar—even in microperthitic microcline, which should have some internal strain energy, owing to the presence of deformation twins and exsolution lamellae—suggests that strain energy may not contribute directly to nucleation of myrmekite either, at least in many instances. However, deformation appears to contribute indirectly, by facilitating access of fluids to growth sites, thereby altering the local chemical environment and promoting the development of myrmekite. Myrmekite appears to recrystallize relatively readily in deformed felsic rocks, and so is one of the main contributors to the development of folia. Myrmekite is being increasingly recognized in deformed felsic and metapelitic rocks; perhaps some of them will reveal answers to the questions posed in this paper.

Acknowledgements—I thank Scott R. Paterson and Robert P. Wintsch for helpful comments. The work was financed by Australian Research Council Grant No. A38415716 and a U.S.-Australia Bilateral Science and Technology Grant.

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