Myrmekite replacing albite in prograde metamorphism

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ABSTRACT

In pelites from the central Menderes massif, Turkey, myrmekite partly or completely replaces albite in rocks that had developed, at a slightly earlier stage of metamorphism, two plagioclases coexisting across the peristerite gap. The quartz proportion in the myrmekite is consistent with the Al and Si immobility theory of myrmekite origin. This requires exchange of Ca for Na with the rest of the rock: $(1 + x)NaAlSi_3O_8 + xCa^{2+} \rightarrow Na_{1-x}Ca_xAl_{1+x}Si_{3-x}O_8 + 4xSiO_2 + 2xNa^+$. Myrmekite produced by prograde replacement of albite has the same properties, and develops under the same controls, as myrmekite produced by retrograde reaction from K-feldspar. Poikiloblastic oligoclase containing blebby quartz may often represent coarsened myrmekite. Myrmekite is important as an indicator of Al and Si immobility in a variety of petrological environments.

INTRODUCTION

Myrmekite is the commonest example of a symplectite, i.e., an intergrowth of minerals the mutual boundaries of which are approximately perpendicular to a reaction interface that moved as the intergrowth formed. The constitution of myrmekite is simple and comprises plagioclase intergrown with a smaller amount of quartz, the latter having a rodlike or wormlike morphology. As a basis for understanding symplectites in general, it is important to understand the origin of myrmekite in its various petrological settings. The study of myrmekite has a long history, reviewed by Phillips (1974). Myrmekite resembles some textures that arise from crystallization of melts (rod eutectics), and in granitic rocks Hibbard (1979) has proposed a melt-grown origin. On the other hand, definitely magmatic quartz-feldspar intergrowths (graphic and granophyric textures) are usually distinguishable from myrmekite (Barker, 1970). It is also found in metamorphic rocks (Phillips, 1980a), including metasedimentary ones in which a magmatic origin is ruled out (Nold, 1984). Ashworth (1976) has inferred that replacement of K-feldspar by myrmekite is part of a reaction that also consumes residual melt in migmatites.

Myrmekite is usually found adjacent to K-feldspar; Phillips (1974) has incorporated this spatial association into his definition of myrmekite. The intergrowth often has a convex boundary toward the K-feldspar, suggesting that it formed from that mineral. Both exsolution and replacement will produce myrmekite from K-feldspar if Al and Si are immobile relative to other cations (Ashworth, 1972). Exsolution in a closed system ("Schwantke hypothesis") and metasomatic replacement ("Becke hypothesis") are thus endmembers of a continuum of mixed reactions in which myrmekite is produced, and in this sense myrmekite is polygenetic (Phillips, 1980b). If Al and Si are quantitatively retained as K-feldspar is made

over to myrmekite, the proportion of quartz in the intergrowth is a function of the plagioclase composition: the relationship is identical for exsolution (Phillips and Ransom, 1968) and for replacement, as shown by Ashworth (1972). Some of the Si segregates from the Al by counterdiffusion within the reaction interface. Carstens (1967) pointed out that this myrmekite-forming interface is incoherent, i.e., there is no crystallographic continuity across it. The formation of the integrowth is analogous to duplex cell growth in metals (Yund and McCallister, 1970).

Both of the recognized metamorphic myrmekite-forming processes (by replacement of and exsolution from K-feldspar, respectively) are retrograde. The replacement process is usually part of a hydration reaction that produces mica in addition to the plagioclase and quartz (Phillips et al., 1972; Ashworth, 1972). K-feldspar may be completely replaced (Ashworth, 1972, Fig. 1b). It has been suggested that the former presence of K-feldspar can be inferred in polymetamorphic rocks by the detection of coarsened myrmekite (Ashworth, 1979).

Myrmekite is reported by Cooper (1972) in metamorphic rocks without K-feldspar, from relatively low grades (associated with the crest of the peristerite gap); Cooper (1972) and Shelley (1973) interpreted these occurrences in terms of prograde reactions. Cooper (1972) proposed a reaction between clinozoisite and albite, producing anorthite component and excess silica, but this does not explain the intimate (symplectic) intergrowth. Shelley (1973, p. 336) found a lack of textural indication that clinozoisite had reacted. He also observed great variations in the quartz proportion in the myrmekite, which grades into normal poikiloblastic oligoclase. Noting that both Schwantke and Becke hypotheses in their classical form require K-feldspar as a precursor to myrmekite, Shelley (1973) favored an alternative interpretation, in which preexisting quartz was supposed to recrystallize with an elon-
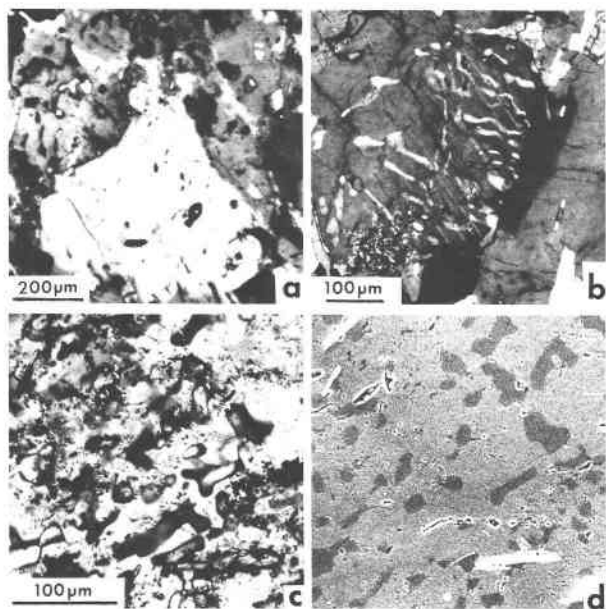
Fig. 1. Myrmekites in pelites from the central Menderes massif. (a)–(c) Transmitted light, crossed polars; (d) back-scattered electron SEM image. (a) Plagioclase with quartz blebs (top left and top right), showing convex boundary toward albite (center). At the top left, the quartz blebs are clearly elongate, so the intergrowth is classified as myrmekite. (b) Clear example of myrmekite (center), in contact with relict albite (in extinction). Nonmyrmekitic oligoclase occurs at the right, and at the top left where it is overgrown by the myrmekite. (c) Confused contrast due to overlap of quartz and plagioclase within the thin section. Dark specks are thought to be graphite, on the basis of the reflected-light properties of the few that are large enough to be identified. (d) BSE-mode SEM photograph of the same area as in (c), showing surface outcrop of quartz (darker gray) and oligoclase (lighter gray). The bright mineral is biotite. Black areas with bright edges are holes in the polished surface. This is the type of image used in the quantitative work to determine the quartz proportion.

gation parallel to the growth direction of the enclosing feldspar. Because of the absence of K-feldspar, Phillips (1973, 1974) did not regard these examples as being myrmekite although their internal features are indistinguishable from classical myrmekite, except perhaps that the quartz rods tend to be coarser (Shelley, 1973).

In this paper, plagioclase-quartz intergrowths are described from another area associated with the peristerite gap and lacking K-feldspar. It is shown that the intergrowths have all the features of true myrmekite and can be attributed to the same fundamental control that produces myrmekite from K-feldspar, the only difference being that the mineral replaced is albite.

REGIONAL SETTING

The rocks studied are pelites from the central Menderes massif, Turkey. As described by Ashworth and Evirgen (1985), the sequence of metamorphic zones developed is garnet, staurolite, staurolite + kyanite, and kyanite. Plagioclases coexisting across the peristerite gap are observed

up to staurolite + kyanite grade (Ashworth and Evirgen, 1985). The reason for development of assemblages of relatively high metamorphic grade compared with other areas (in which the peristerite gap closes in the garnet zone; e.g., Cooper, 1972) appears to be that a_{H_2O} was low, in the presence of graphite (Ashworth and Evirgen, 1985). The specimens studied here come from the part of the staurolite + kyanite zone mapped by Ashworth and Evirgen (1985, Fig. 1). No granitic intrusions are found nearby. Temperature estimates in the range 520–600°C for this zone (Ashworth and Evirgen, 1985) are obtained from garnet-biotite geothermometry using the calibration of Hodges and Spear (1982).

PLAGIOCLASE TEXTURES AND COMPOSITIONS

In many pelites from this area, at grades approximating the crest of the peristerite gap, oligoclase contains ovoid blebs of quartz with dimensions 10–50 μm (Fig. 1a), distinctly smaller than the quartz grains in the surrounding matrix (which are >100 μm in size). Other oligoclase grains contain groups of small flakes of mica, mostly muscovite. Some of the quartz inclusions are elongate (Fig. 1a); where clearly rodlike, they occur as subparallel swarms so that the intergrowth has the internal characteristics of myrmekite (Fig. 1b). To further characterize the plagioclase-quartz intergrowth, three rocks were studied in detail. These are pelites, with the assemblage quartz-plagioclase-biotite-muscovite-chlorite-garnet-staurolite-kyanite. They are homogeneous schists with no migmatization or veining.

Two of these specimens contain small amounts of albite, in addition to oligoclase, which occurs as two textural varieties (with and without quartz rods). There are gradations, with optical continuity, between the two kinds of oligoclase, but both have sharp boundaries against albite (Fig. 1b). Where there is any definite curvature to the boundary between albite and quartz-bearing oligoclase, this is convex toward the albite (Fig. 1a). The coarseness of quartz rods is typified by Figure 1a, but in a few examples, they are thinner in one part of the oligoclase grain, always the part adjacent to albite (Fig. 1b). In previous studies, this fining of quartz toward the interface has often been observed in myrmekite adjacent to K-feldspar (Phillips, 1974, p. 182). Where relatively coarse (Figs. 1a, 1c), the quartz rods tend to be discontinuous, being transitional in shape toward the quartz blebs in poikiloblastic oligoclase.

Plagioclase compositions were estimated in mole percent from electron-microprobe analyses for Na, Ca, and K. Albite is approximately $An_{0.8}$. Adjacent quartz-free plagioclases are approximately An_{13-16}. In these two specimens, plagioclases with quartz rods are in the range An_{16-23}. The third specimen lacks albite but has abundant oligoclase with and without quartz rods, both having approximately the same composition range (An_{18-23}). Figure 2 illustrates the relatively calcic nature of the quartz-bearing oligoclases relative to the peristerite gap (estimated in
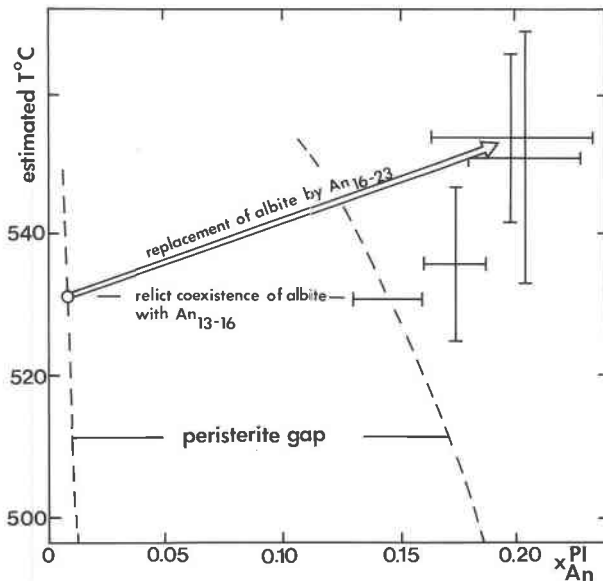
Fig. 2. Observed ranges of myrmekitic plagioclase composition in three specimens plotted against temperature, estimated from garnet-biotite geothermometry by the method of Hodges and Spear (1982). Garnet-rim compositions being rather constant, the plotted ranges of temperature arise from variations in matrix biotite composition (cf. Ashworth and Evirgen, 1985).
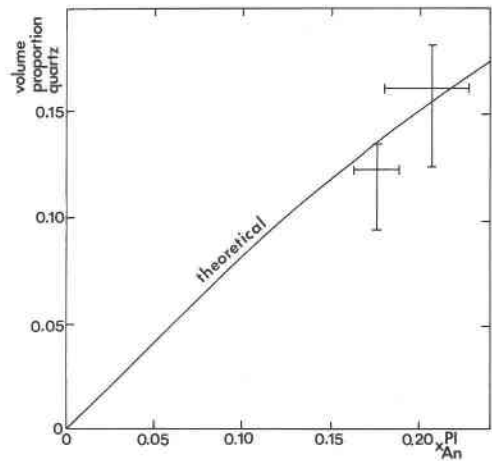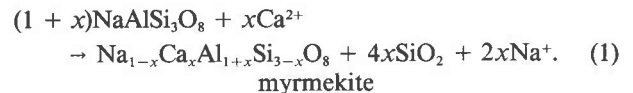

Fig. 3. Means and ranges of the estimated volume proportion of quartz in two specimens, plotted against means and ranges of plagioclase composition measured in the same areas of myrmekite. The theoretical curve refers to Al and Si immobility.

the same area from specimens lacking oligoclase-quartz intergrowths).

PROPORTION OF QUARTZ

In transmitted light between crossed polars, thin-section areas in which quartz and plagioclase are superimposed make it impossible to determine their proportions accurately (Fig. 1c). It is likely that the proportion of quartz has been overestimated in optical studies (Barker, 1970). A surface imaging technique is required. It would be possible to stain the feldspar, but transmitted-light images would still be confused by unwanted detail from below the stained surface. The obvious solution is backscattered electron (BSE) imagery of polished surfaces, which gives atomic-number contrast. Ashworth (1972) used this technique rather crudely, in an electron microprobe. The method has become technically easy with the advent of semiconductor detectors, designed for BSE imaging in the scanning microscope (SEM), together with suitable electronics to manipulate the contrast (Hall and Lloyd, 1981). The mean atomic number $\bar{Z}$ of sodic plagioclases is close to that of quartz; the difference from quartz, $\Delta\bar{Z}$ increases in more calcic oligoclases. Figure 1d shows that adequate contrast is obtained between quartz and oligoclase of approximately An_{21} composition, where $\Delta\bar{Z} \approx 0.17$; in high-contrast prints, quartz was distinguished from An_{16}, in which case $\Delta\bar{Z} \approx 0.10$, close to the practical limit for discriminating between phases by this technique (Hall and Lloyd, 1981, p. 363).

BSE micrographs were obtained from the two specimens with the most abundant plagioclase-quartz intergrowths.

For quantitative measurement, in each specimen, five areas of $4-7 \times 10^4$ μm^2 (roughly 0.5-1 times the area in Fig. 1d) were selected on the criterion that quartz appeared evenly distributed. Even so, it is possible that small areas of quartz-free oligoclase were accidentally covered or, conversely, that quartz may be overestimated by encountering chance inclusions of quartz not truly belonging to the intergrowth. The photographs were digitized, and areas of minerals were computed in the manner of Mongkoltip and Ashworth (1983, p. 645). Inclusions other than quartz (e.g., biotite, Fig. 1d) were subtracted from total areas. The areal proportion was then taken as the estimate of volume proportion of quartz in an intergrowth. The results are summarized in Figure 3, in which the theoretical curve is for quantitative retention of Al and Si in the reaction

$$(1 + x)NaAlSi_3O_8 + xCa^{2+}$$
$$\rightarrow Na_{1-x}Ca_xAl_{1+x}Si_{3-x}O_8 + 4xSiO_2 + 2xNa^+. \quad (1)$$
$$\text{myrmekite}$$

Since the Ca content of the albite is negligible, the theoretical curve is the same as that for the production of myrmekite from $KAlSi_3O_8$ and is given by Equation 1 of Ashworth (1972).

INTERPRETATION

In view of the possible sources of error outlined above, the agreement between observed quartz proportions and theory is reasonable (Fig. 3). Unfortunately, it is not possible to test for systematic dependence on plagioclase composition, since the range of oligoclase compositions in the rocks is restricted. Nevertheless, the data support the interpretation of the plagioclase-quartz intergrowths in terms of Al and Si immobility, exactly as in the case of myrmekite formed from K-feldspar (Ashworth, 1972). Since

the textural features also agree with those of classical myrmekite, it would be unreasonable to use a different name for the present intergrowths; they are myrmekite formed from albite, as distinct from the commoner occurrences of myrmekite formed from K-feldspar.

In cases with K-feldspar as precursor, it is often difficult to distinguish exsolution from replacement myrmekites, and the two processes can occur simultaneously (Ashworth, 1972; Phillips, 1980b). In the present case, exsolution can be ruled out; only tiny proportions of oligoclase could unmix from the observed albites, whereas the myrmekite-forming process has removed albite altogether from some rocks. This is clearly a replacement effect, and a particularly simple one in which one mineral is replaced by a two-mineral symplectite at approximately constant Al and Si, according to Reaction 1.

In these specimens, nonmyrmekitic oligoclase and albite are interpreted as representing a relict coexistence across the peristerite gap (Fig. 2). The geothermometry indicates a prograde myrmekite-forming reaction (Fig. 2) in which albite is replaced as the peristerite gap ceases to operate. However, the overall effect on plagioclase composition is not simply to homogenize it at a Ca content intermediate between those coexisting at the gap. The new plagioclase is more calcic than the range spanned by the relict, coexisting ones (Fig. 2). The specimen without albite, and with compositions around An_{20} in both myrmekitic and nonmyrmekitic plagioclase, represents an advanced stage of this evolution. Thus a source of Ca is implied. It is likely that a calcic mineral in the rocks was consumed. Though there is no epidote-group mineral in the present assemblage, it is plausible to speculate that one was formerly present and broke down by prograde dehydration as the myrmekite was forming (it is possible that the plagioclase with muscovite inclusions represents relict Al-rich domains where this mineral was situated). Thus some overall reaction can be envisioned that is similar to that proposed by Cooper (1972) (though this still does not describe the reaction completely): albite + clinozoisite → anorthite component + quartz + Na_2O + H_2O. The production of quartz by an overall reaction of this kind is not the reason for the occurrence of myrmekite; the quartz in the myrmekite results from local conservation of Al and Si in the partial reaction affecting the reactant albite volume.

It is interesting that coarsening of quartz rods away from the reaction interface is observed here in the prograde case (Fig. 1b) as well as being common in the retrograde case (Phillips, 1974). This suggests that the effect is not due to any change in reaction kinetics with changing temperature (which would be expected to produce opposite effects in the two cases), but may simply be due to coarsening of quartz in already-formed myrmekite while the reaction was still producing fine quartz rods at the advancing interface. The simplest interpretation of the coarsening process is Ostwald ripening, in which larger particles (of quartz in this case) grow at the expense of smaller ones; interfacial free energy will also be reduced by loss of elongation of quartz. Spatial fluctuations in the quartz proportion will arise. In the present area, the common oligoclase with ovoid quartz blebs is interpreted as coarsened myrmekite.

CONCLUSIONS

The myrmekite described here is clearly of metamorphic origin, since the rocks are metasedimentary with no sign of granitic injection and the inferred temperatures are too low for anatexis. This myrmekite, replacing albite as a result of prograde metamorphism, formed under exactly the same controls as myrmekite replacing (or exsolving from) K-feldspar under retrograde conditions. It is possible that myrmekite may be discovered replacing yet other minerals that have lower Al/Si ratios than the product plagioclase.

Where replacement of the reactant mineral is complete, myrmekite after albite might be confused with myrmekite after K-feldspar, but they may be distinguishable by occurrence in different metamorphic settings. In pelites, K-feldspar is abundant only when the prograde muscovite-quartz dehydration reaction has operated; retrograde replacive myrmekite is then produced by the reverse of that reaction: K-feldspar + Al_2SiO_5 + H_2O → muscovite + quartz + plagioclase, where the quartz and plagioclase occur partly as myrmekite. K-feldspar is particularly thoroughly removed where this reaction is coupled with crystallization of residual melt, as in some migmatites (Ashworth, 1976). Complete replacement of K-feldspar is therefore expected mainly in the upper amphibolite facies, whereas the prograde replacement of albite described in this paper is characteristic of the greenschist-amphibolite facies transition.

Retrograde myrmekite is often well-preserved, because reaction was short-lived: obscure, coarsened varieties reflect complex metamorphic histories (Ashworth, 1979). Prograde myrmekite, on the other hand, is expected to be coarsened as a general rule. The present examples occur where the climactic metamorphic temperatures were those at which the myrmekite was produced. Any further heating would obscure the myrmekite texture. This consideration explains the apparent rarity of prograde myrmekite. Many examples of poikiloblastic oligoclase, in which the inclusions are quartz blebs, may have originated as myrmekite, and it may prove possible to recognize some examples in the light of the present study.

Myrmekite forms because Al and Si are inherited from the reactant mineral. These elements have also been shown to control the development of another symplectite (Mongkoltip and Ashworth, 1983). Of course, Al and Si will not invariably be immobile. Not all symplectites contain Al and Si, and even where both elements are present, it seems possible that others control the texture if segregation of the Al and Si is unimportant [as in the pyroxene-exsolution reaction studied by Boland and Otten (1985)]. However, immobility of Al and Si appears to be common, as indicated by the commonness of myrmekite itself. Immobility here refers to a restricted range of segregation in

the reaction interface, over distances that are reflected in the spacing of the quartz rods as they form at this interface. The transport mechanism is a variety of grain-boundary diffusion (Yund and McCallister, 1970), and different transport kinetics will operate in a fluid phase (which may be present in the same rocks where the myrmekite is growing). Nevertheless, where myrmekite (or another Al- and Si-controlled symplectite) occurs, slow diffusion of Al and Si is a constraint that should be valuable in interpreting other features of the rock, such as zoning and reaction textures. Myrmekite is a clear indicator of restricted diffusion range of Al and Si.

ACKNOWLEDGMENTS

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