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Flame perthite in metapelitic gneisses at Cooma, SE Australia

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ABSTRACT

Flame perthite occurs locally in high-grade migmatitic gneisses of pelitic composition at Cooma, SE Australia. It is developed best in leucosomes and rocks in which cordierite is largely unaltered. Such rocks are inferred to have been stronger than more-altered rocks, causing local stress concentrations sufficient to promote the nucleation of flames. The variability in the abundance of flames could be due to variability in stress concentrations in relation to orientation of the microperthite grains, if the Pryer-Robin model for flame perthite is applicable to these rocks.

Possible sources of Na are (1) release of Na as cordierite and potassium feldspar were replaced by biotite-andalusite-quartz symplectite at upper amphibolite-facies conditions and (2) release of Na as microperthite was replaced by muscovite. Both these reactions appear to have occurred at amphibolite-facies conditions, because late fibrous sillimanite has replaced all minerals, including myrmekite, albite flames, and much of the muscovite; conceivably some muscovite that has not been replaced by sillimanite may have formed at greenschist-facies conditions. Alteration of plagioclase does not appear to have been a major source of Na for the flames, because plagioclase is absent from many of the Cooma metapelitic rock and, where present, is unaltered.

INTRODUCTION

This paper is concerned with the occurrence of flame perthite in high-grade metapelitic gneisses in the Cooma Complex, southeastern Australia. It discusses the possible effects of stress on development of the flames and possible sources of Na.

Pryer and Robin (1995, 1996) proposed an elegant model for the origin of flame perthite during the deformation of granitoid rocks at greenschist-facies conditions involving high differential stress and a relatively dry situation. The albite flames grow by replacement of potassium feldspar through alkali exchange, without a nucleation step. The Na is released from plagioclase during reaction to form muscovite (Ca entering epidote), while the K for muscoide is provided by the replacement of potassium feldspar by albite, in a set of linked or cyclic reactions. The albite flames generally grow parallel to the normal perthite crystallographic plane (the Murchison plane), which is the orientation of least lattice misfit between potassium feldspar and albite.

Pryer and Robin (1996) observed flames preferentially oriented approximately normal to S planes in S/C mylonites, indicating that the flames grew parallel to the local $\sigma 1$. They inferred that if a potassium feldspar grain is oriented with its Murchison plane approximately parallel to $\sigma 1$, replacement by albite can proceed, owing to reduction of the lattice misfit between potassium feldspar and albite by compression parallel to the Murchison plane. Grains in other orientations should not develop flame perthite.

Pryer and Robin (1996) noted that grain-scale stress perturbations should be expected, owing to the strength of the feldspar. For example, they observed higher concentrations of albite flames at points of stress concentration along boundaries where potassium feldspar is close to other feldspar grains (see in Fig. 1b, Pryer and Robin 1996).

METAPELITIC GNEISSES AND MIGMATITES

A "regional aureole" sequence of low-pressure/high-temperature metamorphic zones occurs adjacent to the Cooma Granodiorite in south-eastern New South Wales, Australia (Joplin 1942; Hopwood 1976; Johnson et al. 1994; Johnson and Vernon 1995). The rocks are mainly metapelites and interbedded metapsammites. The highest-grade metapelites are migmatitic gneisses consisting of quartz, potassium feldspar, cordierite, andalusite, sillimanite, and biotite. Plagioclase is commonly absent from the metapelitic rocks, but occurs rarely in some rocks as independent grains or inclusions in potassium feldspar. Myrmekite may or may not occur at the plagioclase–potassium feldspar grain boundaries.

Late reactions are common, and include (1) local growth of muscovite in potassium feldspar, biotite, and cordierite; (2) replacement of cordierite by symplectic intergrowths of biotite, andalusite, and quartz (Vernon 1978; Vernon and Pooley 1981); (3) replacement of potassium feldspar by sodic plagioclase in the form of myrmekite and flames in microperthite; and (4) local replacement of all minerals (including the retrograde muscovite, flames, and myrmekite) by fibrous sillimanite

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(Vernon 1979). All these reactions appear to have occurred at amphibolite-facies conditions, as suggested by the late sillimanite. However, some of the muscovite that is not replaced replaced by sillimanite conceivably could have grown at greenschist-facies conditions.

Generally the high-grade rocks are "bedded migmatites," in which the leucosome has remained in the metapelitic beds and which do not appear to have undergone strong deformation. However, migmatites closer to the Cooma Granodiorite are mostly stromatic, locally with high-strain zones. Retrograde muscovite is abundant in the these higher-strain rocks.

Potassium feldspar appears in the metamorphic assemblage at the cordierite –potassium feldspar isograd and is soon joined by andalusite and eventually fibrous sillimanite (e.g., Johnson et al. 1994; Johnson and Vernon 1995; Vernon and Johnson 1999). Initially the potassium feldspar is weakly to non-perthitic, and is devoid of albite flames and rims. However, all these features begin to appear very locally in rocks with incipient leucosome, which occurs as small patches. Initially, the exsolution lamellae are patchy (possibly suggesting strain assistance in the exsolution) and, in rare rocks, rim albite is present even though exsolution lamellae appear to be absent. However, at slightly higher grade and in the higher-grade part of the migmatite zone adjacent to the Cooma Granodiorite (Johnson et al. 1994; Vernon and Johnson 1999), potassium feldspar is generally microperthitic and rim albite is abundant, although flames are generally few and local.

Flame perthite is abundant locally in the high-grade rocks. It is best developed in coarser-grained quartzofeldspathic rocks, especially leucosomes and rocks with coarse-grained cordierite that has not been replaced extensively by symplectite. Rocks rich in the fine-grained symplectic aggregates replacing cordierite—the typical Cooma "mottled gneisses" (e.g., Joplin 1942; Hopwood 1976; Vernon 1978; Johnson et al. 1994)—generally contain optically non-perthitic potassium feldspar, uncommon rim albite, and rare flames.

Metapsammitic rocks ("banded gneisses") interbedded with the "mottled gneisses" contain plagioclase. They have been extensively recrystallized and contain abundant myrmekite, but flame perthite is rare to absent.

Where stromatic migmatites begin to appear (closer to the Cooma granodiorite than most of the bedded migmatites), the rocks are more strongly deformed and tend to be richer in muscovite, probably owing to increased fluid activity in this area. In these rocks, the potassium feldspar shows more irregular exsolution lamellae, some rim albite, and much more abundant "normal" myrmekite, especially in rocks with more abundant plagioclase. Flames are locally abundant in some rocks, but commonly are absent. Very local microcline twinning may be developed in the potassium feldspar, reflecting deformation (Eggleton and Buseck 1980). The absence of microcline twinning at lower grades (but still in the high-grade zones) may suggest that those rocks were not as strongly deformed, which correlates with the fact that their leucosomes mostly have remained in the metapelite beds in which they were generated (Vernon and Johnson 1999).

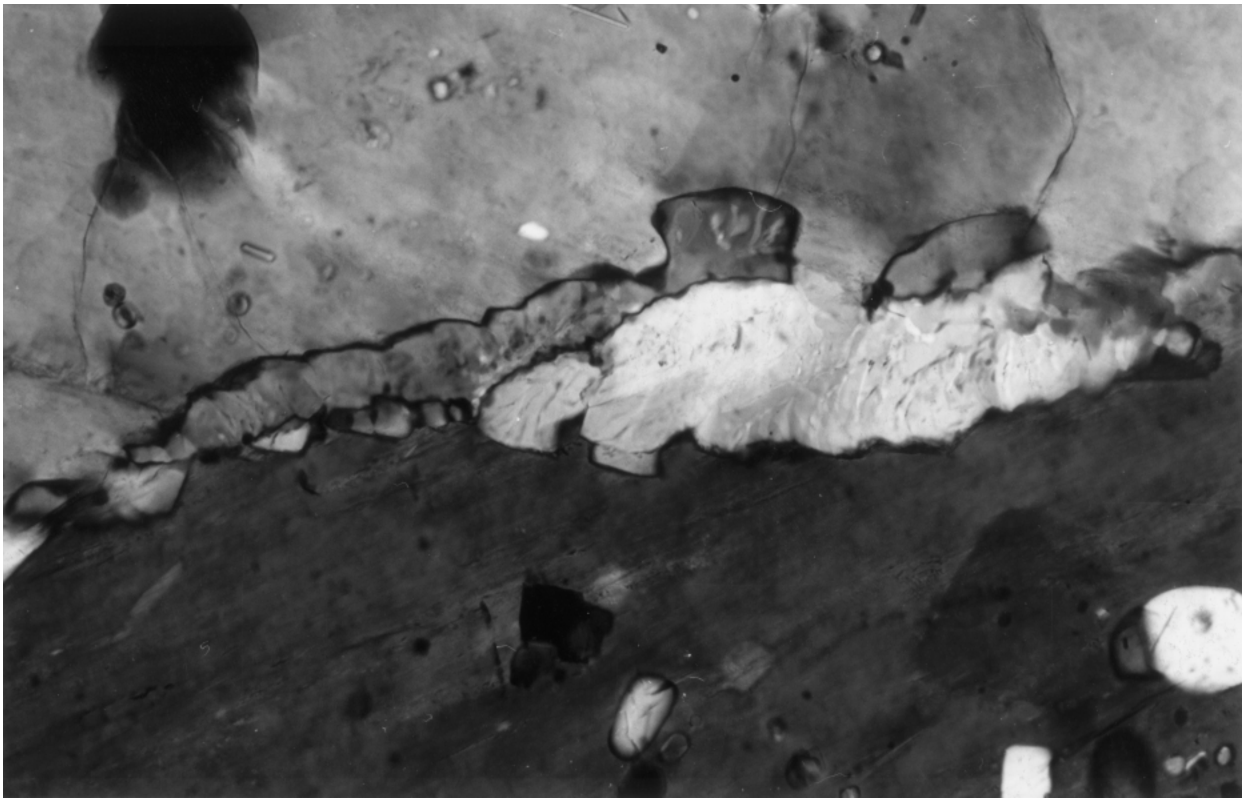

FIGURE 1. Lobes and more continuous rims of myrmekitic plagioclase along microperthite grain boundaries. The orientations of the plagioclase in the myrmekite and the microperthite lamellae indicate that these are "swapped rims." Crossed polarizers; base of photo = 0.7 mm.

COOMA GRANODIORITE

In the Cooma Granodiorite, plagioclase is abundant, providing a substrate for the nucleation of myrmekite, which is of the normal type. This also applies to incipient injection of material resembling the Cooma Granodiorite in high-strain zones in the migmatites (Vernon and Johnson 1999). Some of the myrmekite appears to have grown with muscovite in these rocks, presumably in response to release of Na during the replacement of alkali feldspar by retrograde muscovite (Ashworth 1972; Phillips et al. 1972), in conjunction with retrograde breakdown of plagioclase. Although irregular albite exsolution lamellae are common, flames are generally absent from these rocks, perhaps because the deformation and extensive recrystallization of quartz, feldspar, and mica, probably assisted by water, accommodated the strain and did not allow local stress concentrations to develop sufficiently for flames to nucleate (see below).

MYRMEKITIC RIM ALBITE

Sodic plagioclase occurs typically as lines of lobes along microperthite grain boundaries (Fig. 1) and locally as more continuous rims (Figs. 1 and 3). Mostly it is myrmekitic, but not invariably. The lobes project into and evidently have replaced the microperthite. Some have planar terminations suggestive of crystal faces. ”Swapped rims” (Voll 1960, p. 523–524) are typical, the sodic plagioclase having nucleated on albite exsolution lamellae of the opposite microperthite grain (Voll 1960), as shown in Figure 1. The myrmekitic plagioclase is very fine-grained (much finer-grained than normal myrmekite), but the refractive indices of the quartz blebs are always higher than those of the enclosing plagioclase in all orientations, indicating that the plagioclase is very sodic, approaching or within the albite range.

Generally rim albite with swapped rims and relatively wide albite lamellae, such as flames, are regarded as having formed by the action of deformation and/or fluids on alkali feldspar that had previously undergone normal solid-state (closed-system) exsolution (Smith and Brown 1988, p. 560–561). This interpretation is consistent with observations on the Cooma rocks.

Some rocks with primary plagioclase contain more coarsely vermicular myrmekite, which has nucleated on the plagioclase in the usual way. However, normal myrmekite may be absent from the plagioclase-bearing rocks, although rim albite is invariably present. This suggests that the rim albite is of local origin (i.e., within the host potassium feldspar grains), even if external water was involved, whereas the normal myrmekite may have needed an outside source of Ca (e.g., Simpson and Wintsch 1989).

FLAME PERTHITE

In rocks with flame perthite, the microperthite (Fig. 2) occurs as large, irregular grains with abundant inclusions of quartz, biotite, zoned plagioclase and, less commonly, cordierite. The microperthite contains albite lamellae of two types: (1) very narrow, semi-parallel lamellae, inferred to be of exsolution ori-

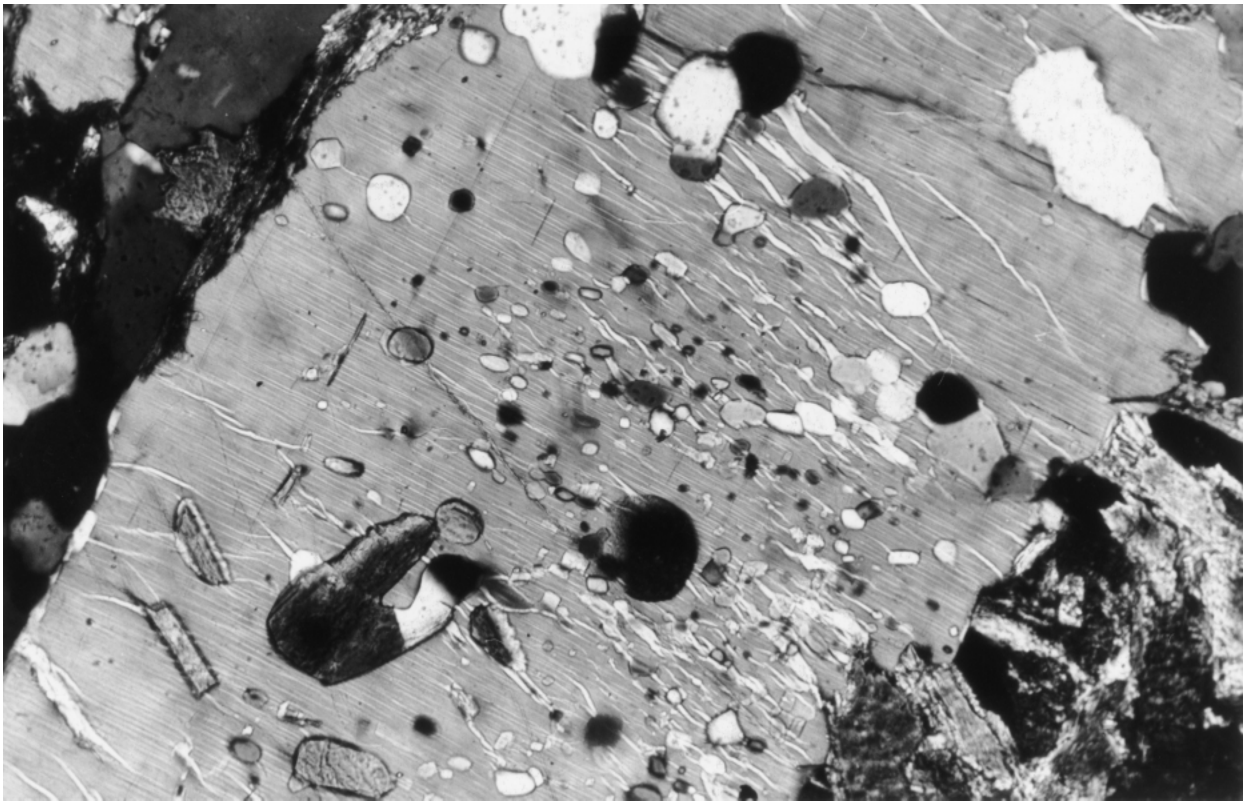

FIGURE 2. Microperthite with thin, parallel exsolution lamellae and less-regular, commonly wider, commonly transgressive albite flames, some of which appear to have nucleated on inclusions of quartz, plagioclase, and biotite in the microperthite. Crossed polarizers; base of photo = 1.75 mm.

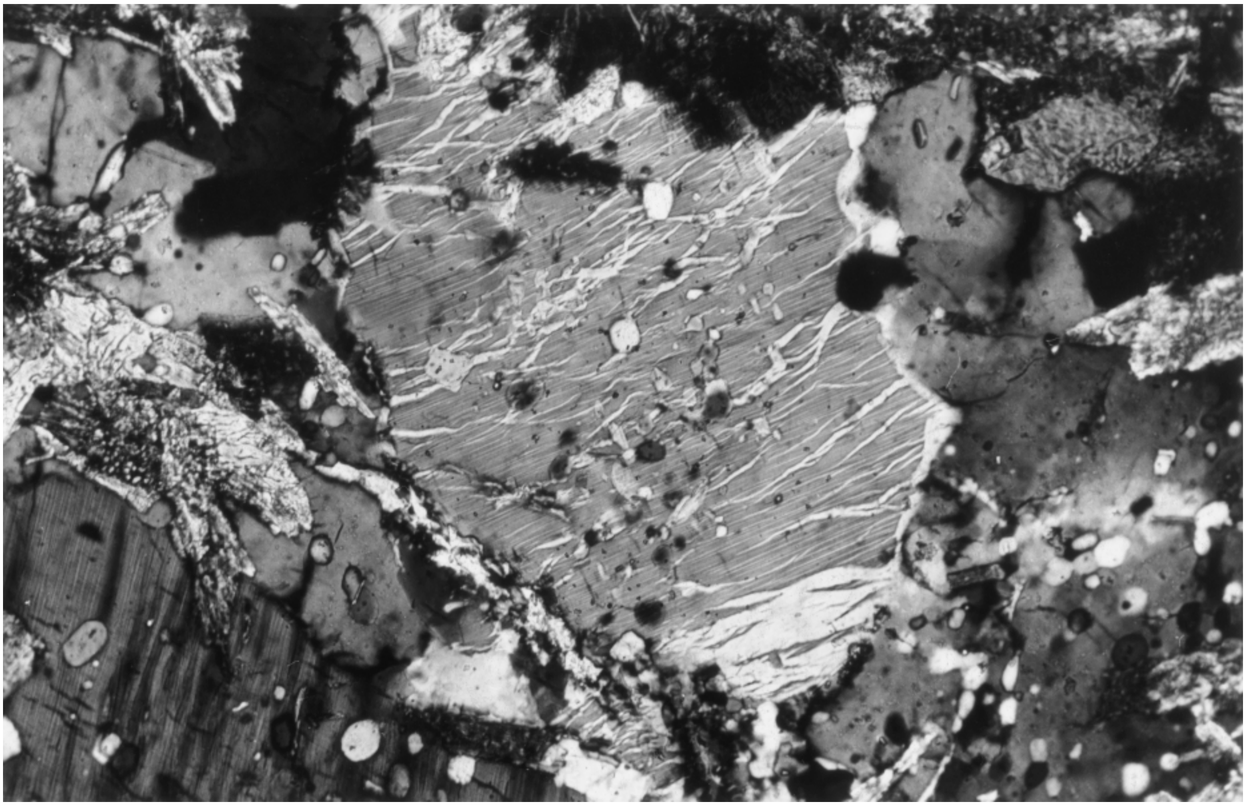

FIGURE 3. Microperthite with thin, parallel exsolution lamellae and less-regular, commonly wider, commonly transgressive albite flames, some of which have the same optical orientation as albitic rims on the microperthite. The flames are very variable in abundance, so much so that the bottom end of the original microperthite grain is largely albite. Crossed polarizers; base of photo = 1.75 mm.

gin, and (2) flames roughly parallel to the exsolution lamellae, but commonly transgressing them. In rocks with flame perthite, all the potassium feldspar grains observed (where orientation permitted) have exsolution lamellae, but some are devoid of flames. The flames vary greatly in abundance within and between potassium feldspar grains (Figs. 2 and 3), parts of some grains consisting mainly of albite, whereas others are mainly potassium feldspar (Fig. 3). Some flames pass into veinlets that are markedly transgressive to the exsolution lamellae, whereas others pass into exsolution lamellae. The flames commonly nucleated on grain boundaries or on inclusions in the microperthite (Fig. 2). Some flames appear optically to be zoned.

POSSIBLE EFFECTS OF STRESS ON THE FORMATION OF FLAMES

As mentioned above, flame perthite is rare where cordierite has been replaced extensively by symplectic aggregates of biotite, andalusite, and quartz. The symplectite aggregates preferentially accumulate strain, forming foliated aggregates, probably owing mainly to their finer grain size.

The flames are best developed in quartzofeldspathic rocks, such as leucosomes and rocks with coarse-grained cordierite that has not been replaced extensively by symplectite. These rocks tend to be more resistant to deformation, as shown, for example, by the common occurrence of leucosome as boudins. Their greater resistance to deformation may have allowed stress to concentrate at grain boundaries and so promote the nucleation of flames, as predicted by the Pryer-Robin model. The potassium feldspar in these rocks appears to be more deformed, as suggested by abundant undulose extinction in the potassium feldspar, which appears to correlate with the development of flames within individual potassium feldspar grains. The potassium feldspar in these rocks also shows more abundant and continuous exsolution lamellae, which also possibly may be correlated with stress concentrations.

The model of Pryer and Robin (1995, 1996) implies that flame perthite is favored by high differential stress. The fact that flames typically nucleated at grain boundaries and inclusions, which are probable sites of high differential stress in a deforming rock, as well as the extreme variability in the concentration of flames from grain to grain and within individual grains, suggest that differential stress may have contributed to the development of flames in the Cooma metapelitic gneisses. This variability of flame development and their absence from some potassium feldspar grains could be due to local variability of stress concentrations in relation to grain orientations, if the Pryer-Robin model is applicable to nucleation of the flames. Because local stress concentrations can be independent of total strain, the flame perthite may occur in rocks that have not been as strongly deformed as adjacent rocks.

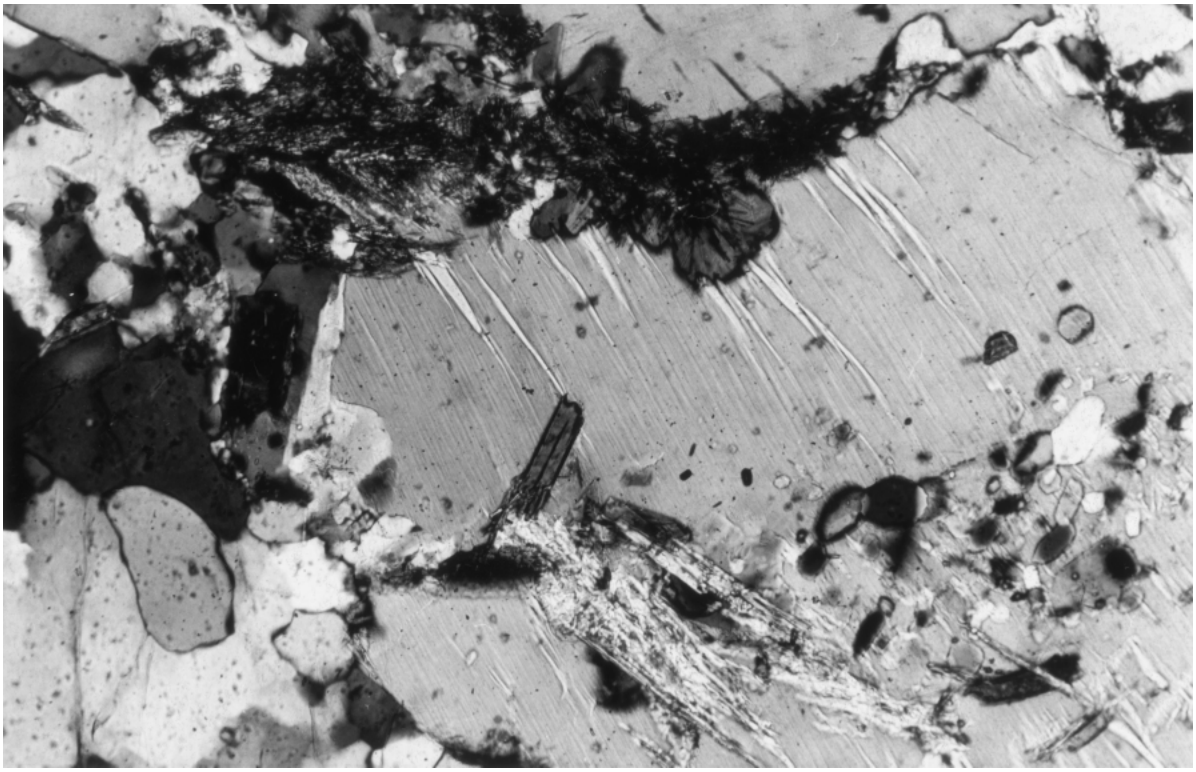

FIGURE 4. Flames that appear to have nucleated on lobes of myrmekite, which in turn have been partly replaced by fibrous sillimanite (also see Fig. 5). Crossed polarizers; base of photo = 1.75 mm

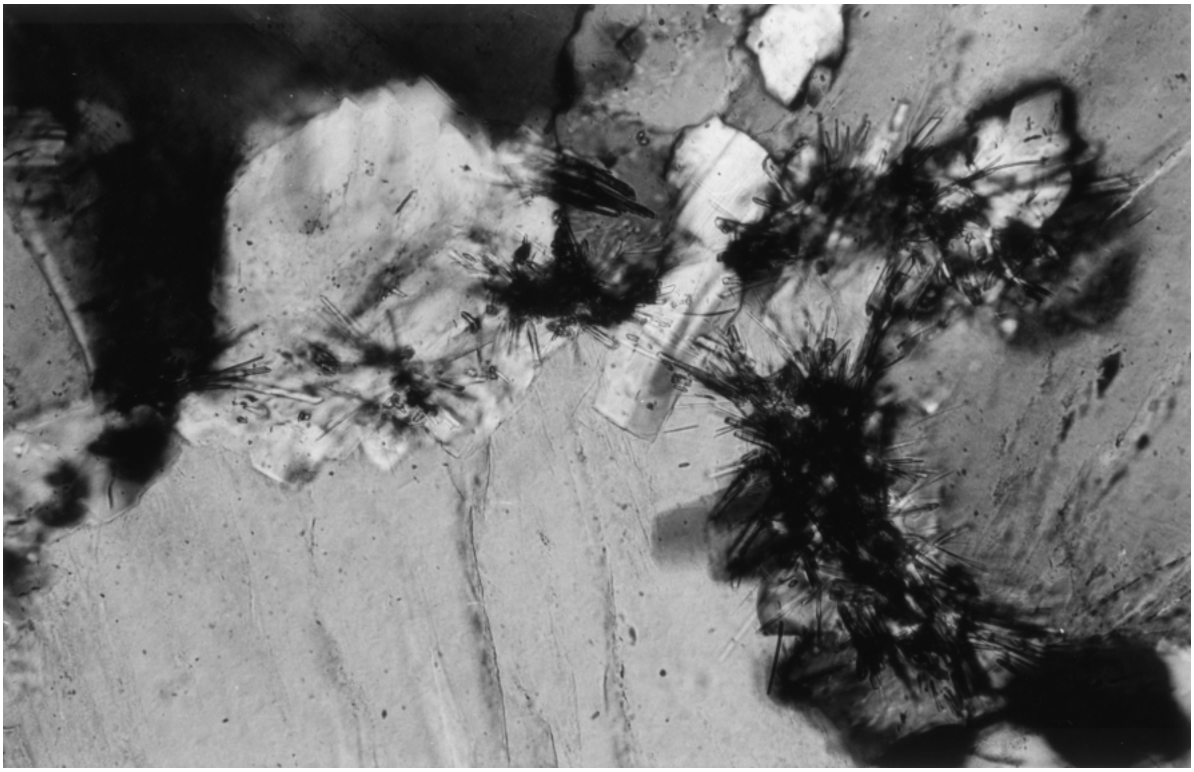

FIGURE 5. Radiating sprays of fibrous sillimanite that appear to have grown in sodic plagioclase lobes and as crystals projecting into microperthite. Crossed polarizers; base of photo = 0.7 mm.

SOURCE OF SODIUM

As mentioned above, the Na required for the growth of the myrmekitic rim albite may be due to local redistribution of albite previously exsolved from alkali feldspar. However, this source may not be suitable for the flame perthite, because exsolution lamellae and rim albite may be present, regardless of the presence or absence of flames. On the other hand, exsolution lamellae generally are better developed where flames are present, and some flames pass into thin lamellae inferred to be of exsolution origin, although this does not necessarily indicate a temporal connection between the two. However, the number of exsolution lamellae does not decrease where flames are present, and in many places the albite appears to be too abundant for simple exsolution, suggesting an external source of Na.

Alteration of plagioclase does not appear to have been a major source of Na, because plagioclase is absent from many of the Cooma metapelitic rocks and where present, it is generally unaltered.

Possible sources of Na are (1) replacement of cordierite + potassium feldspar by biotite-andalusite-quartz symplectite (Vernon 1978; Vernon and Pooley 1981), which would release the albite component of the microperthite and (2) replacement of microperthite by muscovite. Source 1 (high-temperature reaction) would have been available before source 2 (lower-temperature reaction or series of reactions). Unfortunately, it is difficult if not impossible to distinguish between flames formed by each potential source, as their orientations would be identical. Both reactions appear to have occurred at amphibolite-facies conditions, because late fibrous sillimanite has replaced all minerals, including myrmekite (Figs. 4 and 5), albite flames, and much of the muscovite, although conceivably some muscovite that has not been replaced by sillimanite may have formed at greenschist-facies conditions.

If the cordierite replacement reaction is a source of Na, the fact that symplectite after cordierite may be very abundant in rocks without flames indicates that availability of Na and/or water is not the only factor controlling the formation of flames. Stress concentrations may also be required.

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