ISSN 1526-5757

27. METASOMATIC ORIGIN OF THE COOMA COMPLEX IN SOUTHEASTERN AUSTRALIA

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January 24, 1998

Abstract

The Cooma granodiorite and migmatites in southeastern Australia are formed by replacement of metapelites and metapsammites. Evidence to support this hypothesis include: (1) zoned plagioclase and myrmekite in high-grade gneisses, migmatites, and granodiorite, (2) presence of myrmekite and absence of graphic textures in pegmatites, and (3) relatively-calcic plagioclase inclusions in large orthoclase crystals and absence of plagioclase in the ground mass in leucosomes.

Introduction

The much-studied Cooma Complex (Fig. 1 and Fig. 2) in southeastern Australia consists of a granodiorite pluton with an enclosing envelope of metasedimentary rocks and migmatites (Munksgaard, 1988; Ellis and Obata, 1992). In the east side of the pluton, amphibolite enclaves occur (Fig. 2, site xx). In the core of the pluton (midway along Hawkins Street in Cooma) the granodiorite consists of cordierite, biotite, plagioclase, and quartz; orthoclase is less than one percent, and myrmekite is absent (Table 1; Fig. 2, site a). Elsewhere in the pluton orthoclase and plagioclase are nearly equal in abundance, and myrmekite is common (Fig. 3, Fig. 4, and Fig. 5). Outside the pluton lenses of granodiorite occur in the wall rocks (Fig. 2, sites b and c). *In situ* anatexis of pelitic and psammitic metasediments that surround the pluton has been proposed as the origin of the main Cooma granodiorite (White *et al.*, 1974), although geochemical studies indicate that the high grade gneisses and pluton are slightly more calcic than the low grade rocks (Ellis and Obata, 1992). Flood and Vernon (1978) suggest that following anatexis the pluton rose diapirically, drawing up an envelope of high-grade metamorphic rocks along its borders.

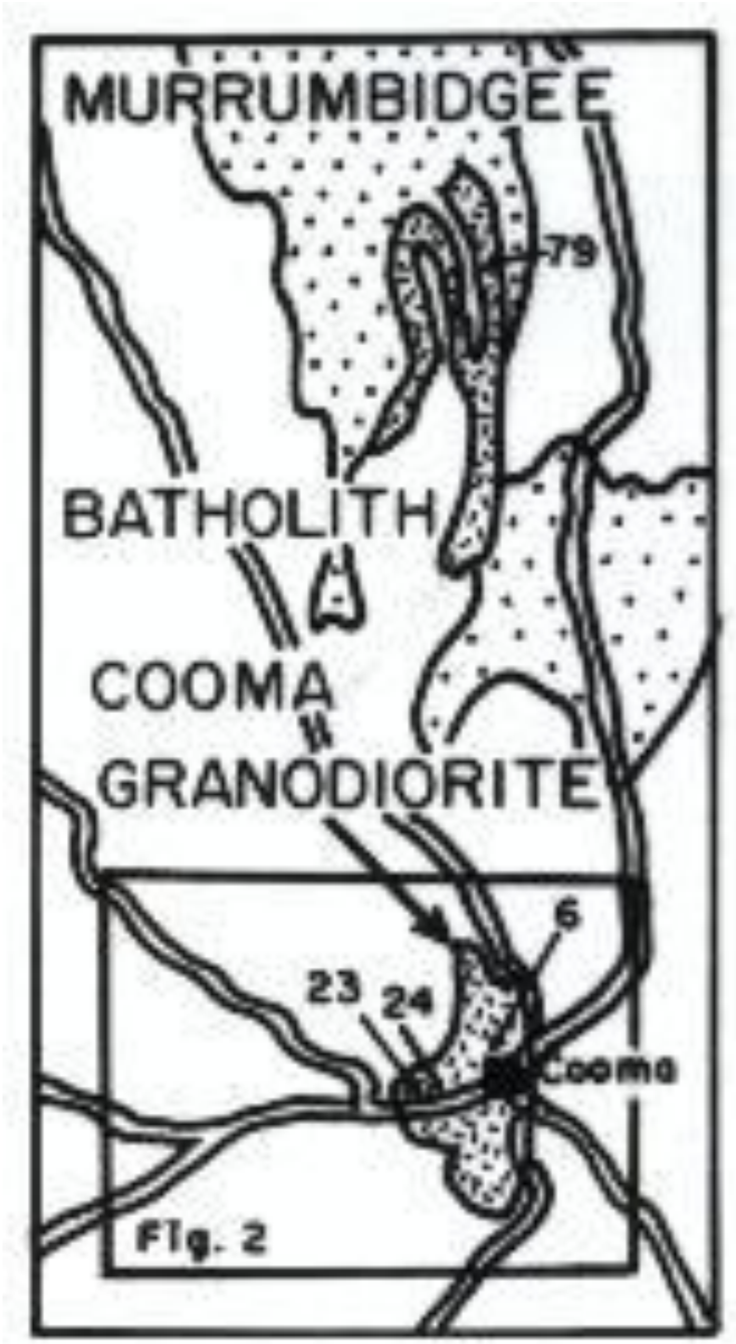

Fig. 1. Location map of Cooma granodiorite south of the Murrumbidgee batholith. One facies occurs at south end of the batholith. Locations of samples CGA-6, CGA-23, CGA-24, and CGA-79, which are shown on figure, are included in Table 1.

TABLE I. MODAL AND CHEMICAL COMPOSITIONS OF THE COOMA GRANODIORITE: MODES IN VOL. %, MAJOR ELEMENT IN WT. %, AND TRACE ELEMENTS IN PARTS /10^6.

Sample	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	P_2O_5	LOI	Sum
CGA-23	71.3	14.2	0.75	1.63	1.86	3.53	3.88	0.05	0.57	0.14	1.93	100.0
CGA-24	70.2	14.9	0.80	1.57	1.66	3.94	3.89	0.06	0.55	0.14	1.70	99.6
CGA-6	67.0	14.4	1.51	2.83	1.48	2.46	7.47	0.10	1.02	0.09	0.85	99.4
CGA-79	67.2	14.7	3.52	2.08	2.25	2.28	4.65	0.07	0.59	0.15	1.08	98.7

Sample	Cr	Rb	Sr	Y	Zr	Nb	Ba
CGA-23	76	223	102	49	173	24	538
CGA-24	73	200	149	47	144	13	582
CGA-6	138	155	154	60	399	17	541
CGA-79	68	139	191	32	173	14	455

Modes	Plag.	Ortho.	Myrm.	Qtz	Cord.	Bio.	Musc.	Andal.	Sil.	Acces.
CGA-23	13.1	7.4	2.4	49.0	0.0	18.5	5.8	1.3	2.2	0.0
CGA-24	9.7	12.2	1.8	52.4	0.2	14.1	7.2	1.6	0.5	0.3
CGA-6	21.4	0.7	0.0	39.7	4.4	26.5	0.3	1.8	4.0	1.2
CGA-79	41.0	0.0	0.0	28.1	2.9	24.3	2.1	0.5	1.1	0.0

CGA-23 and CGA-24 are from west side of Cooma Pluton along Highway 23.
CGA-6 is from east center of pluton, midway along Hawkins Street.
CGA-79 is from satellite body south of Murrumbidgee Batholith.
Chemical analyses by X-ray Assay Laboratories, Ontario. Fe_2O_3 = total Fe.

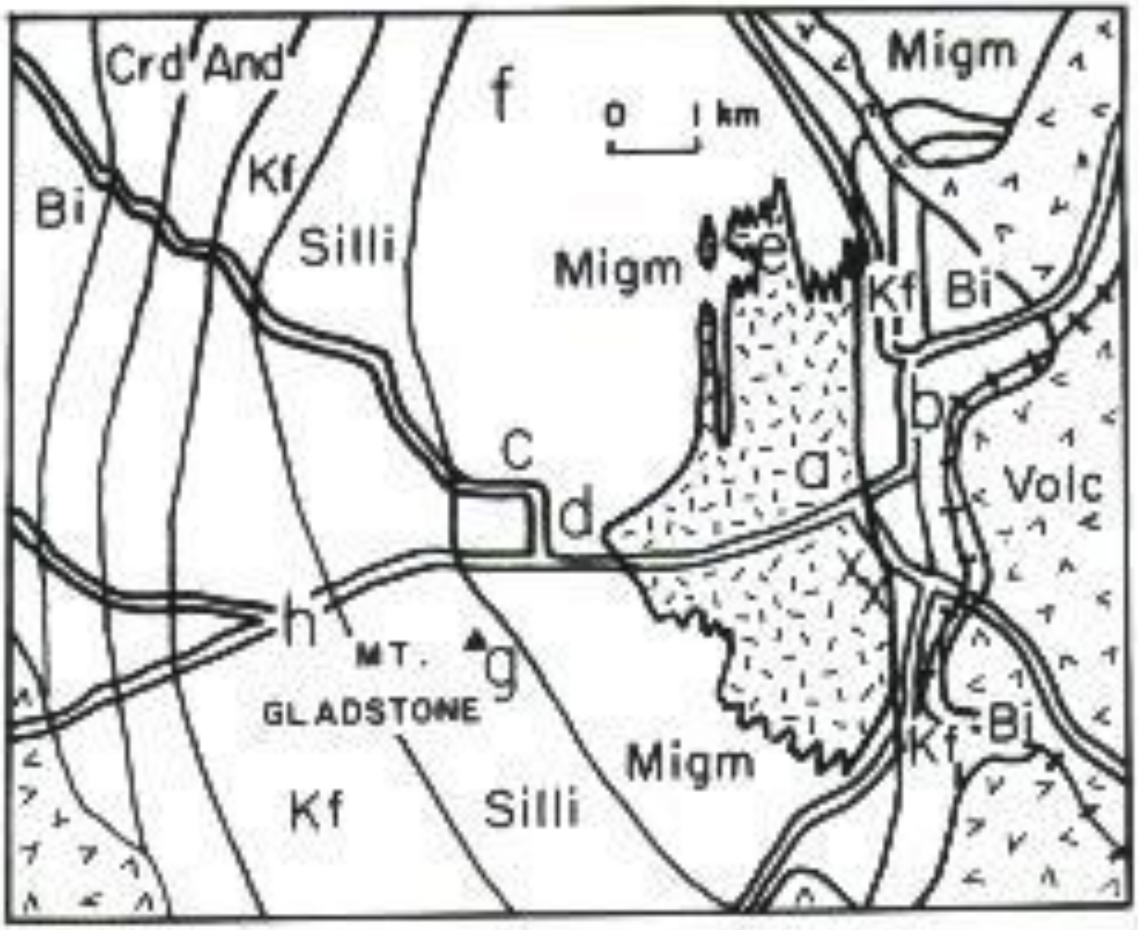

Fig. 2. Geologic map of Cooma Complex. Bi = biotite; Crd = cordierite; And = andalusite; Kf = orthoclase; Silli = sillimanite; Migm = migmatite. Dash pattern = Cooma granodiorite; Volc = younger volcanic cover. East side of Cooma pluton has sillimanite through biotite zones, but zones are too narrow to plot on figure; the migmatite zone is missing. Letters a, b, c, d, e, f, g, h, and x are explained in text.

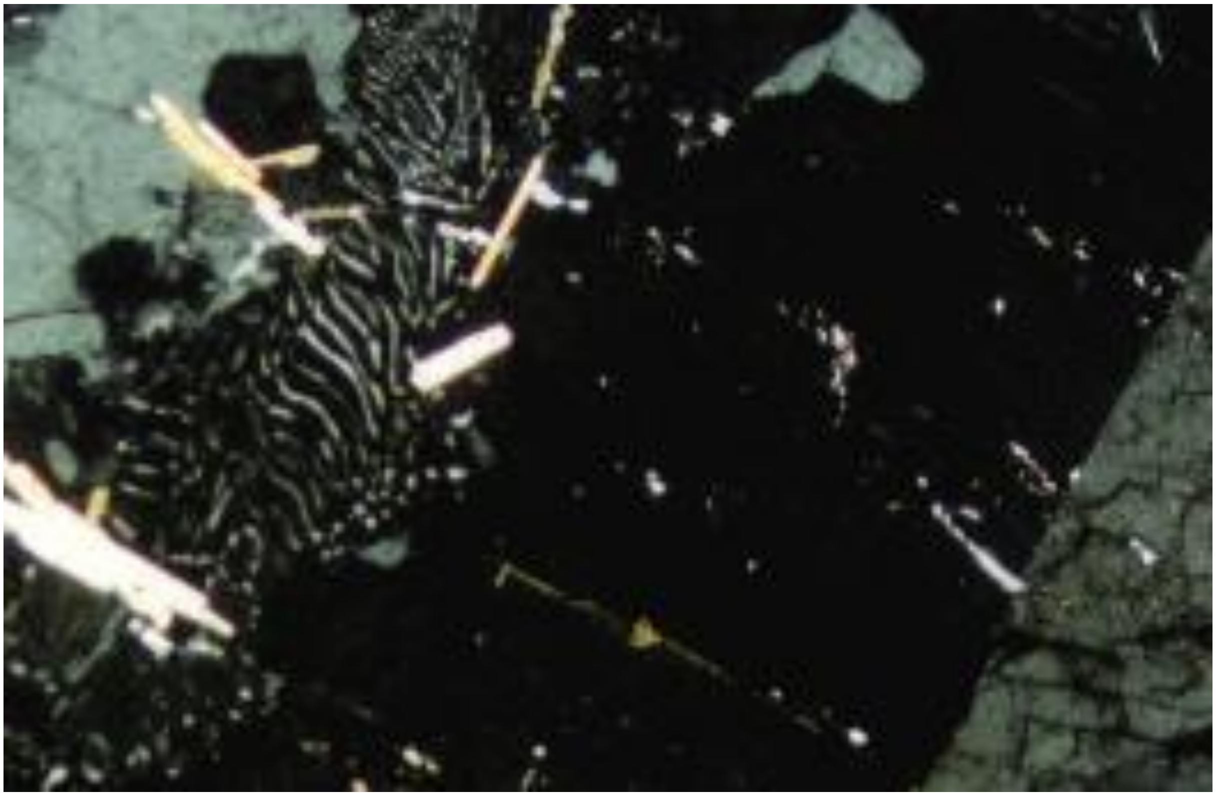

Fig. 3. Myrmekite (white quartz vermicules) left side of Carlsbad-twinned orthoclase (black and gray, right side). Colored blades are muscovite.

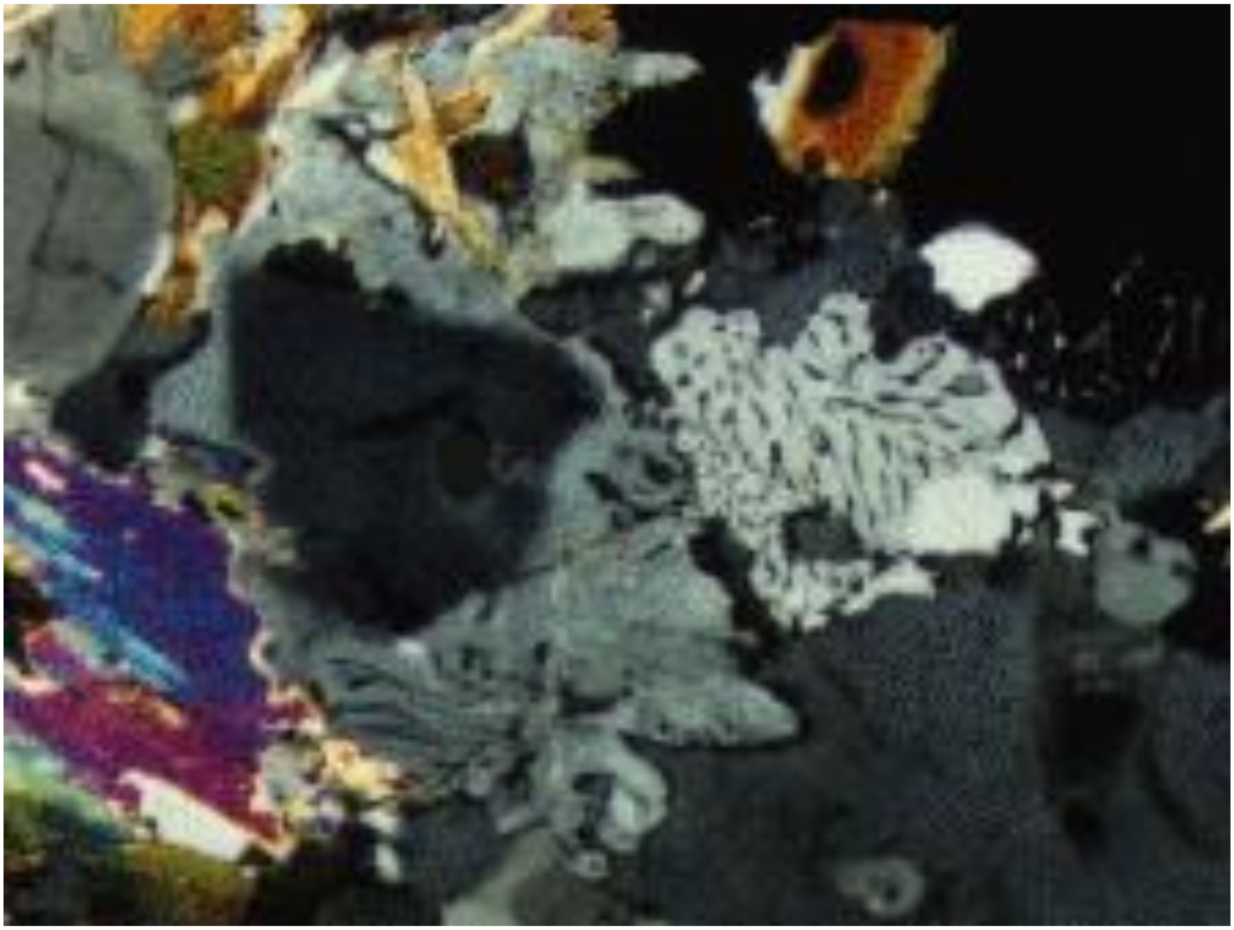

Fig. 4. Myrmekite (white and gray with quartz vermicules) bordering orthoclase (gray; right side). Zoned plagioclase with relatively calcic core (dark gray; left side) and broad, more-sodic, myrmekitic rim (light gray). Many colored grains are biotite and muscovite.

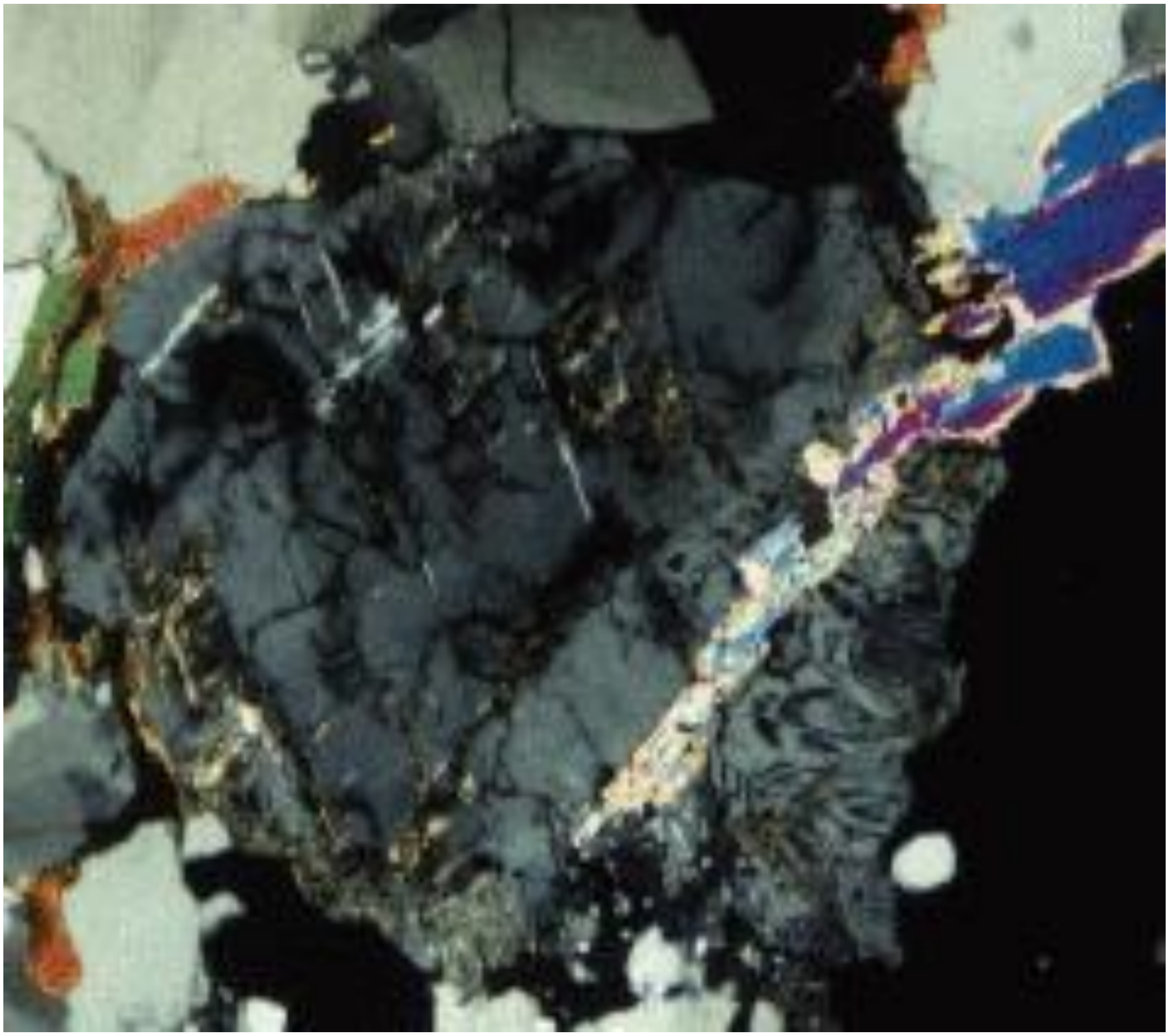

Fig. 5. Myrmekite on broad sodic rim (light gray) of zoned plagioclase with relatively calcic core (darker gray) bordering orthoclase (black; right side). Quartz (white). Colored grains are muscovite and biotite.

Quartz, zoned plagioclase (broad rims $An_{20\text{-}25}$; cores $An_{31\text{-}41}$) (Fig. 4, Fig. 5, and Fig. 6), orthoclase, and biotite are dominant constituents of the high-grade metamorphic wall rocks, melanosomes, and the Cooma granodiorite. Accessory cordierite is commonly replaced by biotite-andalusite-quartz symplectites during retrograde metamorphism (Vernon and Pooley, 1981; Vernon, 1978), and minor muscovite and sillimanite (fibrolite) are secondary alterations.

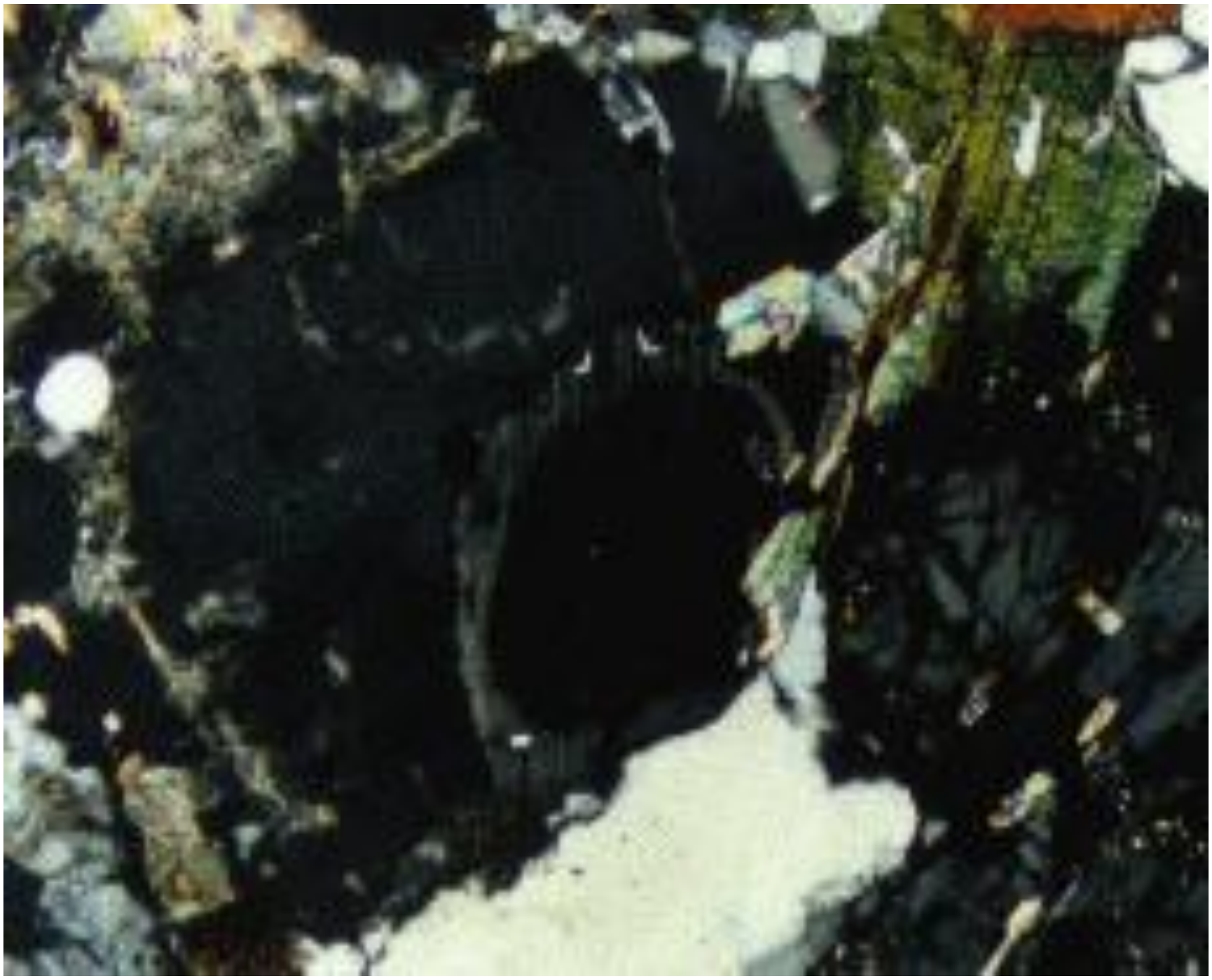

Fig. 6. Albite-twinned, zoned plagioclase crystal with relatively calcic core (center; dark gray) and more sodic rim (oval shape; light gray) enclosed on three sides by orthoclase (gray; left side). Two quartz vermicules (white) occur in top of plagioclase grain. Quartz (white). Biotite (green, brown).

At the north end of the pluton a transition zone occurs (zigzag lines, Fig. 2) in which migmatites are sliced into elongate parallel lenses, and remnant gneiss and migmatites are broken and discontinuous. Progressively into the pluton both gneiss and migmatite gradually lose their banded appearance and become homogenized and massive. Polished bedrock exposures of the transition zone occur in the Cooma Creek stream bed (Fig. 2, site e). In this zone pods of leucosomes (10-20 cm wide and 1-3 m long) are partially bordered by biotite selvedges (Fig. 7) and are surrounded by biotite-cordierite gneiss (melanosomes). In the melanosomes white, subhedral to euhedral, orthoclase porphyroblasts (metacrysts), 1 to 2 cm long, occur as isolated crystals or clusters and stand out in marked contrast to the adjacent dark, fine-grained, ground mass. Wartlike myrmekite borders the orthoclase in both the aggregates (pods) as well as the isolated crystals and clusters (Fig. 7).

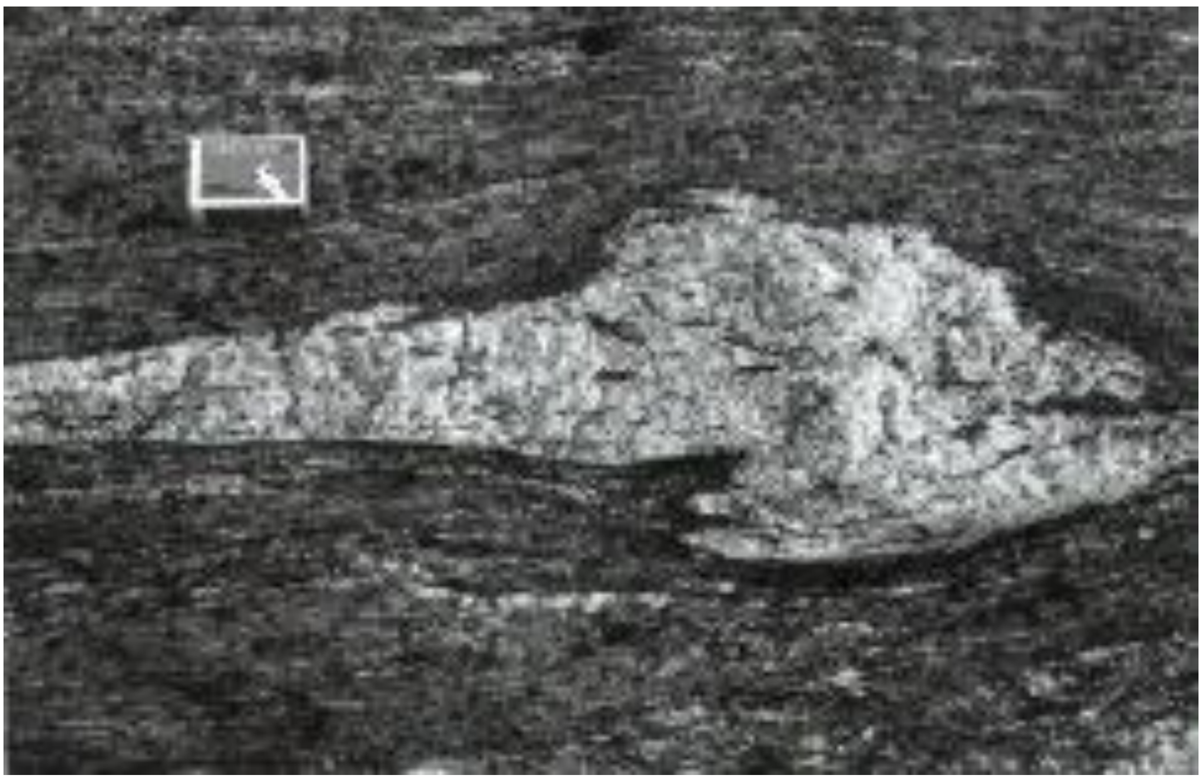

Fig. 7. Leucogranite pod and white orthoclase metacrysts in high-grade metasedimentary gneiss and migmatite in Cooma Creek, one km north of sewage treatment plant at north end of Mulach Street in Cooma. Match box for scale. Photo: Adrian and Barbara Blake.

A new road cut exposing unweathered migmatite is reported by Ellis and Obata (1992) on the Cooma-Berridale Road 3 km west of the center of Cooma. They studied the mineralogy and chemical composition of leucosomes and melanosomes and concluded that the leucosomes represent cumulates from a melt reaction: Bio + Andal + K-feld + Qtz + Vap = Cord + Liq at about 350-400 MPa P_{H2O}, 670-273º C. They also suggested that the nearby granodiorite pluton formed from a partial melt of about 50 wt % and that the melt contained xenocrystal restite of 20 wt % quartz, 15 wt % biotite, and 8 wt % plagioclase.

On the basis of the aforesaid information previous investigators tend to agree that the Cooma granodiorite has reached melting temperatures, although its quartz-rich composition and relatively calcic plagioclase An_{31-41} mean that much of the quartz and plagioclase is unmelted restite. However, zoned plagioclase, occurring both in the pluton as well as in the high-grade metasedimentary rocks, is puzzling because zoned plagioclase with calcic cores and sodic rims is normally found only in rocks crystallized from magma. Furthermore, the presence of myrmekite in the metasedimentary wall rocks and migmatites as well as in the pluton provides the basis for proposing that none of the rocks in the Cooma Complex reached melting temperatures and that metasomatic fluids modified the mineralogy and chemical compositions of these rocks.

Wartlike myrmekite near Pala, California, and in the Cooma Complex

The world-wide occurrences of wartlike myrmekite in deformed plutonic igneous rocks and high grade gneisses have been studied for nearly 120 years, resulting in many hypotheses for its origin. See Collins (1988) and Hunt and others (1992) for extensive reference lists. Because wartlike myrmekite protrudes into large K-feldspar crystals, the resulting texture is generally interpreted to be formed either by exsolution or by Ca- and Na-metasomatism (Phillips, 1974). Moreover, the large K-feldspar host crystals are usually interpreted as having a primary origin, while the penetrating myrmekite is assumed to be a secondary alteration. Nevertheless, occurrences of myrmekite show that it forms where secondary K-feldspar replaces primary plagioclase. For example, in a transition zone between cataclastically sheared diorite and granite gneisses near the Pala pegmatites in southern California, K-feldspar and myrmekite are shown to replace primary plagioclase of the diorite (Collins, 1988). These same myrmekite-bearing granitic gneisses can be traced laterally and gradationally into the zoned Pala pegmatite dikes. The dikes contain "line garnet" in border zones, graphic-granite textures in intermediate zones, and large euhedral crystals of quartz, tourmaline, kunzite, and lepidolite in their cores (Jahns and Tuttle, 1963). The pegmatites have clearly crystallized from a melt because oxygen isotopic studies indicate temperatures of 700-730º C in bordering minerals and 520-565º C in the core (Taylor *et al.*, 1979). Where the granitic rock crystallized from a melt, myrmekite is absent. Myrmekite is notably present, however, in the granitic gneisses that grade from the pegmatites to the unaltered diorite. It is clear in the Pala area that the myrmekite has formed by replacement in solid but sheared mafic rocks below melting temperatures by K-replacement processes but is destroyed where melting has occurred (Collins, 1988; Hunt *et al.*, 1992).

On the basis of these relationships, melting can be shown to be absent in the Cooma Complex. For example, myrmekite-to-graphic-granite transitions are missing in the pegmatites and migmatites in the Cooma Complex (Fig. 2, sites d and e). Only myrmekite is found. Moreover, wartlike myrmekite bordering orthoclase first appears in high-grade zones where sedimentary structures of pelitic and psammitic metasedimentary rocks can still be recognized and where no leucosomes of possible anatectic origin exist (Fig. 2, site h and northward). Orthoclase and myrmekite, from their first appearances, occur continuously and increasing abundance into the migmatites and then into the pluton. The myrmekite had to form during progressive metamorphism because original grain sizes in low-grade metasedimentary rocks are too tiny for the myrmekite to be detrital grains from former igneous rocks. After its formation, melting temperatures could not have been reached because myrmekite is not destroyed in the migmatites or the granodiorite of the pluton (Fig. 3, Fig. 4, and Fig. 5). Moreover, a replacement origin for the myrmekite by Ca- and Na-metasomatism of orthoclase following crystallization of a partial melt in the pluton and migmatites, is unreasonable because such replacements do not logically occur where orthoclase is just forming in the outer K-feldspar zone (Fig. 2) by destruction of muscovite or biotite. Plagioclase was produced first in these rocks at lower temperatures; orthoclase came later at higher temperatures and replaced the plagioclase, not vice-versa. Additional evidence to support this conclusion is provided by the mineralogical relationships described in the next two sections.

Mineralogical compositions of melanosomes and leucosomes

Ellis and Obata (1992) after studying unweathered migmatites in a new road cut, reported that in this locality plagioclase is scarce in the leucosomes and adjacent melanosomes. On that basis, these investigators assumed that the orthoclase is primary and that experimental work in a KMASH system is adequate to explain the origin of the leucosomes. These orthoclase-rich rocks, however, are typical only of a small area of the migmatite zone in the southwestern part of the area and the adjacent inner sillimanite zone on Mt. Gladstone (Fig. 2, site g), but they are atypical of the larger parts of these two zones. Therefore, arguments by Ellis and Obata for a melt origin of these rocks are based on an acknowledged narrow sampling.

Ellis and Obata (1992) do not report myrmekite in the migmatites in the new road cut, but myrmekite is most likely present there because it occurs in all other adjacent orthoclase-rich migmatites (both leucosomes and melanosomes) in the western part of the Cooma Complex (Fig. 2, site f) and extending to the orthoclase-rich rocks of Mt. Gladstone area (Fig. 2, site g). Ellis and Obata (1992) suggested that the leucosome pods represent cumulates from a melt, but evidence against this hypothesis is provided also by the afore-mentioned isolated, large, euhedral, white, orthoclase crystals, up to 2 cm long, which occur in the northern part of the pluton in the transition from the migmatite zone into the pluton (Fig. 2, site e). These crystals occur in adjacent melanosomes in random orientation and as smaller, isolated, white, orthoclase crystals (0.2-0.5 cm long) which occur adjacent to white orthoclase stringers that extend parallel to the foliation (Fig. 7). These isolated, small and large, rectangular orthoclase crystals are indistinguishable from the orthoclase aggregates in the leucosome stringers and pods, and in both places they are bordered by wartlike myrmekite. Isolated rectangular melt cumulates in the midst of melanosomes are illogical.

Zoned plagioclase

A second argument against melting temperatures being reached in the Cooma Complex is the occurrence of zoned plagioclase crystals. These crystals occur in the Cooma granodiorite, migmatites, and high grade gneisses and contain calcic cores An_{31-41} that exhibit an abrupt change to a broad sodic rim An_{20-25} (Granath, 1978; Ellis and Obata, 1992). The continuous presence of zoned plagioclase in high grade gneisses (K-feldspar and sillimanite zones, Fig. 2) beyond the migmatite zone progressively into the pluton eliminates the hypothesis that the zoning is due to cooling during crystallization from a melt. Moreover, if some plagioclase crystals are supposed to exist as restite in the pluton while others became melted (Ellis and Obata, 1992), then following solidification, some plagioclase crystals should have a different appearance. Instead, all plagioclase crystals have the same zoned appearance, which suggests that none of the plagioclase ever reached melting temperatures. The relatively calcic cores represent stable phases that were created during deep-burial metamorphism. Where orthoclase replaces some of these plagioclase crystals during folding of the rocks, both Na and Ca are displaced from the plagioclase. Some of this Na and Ca forms the overgrowths (An_{20-25}) to produce the zoning in the high grade gneisses, migmatites, and both kinds of granodiorites in the pluton (Table 1; Fig. 2).

Discussion

Arguments by Ellis and Obata (1992) for melting are based in part on the absence of plagioclase in the high-grade, orthoclase-rich, metamorphic rocks southwest of the pluton (Fig. 2), which is not typical of most of the area. Near the pluton the strongest degree of replacement of plagioclase by orthoclase occurs in definite bands (shear zones bordering the rising diapir) that become the leucosomes of the migmatites. Myrmekite indicates that the diapir was a hot, plastic solid. Excess Al released from calcic portions of the replaced plagioclase contributes to fluids that produce secondary fibrolite sillimanite in biotite while displacing Mg and Fe from the biotite (see also Vernon and Flood, 1977; Vernon, 1979).

In leucosomes of the road cut, orthoclase encloses minor euhedral plagioclase An_{31-35} (and locally An_{15}), and plagioclase is absent in the groundmass (Ellis and Obata, 1992). These inclusions represent remnants of cores and rims of zoned crystals. The absence of plagioclase in the groundmass and its occurrence as inclusions in orthoclase of the leucosomes do not fit experimental results for granitic melts in which orthoclase dominates over plagioclase. Under such conditions plagioclase should form in the groundmass. Its absence there and occurrence as inclusions in the large orthoclase crystals of the leucosomes only make sense where replacement below melting temperatures occurs.

The deficiency of Ca in the Ordovician, low-grade, metasedimentary rocks (less than 1 % calcium carbonate) suggests why the high grade rocks in the Cooma Complex are Ca poor, but chemical analyses of the orthoclase-deficient granodiorite in the core of the pluton show that these rocks contain 1.51 wt % CaO (GSA-6, Table 1) whereas the orthoclase-bearing granodiorite (GSA-23, 24) contains 0.75-0.80 wt % CaO. This difference suggests that Ca is lost from the primary high-grade gneisses and granodiorite of the pluton during orthoclase- and myrmekite-replacement of the plagioclase. The increase of Na from 1.48 wt % Na_2O in the core granodiorite to 1.66-1.86 wt % Na_2O in the replaced rocks indicates the retention of some of the Na in plagioclase rim-overgrowths.

On the basis of the aforesaid discussion, a metasomatic model for the Cooma Complex does not invalidate the restite hypothesis for magmatic S-type granites in other terranes. An early-replacement model applied to Cooma rocks supplements the restite hypothesis by suggesting that prior to partial or complete melting deformation of solid rocks allows dehydration of the source rocks. The escaping vapor carries Ca, Mg, Fe, Na, Al, and other elements with it so that the chemical composition of the source rocks is modified by metasomatism prior to possible melting. How mafic and calcic the source sedimentary rock is would determine the degree of enrichment of Ca and other elements in the overlying plutons and volcanic rocks which eventually receive these elements (Wyborn *et al*., 1981).

Acknowledgments

R. H. Vernon and R. H. Flood provided geologic maps, field notes, field guides, and thin sections, which are in addition to thin sections of rocks from my own sampling.

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This article was previously published in Contributions to Theophrastus Research, v. 1, p. 105-112, 1996.

Addendum

Since publishing the aforesaid material, Bruce Chappell collected a sample from the fresh, road cut outcrop in the migmatite zone on which Ellis and Obata (1992) based their interpretations of a magmatic origin for the Cooma granodiorite, and Doone Wyborn sent me this sample and two samples of fresh Cooma granodiorite from the pluton. (The road cut outcrop is along the main road extending through the pluton and occurs on a line that projects between the letters "c" and "g" on Fig. 2; the fresh granodiorite samples came from an outcrop on the south side of this same road, 1 km east of the western border of the pluton.) Thin sections of all three samples show the presence of myrmekite with tiny quartz vermicules. On that basis, it appears that Ellis and Obata (1992) decided that the myrmekite was unimportant or they overlooked it.

The samples of the granodiorite, provided by Doone Wyborn, show excellent illustrations of progressive interior replacement of some of the primary plagioclase grains in the granodiorite by orthoclase. Locally, veins of orthoclase penetrate a plagioclase grain along fractures. In other places more extensive but incomplete replacements of plagioclase grains by orthoclase leave islands of albite-twinned plagioclase in optically-parallel orientation in the orthoclase. In some places orthoclase grains that are bordered by myrmekite contain clusters of quartz blebs (ghost myrmekite) whose individual sizes are the same dimensions as the maximum sizes of the quartz vermicules in the nearby myrmekite. All of these replacement features and the myrmekite provide additional support for the hypothesis that the mobilized Cooma granodiorite was formed by replacement processes and never reached melting temperatures.