Granitic Development and Emplacement in the Tumbarumba-Geehi District, N.S.W.

(1) The Foliated Granites

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Abstract—In the Tumbarumba-Geehi district some of the granitic bodies that are in part foliated display a close association in mineralogy, chemistry and field relationships with the surrounding regionally metamorphosed psammopelitic sequence. These foliated rocks—the Cooma-type granites—are characterized by the presence of clusters of biotite, occasional cordierite and patchy zoning in the plagioclases. Chemically the rocks display low Ca contents and a high K:Na ratio, features that are evident in the associated metamorphics. There is a distinct similarity in the chemistry of biotites from the granites, their inclusions, and the high-grade metamorphics.

The following sequence of events is envisaged for the formation and emplacement of the Cooma-type granites: (a) high-grade metamorphism of a psammopelitic sequence, segregation of quartzo-feldspathic and biotite-rich sections, and some increase in Ca contents; (b) introduction of sodium, breakdown of micas and the formation of a partial melt, with development of alkali feldspars. Such reactions involve an increase in volume and thus a decrease in specific gravity of the granites with consequent migration and emplacement to higher levels in the crust.

Introduction

The granitic* rocks of the Tumbarumba-Geehi district, N.S.W. may be classified into several groups on the basis of their textural and mineralogical features and field association with regional metamorphic zones. The aim of this paper is to describe and consider the development of one of the groups—the Cooma-type granites (Vallance, 1967)—with particular reference to its relationship to the surrounding regional metamorphics. The other granitic rocks present (Khancoban, Mannus Creek and Dargals granites) post-date the regional metamorphism and will be discussed in a later paper. The distribution of rocks in the Tumbarumba-Geehi district has been noted elsewhere (Guy, 1969).

The Cooma-type granites of south-east Australia include the Cooma gneiss (Joplin, 1942), Albury gneiss (Joplin, 1947), Wantabagery granite (Vallance, 1953), Mt. Wagra gneiss (Tattam, 1929) as well as the Corryong and Geehi granites of the Tumbarumba-Geehi district. The Corryong granite forms part of a south-easterly extension of the Corryong granite but no investigation concerning the continuity of these bodies has been undertaken in connection with this study.

Portions of the mass were described by Edwards and Easton (1937) and later by Hall and Lloyd (1950), the latter authors applying the term Maragle Batholith. Vallance (1953) applied the name Green Hills granite to that section of the mass to the north of Tumbarumba. The Geehi granite forms part of a south-easterly extension of the Corryong granite but no investigation concerning the continuity of these bodies has been undertaken in connection with this study.

The Corryong and Geehi granites are medium grained, remarkably uniform rocks with a high biotite content and free from hornblende; massive in part but generally foliated. This foliation is delineated by a parallelism of bladed micas and elongated xenoliths. The foliation is steeply dipping and has a general trend north-south, and locally parallel to the contacts with the surrounding psammopelitic sequence of Ordovician rocks.

Mineralogy and Petrology

The normal granitic rocks vary from granits (s.s.) to granodiorite, with the bulk of the rocks being grey adamellites (Table 1). The grain size is even (1-2 mm.) though coarser types with alkali feldspars to 8-10 mm. occur and also some tendency for minerals to be present in clusters, especially biotite. Cell structures with-
in the quartz grains are evident and sometimes assume a typical polygonal arrangement (Plate 1a). The larger alkali feldspars enclose quartz and plagioclase, suggesting their development later than other phases. Alkali feldspars are optically monoclinic although some cross-hatch twinning occasionally occurs. The triclinicity, 

\[ \Delta, \text{ (Goldsmith and Laves, 1954) is in the range 0.25-0.40, and } 2\nu_x = 80-90^\circ. \text{ The } K : Na \text{ ratio of the alkali feldspars may be estimated utilizing modal and chemical data (including plagioclase and biotite compositions), for specimen 21800 and for the biotite-granite from Vallance (1953, 1960). If assumptions are made as to the compositions of the micas and the accessory minerals, the } K : Na \text{ ratio may also be estimated for specimens 21805, 21777. All such } O_r \text{ percentages fall in the range 62-68%}. \]

The plagioclases are more calcic than those noted by Vallance (1953) in the area north of Tumbaramba, where most contain 30-35% anorthite molecule. The average composition for plagioclases from the present area is \( \text{An}_{34-40}^* \), variation being from \( \text{An}_{55} \) (at core) to \( \text{An}_{66} \) (at margin). The calcic character of these plagioclases is of interest considering the relative low Ca contents of the rocks (Table 1). Most of the plagioclase grains are twinned, with up to four laws being present. A large number of plagioclases contain small areas, somewhat irregular in shape and distribution, that are at a slightly different optical orientation from the main portion of the crystal (Plate 1b). This “patchiness” displayed by the plagioclase is more evident in varieties where zoning rather than twinning is prominent. The outlines of these small areas is often partly controlled by twinning. Such small patches differ in optical orientation by only a few degrees from the host and do not obey any recognizable twin law. Most plagioclases have \( 2\nu_y = 70-85^\circ \), although sodic varieties have \( 2\nu_y = 85-88^\circ \). Biotite is present in clusters with blades being intergrown and occasionally twinned. Generally it is pleochroic red-brown, although some dark olive-brown biotites have been recorded. \( \gamma \)-ranges from 1.643 to 1.651. One red-brown biotite has been analysed from the present area (Guy, 1964) and its composition is summarized below (No. 1)—specimen 21800†, together with a biotite (No. 2) from the area to the north of Tumbaramba (Vallance, 1960).

| Chemical Analyses, Barth Mesonorms and Modes of Corryong and Geehi Granites |
|----------------|----------------|----------------|----------------|----------------|
|                | 1              | 2             | 3              | 4              |
| SiO₂            | 70.25          | 69.40         | 69.70          | 69.05          |
| TiO₂            | 0.41           | 0.49          | 1.15           | 0.29           |
| Al₂O₃           | 13.78          | 13.58         | 13.30          | 15.78          |
| Fe₂O₃           | 0.41           | 0.75          | 0.27           | 0.22           |
| FeO             | 3.04           | 3.87          | 3.60           | 3.62           |
| MnO             | 0.07           | 0.11          | 0.05           | 0.05           |
| MgO             | 1.49           | 2.04          | 1.66           | 2.15           |
| CaO             | 1.80           | 0.92          | 1.92           | 2.50           |
| Na₂O            | 2.41           | 2.01          | 2.51           | 2.49           |
| K₂O             | 4.86           | 5.14          | 4.25           | 3.85           |
| P₂O₅            | 0.16           | 0.14          | 0.15           | n.d.           |
| H₂O²⁺           | 1.13           | 1.64          | 0.94           | 0.28           |
| H₂O⁻             | 0.07          | 0.04          | 0.09           | 0.13           |
| Total           | 99.88          | 100.03        | 99.59          | 100.41         |

(1) Included pelitic fragments (mainly muscovite, chlorite and quartz).
(2) Apatite, sillimanite, tourmaline, rutile.

2. Spec. No. 21847. Biotite adamellite. G.R.284.6-139.6° (Geehi granite).

Analyst: B. Guy.

* Snowy Mountains Authority grid reference (see Guy, 1969).

† Further details of the analysed biotites will be published in a later communication.
Muscovite is significant as large blades in the Cooma-type granites but cross-cutting other constituents, and is associated with biotite which may be replacing. The percentage of muscovite increases with increasing alkali feldspar content. About 2–3% of the granitic rocks is composed of cordierite or inclusions of pelitic material. The cordierite appears as anhedral grains (1–2 mm.) in part replaced by muscovite. It is homogeneous with $2V_\alpha=90^\circ$. Patches of sheet silicates, assuming ovoid shapes and 1–3 mm. in size, are ubiquitous in the granitic rocks. They are composed of chlorite, muscovite with some quartz, biotite and sillimanite. Texturally these micaceous aggregates appear as inclusions in the host granite. They may in part represent pseudomorphs after cordierite. Accessory minerals in the granitic rocks are opaque oxides, tourmaline, apatite, sillimanite, zircon, rutile, monazite, calcite and epidote. Marginal phases of the granites have high tourmaline and muscovite contents, with biotite being replaced by these two minerals.

Throughout these granites shear zones are numerous, varying from 5 cm. to a metre in width, though Vallance (1953) and Beavis (1961) describe crush bands several hundred metres wide in similar granitic rocks. Shearing effects produce some reduction in grain size with assemblages such as "quartz-feldspar-chlorite-muscovite" being produced.

Aplites, pegmatites and graphic granites form significant occurrences in the Cooma-type granites. Aplites occur as small veins occupying joints. Quartz, optically monoclinic alkali feldspar and oligoclase are the dominant phases, being in approximately equal quantities. Dark-green biotite, muscovite, tourmaline, apatite and opaque oxides are accessories. Tourmaline-rich bands characterize many of the aplitic veins. Pegmatites are mineralogically similar to the aplites, but oligoclase is subordinate. Tourmaline in the pegmatites has a basal parting (up to 0.5 mm. wide) filled with quartz and iron oxides.

Associated with the aplitic and pegmatitic phases are dark, fine grained dykes consisting essentially of chlorite and tourmaline with some quartz and opaques. These rocks are prevalent in the area south of Tumbarumba and are associated with shear bands in the granite and quartz-sulphide veins. Although the original composition has presumably been extensively modified, they may represent basic dykes that have been sheared and altered by hydrothermal activity.

Large inclusions (>5 cm.) are prominent throughout the Corryong and Geehi granites, being of psammitic to pelitic character and mineralogically and texturally similar to the high-grade regional metamorphics of the district (Guy, 1969). Some quartz nodules (5–10 cm. in size) are also common throughout the Cooma-type granites. Most inclusions differ from the country rocks in that plagioclase is significant in the former rock type as porphyroblasts of An$_{45}$ composition. The plagioclase is euhedrally zoned with cores of An$_{50}$, and $2V_\gamma=80–90^\circ$; some "patchiness", as described for plagioclases of the granitic rocks, is evident. Biotite is present throughout all the inclusions, and is frequently concentrated around the margins of the larger sandier types. Structural formulae for some biotites are noted below. Nos. 1 and 2 are red-brown types ($\gamma=1.645$) common to most inclusions, while Nos. 3 and 4 are yellow-brown varieties ($\gamma=1.625$) noted in some of the sandier rocks. No. 1 is from Vallance (1960) and the remainder from Guy (1964). Modal analyses of the host inclusions are noted in Table 2.

1. ($K_{0.82} Na_{0.12} Ca_{0.08}$) ($Al_{0.37} Ti_{0.17} Fe_{0.20}^{3+} Fe_{0.11}^{2+} Mn_{0.04} Mg_{0.14}$) ($Si_{2.65} Al_{1.35}$) O$_{10}$ (OH)$_2$
2. (Spec. 21798) ($K_{0.50} Na_{0.12} Ca_{0.08}$) ($Al_{0.44} Ti_{0.12} Fe_{0.11}^{3+} Fe_{0.10}^{2+} Mn_{0.01} Mg_{0.07}$) ($Si_{2.67} Al_{1.33}$) O$_{10}$ (OH)$_2$
3. (Spec. 21807) ($K_{0.51} Na_{0.12} Ca_{0.09}$) ($Al_{0.39} Ti_{0.05} Fe_{0.09}^{3+} Fe_{0.09}^{2+} Mn_{0.01} Mg_{0.17}$) ($Si_{2.89} Al_{1.11}$) O$_{10}$ (OH)$_2$
4. (Spec. 21787) ($K_{0.79} Na_{0.08} Ca_{0.03}$) ($Al_{0.32} Ti_{0.05} Fe_{0.09}^{3+} Fe_{0.08}^{2+} Mn_{0.01} Mg_{0.15}$) ($Si_{2.80} Al_{1.29}$) O$_{10}$ (OH)$_2$

The Mg-rich micas (Nos. 3 and 4) have only been observed or suspected in these inclusions, whereas they appear to be lacking in the granite and regional metamorphics. The lower grade metamorphics may prove to contain some exceptions (Guy, 1969, Table 1). The silica content is appreciably higher for these Mg-rich varieties.

Cordierite is abundant in the pelitic inclusions as ragged crystals with a distortion index, $\Delta$, (Miyashiro, 1957) of $0.19 \pm 0.03$ and $\beta=1.553 \pm 0.003$, indicating (ca.) 25% Fe substitution for Mg. Sillimanite is present in the fibrolite form, although numerous needle-like crystals are associated with the matted fibrolite. Muscovites in the inclusions vary from large blades (2–3 mm. long), cross-cutting other minerals,
to sericitic varieties which replace nearly all the phases except quartz. Chlorite, in part after cordierite, may be associated with the fine matted micas.

### Table 2

**Chemical Analyses, Barth Mesonorms and Modes for Inclusions in Cooma Type Granites**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>SiO₂</td>
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<td>0.13</td>
<td>2.50</td>
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<tr>
<td>Fe₂O₃</td>
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<td>0.28</td>
<td>2.01</td>
<td>1.79</td>
<td>1.05</td>
<td>0.26</td>
</tr>
<tr>
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<td>8.01</td>
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<td>MnO</td>
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<td>0.14</td>
<td>0.14</td>
<td>0.06</td>
<td>0.26</td>
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<tr>
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<td>0.27</td>
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<tr>
<td>K₂O</td>
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<td>8.17</td>
<td>3.71</td>
</tr>
<tr>
<td>P₂O₅</td>
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<td>n.d.</td>
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<td></td>
</tr>
<tr>
<td>H₂O</td>
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<td>4.00</td>
<td>3.40</td>
</tr>
<tr>
<td>F₂</td>
<td>0.18</td>
<td>0.23</td>
<td>0.22</td>
<td>0.36</td>
<td>0.40</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Analysts: 1, 2, 6—B. Guy. 3—T. G. Vallance. 4, 5—C. M. Tattam.

* Data not available.

### Chemical Data

(i) Granitic Rocks. Four new analyses of granitic rocks from the Cooma-type granites are presented in Table 1. The granites are characterized by high Al₂O₃ contents, low CaO and a K₂O : Na₂O ratio higher than unity. Chemical data have been summarized in Fig. 1.

![Fig. 1—AKF diagram for the Cooma-type granites.](image)

**Analytical data from Table 1, this paper (Nos. 1, 2, 3, 4) ; Tattam, 1929 (T) ; Edwards and Easton, 1937 (E) ; Joplin, 1942 and 1947 (J) ; Vallance, 1953 (V).**

Many of the rocks contain less than 80% normative AB₂ + Or + Q and thus would not be classified by Tuttle and Bowen (1958) as granites* (s.s.).

(ii) Inclusions. Three new analyses are listed for inclusions from the Cooma-type granites in Table 2, together with analyses from Vallance (1953) and Tattam (1929). An examination of modes and the analytical data for the inclusions reveals a close correspondence indicating that the phases have compositions close to the ideal normative minerals calculated. Utilizing the biotite analysis for specimen 21798, together with the modal data, the Mg : Mg + Fe + Mn value for the cordierite of this specimen may be estimated at (ca.) 0.6. The associated biotite has a value of 0.44.

The Mg : Mg + Fe + Mn ratio averages 0.40 both for the Cooma-type granites in South-east Australia and the pelitic rocks in the associated Or dovician sequence, while the associated psam mopelites and the psammites average 0.33. Inclusions of the latter rock type (Table 2) have an Mg : Mg + Fe + Mn ratio of 0.67.

* Tuttle and Bowen utilized C.I.P.W. norms, whereas Barth mesonorms have been used in Table 1.
Anions associated with 100 cations in the Cooma-type granites, their inclusions and the Ordovician metasediments are listed in Table 3. The metasediments show a general trend of decrease in the number of associated anions from low grade through to the inclusions with an increase of (ca.) 4% from the inclusions to the granites.

Figures 1 and 2 summarize some of the chemical features of the metasediments, the inclusions and the Cooma-type granites.

### Origin of the Granitic Rocks

The spatial distribution of the Cooma-type granites relative to the regional metamorphic zonal sequence and the high amount of included material in the granite suggest a close association between granite and surrounding country rock material. Mineralogically this is evident in that cordierite may be present in the granitic rocks and there is a similarity in the optical and chemical properties of the biotites in the metasediments and granite. The metasediments are characterized by a restricted chemical nature (Guy, 1969) being rich in alumina and potash, low in lime and soda, while the Cooma-type granites display a similar nature in that alumina and potash contents are high, with lime being low but slightly more significant than in the metasediments. Soda, however, is present in appreciable proportions in the granites. Valance (1953) estimated the country rocks in the Wantabadgery area have an average composition of a psammopelite, with the ratio pelite:

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**Table 3**

Anions Associated with Cations* in Metasediments, Inclusions and Granites

(a) Psammites and Psammopelites

<table>
<thead>
<tr>
<th>(?) Unmetamorphosed or Low-grade Zone</th>
<th>Biotite Zone</th>
<th>Knotted Schist Zone</th>
<th>High-grade Zone</th>
<th>Inclusions</th>
<th>Granites</th>
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</thead>
<tbody>
<tr>
<td>186.55</td>
<td>182.17</td>
<td>188.06</td>
<td>174.46</td>
<td>169.53</td>
<td>170.04</td>
</tr>
<tr>
<td>185.64</td>
<td>185.64</td>
<td>181.39</td>
<td>178.01</td>
<td>167.80</td>
<td>170.94</td>
</tr>
<tr>
<td>Average:</td>
<td>183.61</td>
<td>188.06</td>
<td>177.95</td>
<td>168.67</td>
<td></td>
</tr>
</tbody>
</table>

(b) Pelites

| 162.13                               | 175.18      | 172.39              | 167.13         | 163.96     | 174.75  |
| 173.58                               | 175.74      | 172.45              | 167.22         | 167.07     | 175.36  |
| 173.67                               | 177.13      | 172.77              | 167.67         | 167.86     | 175.41  |
| 175.52                               | 173.44      | 169.41              | 167.89         | 175.34     |         |
| 178.65                               | 174.80      | 170.19              | 172.08         | 175.78     |         |
| 179.22                               | 175.41      | 161.81              | 172.08         | 179.89     |         |
| 185.14                               | 181.81      |                    |                |            |         |
| 185.67                               | 183.10      |                    |                |            |         |
| Average:                             | 176.02      | 174.65              | 169.29         | 166.70     | 173.92  |

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* Cations summed to 100.00.

See Figs. 1 and 2 for references to analytical data on granites, and Guy (1969) for data on metasediments.
psammopelite : psammites being 20 : 60 : 20. This approximation appears to be a satisfactory estimate of the relative proportions of such rocks in the Tumbarumba-Geehi district. Vallance observed that such an average "psammopelite" was chemically similar to the granite except for a deficiency in the Na and Ca in the former rock, and suggested that granites were derived largely from materials of the sedimentary pile.

Joplin (1962) has postulated the idea of an oligoclase magma being added to the "psammopelitic" sequence to produce the Cooma-type granites. It is doubtful if such a magma is really necessary to form such granites; indeed Kolbe and Taylor (1966) have argued against this mainly on the basis of K : Rb ratios in these rocks. These latter authors, together with Pidgeon and Compston (1965), have suggested derivation of the Cooma-type granites entirely from the surrounding metasedimentary sequence. Joplin (1962) does not adhere to the idea of melting in situ alone because of the steep thermal gradients as indicated by the metamorphic zones surrounding the granite masses. Field relationships between granitic and metamorphic rocks in the Wantabagery area led Vallance (1953) to suggest that the granites there probably developed at some lower level and were later emplaced at a higher level in the crust. Similar relations exist in the Tumbarumba-Geehi district.

Previous investigations of the Cooma-type granites have demonstrated that such rocks are derived primarily from metasediments similar to those exposed in Ordovician areas of southeast Australia. As yet there is little detailed information regarding the mineralogical processes involved in the transformation to such granites, or on the physical state of the metasediments during transformation. Before considering these aspects several important features of the Cooma-type granites should be emphasized. The granites are broadly homogeneous in that textural and mineralogical features are reasonably constant throughout the various bodies. However, on the scale of an outcrop (several square metres), such rocks are characteristically heterogeneous with numerous inclusions (>2 cms.) occupying up to 10-15% of an exposure. Smaller inclusions (<2 cms.), not always readily discernible macroscopically, may occupy 5% (see Table 1) of such granites. Clustering of mineral phases is particularly evident with the micas but also present in quartzo-feldspathic sections. Thus a granite analysis as quoted in the text and figures represents but an average of these features, while the bulk chemistry of, say, the Corryong granite cannot possibly be represented by "granite" analyses alone.

The predominance of included country rock material in the granites, the similarity in mineralogical features to both the metasediments and the granitic rocks, and the textural features outlined above suggest that the inclusions are at an intermediate stage in the transformation to granitic material rather than a "by-product" of granitic development. Most of the inclusions contain mainly quartz and biotite with minor plagioclase feldspar as well as cordierite, sillimanite, etc. The inclusions are mica-rich and from the analytical data (see Fig. 2) contain markedly lower quantities of silica than the metasediments. Thus transformation from metasediment to inclusion may involve a segregation into a quartz or quartzo-feldspathic section and a mica-rich section. The mica-rich sections are obvious on a microscopic to a macroscopic scale. The lighter coloured portions are not immediately apparent in the vicinity of biotite-rich areas. The quartzo-feldspathic components may have been able to diffuse into their surroundings or migrate some distance—perhaps to contribute to the aplitic, pegmatitic and graphic granite phases that are common throughout the Cooma-type granites. The predominance of quartz over feldspars in the metasediments could have resulted in the segregation of quartz-rich areas. Quartz nodules throughout the granite may be representatives of this segregation. The process of segregation is conceivably a continuation of the regional metamorphic processes with diffusion being a principal agent by which rearrangement of material takes place. Most of the inclusions contain small amounts of plagioclase. This plagioclase is somewhat similar to that observed in the granitic rocks and is reasonably calcic (cores of An_50 have been recorded). The feldspars are discussed in more detail below (see p. 17). From an examination of Table 3, it is evident that the number of anions associated with 100 cations decreases with increasing grade of metamorphism. This effectively means that with increase in grade (until the stage of inclusions) there is a decrease in the overall volume of the rocks (~7%) and a corresponding increase in density.

Although there is a large variation in the degree of disintegration of the inclusions, transformation of inclusions to granite is very difficult to interpret. One of the most interesting features of the granitic rocks is that whereas bulk calcium contents are low (as are those of
the original metasediments) calcic cores are not uncommon in the granite plagioclases. Such cores are unlikely to from unless temperature conditions were sufficiently elevated or calcium was locally concentrated relative to sodium. It is unlikely that P-T conditions in Tumbarrumba-Geehi district were elevated enough for large scale melting to occur, and it is thus conceivable that in the early stages of transformation to granite there has been local concentration of calcium.

The rather patchy zoning of the plagioclases may reflect a later introduction of sodium into the system of the granitic rocks. Certainly Na2O is deficient in the metasediments compared with the granites. Vance (1965) favours magmatic resorption due to the release of confining pressure associated with emplacement as a major cause of patchy zoning in plagioclase. This factor cannot be overlooked here although there are no criteria directly supporting such an explanation. Subhedral or euhedral crystals do not display any obvious embayments while many of the patchy areas terminate along twin boundaries (see Plate 1) that are essentially low energy boundaries and should not be a general limitation in resorption. It is noteworthy that the Cooma-type granites do not display the degree of oscillatory or sharp normal zoning that is evident in the Khancoban, Mannus Creek and Dargals granites (Guy, 1964). These later bodies are interpreted as having migrated rather further from their position of origin than the Cooma-type granites, and hence are more likely to contain mineralogical features compatible with a history of such emplacement.

It is considered that the features display by the plagioclases in the Cooma-type granites are a direct result of local concentration of calcium followed by an influx of sodium into the granitic rocks. Such an influx of sodium may have taken place by diffusion in the solid state, or through the introduction of melt or solution. Either process would be aided by an increase in temperature conditions. The physical state of the granitic rocks during the introduction of sodium may conceivably have been that of a partial melt. This aspect will be discussed in more detail below (p. 19).

The nature of the alkali feldspars is of interest in the granitic rocks. Marmo (1967) contends that potash feldspars of most synkinematic granites are highly triclinic microcline, although potash feldspars that form porphyroblasts not uncommonly have lower triclinicities. Such feldspars are younger than other constituents in these rocks. He suggests that where there has been reasonably rapid introduction of potassium with little time for Al-Si ordering in the developing feldspars, orthoclase may be formed, whereas if the introduction rate is slow, ordering results and microcline will develop. The optical properties of the alkali feldspars in the Cooma-type granites of the present area indicate that the alkali feldspars are not highly triclinic and form "porphyroblasts" and thus they may have formed in a manner envisaged by Marmo. However, according to the scheme of Laves and Viswanathan (1967), the feldspars with low Δ values and high 2V may consist of domains with a high degree of order, i.e. the alkali feldspar are submicroscopically twinned. Thus Δ values for this suite may not be as low as indicated. The reason for the paucity of twining in such feldspars is difficult to interpret and growth may be similar to that suggested by Marmo, i.e. growth is rapid so that the phase grew essentially as a monoclinic phase and not as "microcline". The influence of post crystallization deformation cannot be neglected here. Microcline with higher obliquity than orthoclase should twin less readily, however, this does not appear to be the case for most natural occurrences. Possibly the optically monoclinic feldspars of these granites have a high triclinicity and do not display a great deal of obvious twinning due to a rapid fall in temperature conditions after their formation, and the lack of any major deformation.

The K : Na ratio of the alkali feldspars in the Cooma-type granites is somewhat lower than that observed in other granitic suites of the Tumbarrumba-Geehi district. This may be related to high degree of unmixing in the latter rock types and perhaps the Cooma-type granite alkali feldspars have developed when there was a relatively greater availability of sodium.

Marmo (1967) considers that many of the synkinematic granites have experienced addition of K and to a minor degree Na. Chemical data from the present investigation is more suggestive of introduction of sodium, as potassium contents of the granitic rocks (considering the composition of the inclusions as well) does not appear to differ markedly from that of the metasediments. Textural evidence indicates that the alkali feldspars and muscovite have formed somewhat later than other constituents, however, it is considered that such potassium is derived locally from the disintegration of muscovite and biotite in the inclusions, perhaps associated with a rise in temperature conditions. Stability of micas until late in the transformation process may be
responsible for survival (or perhaps production—see below) of cordierite in some of the granitic rocks.

It may be significant that the Mg : Mg + Fe + Mn ratio for the Cooma-type granites is slightly greater than that of an average psammopelitic metasediment (p. 8). This may imply that there has been a slight enrichment in Mg relative to Fe in the granitic rocks. The high value for this ratio in some of the analysed psammopelitic inclusions may be the result of such enrichment.

The transformation of inclusions to granitic material would require some addition of silica (see Fig. 2). This would be consistent with the expected reaction of micas (Si : O ratio \(\sim 1 : 3.3\)) transforming to feldspars (Si : O ratio \(\sim 1 : 2.7\)). Winkler (1967) suggests a reaction such as

\[
2 \text{ biotite} + 6 \text{ sillimanite} + 9 \text{ quartz} \rightarrow 2 \text{ K-feldspar component} + 3 \text{ cordierite} + 2 \text{ H}_2\text{O}.
\]

This reaction may in part be responsible for the paucity of quartz-rich or quartzo-feldspathic segregations immediately adjacent to mica segregations. The average bulk composition of the granite and biotite-rich inclusions would be markedly lower in SiO\(_2\) than an average psammopelite. The transformation of inclusion to homogeneous granite would involve an increase in the number of anions associated with 100 cations (see Table 3) and hence an increase in volume or decrease in density. This may have influenced migration of granitic rocks to higher levels in the crust. The granites are in places surrounded by lower grade sections of the high grade zone or upper knotted schist zone rocks (Guy, 1969)—apart from where faulting has been operative. Such metasediments would have a similar specific gravity to that of the granites.

The bulk composition of the granitic rocks is such that few samples contain more than 80% Q+Or+Ab or fall in the low-temperature through of Tuttle and Bowen (1958). The normative ratio of Q : Or : Ab is approximately 45 : 30 : 25, although biotite clusters frequently have granular quartz associated with them, thus the Q content of portions of the granites capable of melting may be less than that indicated by the above ratio.

Von Platen (1965) has suggested that the Ab : An ratio is an important factor on the “minimum melting point” (Winkler, 1967) in the system Q–Ab–An–Or at \(P_{\text{H}_2\text{O}} = 2000\) bars. With increase in Ab : An ratio the “minimum melting temperature” decreases and is relocated towards the Ab corner, restricting the plagioclase field. A plot of some Cooma-type granites is noted in Fig. 3 with reference to this system. These analyses are presented on two Q–Ab–Or projections to illustrate the influence of Ab : An ratio on their crystallization history. Those rocks with low Ab : An ratio (<3.0) generally lie on the Ab side of the cotectic curve. Thus if such (or similar) rocks were melting plagioclase would be the last phase (neglecting biotite, etc.) to go into the melt. This may imply that any

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**Fig. 3**—Projections of sections through the system Q–Ab–An–Or–H\(_2\)O at \(P_{\text{H}_2\text{O}} = 2000\) bars. Points of “minimum melt” composition are indicated (○) and some cotectic curves for various Ab : An ratios. (After Von Platen, 1965.)

(a) Plot of Cooma-type granites (×) with Ab : An < 3.0. The boundary between the plagioclase and K-feldspar fields (for Ab : An = 1.8) is indicated.

(b) Plot of Cooma-type granites (×) with Ab : An > 3.0. Figures against (×) symbols refer to the Ab : An ratio of the granites.
quartz-alkali feldspar-rich or quartz-rich segregations that may have developed in such granitic rocks through a segregation process, would be particularly susceptible to melt conditions.

If introduction of sodium followed some melting of rock types represented by Fig. 3a, there would be a marked change in the ratio of Ab : An (as the An contents are generally not large) as well as depressing the "minimum melting temperature". The "minimum melt" and the coethnic line would be relocated towards the Ab corner. As such sodium introduction would not greatly change the amount of Ab relative to Or and Q, the plot of the granitic rocks on the diagram Q-Ab-Or would not be significantly altered.

If associated with sodium introduction, there was breakdown of micas (see p. 18) and perhaps some incorporation of quartz-rich segregations (cf. Fig. 2), the bulk composition of the granitic phases would be relocated away from the Ab corner. Thus the distribution of granitic rocks noted in Fig. 3b—i.e. those with high Ab : An ratio—may be explained by such a sequence of events. It is interesting that in the latter case those rocks with high Ab : An ratio, would lie on the Q side of the coethnic and thus quartz would be the last phase to melt. Thus fluctuation in temperature, pressure, breakdown of biotites, or introduction of Na would have a marked influence of the phase(s) in equilibrium with the melt. The patchy zoning of the plagioclases may be a direct result of such a crystallization history.

Some recent investigations by Weill and Kudo (1968) have thrown some doubt on the work of Von Platen. The former authors suggest that the Q-Or-Ab system does not have a unique melting point or a unique composition of initial melt. This does not detract from the suggestion by Winkler (1967) that for any Ab : An ratio there is still a minimum melting point for the system. Some doubt exists as to whether the minimum melting points determined by Von Platen is the absolute minimum in the system Q-Ab-An-Or for a fixed Ab : An ratio. Weill and Kudo's suggestion that there is a unique melting point for a given Ab : Or ratio may not be particularly significant for the Cooma-type granites considering that the development of such rocks is related to breakdown of the micas. If it is assumed that Von Platen's experimental study does suggest a trend for minimum melt composition with variation in Ab : An ratio, a feasible theory may be proposed for the development of the Cooma-type granites.

The sequence of events envisaged in the formation of these granites may be summarized as:

1. Very high grade metamorphism of a sequence of rocks with a compositional range close to that of a psammopelite. The metamorphism involves a decrease in volume with increase in grade. The principal phases would be quartz, micas (mainly biotite) and minor, but rather calcic plagioclase. Calcium and magnesium may have been locally concentrated at this stage. Some segregation of constituents may have taken place producing quartz-rich or quartzo-feldspathic-rich, and mica-rich sections. Diffusion would presumably have been the main process involved in migration of material. Melt is considered not to have been of much significance at this stage.

2. Introduction of sodium, possibly by local concentration from the metasediments, but more likely by diffusion from lower levels in the crust. Such diffusion of sodium would be favoured by elevated temperatures. Both controls (elevated temperature and Na introduction) would be conducive to the production of a partial melt and migration of the coethnic line of the system Q-Ab-An-Or-H₂O towards the Ab corner. Breakdown of micas, also compatible with increase in temperature would favour a change in the phase co-existing with the melt. Such conditions are considered to have been a significant factor in producing the patchy zoning in the plagioclase and the production of alkali feldspars in granitic rocks. The reactions involved in this transformation to granite may have resulted in an increase in volume (cf. Table 3) and a decrease in density. This may have been a factor in the migration of Cooma-type granites to higher levels in the crust. It is possible that these rocks have been annealed after emplacement with a significant modification of their textures. The cell structures noted in the quartz grains and some undulatory character of the feldspars may have developed through such a process as annealing.

Pidgeon and Compston (1965) have suggested an age of 415±12 m.y. for the Cooma granite and the surrounding high grade metamorphics at Cooma. More distant greenschist facies rocks are reported to have an age of 460±11 m.y. These authors indicate there is no evidence to suggest any metamorphism later than that developed in the high grade zone and propose that the Cooma granite is locally derived from rocks in the high grade zone. In the Khan-coban area (Guy, 1969) there is evidence that the regional metamorphism is multiple in
character and that this is discernible only in the higher grade metamorphics. Pidgeon and Compston have not discussed fully the significance of similar ages obtained for the Cooma granite and a section of the Murrumbidgee batholith.

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