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A Cordierite-Bearing Granite Suite from the New England Batholith, N.S.W., Australia

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Abstract. A suite of cordierite-bearing biotite-muscovite intrusive granites in the New England Batholith, New South Wales, outcrops over 3400 sq km and is the largest reported occurrence of granites of this type. Compositionally the granites are close to the low temperature minimum and display only limited chemical variation. The corundum-normative nature of the granites suggests a pelitic sedimentary parentage. Cordierite with an average 100 Mg/Mg+Fe of 55 occurs as large tabular crystals and is considered to be a refractory phase brought up from the zone of partial melting. The presence of cordierite and the absence of garnet in these granites suggests a partial melting at a pressure maximum of 6 kb, equivalent to 22 km depth.

Introduction

In the Palaeozoic and younger circum-Pacific Batholiths of North and South America granodiorite, tonalite, and diorite predominate over granite[1] (Moore, 1959; Bateman and Eaton, 1967; Cobbing and Pitcher, 1972; Roddick and Hutchison, 1974). These batholiths typically contain hornblende and biotite, and are considered by Presnall and Bateman (1973) to have formed by the partial fusion of diopside-normative mafic rocks in the lower crust followed by differentiation. Models for the production of granitic magma in batholithic proportions by partial fusion favour the proposal that granodiorite and more mafic magmas are generated at greater crustal depths and higher temperatures than granite magma (Brown and Fyfe, 1970; Brown, 1973). However, granite is by far the most abundant rock in the Upper Palaeozoic New England Batholith of northern N.S.W., Australia; granodiorite, tonalite, and diorite are present in minor amounts only.

Whereas most of the New England plutons contain biotite and hornblende or biotite alone, one suite of granite intrusions (the Bundarra Plutonic Suite) contains biotite and muscovite and is significantly corundum-normative. This suite is also characterised by ilmenite and large megacrysts of cordierite, both in amounts less than 1%. Although cordierite is known in granitic rocks, e.g.

[1] The term "granite", as used in this paper, conforms to the recommendation of the I.U.G.S. Subcommission on the systematics of igneous rocks (Streckeisen *et al.*, 1973) and includes both "adamellite" and "granite" as traditionally used by British and Australian geologists.

Dartmoor (Brammall and Rao, 1936), Oregon (Taubeneck, 1964), and Victoria, Australia (Baker, 1940), this paper documents the presence of cordierite in a suite of rocks many times the size of previously reported occurrences. Accidental inclusion of cordierite crystals is therefore unlikely. Our purpose is to discuss the petrogenetic significance of cordierite-bearing granites in the light of experimental data and to relate this to recent theories of batholith evolution. We suggest that other cordierite-bearing granites may be found among muscovite granites.

Petrology

The Bundarra Plutonic Suite outcrops over 3400 sq km as a narrow meridional belt along the western margin of the New England Batholith (Fig. 1). This constitutes about one quarter of the total outcrop area of the Batholith. A Rb/Sr age determination from one granite specimen gave 281 m.y. (Wilkinson, 1969), which indicates that this Suite may be the oldest in the Batholith. The main hornblende-biotite granites of the Batholith were intruded during the upper Permian concluding with leucocratic hornblende-biotite and biotite granites in the Lower Triassic (Evernden and Richards, 1962; Binns, 1966).

The cordierite-bearing granite plutons mapped to data are elliptical with outcrop areas of 100–200 sq km. In common with most other intrusions of the Batholith they have sharp contacts and distinct thermal aureoles up to hornblende hornfels facies in the surrounding sediments, grading out into regional metamorphic prehnite-pumpellyite metagreywacke facies (Leitch, 1974) over distances of 2 to 5 km. Typically they exhibit no foliation, flow banding, or compositional zonation. Xenoliths are rare, but where present are less than 15 cm across and are foliated. To date no cordierite crystals have been found in xenoliths. Small quartz-K-feldspar-tourmaline veins and pegmatite segregations are general features of the Suite, particularly at the margins.

The Suite is coarse-grained, most grains exceeding 1 cm across. Where fresh, the feldspars are pale grey to grey-blue in hand specimens and most plutons contain large K-feldspar megacrysts up to 8 cm in length. Cordierite is ubiquitous and varies from one percent in the most biotite-rich granites to trace amounts in the more leucocratic granites. The abundance of cordierite appears to be related to that of biotite rather than to either distance from an intrusive contact or proximity to sparse xenoliths. The cordierite forms euhedral crystals up to 2 cm long with well developed prismatic faces and is free of inclusions. The cordierite prisms are rimmed by muscovite which also occurs along cleavage planes. The cordierite within the muscovite shell is commonly pseudomorphed by a dull green amorphous aggregate of "pinite".

The rocks show only limited variation in composition (Table 1) and are consistently corundum-normative, this being due to cordierite, muscovite, and an aluminous biotite. The Fe_2O_3/FeO ratio in the Suite is extremely low, as is shown by an almost Fe^{3+}-free biotite and the presence of ilmenite rather than the association magnetite-sphene. Electron microprobe analyses of the cordierite (Table 2) show that the average value of 100 Mg/Mg+Fe is 55.3 with a variation from 50.1 to 59.9.

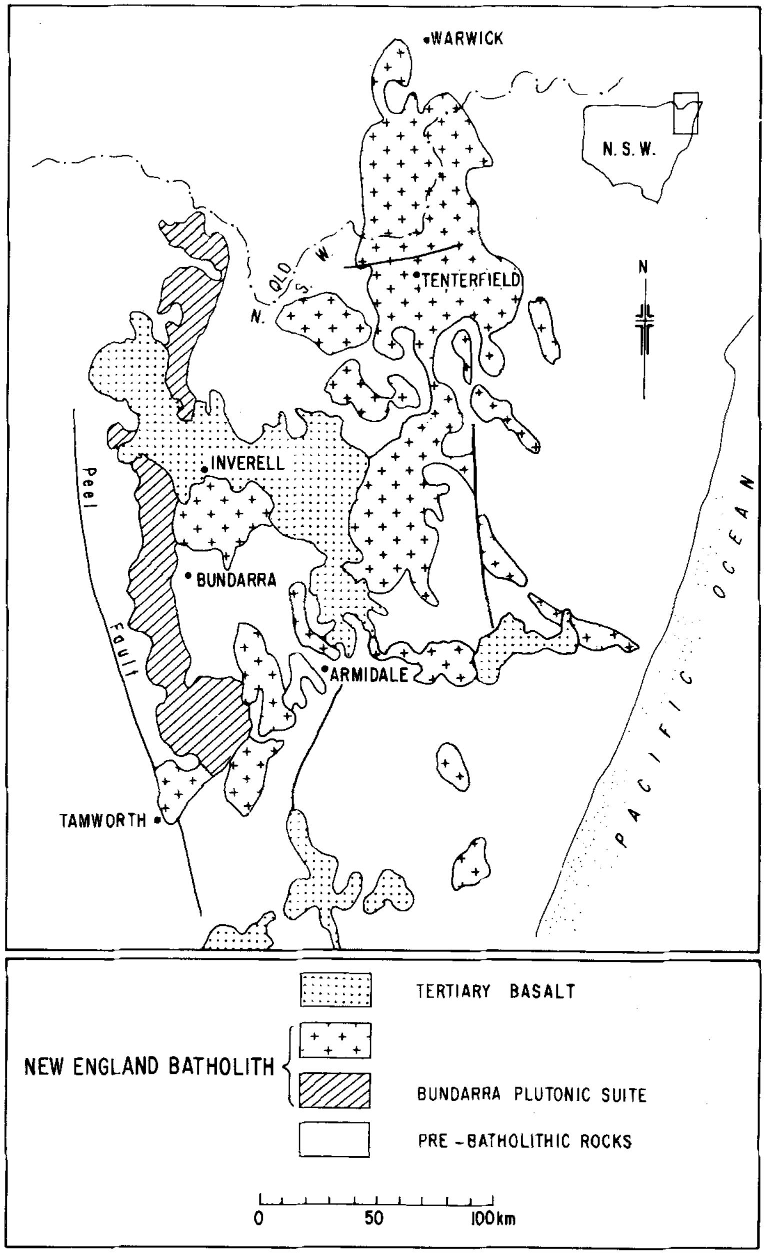
WARWICK
N.S.W.
N
TENTERFIELD
QLD.
N.S.W.
INVERELL
Peel
Fault
BUNDARRA
ARMIDALE
TAMWORTH
PACIFIC OCEAN
TERTIARY BASALT
NEW ENGLAND BATHOLITH
BUNDARRA PLUTONIC SUITE
PRE-BATHOLITHIC ROCKS
0
50
100km

Fig. 1

Table 1. Analyses of the Bundarra Plutonic Suite

Average of 32 total rock specimens	Mean	Std. Dev.	C.I.P.W. Norm (weight percent)	Mean	Std. Dev.
SiO_2	73.53	1.45	q	33.16	2.76
TiO_2	0.28	0.09	or	27.32	2.03
Al_2O_3	13.61	0.47	ab	26.60	1.51
Fe_2O_3	0.22	0.09	an	5.69	2.02
FeO	1.62	0.36	c	1.34	0.47
MnO	0.04	0.01	hy	3.83	0.92
MgO	0.57	0.18	mt	0.32	0.14
CaO	1.34	0.40	il	0.53	0.18
Na_2O	3.15	0.18	ap	0.33	0.06
K_2O	4.62	0.34			
P_2O_5	0.15	0.02			
	99.13				

Table 2. Microprobe Analyses of Cordierite Megacrysts, Bundarra Plutonic Suite (summed to 100 percent)

	MU 8400		*MU 8401*	
	Core (Av. of 8)	Margin (Av. of 3)	Core (Av. of 3)	Margin (Av. of 3)
SiO_2	48.57	48.70	48.46	47.93
Al_2O_3	33.36	33.38	33.39	33.18
FeO (total)	9.53	9.13	9.63	11.37
MnO	0.11	0.17	0.14	0.33
MgO	7.58	7.67	7.37	6.41
Na_2O	0.77	0.85	0.92	0.76
K_2O	0.08	0.10	0.09	0.02
Structural formulae (based on 18 oxygens)				
Si	4.96	4.97	4.96	4.94
Al	4.01	4.01	4.02	4.03
Fe^{2+}	0.81	0.78	0.82	0.98
Mn	0.01	0.02	0.01	0.03
Mg	1.15	1.17	1.12	0.98
Na	0.15	0.17	0.18	0.15
K	0.01	0.01	0.01	0.00
100 Mg/Mg+Fe Cordierite	58.7	59.9	57.7	50.1
100 Mg/Mg+Fe Biotite	30.5	–	29.0	–
Distribution coefficient				
Cord-Bi $K_{D(Fe)}$	0.31	–	0.30	–

Origin of the Cordierite

The presence of cordierite crystals in the Bundarra Plutonic Suite could result from one of the following mechanisms:

1. Contamination of the magma from the surrounding aluminous wall rocks.
2. Reaction of primary muscovite with biotite or the residual melt to form cordierite at P_{H_2O} below the stability limit of muscovite, after the magma intruded to higher crustal levels.
3. Reaction of refractory garnet residuals to form cordierite as the magma intruded to higher crustal levels.
4. Crystallisation of cordierite phenocrysts from the magma.
5. Refractory cordierite from the zone of partial melting.

Many of the metasediments adjacent to the granite contain cordierite but, in contrast to the large inclusion-free cordierite of the granites, it is fine-grained and sieved with inclusions of quartz and biotite. This, together with the distribution of the cordierite in the granites and the scarcity of xenoliths, argues against derivation from these metasediments.

The muscovite rimming the cordierite is coarse-grained and, like the discrete muscovite grains, is regarded as having formed in the magma. If this is so, it excludes the second mechanism. The presence of primary muscovite (Chappell, 1969), the coarse grainsize of the plutons, and the pegmatitic veins all indicate final crystallisation of the magma under water vapour pressure greater than 4 kb.

No textural evidence is present to support the third mechanism. The small iron-rich cordierite crystals in the Victorian rhyodacites (Birch and Gleadow, 1974) may have this origin, but the relatively magnesian cordierites discussed here are unlikely to have formed from the almandine-rich garnets observed in calc-alkaline rocks (Green and Ringwood, 1968; Wood, 1974). Certainly the iron cordierite of the rhyodacites seems incompatible with suggestions of a refractory origin. The reverse zoning of these iron cordierites can be explained in terms of initial reaction of the outer iron-rich rims of the large (1 cm) garnets to produce the first cordierite which then becomes more magnesian as resorption allows reaction of the more pyrope-rich central part of the refractory garnets. Iron-rich cordierite could also be formed by the second mechanism if muscovite reacted with an iron-rich residual liquid, but this would not explain the reverse zoning present in the cordierites from Victoria.

The choice of the two remaining possibilities, i.e. phenocrysts or refractory residuals, is more difficult. The partition of Mg and Fe between coexisting cordierite and biotite could indicate whether these two minerals are in equilibrium, but insufficient data are available from igneous rocks elsewhere for comparative purposes. Comparison with metamorphic rocks, although of limited value, indicates that the distribution coefficient $K_{D(\mathrm{Fe})}$ in the Bundarra Plutonic Suite (0.30, Table 2) is much lower than in metamorphic rocks (Saxena and Hollander, 1969; Dallmeyer and Dodd, 1971; Hess, 1971), irrespective of grade, suggesting that sub-solidus equilibrium based on a simple ion exchange model was not achieved.

The low distribution coefficient could be due to an early Mg-rich cordierite and a late Fe-rich biotite.

Since the granite closely approximates the ternary minimum composition, partial melting is presumed to have taken place at temperatures close to the solidus. Thus experimental evidence that cordierite is moderately refractory in the melting of pelitic rocks (Winkler, 1967; Kilinc, 1972; Hensen and Green, 1973) and the relatively magnesian composition indicate that the cordierite is best explained as a refractory phase brought up from the zone of melting. Analogous mechanisms have been proposed for the mafic minerals of the Sierra Nevada Batholith (Bateman and Eaton, 1967; Piwinskii, 1968). Minor precipitation of cordierite onto the refractory grains may have given rise to the zoning observed in one cordierite grain (Table 2). The well developed prism faces of the cordierite may also have resulted from shape adjustments after melting. The absence of other aluminous refractory phases (e.g. sillimanite or andalusite) may be due to replacement of these phases by micaceous products or the unfavourable composition of the pelitic parent rocks.

Experimentally obtained upper pressure limits of cordierite (Hensen and Green, 1972, 1973; Green and Vernon, 1974) determine maximum depths of generation for magmas containing refractory cordierite. If cordierite and garnet are present as refractory phases the pressure could be as high as 11 kb, but cordierite alone suggests a pressure of 6 kb or less (Hensen and Green, 1973). If this is correct, then temperatures of 750° C (Brown, 1973) were present at depths of 22 km at the outset of plutonism in New England, N.S.W. The pelitic metasediments adjacent to the cordierite-bearing granites would provide suitable source rocks if they extended to sufficient depth. The abundant graphite in these metasediments could also explain the low Fe^{3+}/Fe^{2+} ratios in the biotites of these granites (Eugster, 1972). The sharp intrusive contacts and distinct thermal aureoles of the Bundarra Suite granites indicate that the magmas were sufficiently water-undersaturated to allow intrusion to higher levels (Burnham, 1967; Cann, 1970). However, the water content was sufficiently high to allow crystallisation of primary muscovite.

The dominance of diopside-normative plutons (the "I" type of Chappell and White, 1974) in orogenic regions such as the American Cordillera is evidence for the partial melting of an igneous lower crust of basic or intermediate composition. The development of sub-equal amounts of this type and corundum-normative granites (the "S" type of Chappell and White, 1974) in the New England Batholith, N.S.W. is in marked contrast, indicating the presence of both igneous and pelitic metasedimentary source rocks. The shallow depths of partial melting indicated by the cordierite granites suggest that a greater vertical range of magma generation in New England may have been a significant factor in determining the differences between the American and Australian batholiths.

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