

## PETROLOGY OF THE STRATHBOGIE BATHOLITH: A CORDIERITE-BEARING GRANITE

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### ABSTRACT

The Strathbogie batholith is a high-level, discordant, composite granitoid intrusion in southeastern Australia. Granitic rocks containing magmatic garnet, cordierite and biotite predominate in the batholith. Intrusion involved marginal faulting, roof lifting and "shouldering aside" of the country rocks, which include the Violet Town volcanic complex of similar Late Devonian age. Textural evidence indicates early crystallization of biotite together with garnet, plagioclase ( $\sim An_{45}$ ) and some quartz. The bulk of the quartz, cordierite and K-feldspar crystallized later during emplacement. Early magmatic crystallization occurred with  $P \cong 4$  kbar,  $T \cong 800^\circ\text{C}$  and water contents in the magma of about 4 wt. %. Thus the Strathbogie magma was relatively hot and water-undersaturated. Emplacement occurred at  $P \sim 0.5$  kbar with initial temperatures well in excess of the wet granite solidus. Oxygen fugacity was  $< QFM$  throughout the magma's history. The Strathbogie rocks have  $SiO_2$  contents in the range 70–76 wt. % with high  $K/(K + Na + Ca)$ , normative corundum around 2 wt. % and  $Mg/(Mg + Fe) = 0.4\text{--}0.5$ .  $CaO$ ,  $MgO$ ,  $TiO_2$  and  $P_2O_5$  decrease linearly as  $SiO_2$  increases. These chemical trends cannot be fully explained by removal or variable incorporation of restite materials, as inclusions of any kind are scarce in all variants. Differentiation mechanisms involving separation and accumulation of early magmatic biotite, plagioclase and accessory phases are favored over batch partial-melting processes to model the chemical variation. Magma chemistry, together with inferred early magmatic conditions, and the mineralogy of inclusions in the granites suggest initial formation of the Strathbogie magma by partial fusion of biotite-bearing quartzofeldspathic and pelitic rocks under granulite-facies conditions. These source rocks are apparently below the presently exposed lower Paleozoic sequences of southeastern Australia. The transitional orogenic–anorogenic setting of the batholith is compatible with the partial-fusion event having resulted from intrusion of mafic magma into the deep crust.

**Keywords:** peraluminous granite, granite petrogenesis, granite geochemistry, granite emplacement, cordierite, garnet, Australia, Strathbogie.

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### SOMMAIRE

Le batholithe de Strathbogie (Sud-Est de l'Australie), dont le toit se trouve à faible profondeur, est discordant et composite. Les roches granitiques qui contiennent grenat, cordiérite et biotite magmatiques y sont dominantes. L'intrusion s'est produite par glissement le long de failles marginales, soulèvement du toit et repoussement latéral des roches encaissantes, dont le complexe volcanique Violet Town, aussi d'âge Dévonien tardif. D'après les textures, la biotite a cristallisé tôt, avec grenat, plagioclase ( $\sim An_{45}$ ) et un peu de quartz. Quartz, cordiérite et feldspath potassique ont, en majeure partie, cristallisé plus tard, lors de la mise en place. Le stade initial de la cristallisation a eu lieu à une pression d'au moins 4 kbar, à une température de  $800^\circ\text{C}$  ou plus et à partir d'un magma contenant environ 4% d'eau (en poids). Le magma était donc relativement chaud et sous-saturé en eau. Pendant la mise en place, à une pression d'environ 0.5 kbar, la température initiale surpassait le solidus du système granitique saturé en eau. La fugacité d'oxygène est restée inférieure au tampon *QFM* pendant toute l'évolution du magma. Les granites contiennent de 70 à 76% de  $SiO_2$  (en poids), et possèdent un rapport  $K/(K + Na + Ca)$  élevé, environ 2% de corindon normatif et un rapport  $Mg/(Mg + Fe)$  situé entre 0.4 et 0.5. Les concentrations de  $CaO$ ,  $MgO$ ,  $TiO_2$  et  $P_2O_5$  décroissent linéairement quand  $SiO_2$  augmente. Ce comportement ne peut s'expliquer entièrement par élimination ou incorporation variable de matériaux résiduels, vu la rareté des xénolithes dans tous les facies. On préfère les mécanismes de différenciation qui impliquent la séparation et l'accumulation, dans le bain fondu, de biotite, plagioclase et phases accessoires, toutes hâtives, aux processus discontinus de fusion partielle pour expliquer la variation de composition. D'après la chimisme du magma, les conditions magmatiques initiales et la minéralogie des xénolithes dans les granites, une fusion partielle de roches quartzofeldspathiques à biotite et de roches pélitiques, équilibrées dans le facies granulite, serait à l'origine du magma. Ces roches forment le socle sous-jacent des séries du Paléozoïque inférieur qui affleurent à présent dans le Sud-est de l'Australie. Le milieu de transition orogénique–anorogénique du batholithe concorde avec la fusion partielle qui fut le résultat de l'intrusion d'un magma mafique dans la croûte profonde.

(Traduit par la Rédaction)

*Mots-clés:* granite peralumineux, pétrogenèse granitique, géochimie du granite, mise en place des granites, cordiérite, grenat, Australie, Strathbogie.

### INTRODUCTION

Peraluminous granitoid and volcanic rocks are widespread in the Tasman fold belt of eastern Australia. These dominantly post-tectonic batholiths and volcanic complexes contain one or more of the peraluminous phases cordierite, garnet, biotite, andalusite, sillimanite and mus-

covite. On the basis of studies of granites in southeastern New South Wales, Chappell & White (1974) have proposed the term "S-type" for these chemically and mineralogically distinctive rocks, inferring their origin as a result of partial melting of metasedimentary material.

Recent field and petrological studies (Birch & Gleadow 1974, Flood & Shaw 1975) have suggested that the peraluminous phases (cordierite and garnet) are largely of residual metamorphic character (*i.e.*, restite) derived from the source region of the partial melts. Here we describe a

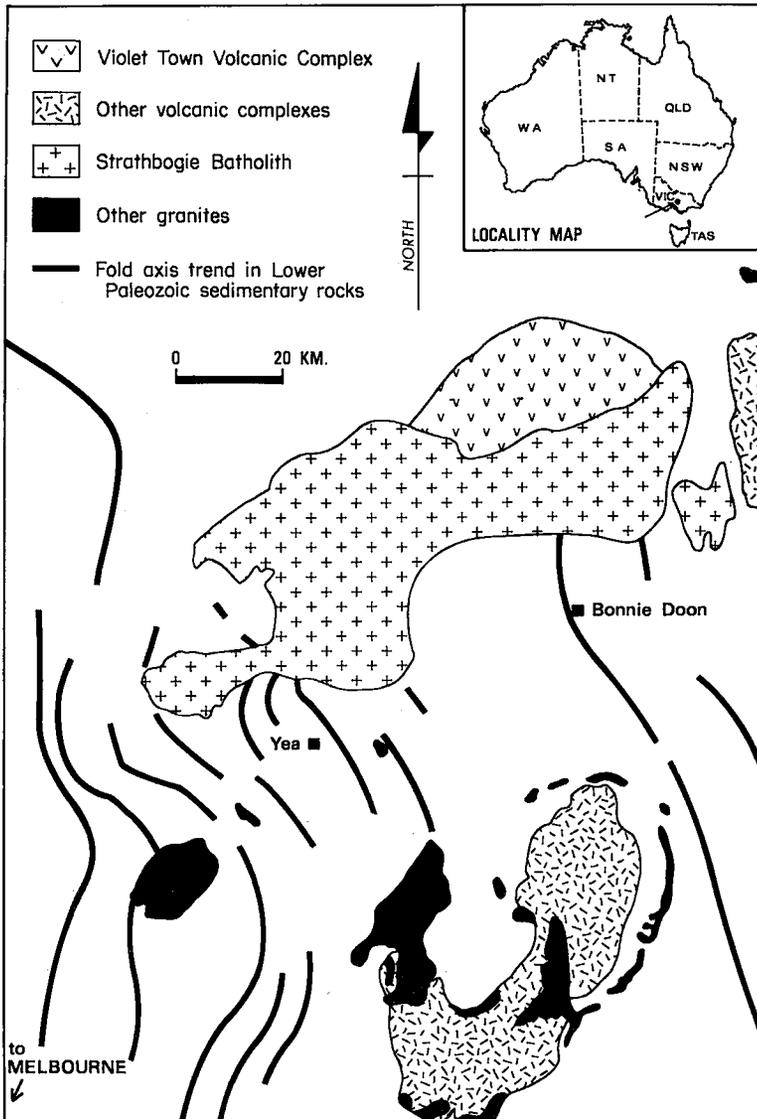


FIG. 1. Regional geological setting of the Strathbogie batholith and other felsic igneous complexes of central Victoria.

contrasting situation in which textural features in a high-level pluton, subject to little solid-state readjustment, indicate a magmatic origin for the bulk of the cordierite, garnet and biotite. The implication is that moderately peraluminous melts may be generated in the lower crust and evolve by processes largely independent of the presence of restite phases.

## FIELD RELATIONS

### General setting

The Strathbogie batholith is a large, discordant, composite body more than 1500 km<sup>2</sup> in area situated 150 km north-northeast of Melbourne (Fig. 1). The batholith, of Late Devonian age ( $365 \pm 5$  Ma, K/Ar, J.R. Richards, written comm. 1975) intruded folded Siluro-Devonian sedimentary rocks of the Melbourne Trough (Phillips & Wall 1980) and on its northern margin, the Violet Town volcanic complex (Birch *et al.* 1977) of Late Devonian age. The Barjarg granite of White (1954) is here con-

sidered as part of the batholith but separated from the rest of the Strathbogie mass by a narrow zone without outcrop. The Strathbogie batholith, which is markedly elongate in an E-W direction, cuts across major structures in the Paleozoic sedimentary rocks.

A broad contact-metamorphic aureole surrounds the batholith and is particularly well developed in the Paleozoic sedimentary rocks. At Bonnie Doon, spotted slate, biotite-muscovite, cordierite-muscovite and cordierite-K-feldspar zones have been delineated in the 3-km-wide aureole (Phillips & Wall 1980). Contact-metamorphic effects are present in the Violet Town volcanic complex up to several hundred metres from the granite contact (Birch *et al.* 1977, Clemens & Wall 1979).

### Emplacement

The undeformed Violet Town volcanic complex postdates major folding, low-grade regional metamorphism and erosion of the Siluro-Devonian sedimentary rocks (Birch *et al.* 1977); all these processes are presumably associated with

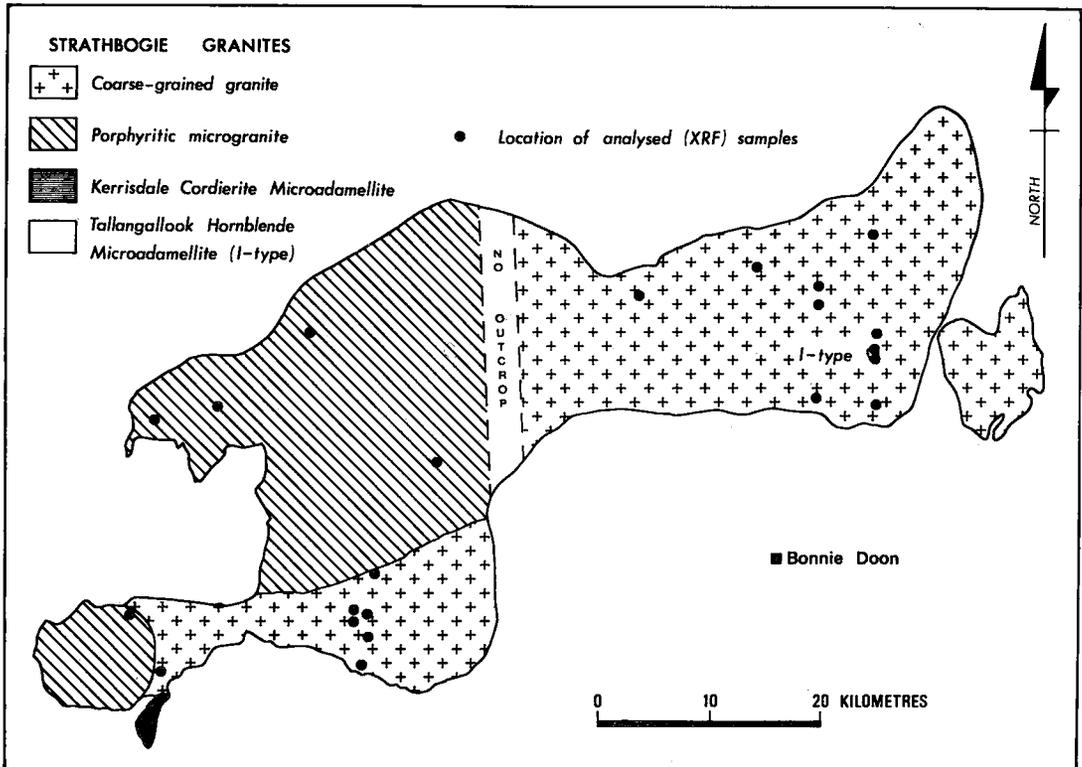


Fig. 2. Distribution of granite types within the Strathbogie batholith. Cordierite and garnet are present in all variants except the I-type Tallangalook hornblende microadamellite.

the Tabberabberan orogeny (Middle-Late Devonian: Talent 1965). Similar volcanic rocks in the Cerberean cauldron in Victoria have been dated as post-Tabberabberan (McDougall *et al.* 1966). Thus, at least the northern margin of the Strathbogie batholith, which intruded the subaerial volcanic pile (present thickness 300 m: Birch *et al.* 1977), was probably emplaced at a very high level, *i.e.*, pressures < 1.0 kbar. The character of the contact-metamorphic assemblages at Bonnie Doon also suggests very low pressures (0.5–1.0 kbar) and indicates peak metamorphic temperatures of around 600°C (Phillips & Wall 1980). Hence, taking into account the temperature drop (approximately 150°C) across the intrusive contact (Jaeger 1957), the presently exposed granite was emplaced at shallow depth (*ca.* 3 km) and relatively high temperatures.

On a regional scale, the batholith is bounded by several nearly straight E–W and N–S contacts (Fig. 2). Major structures in the Paleozoic sedimentary rocks on the southern side of the granite are truncated by the contact. However, the strike of the sedimentary rocks appears to be deflected near the western end of the batholith (Vandenberg & Garratt 1976), with the divergence becoming apparent within 20 km of the granite contact (Fig. 1). On a mesoscopic scale, abrupt right-angled steps occur along the contact. Between these steps the contact is straight for distances of 10 to 100 m. The contacts are generally near-vertical, with marginal zones of finer-grained granite up to 10 m wide. Rare aplitic apophyses penetrate the country rock.

The development of high-grade contact metamorphic rocks adjacent to the granite appears to rule out major postemplacement faulting as

an explanation of the geometry of the contact. Penetrative deformational fabrics are completely absent from the granite and hornfels. Faulting during emplacement (brittle country-rock deformation) may, however, account for the stepped nature of the contact. Marginal faulting is well shown in the northern region where adjacent volcanic rocks are block-faulted and tilted away from the granite. In view of the paucity of country-rock xenoliths, stoping is unlikely to be the major mechanism of granite emplacement. The composite character of the batholith is also evidence against stoping (White *et al.* 1974). From the above evidence we infer that emplacement was dilational in character, with some “shouldering aside” of the country rocks, marginal faulting and lifting of the roof of the magma chamber. This scheme differs from proposals of wrench-fault-controlled emplacement of other discordant batholiths in southeastern Australia.

In summary, the Strathbogie batholith is a discordant, high-level, post-tectonic batholith of composite character. The northern and eastern marginal portions (at least) represent near-roof zones, as they intruded the Violet Town volcanic complex. Clemens *et al.* (1979) suggested that the Violet Town volcanic complex and the Strathbogie batholith are comagmatic in view of their close temporal and spatial association and similar geochemistry.

## PETROGRAPHY

### Granitoid rocks

We have subdivided the Strathbogie batholith into four mappable variants on the basis

TABLE 1. PETROGRAPHY

Rock Type	% Exposure of Batholith	Fabric	Phenocrysts	Groundmass	Accessories
Porphyritic microgranite	34.0	porphyritic usually with 10 - 25% euhedral phenocrysts	quartz, 5 - 10 mm plagioclase (An <sub>40-17</sub> ), 5 - 10 mm orthoclase, 4 - 10 mm cordierite, <6 mm biotite, <5 mm garnet (Type A)	0.5 - 1.5 mm quartz, orthoclase plagioclase minor biotite cordierite and garnet (Type B)	ilmenite pyrrhotite apatite zircon monazite xenotime
Coarse-grained granite	65.0	mostly equigranular 4 - 10 mm	some orthoclase, 30 - 50 mm	quartz plagioclase (An <sub>54-79</sub> ) orthoclase biotite cordierite garnet (Type A) minor	ditto
Kerrisdale Cordierite Microdamellite	0.5	"Porphyritic" - continuous range in grain size .5 - 5 mm with finer sized dominant	quartz orthoclase plagioclase (An <sub>54-28</sub> ) biotite (minor)	quartz, plagioclase orthoclase, biotite cordierite	ditto
Tallangalook Hornblende Microdamellite	<0.1	porphyritic with ~ 2% euhedral phenocrysts	quartz, 6 mm plagioclase, 4 mm	~ 0.8 mm quartz, orthoclase plagioclase (An <sub>2</sub> ) hornblende, biotite	sphene magnetite ilmenite apatite zircon

Average plagioclase compositions are quoted core to rim.

of textural and mineralogical characteristics (Table 1). Although outcrop is good, contacts between the major variants have not been observed, and hence their temporal relations are not clear. The distribution of the four variants is shown in Figure 2. The map shows two areas of porphyritic microgranite, one in the centre of the batholith and another smaller body in the southwest. [The terms "granite" and "adamellite" used in this paper are taken from the normative classification of O'Connor (1965).] The latter microgranite body appears to have intruded coarse grained granites. Such granites occupy two areas in the east and the south. The north-south boundary between these two main rock types is marked by a prominent scarp and a zone of no outcrop that is probably the expression of a fault. Areas delineated as coarse grained granite contain small ( $\sim 1 \text{ km}^2$ ) scattered bodies of porphyritic microgranite, particularly in the eastern half of the batholith.

A small, separate pluton, the Kerrisdale cordierite microadamellite, granite in IUGS terms (Streckeisen 1973), lies at the extreme southwestern end of the batholith. The Tallangalook hornblende microadamellite, the only metaluminous variant observed in the Strathbogie batholith, forms a small ( $< 1 \text{ km}$  wide) stock intruded into coarse grained cordierite granites in the east (Fig. 2).

Modal and chemical variation throughout the batholith is limited. All outcrops (except the Tallangalook hornblende microadamellite) exhibit cordierite and peraluminous biotite, although garnet is less commonly developed. Tables 1 and 2 and Figure 3 show the main modal and textural variations observed. All rocks are granites according to the IUGS classification. In all the granites some of the quartz forms large euhedra, commonly with hexagonal-bipyramidal ( $\beta$ -quartz) habit. Inclusions of biotite and plagioclase are found in this type of large phenocrystal quartz. Plagioclase has a tabular habit and shows complex twinning and slight normal zoning with superimposed fine-scale, low-amplitude oscillatory zoning. Plagioclase compositions are given in Table 1. Aggregates of plagioclase suggest accumulation of this phase during magmatic evolution. Quartz and biotite are the only inclusion phases found in the plagioclase. Orthoclase micropertite forms large, simply twinned subhedra that contain inclusions of cordierite, biotite, quartz and plagioclase. Red-brown biotite forms large, discrete euhedral booklets in all granite variants.

Cordierite and garnet types in the granites are listed in Tables 3 and 4 (also see Figs. 3d,

4). Nearly all the cordierite forms euhedral prisms (type A), rarely twinned and inclusion-poor, although some encloses small, euhedral biotite flakes. In the coarse grained granites, cordierite is similar in size (4–10 mm; Fig. 3d) to plagioclase, biotite and quartz. In the finer grained Kerrisdale cordierite microadamellite, cordierite, like all other phases, has a grain size of 1–5 mm (Fig. 3b). Cordierite in the aplitic rocks also has a grain size similar to that of other phases present (0.5–1 mm).

Many of the large, corroded (type-A) garnets have been partly pseudomorphed by cordierite that preserves the shape of the original euhedral, inclusion-free garnet. Textural and chemical features of the type-B garnets are summarized in Tables 3 and 5.

The more leucocratic porphyritic microgranites, especially near the edges of the batholith, contain patches of tourmaline intergrown with the groundmass phases. This feature is most common in variants with a relatively coarse grained groundmass. A late-stage magmatic origin is favored for much of the tourmaline, as it rarely exhibits replacement textures. In some porphyritic microgranites, the groundmass contains small patches of microgranophyre, *i.e.*, eutectoid-like intergrowths of quartz and orthoclase.

S-type granites hitherto described (Flood & Shaw 1975, White & Chappell 1977, Chappell 1978, Hine *et al.* 1978) display textural features interpreted by these authors as indicating that much of the cordierite, garnet, biotite and, perhaps, plagioclase in these rocks is residual (*i.e.*, restite) material. The corroded, highly calcic cores of plagioclase crystals in some granites are considered by White & Chappell (1977) to be restite grains mantled by magmatic feldspar.

TABLE 2. MODAL ANALYSES

Mineral	1	2	3	4	5	6
quartz	37	40	33	36	37	36
orthoclase	25	29	25	28	19	22
plagioclase	28	19	16	24	32	34
cordierite	1	6	5	3	4	-
biotite	9	5	17	9	8	3
garnet	Tr	1	4	Tr	Tr	-
hornblende	-	-	-	-	-	4
sphene	-	-	-	-	-	1

1, typical porphyritic microgranite (864); 2, cordierite-rich porphyritic microgranite (756); 3, garnet-rich porphyritic microgranite (889); 4, coarse grained granite (average of 801 and 803); 5, Kerrisdale cordierite microadamellite (765); 6, Tallangalook hornblende microadamellite (861). All modes are based on >1000 points. Both phenocryst and groundmass phases were counted.

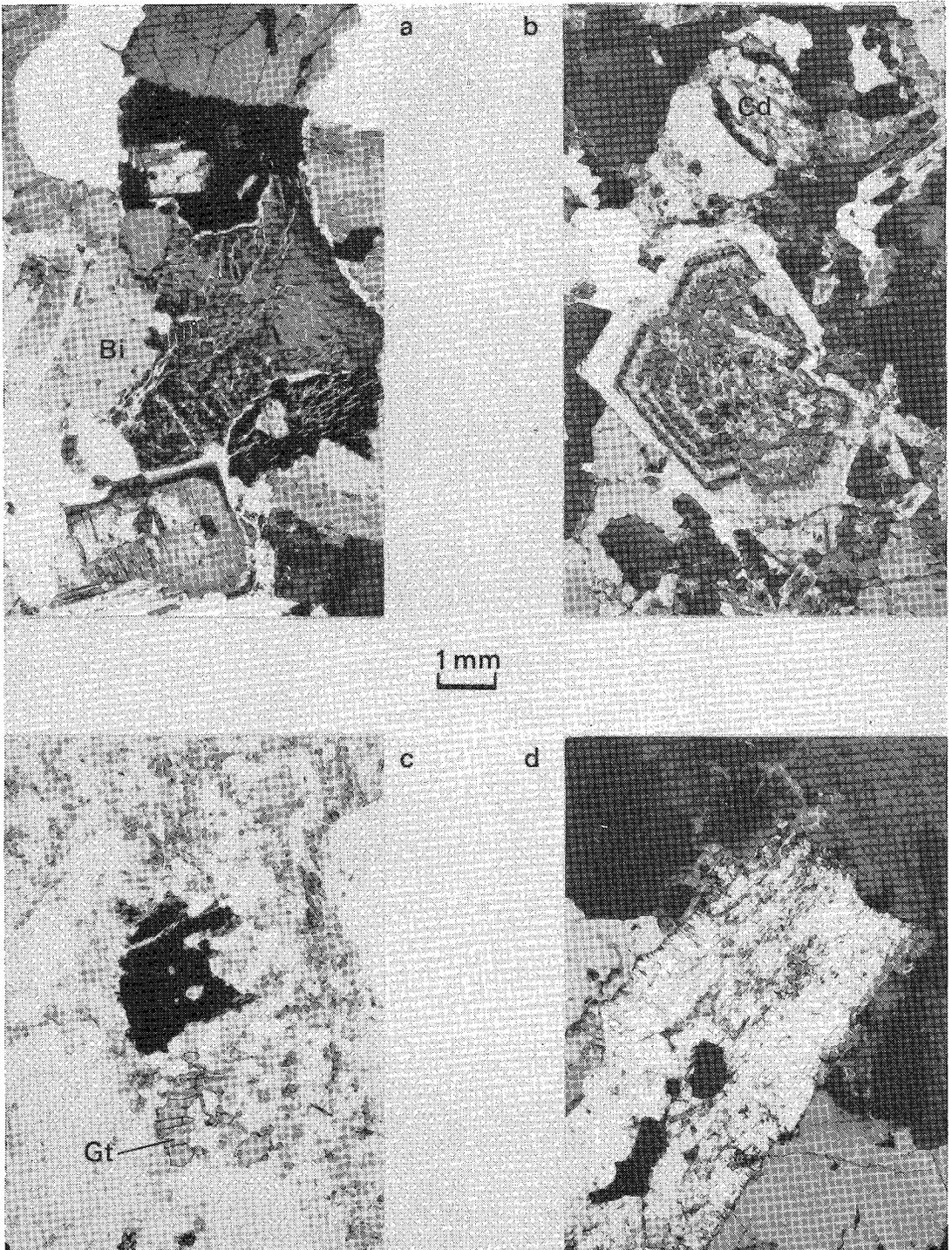


FIG. 3. (a) Coarse grained granite showing large magmatic biotite plates (Bi) texturally dissimilar to metamorphic micas. Crossed polars. (b) Kerrisdale cordierite microadamellite showing a *small* type-A cordierite (Cd). Crossed polars. (c) Porphyritic microgranite with phenocrystal biotite (black) and skeletal, late-magmatic (type-B) garnet (Gt). (d) *Large* euhedral (type-A) cordierite in coarse grained granite (*cf.*, smaller cordierite of the finer-grained rock in Fig. 3b).

TABLE 3. GARNET TYPES

Occurrence	Garnet Type	Form and Paragenesis	Average Composition (Mol. %)				Relative Abundance	Origin
			Py	Alm	Sp	Gr		
granitic rocks	A	rounded, corroded crystals (< 15 mm) with cordierite-biotite reaction coronas; ilmenite, apatite, zircon inclusions	16	75	5	4	the most common type scattered distribution	early magmatic
"	B	1 - 2 mm anheda intergrown with ground-mass felsic phases in porphyritic microgranites	5	80	13	2	common	late magmatic or subsolidus
inclusions of high-grade regional metamorphic rock	-	very small embayed crystals included in quartz and feldspar	-	-	-	-	rare	restite, readjusted restite or xenolithic

N.B. Type A and B garnets in the Strathbogie granites are analogous to Birch and Gleadow's (1974) Type 2 and 1 garnets (respectively) from Upper Devonian acid volcanic rocks in the Cambrian Cauldron, central Victoria.

Plagioclase in the Strathbogie granite does not contain obviously distinctive cores. Indeed, the progressive oscillatory zoning exhibited by the plagioclase (e.g., Fig. 3b) appears to be incompatible with a metamorphic origin for this feldspar. Features expected in restite micas (sillimanite inclusions and coarse, foliated aggregates) are entirely lacking in the Strathbogie biotites. Cordierite from metamorphic terranes is commonly anhedral, ovoid in shape and inclusion-rich. Such metamorphic cordierites are a component of the rare gneissic inclusions in the Strathbogie batholith. The euhedral, inclusion-free character of the type-A cordierite in the Strathbogie rocks and the correlation between grain size of the cordierite and the enclosing rock are compelling evidence for emplacement-stage magmatic crystallization of the cordierite. The initial euhedral shape and inclusion-free character of the type-A garnets suggest a magmatic origin for this phase also. The grain shape, composition and lack of reaction of type-B garnets with the magma are compatible with a late-stage magmatic or subsolidus origin. Thus, the textural evidence indicates that the great bulk of the garnet, cordierite, biotite and plagioclase has an entirely magmatic origin in the Strathbogie granites.

Liquidus phase-relations of a particular magma composition depend on variables such as P, T,  $f(\text{O}_2)$  and the  $\text{H}_2\text{O}$  content of the magma; hence, the inferred sequence of crystallization of a rock can yield information on these parameters. In deducing the sequence of crystallization in the Strathbogie granite (Fig. 5), inclusion relations, reaction relations and grain shape are critical. We have assumed that small euhedral inclusions in the core of a large euhedral phenocryst are likely to have nucleated no later than the enclosing phenocryst (Vernon 1977). Inclusion relationships in the Strathbogie rocks are shown in Table 6. It has further been assumed that crystals growing suspended in a magma are likely to grow as euhedra, whereas during the later stages of magmatic crystallization crystals will mutually interfere, forming anhedral grains and interstitial fabrics.

In the Strathbogie rocks, quartz, plagioclase and biotite are early-crystallizing phases that form large euhedral crystals with few inclusions. Apatite, rare-earth phosphates, zircon, ilmenite and pyrrhotite found included in the biotite suggest that these accessory phases also crystallized early. Cordierite began crystallization before K-feldspar, which is commonly interstitial and anhedral. Quartz and alkali feldspar domi-

TABLE 4. CORDIERITE TYPES

Occurrence	Cordierite Type	Form and Paragenesis	$\sim 2V_\alpha$	Mg/(Mg+Fe)	Relative Abundance	Origin
granitic rocks	A	euhedra (< 6 mm) with rare inclusions of biotite, ilmenite and zircon	+ 60°	0.56	always present	primary magmatic
"	B	large anheda with biotite and/or sillimanite and green spinel inclusions	- 80°	0.46	rare	readjusted restite
"	C <sub>1</sub>	small anheda or, more rarely, euhedral in aggregates comprising reaction rims on Type A garnets	- 80°	0.34	accompanies Type A garnets	magmatic
"	C <sub>2</sub>					
inclusions of high-grade regional metamorphic rock	-	large and small anheda with inclusions of biotite and/or sillimanite and zirconian hercynite	- 80°	0.46	in all enclaves of readjusted restite high-grade regional or xenolithic metamorphic rock	

TABLE 5. MINERAL CHEMISTRY#: RESULTS OF ELECTRON-MICROPROBE ANALYSES

Mineral:	Spinel	Gt(A)	Gt(A) Core	Gt(A) Rim	Gt(B)	Bt	Bt	Bt	Bt	Bt	Bt (Gt.rim)	Bt (Inclusions)	Cd(A)	Cd(A)	Cd(A)	Cd(B)	Cd(C) Inclusions	Cd	
Rock No.	872	1589	846	846	754	1589	754	831	1597	846	872	872	754	831	1597	846	1599	846	872
SiO <sub>2</sub>	-	0.21	37.08	37.46	36.08	35.88	35.43	33.79	34.52	35.26	n.d.	35.43	49.30	49.26	49.13	49.20	48.44	49.29	48.55
TiO <sub>2</sub>	-	-	-	0.06	-	0.12	4.76	4.47	4.41	4.41	0.71	4.49	-	-	-	-	-	-	-
Al <sub>2</sub> O <sub>3</sub>	57.32	56.64	21.48	21.03	20.68	20.69	17.86	17.04	18.14	17.95	n.d.	16.58	33.42	33.49	32.59	32.49	32.69	32.27	32.58
FeO*	32.44	30.47	33.56	33.64	35.19	35.76	23.48	25.65	24.14	23.17	22.34	24.45	10.24	9.46	9.97	9.90	11.85	13.09	12.70
MnO	0.09	0.42	2.80	2.00	5.33	3.55	0.09	0.04	0.11	0.21	0.20	-	0.13	0.18	0.47	0.37	0.50	0.75	0.50
ZnO	8.03	9.86	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	2.12	1.37	3.82	4.41	1.69	1.37	6.33	5.02	5.76	6.61	6.72	7.01	7.01	7.61	6.83	6.58	5.90	4.61	5.71
CaO	-	-	1.27	1.35	1.02	0.62	-	-	-	-	0.14	-	-	-	-	0.04	-	-	-
BaO	n.d.	0.62	n.d.	-	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Na <sub>2</sub> O	n.d.	0.42	-	0.05	-	0.42	-	0.09	-	n.d.	-	-	-	-	-	-	-	-	-
K <sub>2</sub> O	-	-	-	-	-	-	8.94	8.72	8.96	9.08	n.d.	9.66	-	-	-	-	-	-	-
Cations	3	3	8	8	8	8	0=22	0=22	0=22	0=22	0=22	0=22	11	11	11	11	11	11	11
Si	-	0.006	2.970	2.992	2.945	2.939	5.381	5.349	5.332	5.375	5.404	5.413	5.029	5.016	5.020	5.108	4.987	5.126	5.017
Al(IV)	-	-	0.030	0.008	0.055	0.061	2.619	2.651	2.668	2.625	2.596	2.587	-	-	-	-	0.013	-	-
Al(VI)	1.952	1.961	1.997	1.972	1.934	1.936	0.578	0.530	0.636	0.601	0.915	0.400	4.020	4.015	4.047	3.977	4.030	3.955	3.961
Fe	0.784	0.748	2.248	2.248	2.402	2.449	2.982	3.396	3.119	2.954	3.224	3.124	0.874	0.805	0.852	0.860	1.020	1.380	1.098
Ti	-	-	-	0.004	-	0.007	0.544	0.532	0.512	0.523	-	0.516	-	-	-	-	-	-	-
Mn	0.002	0.011	0.190	0.135	0.368	0.385	0.012	0.005	0.014	0.027	0.040	-	0.011	0.016	0.041	0.033	0.044	0.066	0.044
Zn	0.171	0.214	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mg	0.091	0.060	0.455	0.525	0.206	0.167	1.433	1.184	1.326	1.502	1.718	1.596	1.066	1.154	1.040	1.018	0.906	0.714	0.880
Ca	-	-	0.109	0.116	0.090	0.054	-	-	-	-	-	-	-	-	-	-	-	-	-
Ba	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Na	-	-	-	-	-	-	0.124	-	0.027	-	-	-	-	-	-	-	-	-	-
K	-	-	-	-	-	-	1.732	1.761	1.766	1.766	1.890	1.883	-	-	-	-	-	-	-
TOTAL							15.405	15.409	15.400	15.372	15.787	15.519							
Mg/(Mg+Fe)	0.10	0.07	0.17	0.19	0.08	0.06	0.33	0.26	0.30	0.34	0.35	0.34	0.55	0.59	0.55	0.54	0.47	0.34	0.45

\*total Fe expressed as FeO

# all analyses normalized to 100% except those of biotite

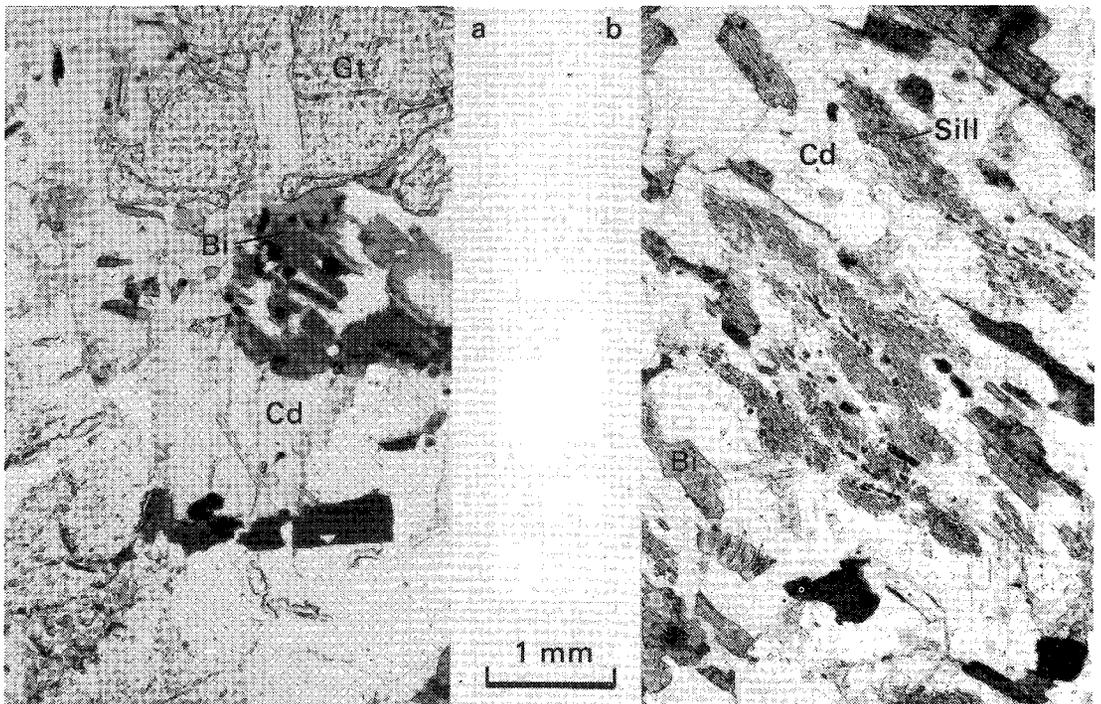


FIG. 4. (a) Large, corroded, early-magmatic (type-A) garnet (Gt) with a cordierite (Cd) - biotite (Bi) reaction rim. Note the euhedral character of the cordierite. (b) Elongate xenoblastic cordierite with sillimanite (Sill), spinel and biotite in a gneissic inclusion.

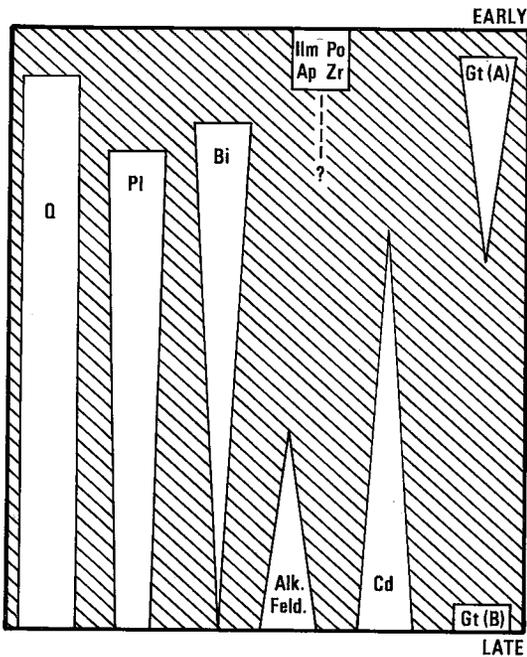


FIG. 5. Schematic sequence of crystallization for the Strathbogie granites.

nated the final stages of magmatic crystallization. The role of garnet varies. The large, corroded (type-A) garnets are apparently early and have undergone considerable textural and some chemical modification. The small, groundmass (type-B) garnets are a late-crystallizing phase in the porphyritic microgranites. The deduced sequence of crystallization is portrayed in Figure 5.

Although sequences of crystallization for granitic magmas based on the above criteria are commonly equivocal, the grain shapes and grain-boundary relations of the Strathbogie rocks indicate little subsolidus readjustment. Furthermore, the crystallization sequence deduced for the Strathbogie magma closely matches that inferred for the related Violet Town volcanic suite (Clemens *et al.* 1979). Strathbogie specimen 889 (Tables 2 and 7), the most mafic variant of the

batholith, demonstrates our scheme of mineralogical evolution. This rock has a high phenocryst content (50%) set in a fine grained groundmass. Relatively high concentrations of type-A garnets and biotite crystals are present, and plagioclase phenocrysts are rather calcic ( $An_{45-20}$ ). Cordierite occurs mostly in reaction rims on garnets, although some euhedral phenocrystal cordierite is also developed. K-feldspar phenocrysts are rare and the groundmass comprises fine grained alkali feldspar and quartz. The groundmass appears to represent chilled (pressure-quenched?) liquid. Thus K-feldspar did not reach saturation in the 889 magma until the emplacement stage, when this composition was still more than 50% liquid. The high concentration of garnet and biotite in 889 suggests that these phases represent accumulations and emphasizes their importance in the differentiation of the Strathbogie magma(s).

#### Inclusions in the granitic rocks

Although generally scarce ( $\sim 1\%$ ) in the Strathbogie batholith, three types of inclusions have been recognized. Micro-adamellite inclusions are the most numerous, with those of high-grade regional metamorphic rocks next in abundance. Near the margins of the batholith, the granitic rocks contain rare angular xenoliths of quartz-rich and pelitic hornfels. These accidental hornfels inclusions are derived from the surrounding country rock.

The micro-adamellite inclusions are rounded, 10–100 mm in diameter, composed of large (5 mm) interlocking anhedral of quartz and orthoclase, sieved with inclusions of plagioclase laths ( $An_{43}$ ) and small euhedral biotite flakes. Accessory zircon, ilmenite, apatite and rare cordierite euhedra are also present. The micro-adamellite inclusions are interpreted as accumulations of small, early-formed biotite, plagioclase and cordierite crystals in interstitial liquid that crystallized as quartz and orthoclase. These rocks probably represent a chilled phase of the granite formed during the early stages of crystallization and later dislodged from the wall or roof of the magma chamber and reincorporated in the main bulk of the magma (*cf.*, Bateman & Chappell 1979, pp. 474–475). The micro-adamellite inclusions resemble the Kerrisdale cordierite micro-adamellite in both texture and composition.

The inclusions of high-grade regional metamorphic rocks (10–100 mm in diameter) are rounded in shape, fine- to medium-grained, and always have a pronounced foliation (Fig. 4b). Biotite and cordierite are segregated into melano-

TABLE 6. INCLUSION RELATIONS IN STRATHBOGIE MINERALS

Accessories	Gt(A)	Bt	INCLUSION PHASE			HOST PHENOCRYST
			Cd	Pl	Q	
X						Gt(A)
X						Bt
X		X				Cd(A)
X		X	?			Pl
X		X	?	X		Q
X	X	X	X	X	X	Kfs

TABLE 7. BULK-ROCK CHEMICAL DATA (XRF) AND CIPW NORMS

	1	2	3	4	5	6
SiO <sub>2</sub>	69.78	72.21	74.63	71.83	72.78	71.64
TiO <sub>2</sub>	0.57	0.34	0.09	0.36	0.33	0.30
Al <sub>2</sub> O <sub>3</sub>	14.56	14.64	13.66	14.25	14.01	14.22
FeO *	3.66	2.42	1.05	2.73	2.32	1.81
MnO	0.01	-	-	-	0.01	0.04
MgO	1.40	1.02	0.59	1.04	0.95	0.71
CaO	1.85	1.67	1.29	2.14	1.57	1.85
Na <sub>2</sub> O	2.60	2.86	2.94	3.08	2.65	4.25
K <sub>2</sub> O	4.74	4.50	4.91	3.93	4.52	4.69
P <sub>2</sub> O <sub>5</sub>	0.19	0.22	0.22	0.28	0.19	0.09
SO <sub>3</sub>	0.10	0.08	0.13	0.10	0.06	0.06
Loss **	0.71	0.47	0.61	0.50	0.54	0.33
Total	100.17	100.45	100.12	100.25	99.93	99.95
Mg/(Mg+Fe)	.40	.43	.50	.40	.42	.41
Q	28.47	32.12	35.10	31.57	34.12	23.46
C	2.24	2.57	1.71	1.70	2.36	-
Or	28.19	26.60	29.20	23.29	26.72	27.72
Ab	22.17	24.20	24.96	26.14	22.42	35.96
An	7.99	6.85	4.96	8.84	6.55	5.88
Di	-	-	-	-	-	2.28
Hy	9.32	6.42	3.25	7.03	6.10	3.52
Il	1.08	0.65	0.17	0.68	0.63	0.57
Ap	0.45	0.52	0.52	0.66	0.45	0.21

\* Total Fe expressed as FeO. \*\* Fusion loss. 1. Specimen 889, the most mafic variant of the Strathbogie granite; 2. specimen 717, representative coarse grained granite, Strathbogie batholith; 3. specimen 754, representative porphyritic microgranite, Strathbogie batholith; 4. specimen 765, Kerrisdale cordierite microadamellite; 5. average of 21 S-type Strathbogie granitoid rocks; 6. average of 2 analyses of Tallangalook hornblende adamellite.

cratic layers separated by layers of felsic phases. Significant assemblages developed include (a) Or-Gt-Bi-Cd-Pl-Ilm-Ap-Po-Q and (b) Hc-Cd ± Sill. [Abbreviations are listed in Appendix 1.]

Descriptions of the garnet and cordierite types from these inclusions are given in Tables 3 and 4. Garnet is very rare, although at one time, it was probably present in all the regional metamorphic inclusions, as evidenced by pseudomorphs of garnet by minerals of assemblage (b) above. Readjustment of the regional metamorphic mineral assemblage by equilibration with the enclosing granitic magma has occurred, as indicated by the low-pressure assemblages. The alkali-poor, silica-depleted character of these inclusions is compatible with a restite origin, although their low-pressure mineralogy precludes estimation of source-region conditions.

Inclusions of country-rock hornfels are recognizable by their modal and mineralogical similarity to the Paleozoic rocks in the contact aureole (Phillips & Wall 1980). In contrast to the regional metamorphic inclusions, the hornfels inclusions lack well-developed foliations. The paucity of hornfels xenoliths and their restriction to marginal variants in the Strathbogie batholith imply that high-level contamination is of little importance in Strathbogie petrogenesis and that stoping of wall rocks is not a major factor in the emplacement of the Strathbogie magmas.

## GEOCHEMISTRY

### Mineral chemistry

Ferromagnesian phases and plagioclase in the porphyritic microgranites and coarse grained granites were analyzed using the T.P.D. energy-dispersive electron microprobe at the Research School of Earth Sciences, Australian National University. Some analyses were performed on the Jeol JXA-5A and the ARL EMX microprobes at the Departments of Geology, Melbourne and Monash universities, respectively. The compositions of the various garnet and cordierite types are of particular interest.

All Strathbogie garnets are almandine-rich pyrralspites (almandine: 74–80 mol. %). The Mg and Mn contents show the greatest variation (Table 3). Garnet in the fine grained groundmass, free of reaction coronas (*i.e.*, type B), is relatively spessartine-enriched, with only minor pyrope and grossular (*e.g.*, specimen 754). Large garnets with reaction rims (type A) are relatively enriched in pyrope and grossular, with only 4.5% spessartine. Rims of type-A garnets are Fe-Mn-enriched and Mg-depleted. The reason for the Mn enrichment is the strong partitioning of this element into the garnet relative to the cordierite in the reaction rim.

Euhedral (type-A) cordierites generally have Mg/(Mg + Fe) in the range 0.54–0.59. (Throughout this paper Fe and FeO refer to total iron in the sample. Structural formulae of the ferromagnesian phases indicate that Fe<sup>3+</sup> is minor in most minerals.) The chemistry and optical properties of type-A and type-B cordierites are quite different (Table 4). Type-B cordierites and cordierites in gneissic inclusions are more Fe-rich [average Mg/(Mg + Fe) = 0.46] and contain more Mn than type-A cordierites. Type-C cordierites are similar in optical properties to type B but have the lowest Mg/

(Mg + Fe) (average = 0.34) of the cordierite types. The significance of these points will be discussed in detail in the section on petrogenesis.

Biotites in the Strathbogie granites do not vary greatly in composition; they are all rather high in siderophyllite-annite, with an average composition  $(K,Na)_{1.8}(Fe_{2.1}Mg_{1.4}Ti_{0.5}Al_{0.6})(Al_{2.6}Si_{5.4})O_{20}(OH,Cl,O,F)$ . Semiquantitative crystal-spectrometer analyses showed that fluor- and chlorine-biotite substitutions are minor (< 5 mol. %).  $Mg/(Mg + Fe)$  is near 0.30, falling between the values for type-A cordierite and garnet and slightly lower than the bulk-rock values (Table 7). The biotite in the cordierite-biotite reaction rims surrounding type-A garnet is similar in composition to other biotites except for its very low Ti content. Normalization of the Ti-rich (primary, magmatic) biotites to 16 cations, assuming no octahedral vacancies (Bohlen *et al.* 1980), suggests extensive  $TiO_2 = (MgFe)(OH)_2$  substitution, a feature in common with other high-temperature biotites (Bohlen *et al.* 1980).

Green spinel (Tables 4, 5) contains considerable amounts of the hercynite and gahnite components in solid solution: hercynite 72%, gahnite 21%. Some Mg and Mn are also present, but the magnetite component comprises < 2 mol. %. Similar zincian hercynites have been reported in inclusions in acid volcanic rocks of the Cerberian cauldron and Violet Town volcanic suite in Central Victoria (Birch *et al.* 1977).

*Rock geochemistry*

Selected bulk-rock analyses (XRF) and CIPW norms of the Strathbogie rocks are presented in

Table 7. Most of the batholith comprises corundum-normative (usually > 1% C) S-type granites, whereas less than 0.1% of the batholith consists of the diopside-normative Tallangalook hornblende microadamellite (I-type).

Compositions of all S-type granitoid rocks are highly silicic (70–76%  $SiO_2$ ) and moderately peraluminous. All have rather high  $K/(K + Na + Ca)$  ratios, reflected in the high proportion of modal alkali feldspar (Table 2). The ratio  $Mg/(Mg + Fe)$  is generally in the range 0.40–0.50 and shows no distinct trend with  $SiO_2$  content. Two exceptionally Fe-rich rocks [ $Mg/(Mg + Fe) = 0.31$  and 0.19] have significantly higher MnO and lower MgO and CaO.

Harker plots show strong correlations between several oxides and  $SiO_2$  content (Fig. 6). The more silicic variants are markedly depleted in  $P_2O_5$ ,  $TiO_2$ , CaO, FeO and MgO. From 70% to 76%  $SiO_2$  there is a 30% decrease in  $P_2O_5$  and about a 70% decrease in the other four oxides. No significant change in  $Al_2O_3$  or  $K/Na$  is observed with increasing  $SiO_2$ , although a large scatter of molar  $K/Na$  ratios (0.7–1.4) is present.

Porphyritic microgranites are commonly more silicic (average 73.4%  $SiO_2$ ) than the coarse grained types (average 72.3%  $SiO_2$ ). Spatial chemical variations within the batholith are also evident. The most silicic rocks are the porphyritic microgranites from the northwest (average 74.6%  $SiO_2$ ). Coarse grained granites from the east have much lower  $SiO_2$  (average 71.4%) and have a different average composition from the coarse grained granites in the west (average 73.0%  $SiO_2$ ).

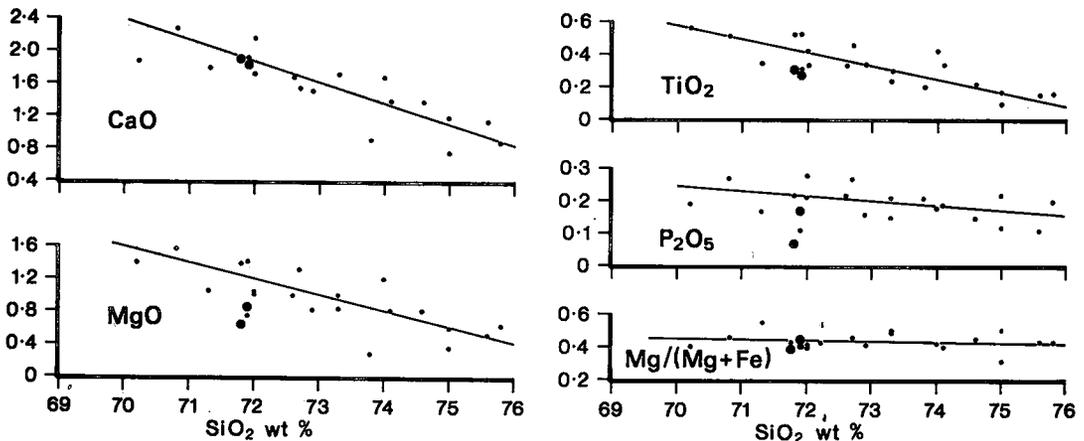


FIG. 6. Harker variation diagrams for 23 analyzed specimens of Strathbogie granite. Large dots are the two analyzed I-type rocks.

Although the Strathbogie I-type micro-adamellites are not well distinguished on the Harker diagrams of Figure 6, their higher  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  and lower ( $\text{FeO} + \text{MgO}$ ) are distinctive. The I-type granitoid rocks are diopside-normative.

## PETROGENESIS

### Conditions of emplacement

**Pressure:** Low confining pressure during emplacement of the exposed granites is inferred from two lines of evidence. The granites intrude the Violet Town volcanic complex, which appears never to have had any significant cover (Birch *et al.* 1977). Hornfels developed on the south side of the batholith contains assemblages indicative of pressures  $\leq 1$  kbar (Phillips & Wall 1980).

**Temperature and  $\text{H}_2\text{O}$  content of melt:** Emplacement temperatures can be limited by assemblages developed in the contact aureole. The high-grade cordierite-K-feldspar assemblages in hornfels adjacent to the granite imply temperatures of the order 580–620°C (Phillips & Wall 1980). Using the methods of Jaeger (1957), this is equivalent to intrusion temperatures of 750°C (above the wet granite solidus) to 820°C, if the country rocks are assumed to have been at temperatures between 100 and 200°C (Phillips & Wall 1980). Emplacement temperatures can be further limited by utilizing the crystal-melt equilibria determined experimentally by Clemens & Wall (1981).

These experimental studies of the crystallization phase relations of the porphyritic microgranite (specimen 889) were carried out at  $P = 1\text{--}7$  kbar,  $T = 600\text{--}900^\circ\text{C}$ ,  $a(\text{H}_2\text{O}) = 0.1\text{--}1.0$  and  $\log f(\text{O}_2) = QFM$  to  $QFM-0.5$ . This rock was chosen for experimental study because of its well-characterized sequence of crystallization and its apparently little-fractionated composition. However, it now appears to us that specimen 889 may have undergone enrichment in phenocrysts of garnet and biotite, although this would have little effect on the conclusions we reach below.

Specimen 889 was inferred (above) to have been at least 50% liquid with few if any K-feldspar crystals present when the magma was intruded. Experiments at 1 kbar (for near-saturation  $\text{H}_2\text{O}$  contents in the melt of 3.5–4.5 wt. %) show that the K-feldspar saturation boundary occurs at about 750°C. This suggests that the emplacement temperature was at least

750°C. The absence of orthopyroxene (or obvious pseudomorphs after this phase) indicates that the Strathbogie magmas were at temperatures below about 800°C at the level of emplacement (Clemens & Wall 1981, Fig. 1).

**Oxygen fugacity:** The occurrences of coexisting ilmenite and pyrrhotite as inclusions in the Strathbogie type-A garnets, the absence of magnetite and the magmatic almandine-rich garnets all suggest that  $f(\text{O}_2)$  was low in the Strathbogie magmas, probably around  $QFM$ . Oxygen fugacity in S-type rocks cannot be calculated using the Buddington & Lindsley (1964) approach owing to the absence of coexisting Fe-Ti oxides.

Froese (1973) has tabulated thermochemical data for the reaction  $\text{Alm} + \text{O}_2 = \text{Cd} + \text{Mt} + \text{Q}$ , which provides an upper limit for  $f(\text{O}_2)$  (since magnetite is absent from the Strathbogie rocks). This yields, at  $P = 2$  kbar,  $\log f(\text{O}_2) < -16.8$  at 700°C and  $< -14.6$  at 800°C.

The low-pressure assemblage spinel-cd-sill is common as pseudomorphs, often around metamorphic assemblages in some inclusions in the Strathbogie batholith. These phases can be related by the reaction  $\text{Cd} + \text{O}_2 = \text{Mt} + \text{Sill} + \text{Q}$ . Assuming that these inclusions equilibrated with the enclosing magma at around 2 kbar, this assemblage can be used to evaluate  $f(\text{O}_2)$  from the data of Froese (1973). Calculations using the analyzed cordierite and coexisting spinel compositions, and assuming  $a(\text{SiO}_2) = 1.0$ , yield  $\log f(\text{O}_2) = -18.3$  at 700°C and  $-15.5$  at 800°C. These figures are compatible with the upper limits for  $f(\text{O}_2)$  set above. The mole fraction of magnetite in the analyzed spinel is small, and this constitutes the major source of error in the calculation. However, an uncertainty of 30% in  $a_{\text{Mt}}^{\text{spinel}}$  corresponds to a change in  $\log f(\text{O}_2)$  of only 0.3. Thus a reasonable estimate of  $f(\text{O}_2)$  for the Strathbogie magma (at the time of equilibration of the cordierite-spinel-sillimanite assemblages) is about an order of magnitude below the  $QFM$  buffer.

### Early crystallization

Experiments by Clemens & Wall (1981) also give an indication of the ranges of  $P$ ,  $T$  and  $\text{H}_2\text{O}$  content during early crystallization of the Strathbogie magmas. The sequence of early crystallization for rock 889 is best modeled by the experimentally determined phase relations for  $P$  between 4 and 7 kbar,  $T$  between 800 and 850°C and water contents of the melt in

the range 3–5 wt. %. For H<sub>2</sub>O contents less than 3 wt. %, the biotite saturation boundary is depressed to temperatures below the K-feldspar saturation boundary. For water contents greater than 5%, the garnet saturation boundary is depressed to such an amount that the inferred sequence of crystallization cannot be duplicated with garnet as a near-liquidus phase.

#### *Summary: conditions of crystallization*

The Strathbogie granite magma, prior to emplacement, was of relatively high temperature (750–850°C) and markedly water-undersaturated. Water saturation of the magma was attained in the 1–2 kbar range, with less than 50% crystallization; by this stage some garnet, plagioclase, biotite and quartz had developed. Cordierite and K-feldspar formed largely at emplacement levels.

#### *Origin of chemical variation in the Strathbogie batholith*

Several mechanisms have been proposed to explain the chemical variation observed in the S-type batholiths (e.g., White & Chappell 1977, Clemens *et al.* 1979). These mechanisms and their relevance to the Strathbogie batholith are examined below.

*“Unmixing” of restite material:* Chemical trends in granites have been explained by a process of progressive “unmixing” of restite (refractory phases) from a “minimum-melt” granitic liquid (Wyllie *et al.* 1976, Wyllie 1977, White & Chappell 1977, Chappell 1978). This process requires that the undifferentiated magma leave its place of origin carrying some residual solid material. For the Strathbogie rocks, possible restite phases include biotite, garnet, orthopyroxene, quartz and plagioclase. Progressive removal of restite plagioclase and biotite during magma migration is essentially the same process described below in the crystal fractionation model, except that the phases involved are considered to be restite material rather than products of magmatic crystallization.

Within the Strathbogie batholith there is no firm evidence for calcic plagioclase of restite origin (*cf.*, White & Chappell 1977) or aggregates of restite biotite. The euhedral single crystals of biotite, in particular, are unlike the biotite segregations in migmatites (Harme 1965). Inclusions of any kind are rare and not markedly concentrated in the more mafic variants. The textural evidence has shown that the

bulk of the cordierite and garnet in the Strathbogie batholith is magmatic in origin. Cordierite with inclusions of spinel and sillimanite is easily recognized (texturally and chemically) as readjusted restite or xenocryst material, but comprises less than 1% of the granite. In such quantities, restite cordierite cannot have played a major part in the chemical evolution. Restite unmixing therefore seems unlikely to account for any significant chemical variation seen in the Strathbogie granite.

*Crystal fractionation:* The petrographic data for the Strathbogie rocks indicate that biotite, plagioclase and quartz are the volumetrically significant early-crystallizing phases. Numerous ilmenite and apatite inclusions are present in the biotite. Based on the modal data, large amounts of cordierite and garnet appear unlikely at this stage.

Qualitatively, fractionation of plagioclase and biotite with inclusions can explain the decrease in TiO<sub>2</sub>, P<sub>2</sub>O<sub>5</sub>, FeO, MgO and CaO as SiO<sub>2</sub> increases (Fig. 6). Quantitative mixing calculations using rock and mineral compositions were performed with the least-squares computer program PETMIX III (Taylor *et al.* 1973). The Strathbogie primary magma was assumed to have a composition similar to the average of the 21 analyzed S-type rocks (SiO<sub>2</sub> ~ 73 wt. %, Table 7). This composition was chosen as an approximation to the overall composition of the magma near its level of emplacement. More mafic variants probably contain accumulations of early-formed phenocrysts, as discussed above. Separation of 8% plagioclase (An<sub>45</sub>), 6% biotite, 3% quartz and 0.1% each of ilmenite and apatite from the primary magma composition can account for the chemistry of the most felsic (SiO<sub>2</sub> ≈ 76 wt. %) Strathbogie granites.

Given the Fe-rich biotite compositions in the rocks (Table 5), problems arise in explaining the large decrease in MgO with increased SiO<sub>2</sub> content. The liquidus biotite, however, was probably more Mg-rich, but re-equilibration with the magma at lower temperatures has caused a drop in the ratio Mg/(Mg + Fe). As cordierite and garnet have substantial effects on Al<sub>2</sub>O<sub>3</sub>, FeO and MgO contents, the role of these phases has been minor. The lack of variation in MnO also suggests that garnet was not a *major* participant in the fractionation processes.

The importance of fractionation processes in the chemical evolution of the Strathbogie magmas is further supported by the distribution of tourmaline in the batholith. Tourmaline, and hence boron, are enriched in the leucocratic

(high-SiO<sub>2</sub>) variants by at least an order of magnitude relative to the bulk of the batholith. Simple removal of even relatively large proportions of restite material could not have produced such strong enrichment in incompatible elements such as boron. However, liquids mechanically separated from univariant or invariant crystalline mushes may exhibit exponential increases in incompatible elements, whereas the major-element contents of the liquids may not vary much. Extreme fractionation processes must therefore have been involved in the development of the highly silicic variants.

*Fractional partial melting:* Progressive partial melting of a particular region of crustal material leads to the production of successively more mafic, less silicic magmas. Thus, removal and emplacement of successive melt fractions may lead to a compositionally zoned or composite batholith. Ideally, unless the site of melting shifts, this process produces a granitic suite in which the younger plutons are the more mafic.

Melting and crystallization experiments on granitic compositions (Winkler 1974, Winkler *et al.* 1975, Yllie 1977, Clemens & Wall 1981) provide some idea of the compositions expected in a fractional partial melting sequence. Near the solidus, liquids are rich in K-feldspar, plagioclase and quartz components and are Fe-Mg-Ti poor. With increasing temperature, Fe-Mg phases become more soluble in the melt, and initially low Mg/(Mg + Fe) ratios are expected. Only at high temperatures do more mafic melts, with a higher Mg/(Mg + Fe) ratio, form. Since garnet crystallization is favored by higher Fe, and cordierite crystallization by higher Mg, such trends would lead to more garnet in the silicic and more cordierite in the more mafic variants. The opposite trend is observed in the Strathbogie batholith. The separate fractions of partial melt should crystallize as plutons in which the mafic minerals have differing Mg/(Mg + Fe) values characteristic of each pluton. The major variants of the Strathbogie batholith all have the same suite of early magmatic phases.

### Summary

Although re-equilibrated restite materials exist in the Strathbogie batholith, their low concentration, even in the mafic granites, suggests that restite unmixing was not a major process involved in the magmatic evolution. Fractional partial melting would produce chemical trends that run counter to those observed. Thus, to

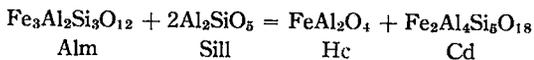
explain the variation in the Strathbogie batholith, we prefer a differentiation mechanism involving separation of early crystallized biotite and plagioclase with minor garnet, cordierite, quartz and accessory phases.

### Nature of the source

The available Sr isotope data (Pidgeon & Compston 1965, McDougall *et al.* 1966, Brooks & Leggo 1973, Flood & Shaw 1977) indicate that initial <sup>87</sup>Sr/<sup>86</sup>Sr isotopic ratios of eastern Australian S-type granites and volcanic rocks have a mean value in excess of 0.710. These high <sup>87</sup>Sr/<sup>86</sup>Sr ratios, together with the peraluminous nature of the granitoid suite, suggest that magma formation involved partial melting of old metasedimentary rocks (Chappell & White 1974, White & Chappell 1977). As pointed out by Flood & Shaw (1977), S-type rocks with lower initial ratios (around 0.706) suggest the involvement of younger or less-evolved crustal sources for the magmas. Experiments carried out by Green (1976, 1977), and Kilinc (1969, 1972) show that liquids formed by partial melting of sillimanite-bearing pelitic materials must crystallize peraluminous minerals. Green's inferred granitic liquids have, in general, more normative corundum than the Strathbogie granites (Table 7). Experimental results reported by Clemens & Wall (1981) for a natural granitic composition from the Strathbogie batholith (specimen 889) seeded with sillimanite show that a liquid of this composition is too poor in alumina for equilibrium with sillimanite. This suggests that sillimanite-bearing pelitic rocks are unlikely to be the *dominant* lithology in the source region of the Strathbogie magma. A muscovite-bearing source region is ruled out by the high temperatures and low water contents inferred for the magma.

The most direct evidence concerning the nature of the source region of the granitic magmas comes from the granites themselves. Apart from high-level hornfels and the magmatic micro-adamellite, the most common inclusions encountered in Strathbogie granites are high-grade pelitic gneisses. Provided that these inclusions represent either source-region material (Chappell & White 1974) or readjusted restite material from the source region, these inclusions indicate some of the probable assemblages in the source area during the extraction of melt. In the Strathbogie batholith the rare gneissic inclusions contain quartz, biotite, sillimanite, plagioclase, minor orthoclase, cordierite and hercynite, and rare garnet. The cordierite-hercynite

assemblage represents a low-pressure readjustment of an original garnet-sillimanite assemblage by reactions similar to



Indeed, some cordierite-hercynite aggregates appear to pseudomorph original idioblastic garnets. Accessory phases include ilmenite, pyrrhotite, apatite and zircon. Thus, the mineralogy of these inclusions suggests that some of the source rocks for the Strathbogie magma contained assemblages involving combinations of plagioclase, quartz, garnet, K-feldspar, biotite and sillimanite along with ilmenite and pyrrhotite.

Thermodynamic calculations based on reactions  $\text{An} = \text{Gr} + \text{Sill} + \text{Q}$  (Ghent 1976) and  $\text{An} + \text{Fs} = \text{Gr} + \text{Alm} + \text{Q}$  (Phillips 1978) indicate that garnet with a composition similar to the early, type-A garnets from the Strathbogie granites could have been in equilibrium with plagioclase (~An<sub>50</sub>) - sillimanite - quartz or plagioclase (An<sub>50</sub>) - orthopyroxene (En<sub>50</sub>) - quartz at ~ 5 kbar and 800°C. Any pyroxene formerly present in the magma or its restite inclusions has reacted out and is no longer found in the assemblages.

The  $f(\text{O}_2)$  during early crystallization of the Strathbogie magma was calculated to be about an order of magnitude below the *QFM* buffer. Together with the inferred low oxidation ratio of the magma, this suggests anatexis of highly reduced source rocks that may have contained graphite during part of their metamorphic history.

Partial melting of a metapelitic rock will commonly yield K-feldspar-bearing restites owing to the high K/(Na + Ca) ratios of these compositions. Thus, magmas derived from such highly aluminous source rocks will usually be saturated with K-feldspar all the way from the source region (Clemens & Wall 1981). However, K-feldspar crystallizes late from the Strathbogie magmas and plagioclase is a near-liquidus phase. We would therefore infer that the bulk of the Strathbogie source region was undersaturated with respect to K-feldspar at the time of magma extraction. Appropriate source rocks for the Strathbogie magmas would include weakly peraluminous metasedimentary rocks or other quartzofeldspathic rocks poor in K-feldspar. Pelitic inclusions in the Strathbogie granites thus probably represent highly refractory, melt-depleted materials not typical of the bulk composition of the source region of the magma.

In summary, for the Strathbogie and other central Victorian S-type granitic magmas, we

postulate an anatectic source-region, characterized by quartzofeldspathic to pelitic, high-grade regional metamorphic rocks. Such rocks are not presently exposed in central Victoria. The mineralogy of these source rocks would most likely involve quartz, orthoclase, plagioclase, almandine-rich garnet, Fe-rich biotite and orthopyroxene. Rocks containing sillimanite, cordierite and hercynite may also have been present but in minor proportions. Accessories in the source rocks would include ilmenite, pyrrhotite, apatite and zircon. Magnetite and hornblende are unlikely. Although the actual mineral assemblages are unknown, this range of mineralogy, the relatively high temperatures and the H<sub>2</sub>O-undersaturated nature of the granitic melts produced are consistent with granulite-facies regional metamorphic conditions in the source region. Considering (1) the high geothermal gradient required to generate the high temperatures at the moderate crustal depths proposed for the source region and (2) the transitional orogenic-anorogenic setting of the Strathbogie batholith, we suggest that this granulite-facies partial-fusion event was brought about by emplacement of mantle-derived material in the lower crust (*cf.*, Wells 1980).

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## APPENDIX 1. TABLE OF ABBREVIATIONS USED

## MINERALS

Q	quartz	Gr	grossular
Kfs	potassium feldspar	En	enstatite
Or	orthoclase	Fs	ferrosilite
Pl	plagioclase	C	corundum
An	anorthite	Cd	cordierite
Musc	muscovite	Sill	sillimanite
Bi	biotite	Hc	hercynite
Gt	garnet	Mt	magnetite
Alm	almandine	Ilm	ilmenite
Py	pyrope	Ap	apatite
Sp	spessartine	Po	pyrrhotite

## PHYSICOCHEMICAL SYMBOLS

P kbar	pressure in kilobars
T°C	temperature in degrees Celsius
$\log f(\text{O}_2)$	$\log_{10}$ oxygen fugacity in bars
$X(\text{H}_2\text{O})^{\text{melt}}$	water content of melt
Fl	supercritical fluid phase
QFM	oxygen fugacity equivalent to that of the quartz-fayalite-magnetite buffer
$a_{(i)}$	activity of species $i$
Liq	magmatic silicate liquid