The field relationships and petrology of the Upper Blessington Granodiorite, Ben Lomond Quadrangle

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Abstract

The Upper Blessington Granodiorite is a high level intrusion, with its original roof being only just above the current level of erosion. Contact aureole widths in the surrounding Mathinna Beds indicate that the pluton shelves southward of its southernmost surface exposure at shallow depth, but probably dips steeply to the west.

The pluton is an unfoliated, medium-grained, equigranular granodiorite consisting of hornblende, biotite and minor relict clinopyroxene in addition to strongly zoned plagioclase, alkali feldspar and quartz. It contains generally ovoid, finer-grained, melanocratic enclaves with a similar mineralogy and mineral chemistry to the host, but containing more abundant biotite, clinopyroxene and plagioclase.

Geochemical, mineralogical and petrographic features identify the intrusion as a relatively reduced, unfractionated I-type granitoid of probably limited metallogenic importance. The melanocratic enclaves may represent globules of a more mafic magma that was injected into the granitic melt before pluton emplacement and partly equilibrated with it during the prolonged cooling process, but a restite interpretation cannot be excluded on the available evidence. Minor aplite segregations probably represent a haplogranitic near-minimum melt and support other evidence for high-level emplacement, at pressures of 1 to 2 kb.

INTRODUCTION

This report was originally intended for inclusion in a projected Geological Survey Bulletin to accompany the Ben Lomond and Snow Hill Geological Atlas 1:50 000 scale maps. As publication of the Bulletin appears to be, at least, some time away, this work is reported separately.

FIELD RELATIONSHIPS

Biotite-hornblende granodiorite (Dsg) is only exposed in the Ben Lomond Quadrangle in three relatively small areas (totalling about 1 km²) on or near the northwestern margin of the sheet (Calver *et al.*, 1988). Subsequent mapping of the adjoining Alberton Quadrangle to the north (McClenaghan *et al.*, 1993) has shown that the granodiorite is part of the small Upper Blessington pluton (25 km² surface exposure) lying at the southern end of the Scottsdale Batholith, which extends northwards to Bass Strait.

The main area of granodiorite in the Ben Lomond Quadrangle was mapped from float and sporadic outcrop along and near the lower part of the Ben Lomond Road. The granodiorite has intruded and metamorphosed the adjacent Mathinna Beds arenite-dominated association (SDs) to metapsammite (SDsm) in this area. South and east of the Ben Lomond tip (EQ500057), where there are deeply weathered outcrops and fresh boulders of granodiorite, the pluton disappears beneath the dolerite-dominated slope deposits (Qptd — talus, scree and rare till) which drape the flanks of the Ben Lomond plateau. There is a small outcrop of similar granodiorite in Pig Run Creek (EQ483044) in a window within the slope deposits, but Mathinna Beds metapsammite (SDsm) crops out about 200 m downstream.

The contact metamorphic aureole on the WSW side of the pluton extends for about 1.5 km to, for example, EQ460050. (There is a slight mismatch in the edge of the aureole between the Ben Lomond and Alberton map sheets, due to the greater difficulty in recognising hornfels in arenitic and quartzitic lithologies compared to pelites. The northeasterly trend of the aureole margin near here, and the small area of unmetamorphosed Mathinna Beds (SDs) around EQ462055, may be spurious.) To the south

the aureole margin has a strong southerly trend, and strongly hornfelsed Mathinna Beds, containing altered andalusite porphyroblasts, crops out in a small creek just above Ragged Jack Road at EQ474028, about 2.5 km from the main contact.

The general mapped distribution of the granodiorite and the width of the aureole suggest that here the pluton has only just been unroofed, and that a spine or shelf extends southwards at relatively shallow depth. To the west the contact is probably steeper.

The numerous small apparent roof pendants of Mathinna Beds within the granodiorite in the adjoining Alberton Quadrangle to the north (McClenaghan *et al.*, 1993) support this interpretation of near roof-level exposure.

FIELD DESCRIPTION

In hand specimen, samples of the granodiorite (003919, 003921, 003922, 003924) are essentially similar. All are tough, equigranular, even-grained, medium-grained (typically 2–5 mm) grey rocks with mesoscopically visible quartz, feldspars, abundant biotite and subordinate hornblende. No grain foliation of mafic minerals nor any phenocrysts were observed, although there are occasional tabular masses, up to 10 mm across, of dull grey hornblende. The limited outcrops are usually of fairly fresh rock, but incipient weathering may impart a pale yellow to orange-brown colour to feldspars.

Fine-grained melanocratic enclaves are locally present but not especially abundant (the term xenoliths is avoided here, as a genetic relationship to the host granodiorite is possible, as discussed below). The enclaves (samples 003922, 003925) are typically crudely rounded to ellipsoidal with long axes 20–100 mm long, but some measuring 200 300 mm were noted. They have sharp, slightly irregular margins against the host rock and an even-grained, saccharoidal texture. All are much finer-grained (typically 0.5 mm) and darker than the host, with particularly abundant black biotite. Some display a diffuse internal banding, with alternating very dark and relatively light bands 1 to 10 mm wide.

Irregular, wavy schlieren about 30 mm wide, composed of fine-grained melanocratic material similar to that of the enclaves, were also observed in the granodiorite.

Also noted, mainly in float blocks, were leucocratic enclaves up to 300 mm across of off-white to pale yellowish, fine-grained (c. 0.5–1 mm) saccharoidal aplite (samples 003920, 003923). These are equigranular apart from sparsely distributed, small (1–2 mm) quartz phenocrysts.

Scattered quartz veins and veinlets, a few millimetres to 10 mm wide, cut and have a similar grainsize to the granodiorite.

All the rocks are essentially non-magnetic, with susceptibilities (measured from hand specimens) ranging from 0.10 to 0.25 10^{-3} SI units in the granodiorites, about 0.30 in the enclaves, and less than 0.01 in the aplites.

PETROGRAPHY

Host granodiorite
(sample 003924, grid reference EQ489054)

In thin section this sample displays a dominantly subhedral granular texture, and consists of interlocking anhedra of quartz (24 volume % visual estimate) and subhedra of plagioclase (50%) and potash feldspar (13%), together with subordinate biotite (8%), minor amphibole (4%) and rare clinopyroxene (<1%). There is a tendency for the ferromagnesian minerals to occur in finer-grained composite glomerocrystic clots.

Textural relationships show the apparent order of crystallisation as clinopyroxene (relict), followed by amphibole and biotite, with quartz and feldspars last. However it is possible that some of these minerals have not crystallised directly from a granitic melt, but were incorporated into it as solid phases, either as fragments of the source ('restite') or as a component of a more mafic magma that mingled with a felsic melt (see below).

Feldspar subhedra are typically rhombs to elongate oblongs, 2–5 mm long. Plagioclase is somewhat more abundant than alkali-feldspar, and neither perthitic nor antiperthitic intergrowths have developed. Marked complex concentric zoning, with rims more sodic than cores, is very common in the plagioclase. The closely spaced multiple twinning is occasionally slightly bent or microfaulted, possibly due to tectonic deformation. The volumetrically subordinate alkali feldspar is mostly untwinned orthoclase, but there is also some cross-hatch twinned microcline, generally as smaller grains. Both plagioclase and alkali- feldspar are incipiently to partially sericitised. The sericite has rarely coarsened (recrystallised?) to secondary muscovite.

Quartz anhedra are typically 1 to 4 mm across and have slightly undulose extinction.

Biotite is the most abundant ferromagnesian mineral and occurs as ragged, stubby, oblong subhedra or anhedra, typically 500 m to 3 mm across, either as isolated grains or in glomerocrysts. Pleochroism is from pale straw yellow-brown *(alpha)* to very dark brown *(beta, gamma)*. Biotite is occasionally altered to colourless to pale green

chlorite with anomalous 'Berlin-blue' interference colours.

Amphibole occurs as ragged anhedra to elongate subhedra up to 1 mm across, with prisms rarely up to 6 mm long, usually as interlocking grains often associated with biotite in glomerocrystic clots. In some places the two minerals seem to be crystallographically aligned, with amphibole cleavage (110) parallel to biotite (001). The characteristic 120° cleavage trace is observable on basal sections. The mineral is generally a hornblende (see also electron microprobe analyses) with distinctive pleochroism (*alpha* pale yellow, *beta* khaki-brown, *gamma* sea-green to brownish green), negative optic sign, and extinction angles of up to 15°. Some green to pale yellow actinolite, lacking a brown tint, is also present.

Clinopyroxene is only a minor phase, and is noted as isolated twinned oblong to anhedral grains up to 1 1.5 mm but commonly 400 900 m, and more typically as relict sieve-textured anhedral remnants surrounded by amphibole in an apparent reaction relationship within the glomerocrystic clots. The clinopyroxene is colourless and biaxial positive, with moderate optic axial angle.

Accessory minerals include acicular apatite (typically 50–100 5–10 m, but up to 700 20 m), small rounded zircons, and rounded opaque blebs (<50 m). These minerals are most abundant as inclusions in biotite and particularly hornblende, but are also found associated with quartz and feldspars. A trace of interstitial carbonate is also present.

Sample 003919 [EQ491056] is very similar to, but slightly more leucocratic than, sample 003924. In thin section amphibole is less abundant, occurring as small (<500 m) anhedral to subhedral grains often associated with biotite in glomerocrystic clots, and clinopyroxene is apparently absent. Some development of secondary sphene and opaque minerals accompanies the alteration of biotite to chlorite.

Sample 003921, from Pig Run Creek [EQ483044], also closely resembles sample 003924, although clinopyroxene is not present at least in the thin section. This sample also contains part of a melanocratic enclave. In thin section the enclave is defined by a finer grain size and more abundant biotite and hornblende. There is no precise border or any obvious reaction textures, and thus the enclave does not appear to be a xenolith.

Melanocratic enclave (sample 003925, grid reference EQ489054)

This enclave consists of a more or less subhedral granular, unfoliated aggregate of biotite (20 vol.%

visual estimate), clinopyroxene (6%), amphibole (2%), quartz (7%), and feldspar (65%), mostly plagioclase with minor alkali feldspar. The minerals are similar to those in the host granodiorite, but are in different proportions: biotite and clinopyroxene are more abundant, and quartz and amphibole less so. Modally the rock is probably classifiable as a quartz monzodiorite (Streckeisen, 1973).

The microtexture of the rock is granitic and, apart from the finer grainsize, resembles that of the host.

Biotite occurs as ragged polygonal to oblong subhedra and anhedra, typically 250 to 500 m across and fairly evenly dispersed throughout the rock. It is pleochroic from pale straw yellow to very dark brown, with darker haloes occasionally developed around minute inclusions of apatite and possibly zircon.

Clinopyroxene is abundant as smaller (100–400 m), clear, mostly subhedral grains, also evenly dispersed. The mineral is biaxial positive with a moderately large 2V.

Amphibole, which is much less common, mostly occurs as irregular glomerocrystic aggregates several millimetres across, in which occur interlocking individual grains of both amphibole and biotite, 50 to 200 m across. The amphibole is a hornblende pleochroic from pale grey-green to darker yellow-brown, and zoning, usually from a paler interior to a darker rim in individual grains, is common. The mineral is biaxial positive with a large 2V.

Feldspar, mainly plagioclase, and quartz form an interlocking mosaic.

Some of the plagioclase grains are strongly zoned. The larger grains, which are 1 to 2 mm across, may have a poikilitic core overgrown by a relatively clear and inclusion-free rim. The poikilitic core encloses numerous tiny (10–50 mm) inclusions of biotite, together with a few needles of apatite and rounded blebs of an opaque phase. A few plagioclases have slightly bent twin lamellae, possibly indicating tectonic strain.

Alkali feldspar is subordinate to plagioclase, and occurs as cross-twinned optically negative grains of microcline, typically measuring about 150 100 m.

Quartz occurs as clear anhedra, generally up to 500 m across.

Mostly rounded opaque blebs, 10–50 m across, are dispersed throughout the rock. Rounded zircon (up to 50 m) and acicular apatite (typically 100–200 m 10–15 m) were also noted as accessory minerals.

Aplite (sample 003923, grid reference EQ484055)

In thin section the rock consists mainly of interlocking clear anhedral quartz and turbid, anhedral to subhedral feldspar (plagioclase and microcline), together with quartz–K-feldspar intergrowths. Biotite, muscovite and opaque minerals occur in accessory to trace quantities only.

Quartz anhedra are equidimensional and typically up to 1.5 mm across, rarely to 2.5 mm. Boundaries between grains and against feldspar grains are irregular to jagged.

The scattered, typically oblong plagioclase grains are up to 500 m long, but usually less. They are mostly anhedral, but may be idiomorphic against quartz and K-feldspar.

K-feldspar occurs as equidimensional to oblong subhedra and anhedra, up to 200 m 200 m. It is often zoned and may show the cross-hatched twinning characteristic of microcline.

Common irregular patches up to 1 mm across consist of micrographic intergrowths of quartz and K-feldspar. Application of the Becke line technique shows that K-feldspar is generally the host phase, with quartz inclusions occurring as amoeboid blebs (20 m to 200 m), rounded to elongate beads and trains of beads, elongate stringers (typically 200 m 30–50 m), and very narrow elongate parallel rods (typically 200 m 10 m). Thus there is a wide variety of textures. Some of the larger stringer or bead-type intergrowths display a crudely radiating 'granophyric' texture.

Scattered ragged fragments and splinters (200 m to 300 m long) of altered dark brown biotite are present, with only a few fresh enough to show pleochroism. Scattered anhedral flakes of clear muscovite are also present.

Opaque minerals occur only as a very tenuous dust of tiny equant grains of less than 2 m, noticeable only under high magnification and strong illumination.

Another aplite sample (003920, EQ480055) consists almost entirely of clear anhedral quartz and turbid alkali-feldspar, which form an interlocking mosaic or are micrographically intergrown. Very few grains have even partial crystal forms. The grainsize of much of the rock is 100 to 200 m, but both quartz and cross-hatched microcline anhedra are both commonly up to 1 mm, and the microcline host to quartz inclusions may be optically continuous for 2 to 3 mm.

Unequivocal multiply-twinned plagioclase is rare, but as both positive and negative optic signs were obtained from the alkali feldspar, both albite and microcline are present, although difficult to systematically distinguish without staining techniques.

As in sample 003923, a wide variety of micrographic textures are present, both in terms of the form and the scale of the intergrowth. Some crudely triangular or wedge-shaped to polygonal, equant quartz inclusions are 200 m across, but finer-grained bead, stringer and rod intergrowth textures are common.

Ragged elongate splinters (mostly 200–500 m 20–50 m) of biotite, pleochroic from pale to very dark grey-brown, are more common and less altered than in 003923, but even so constitute only about 1 to 2% of the rock. Muscovite occurs as rare interstitial anhedral flakes. Opaque minerals occur only as a very tenuous, fine-grained dust, mainly as inclusions in K-feldspar.

MINERAL CHEMISTRY

Reconnaissance electron probe microanalyses of minerals from samples of the granodiorite (003924), a melanocratic enclave (003925), and an aplite enclave (003923) were obtained using the JEOL instrument at the University of Tasmania. All analyses were made using the spot mode, in which a volume of diameter 0.5 m and of depth (beam penetration) 3–5 m is analysed. Results, recalculated to 100% anhydrous, and cation formulae are presented in Tables 1 to 5 and Figures 1 to 5.

Pyroxenes

Four grains were analysed from the granodiorite and three from a melanocratic enclave (Table 1). Assuming that all iron is ferrous (Fe^{2+}), the grains are all very nearly ideally stoichiometric clinopyroxenes. They classify as salites or are just transitional to augite when plotted on the pyroxene quadrilateral (fig. 1). Ferric iron is probably negligible, as recalculation of a portion of total iron as Fe^{3+} would lead to lower, less ideal cation totals.

Pyroxenes in the melanocratic enclave are very similar to those in the host granodiorite, except that the former are slightly more refractory in terms of higher Mg/Mg + Fe.

The only detectable non-quadrilateral component appears to be Al_2O_3 (<0.64%), which probably mainly occupies the octahedral sites, and is perhaps charge balanced against vacancies in these sites. Na_2O and Cr_2O_3 were detected in only one analysis, but as this had an unsatisfactorily high total before recalculation, not too much reliance should be placed on this.

Table 1

Electron probe microanalyses of pyroxenes

	003924 (granodiorite)				W003925 (enclave)		
	1A	5A	6A	6B	2B	2C	3A
SiO_2	51.92	51.85	51.62	52.47	52.49	52.23	53.05
TiO_2	–	–	–	–	–	–	–
Al_2O_3	0.47	0.42	0.64	–	0.45	0.57	0.25
Cr_2O_3	–	–	–	–	–	0.14	–
FeO	15.47	15.12	15.11	14.25	13.78	13.39	12.59
MnO	1.02	0.93	0.81	0.64	0.75	0.67	0.58
MgO	9.88	9.95	9.75	10.12	11.01	10.96	10.87
CaO	21.24	21.72	22.08	22.51	21.53	21.68	22.66
Na_2O	–	–	–	–	–	0.35	–
Total	100.00	99.99	100.01	99.99	100.01	99.99	100.00
Original total	101.47	100.70	95.07	99.12	100.81	190.04	89.47

Cations based on (0) = 6

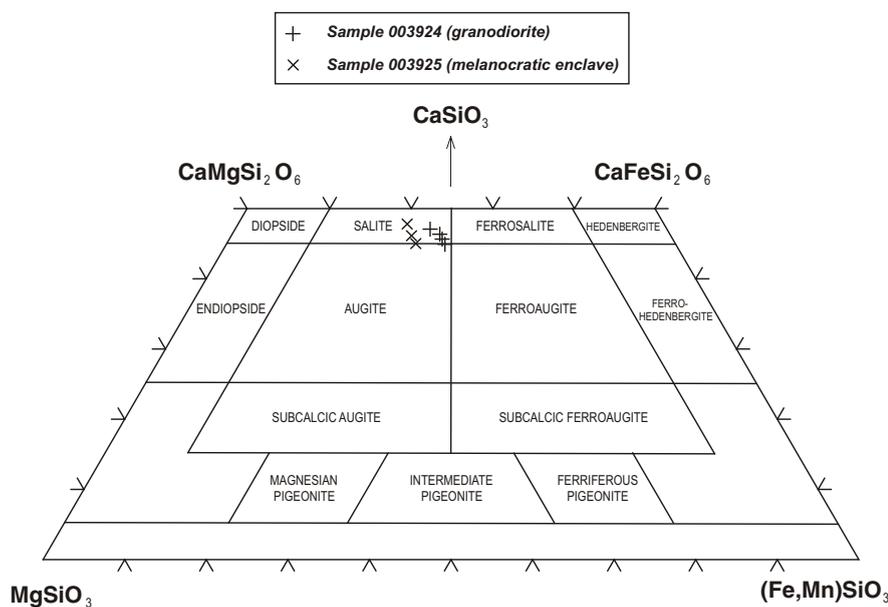|	1A	5A	6A	6B	2B	2C	3A
Si	1.998	1.994	1.987	2.010	2.001	1.992	2.014
Al^{iv}	0.002	0.006	0.013	–	–	0.008	–
Al^{vi}	0.019	0.013	0.016	–	0.020	0.018	0.011
Cr	–	–	–	–	–	0.004	–
Fe	0.098	0.487	0.486	0.456	0.439	0.427	0.400
Mn	0.033	0.030	0.026	0.021	0.024	0.022	0.019
Mg	0.567	0.571	0.559	0.578	0.625	0.623	0.615
Ca	0.875	0.895	0.911	0.924	0.880	0.886	0.922
Na	–	–	–	–	–	0.026	–
Cation total	3.992	3.996	3.998	3.989	3.989	4.006	3.981
Mg/Mg + Fe	0.532	0.540	0.535	0.559	0.587	0.593	0.606

Figure 1

Electron probe microanalyses of pyroxenes from the Upper Blessington pluton, plotted on the pyroxene quadrilateral (Ca:Mg:total Fe, atomic ratios).

The clinopyroxenes differ from those typical of tholeiitic mafic rocks, which are usually much less calcic. Similarly calcic augites and salites occur in alkalic mafic rocks, but these typically contain much more Al_2O_3 and TiO_2 due to the low silica activity in their host magma (e.g. Carmichael *et al.*, 1974, pp. 273–275).

Amphiboles

Five of the six analyses obtained from the granodiorite (Table 2) are very similar and classify as ferro-hornblendes (with Mg/Mg+Fe of about 0.47) in the scheme of Leake (1974) (fig. 2). The relatively low Al_2O_3 content of about 6% is notable and probably indicative of a low crystallisation pressure. Goscombe *et al.* (1992) estimated a crystallisation pressure of 1.3 kb (1 kb) from these data using the calibration of Hollister *et al.* (1977). The other analysis (4B) is an actinolite with low Al_2O_3, TiO_2, Na_2O and K_2O, and is probably a low temperature, retrogressed grain.

Insufficient data (three analyses) are available from the melanocratic enclave, but the amphiboles appear compositionally more variable than in the host. It may, however, be significant that, as for pyroxenes, all have higher Mg/Mg + Fe ratios (0.51–0.61) than the ferro-hornblendes of the host granodiorite.

In terms of calculated cation site occupancies (assuming all Fe as Fe^{2+} as for pyroxenes), all the

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Table 2

Electron probe microanalyses of amphiboles

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	003924 (granodiorite)						003925 (enclave)		
	4A	4B	4C	4E	5B	7A	1A	1B	1D
SiO_2	48.85	54.40	47.62	48.32	47.91	48.09	51.85	45.82	52.29
TiO_2	1.18	0.29	1.27	1.06	1.12	1.15	0.53	1.79	0.27
Al_2O_3	5.72	1.40	6.87	5.79	6.17	6.30	4.79	9.47	4.64
FeO	20.08	17.83	20.36	20.84	20.69	20.49	16.24	17.82	15.60
MnO	0.64	0.69	0.51	0.70	0.57	0.64	0.46	0.43	0.37
MgO	10.37	13.64	9.79	10.19	10.25	9.96	13.02	10.41	13.58
CaO	11.65	11.61	11.96	11.49	11.34	11.55	12.02	12.04	12.41
Na_2O	0.95	–	0.88	0.98	1.12	1.10	0.66	1.24	0.47
K_2O	0.57	0.14	0.74	0.63	0.74	0.72	0.42	0.97	0.37
Cl	–	–	–	–	0.08	–	–	–	–
Total	100.01	100.00	100.00	100.00	99.99	100.00	99.99	99.99	100.00
Original total	98.66	99.00	98.01	99.46	98.09	97.81	98.65	98.68	97.84

Cations based on (0)=23

	4A	4B	4C	4E	5B	7A	1A	1B	1D
Si	7.196	7.818	7.044	7.154	7.100	7.114	7.447	6.731	7.481
Al^{iv}	0.804	0.182	0.956	0.846	0.900	0.886	0.553	1.269	0.519
Al^{vi}	0.189	0.054	0.242	0.164	0.178	0.212	0.258	0.370	0.263
Ti	0.130	0.031	0.142	0.119	0.125	0.128	0.058	0.198	0.029
Fe^{II}	2.473	2.142	2.519	2.580	2.564	2.535	1.951	2.189	1.866
Mn	0.079	0.084	0.064	0.088	0.071	0.081	0.056	0.054	0.044
Mg	2.277	2.922	2.159	2.249	2.265	2.196	2.787	2.279	2.896
Ca	1.838	1.788	1.895	1.823	1.801	1.830	1.850	1.895	1.902
Na	0.107	–	0.251	0.282	0.322	0.316	0.184	0.354	0.131
K	0.272	0.026	0.139	0.118	0.139	0.136	0.078	0.182	0.068
Cation total	15.365	15.047	15.411	15.423	15.465	15.434	15.222	15.521	15.199
Mg/Mg + Fe	0.479	0.577	0.462	0.466	0.469	0.464	0.588	0.510	0.608

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Figure 2

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Electron probe microanalyses of amphiboles from the Upper Blessington pluton (cations calculated on the basis of 23 oxygen): plot of Mg / Mg+Fe against Si , showing nomenclature of Leake (1978).
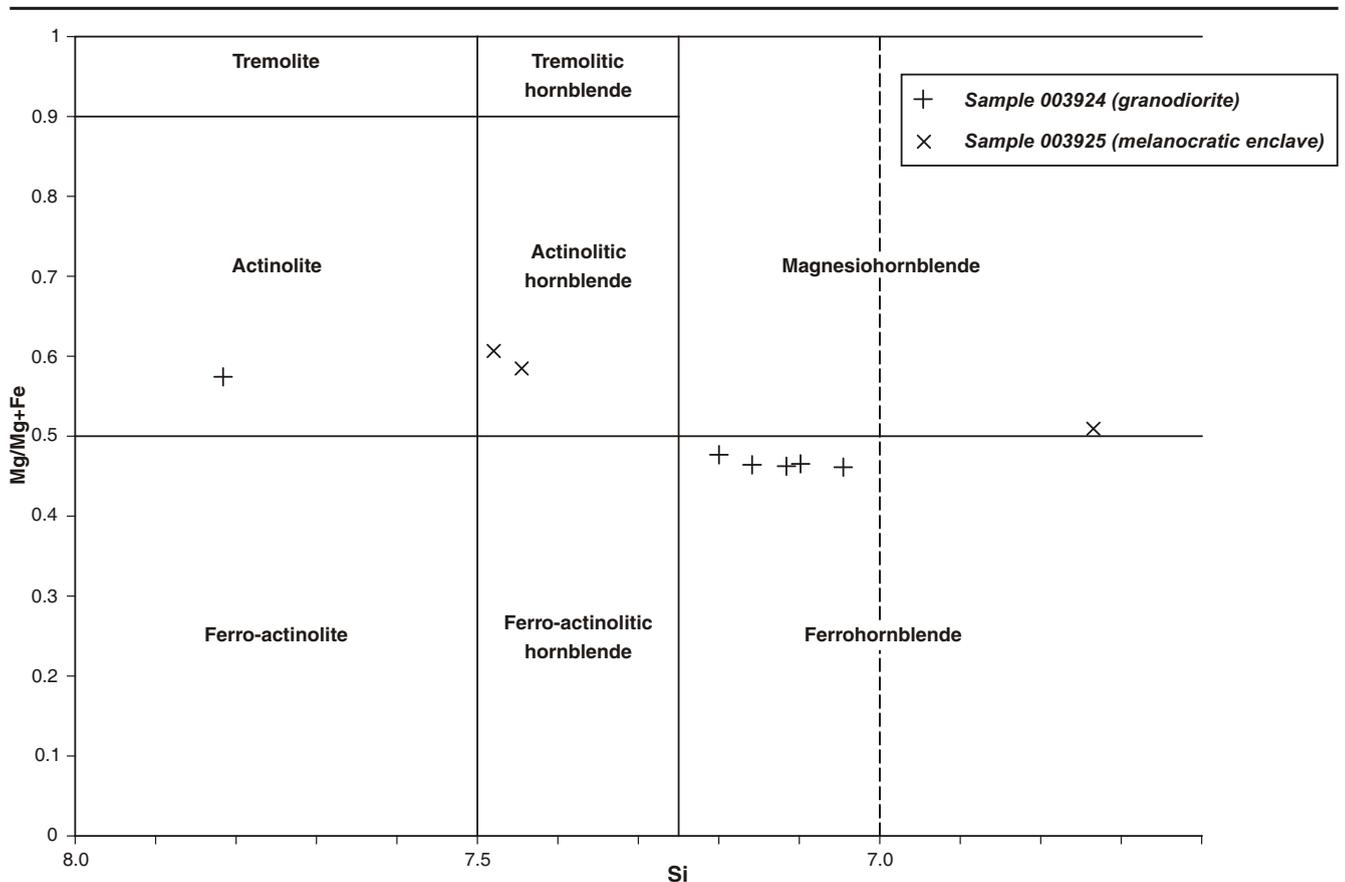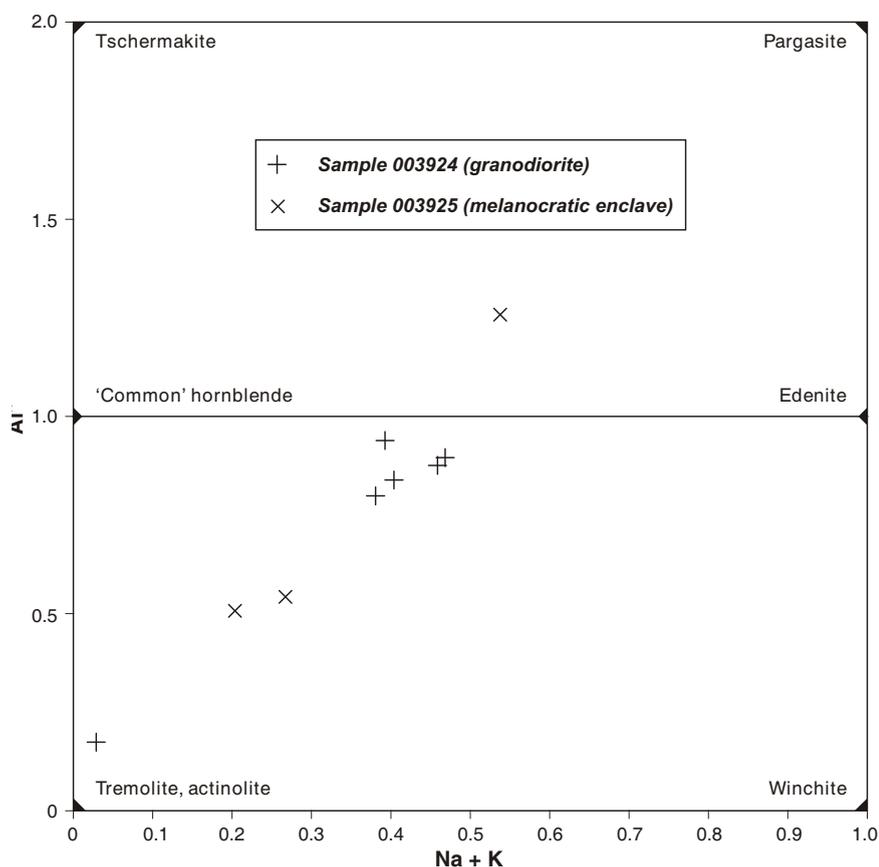
Figure 3

Electron probe microanalyses of amphiboles from the Upper Blessington pluton (cations calculated on the basis of 23 oxygen): plot of tetrahedral Al against Na + K.

amphiboles lie close to the tremolite/actinolite–pargasite join in a plot of tetrahedral Al against total Na + K (fig. 3). A strong correlation between TiO_2 and Al_2O_3 is also evident.

Compositionally similar amphiboles occur in granitoids elsewhere in the Scottsdale Batholith (M. P. McClenaghan, unpublished data) and in the Lachlan Fold Belt of southern NSW (Whalen and Chappell, 1988).

Micas

The tri-octahedral micas in the host granodiorite and in the melanocratic enclave are also very similar (on the basis of five and three analyses respectively), with again those from the enclave tending to have slightly higher Mg/Mg + Fe (Table 3). All classify as true biotites (fig. 4; Deer *et al.*, 1974).

Compositionally the micas fall within the field of biotites from elsewhere in the Scottsdale Batholith (M. P. McClenaghan, unpublished data). In particular they overlap with biotites from the Diddleum suite granodiorites and have slightly higher Mg/Mg + Fe than those from the Russells Road suite. They are also broadly similar to those from I-type granitoids in the Lachlan Fold Belt (Whalen and Chappell, 1988) except for their unusually high TiO_2 (4.62–5.05% versus generally less than 4% in NSW). The relatively low Al_2O_3 and

tetrahedral Al is consistent with the meta-aluminous nature of the granodiorite (see below) and is also a feature seen in I-type granitoids from the Lachlan Fold Belt (Whalen and Chappell, 1988).

A single analysis of a phengite, probably secondary, from the granodiorite is also reported.

Feldspars

The probe analyses (Table 4, fig. 5) confirm that plagioclase in the granodiorite is strongly zoned; the compositional range is at least from intermediate andesine (An_{39}) to albite (An_6). A comparable range in plagioclase composition is present in the melanocratic enclave, but no grains as calcic as andesine were analysed. All the analyses are more-or-less stoichiometric, although a small amount of alkali feldspar and other impurities may contribute to enclave analysis 3D.

Two microcline analyses from the granodiorite are close to end-member potash feldspar. Impurities probably account for the TiO_2 and possibly some of the CaO detected.

The feldspars in the aplite (Table 5) analyse as albite to oligoclase and microcline with apparently very little alkali feldspar solid solution, consistent with low temperature crystallisation.

Table 3

Electron probe microanalyses of micas

	Biotite 003924 (granodiorite)					Muscovite	Biotite 003925 (enclave)		
	1B	3A	3C	3D	8B	8A	2A	2D	3B
SiO_2	38.03	38.21	37.43	37.07	37.89	49.16	38.44	38.23	37.70
TiO_2	4.77	5.01	4.99	4.62	5.05	0.26	4.92	5.00	4.79
Al_2O_3	14.62	14.34	14.33	14.38	14.26	36.53	14.56	14.49	14.25
FeO	23.49	23.35	24.40	24.74	23.98	2.45	22.48	22.3	23.68
MnO	–	0.27	0.25	0.29	–	–	–	0.26	0.35
MgO	9.24	8.60	8.97	9.95	9.29	0.20	9.84	9.80	9.19
CaO	0.16	–	–	0.55	–	–	–	–	–
Na_2O	–	–	–	–	–	–	–	–	–
K_2O	9.69	9.71	9.53	8.31	9.53	11.40	9.67	9.71	9.90
SO_3	–	0.43	–	–	–	–	–	–	–
Cl	–	0.08	0.10	0.09	–	–	0.10	0.13	0.14
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.01	100.00	100.00
Original Total	96.30	91.35	97.74	96.14	96.25	94.75	96.07	120.10	91.67

Cations based on (0) = 22

|									
Si	5.621	5.677	5.573	5.504	5.611	6.255	5.651	5.632	5.608
Al^{iv}	2.379	2.323	2.427	2.496	2.389	1.745	2.349	2.368	2.392
Al^{vi}	0.169	0.187	0.087	0.021	0.099	3.733	0.174	0.148	0.105
Ti	0.530	0.560	0.589	0.516	0.563	0.025	0.544	0.554	0.536
Fe	2.903	2.902	3.038	3.072	2.970	0.261	2.764	2.757	2.946
Mn	–	0.034	0.032	0.037	–	–	–	0.032	0.044
Mg	2.035	1.906	1.990	2.202	2.050	0.037	2.156	2.152	2.037
Ca	0.025	–	–	0.087	–	–	–	–	–
K	1.826	1.840	1.810	1.573	1.800	1.850	1.813	1.825	1.878
S	–	excl	–	–	–	–	–	–	–
Cl	–	0.021	0.026	0.024	–	–	0.024	0.032	0.036
Cation total	15.488	15.429	15.546	15.508	15.482	13.906	15.451	15.468	15.546
Mg/Mg + Fe	0.412	0.396	0.396	0.418	0.408	(0.124)	0.438	0.438	0.409
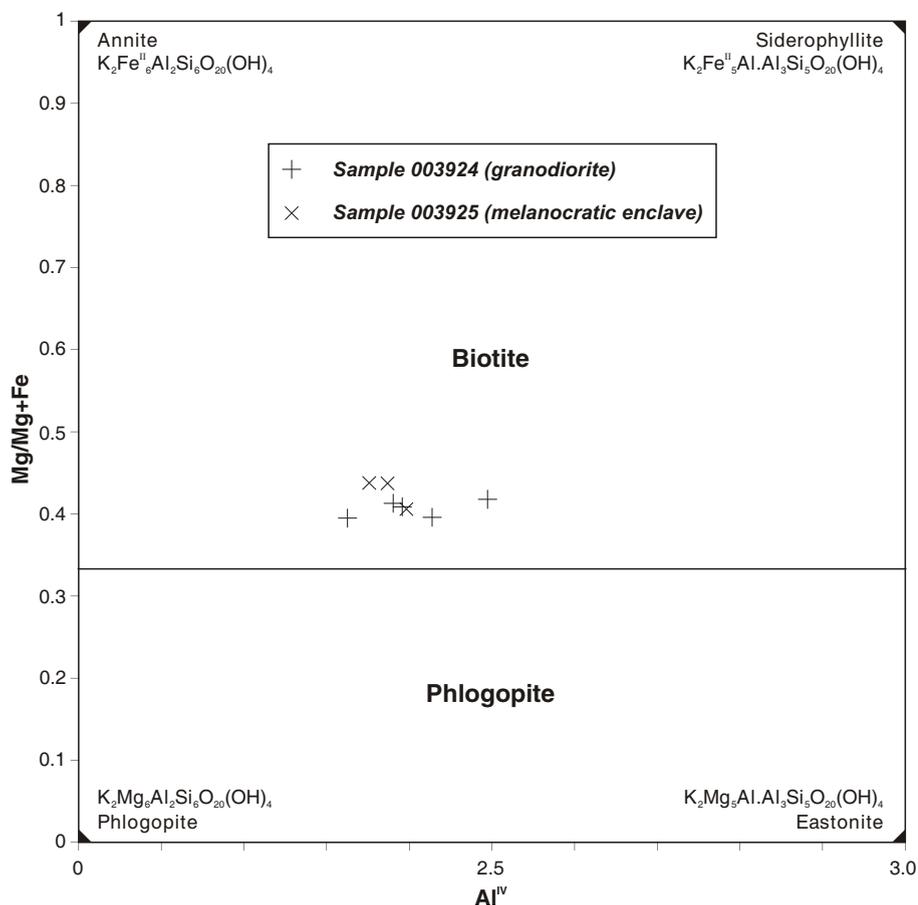
Figure 4

Electron probe microanalyses of biotites from the Upper Blessington pluton (cations calculated on the basis of 22 oxygen): plot of Mg / Mg + Fe against tetrahedral Al.

Table 4
Electron probe microanalyses of feldspars

	Plagioclase 003924 (granodiorite)							003925 (enclave)						Potash feldspar 003924 (granodiorite)	
	2A	3E	3F	4D	5E	7B	7C	2E	2F	3C	3D	3E	3F	1C	5C
SiO$_2$	60.57	62.86	64.37	59.19	67.66	62.32	65.39	62.69	63.33	62.33	60.58	66.39	62.54	65.43	64.26
TiO$_2$	–	–	–	–	–	–	–	–	–	–	–	–	–	0.18	0.21
Al$_2$O$_3$	25.06	23.90	22.71	26.24	20.58	23.96	23.13	23.95	23.42	24.14	26.33	21.92	24.06	18.36	18.19
MgO	–	–	–	–	–	–	–	–	–	–	0.24	–	–	–	–
CaO	6.77	4.58	3.95	7.73	1.17	5.58	1.28	5.11	4.50	5.45	3.06	1.46	5.46	0.24	0.56
Na$_2$O	7.08	7.97	8.63	6.39	10.46	7.89	8.55	8.05	8.53	7.87	6.92	9.47	7.81	0.80	0.41
K$_2$O	0.52	0.69	0.33	0.45	0.12	0.26	1.65	0.19	0.22	0.21	2.67	0.76	0.12	14.99	15.37
SO$_3$	–	–	–	–	–	–	–	–	–	–	0.19	–	–	–	–
Total	100.00	100.00	99.99	100.00	99.99	100.01	100.00	99.99	100.00	100.00	99.99	100.00	99.99	100.00	100.00
Original total	100.72	100.05	100.26	101.25	100.82	100.23	96.22	89.84	90.60	100.10	101.33	98.03	99.63	100.13	98.72
Cations based on (0) = 8															
Si	2.694	2.778	2.834	2.638	2.955	2.758	2.868	2.769	2.795	2.756	2.701	2.906	2.762	3.010	2.979
Ti	–	–	–	–	–	–	–	–	–	–	–	–	–	excl	excl
Al	1.314	1.245	1.178	1.378	1.059	1.249	1.196	1.247	1.218	1.258	1.384	1.131	1.253	0.995	0.994
Ca	0.322	0.217	0.186	0.369	0.055	0.264	0.060	0.242	0.213	0.258	0.146	0.068	0.258	0.012	0.077
Na	0.611	0.683	0.737	0.552	0.886	0.677	0.727	0.689	0.730	0.674	0.598	0.804	0.669	0.072	0.037
K	0.029	0.039	0.019	0.026	0.007	0.015	0.093	0.011	0.012	0.012	0.152	0.043	0.007	0.879	0.909
Cation Total	4.970	4.962	4.954	4.963	4.962	4.963	4.944	4.958	4.968	4.958	4.981*	4.952	4.949	4.968	4.996
an	33.5	23.1	19.8	39.0	5.8	27.7	6.8	25.7	22.3	27.3	16.3	7.5	27.6	1.2	7.6
ab	63.4	72.8	78.2	58.3	93.5	70.8	82.7	73.2	76.4	71.4	66.8	87.9	71.6	7.4	3.6
or	3.1	4.1	2.0	2.7	0.7	1.5	10.5	1.1	1.3	1.3	16.9	4.6	0.8	91.3	88.9

*Mgo, SO$_3$ excluded

Figure 5

Electron probe microanalyses of feldspars from the Upper Blessington pluton: ternary plot of Ca : Na : K, atomic ratios.

Legend:
- × Sample 003924 (granodiorite)
- + Sample 003925 (melanocratic enclave)
- ● Sample 003923 (aplite)
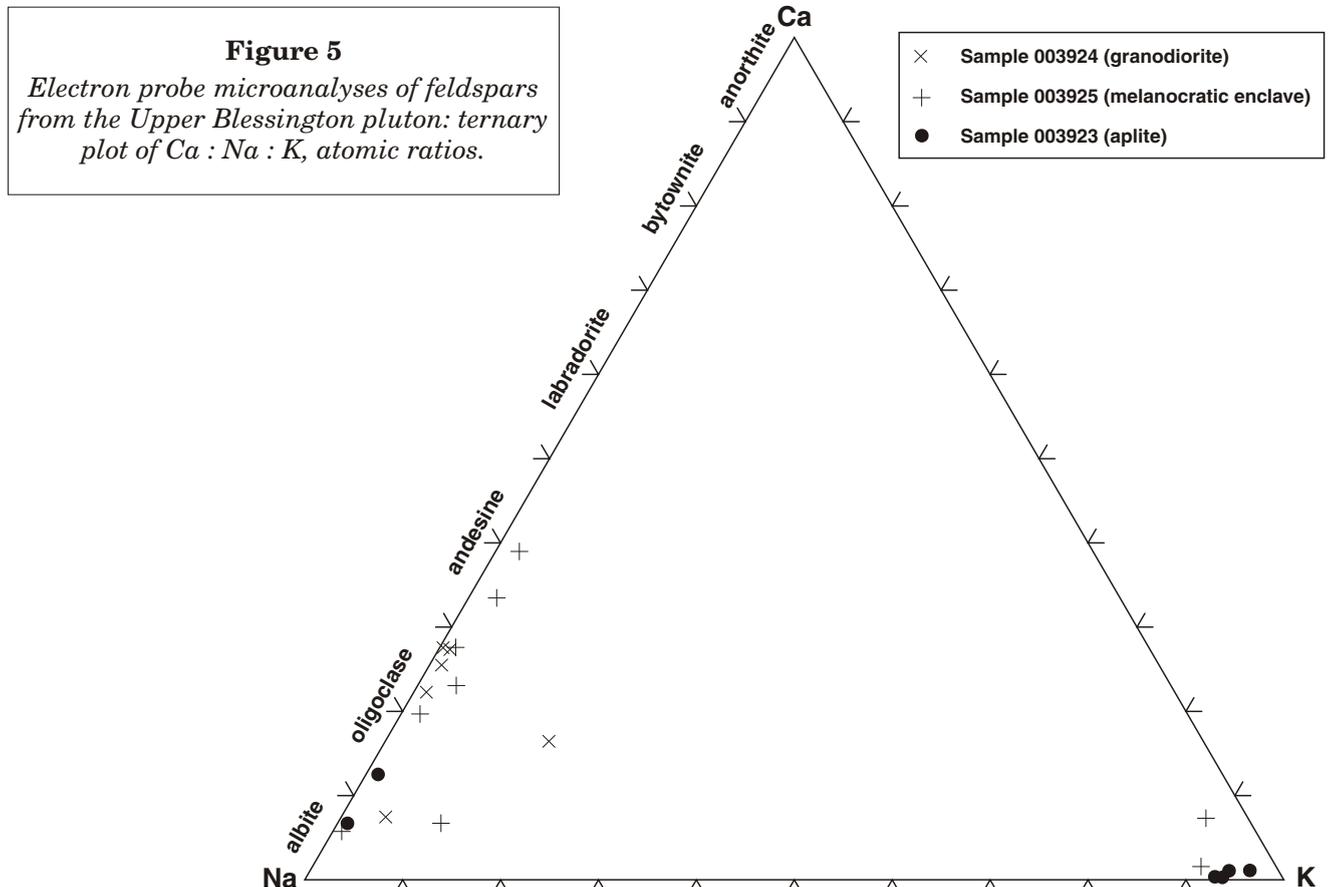
Table 5

Electron probe microanalyses, sample 003923 (aplite)

	plagioclase		potash feldspar				potash feldspar/quartz intergrowth			
	1B	4A	1A	1C	2A	3A	2B	2C	3B	4B
SiO$_2$	65.98	67.32	65.32	65.32	65.60	65.59	82.18	75.75	79.50	79.13
Al$_2$O$_3$	21.81	20.80	18.26	18.48	18.56	18.47	9.36	12.91	11.20	11.25
CaO	2.53	1.36	0.17	0.19	–	–	–	–	–	–
Na$_2$O	9.48	10.38	0.29	0.51	0.68	0.68	–	0.38	0.74	0.84
K$_2$O	0.20	0.15	15.88	15.50	15.16	15.25	8.46	10.96	8.56	8.78
Cl	–	–	0.07	–	–	–	–	–	–	–
Total	100.00	100.01	99.99	100.00	100.00	99.99	100.00	100.00	100.00	100.00
Original total	102.98	103.06	102.56	101.99	106.59	103.10	99.25	102.26	101.70	103.21

Cations based on (0)=8							*Calculated ideal mineralogy (wt%)*			
Si	2.892	2.943	3.012	3.005	3.010	3.012	albite	–	3.9	6.3	6.4
Al	1.126	1.071	0.992	1.002	1.004	1.000	K–feldspar	49.4	63.0	48.6	45.8
Ca	0.119	0.064	0.008	0.010	–	–	muscovite	0.8	1.7	2.8	1.3
Na	0.806	0.880	0.026	0.045	0.060	0.061	quartz	49.8	31.4	42.4	46.5
K	0.011	0.008	0.934	0.910	0.887	0.893	Total	100.0	100.0	100.1	100.0
Cation total	4.954	4.966	4.972	4.972	4.961	4.966					
an	12.7	6.7	0.9	1.0	–	–					
ab	86.1	92.4	2.7	4.7	6.4	6.4					
or	1.2	0.9	96.4	94.3	93.6	93.6					

GEOCHEMISTRY

Major and trace element chemical analyses and CIPW norms for representative samples of granodiorite, melanocratic enclave and aplite are presented in Table 6.

An important parameter in the geochemistry of granitoids is the ASI (alumina saturation index = molar Al$_2$O$_3$/Na$_2$O + K$_2$O + CaO), which for all these rocks is less than 1, indicating that they are meta-aluminous rather than peraluminous. This is reflected in terms of their CIPW norms by the presence of *di* rather than *C*, and mineralogically by the presence of hornblende rather than aluminous minerals such as muscovite, garnet or cordierite.

Of the major elements, SiO$_2$ and K$_2$O are lower in the melanocratic enclave relative to the host granodiorite, and the remainder (CaO, MgO, total FeO, TiO$_2$, Al$_2$O$_3$, Na$_2$O, P$_2$O$_5$ and MnO) are higher. This is consistent with the greater abundance of ferromagnesian minerals and plagioclase in the enclave, and the lower abundance of quartz.

Very nearly the reverse is true of the aplite; SiO$_2$, K$_2$O and Na$_2$O are higher than in the granodiorite, and the other major elements lower.

The granodiorite composition could, for all major elements except Na$_2$O, be reasonably accurately modelled by mixing of subequal amounts of enclave and aplite composition end members.

This simple model is not generally supported, however, by the trace element data. Only V and Co abundances in the granodiorite are roughly the average of their abundances in the enclave and in the aplite. Cr values are suspiciously high for granitoids and may have been affected by contamination during sample preparation.

In general, most trace elements have similar abundances in the enclave and in the host granodiorite; the main exceptions are Cu and U which are anomalously high in the former.

In contrast, the aplite is strongly depleted relative to the granodiorite in most trace elements other than Rb, Y, Pb, Th, U and possibly Nb and Ga.

Further data would be needed to fully assess the reality and significance of these suggested differences.

DISCUSSION

Classification

The Upper Blessington Granodiorite has the characteristics of an I-type granitoid, i.e. one derived from partial melting of an igneous or infracrustal protolith (e.g. Chappell and White, 1974; White and Chappell, 1977, 1983; Hine *et al.*, 1978, etc.). Key criteria are both mineralogical (the presence of hornblende and even clinopyroxene, rather than muscovite or aluminous minerals) and geochemical (the low ASI and meta-aluminous character, and relatively high Na$_2$O and CaO).

The absence of magnetite, low magnetic susceptibility, and low Fe$_2$O$_3$/FeO (0.20) suggest that the granodiorite is moderately reduced (i.e. solidifying at low oxygen fugacities) in contrast to many I-type granitoids which contain magnetite.

The relatively low SiO$_2$ and high total FeO, TiO$_2$, CaO and MgO also indicate that the granodiorite is

<div align="center">

Table 6

Chemical analyses and CIPW norms of granodiorite and related rocks

</div>

Field No.	R1040	BJ642B	BJ641
Reg. No.		003925	003923
Analysis No.	876015	876035	876034
Rock type	Granodiorite	Enclave	Aplite
Location	EQ477058	EQ488054	EQ484055

Major elements (wt%)

SiO_2	67.14	59.18	77.64
TiO_2	0.63	1.14	0.06
Al_2O_3	15.11	16.53	13.11
Fe_2O_3	0.68	1.15	0.02
FeO	3.36	5.00	0.32
MnO	0.06	0.13	<0.01
MgO	1.39	2.85	<0.01
CaO	3.34	5.63	0.54
Na_2O	4.02	4.81	4.62
K_2O	2.95	2.13	4.78
P_2O_5	0.16	0.29	0.01
H_2O^+	0.70	1.08	0.28
CO_2	0.28	0.17	0.07
Total S	<0.05	<0.05	<0.05
F	0.18	0.24	<0.10
O = F corr	-0.08	-0.10	–
Total	99.92	100.23	101.45

CIPW norms

Q	22.04	6.38	31.17
or	17.64	12.80	27.94
ab	34.43	41.38	38.68
an	14.66	17.95	0.91
di	0.88	7.40	0.87
hy	7.79	10.65	–
wo	–	–	0.28
mt	0.99	1.00	0.02
il	1.20	2.19	0.11
ap	0.36	0.67	0.02
Total	99.99	99.99	100.00

Trace elements (ppm)

Sc	<10	17	<10
V	56	110	<3
Cr	110	120	105
Co	11	17	<4
Ni	14	16	4
Cu	<3	45	<3
Zn	54	72	6
Ga	14	15	11
As	11	<10	<10
Rb	130	125	185
Sr	220	230	8
Y	27	26	33
Zr	190	160	61
Nb	16	10	11
Mo	2	3	<2
Ag	<5	<5	<5
Sn	<4	<4	<4
Sb	<5	<5	<5
Ba	580	370	35
La	30	18	<7
Ce	63	48	<7
Nd	28	33	<9
W	<10	<10	<10
Pb	21	26	47
Bi	5	<5	5
Th	13	12	25
U	<5	105	22

relatively unfractionated. Additional criteria are low Rb (130 ppm), which is well below the lower limit of 250 ppm considered to indicate significant feldspar fractionation (Blevin and Chappell 1992), and relatively high Sr and Ba.

A detailed discussion of the petrogenesis of the Upper Blessington Granodiorite requires more data from the greater portion of the pluton, to the north in the Alberton Quadrangle, and its consideration in a regional context. A preliminary comparison with the unpublished data of M. P. McClenaghan from the remainder of the I-type Scottsdale Batholith shows that the present data lie on trends in variation diagrams, interpreted as due to restite separation. In particular, the MgO and CaO contents, at equivalent total FeO, are not as high as in the Diddleum Suite, but fall on trends obtained from the Russells Road Suite.

Origin and significance of the melanocratic enclaves

Microgranitoid enclaves have been reported from granitoids worldwide (e.g. review by Vernon, 1983). Many authors mention features similar to those described here, such as their typically rounded or ovoid shape, sharp margins, finer grainsize, and similar mineralogy but different, more melanocratic modal proportions relative to their host. Several theories, not necessarily mutually exclusive, have been propounded for the origin of those enclaves which are not obviously xenoliths of country rock:

(a) that they represent modified fragments of the source rock (i.e. 'restite'), now depleted in low melting components, that generated the host granitoid by partial melting (e.g. White and Chappell, 1977; Chappell, 1978; Chen et al., 1989);

(b) that they represent early-formed cumulates or chilled marginal phases of the host granitoid, which were subsequently reincorporated as essentially solid 'cognate inclusions' or 'autoliths' (e.g. Dodge and Kistler, 1990; Flood and Shaw, 1995);

(c) that they were formed from a relatively hot, mafic magma which was injected into and chilled against a cooler, more felsic and more viscous host granitoid magma at some level in the crust to form blobs or globules within the host. Because of the large contrast in chemical composition and physical properties such as viscosity and solidus temperature, only partial mechanical mixing and chemical equilibration between the two melts occurred (e.g. Reid et al., 1983; Vernon, 1983, 1984; Elburg and Nicholls, 1995).

The similarity in mineralogy and mineral chemistry between the enclaves and their host granitoid observed here and elsewhere suggests, on the face of it, a close genetic relationship between them, probably of crystal-liquid equilibrium. This is clearly compatible with both partial melting and crystal fractionation, and hence either the 'restite' hypothesis (a) or the 'autolith' hypothesis (b).

However, in relation to the 'autolith' hypothesis (b), it is difficult to explain why the enclaves are invariably finer grained than their host if they represent cumulate fragments or, given a plutonic environment, even detached marginal phases. Even if a chilled marginal facies was able to form during crystallisation of a granitoid melt at plutonic depths, it would be not be expected to be more melanocratic than the bulk of the melt.

An important observation is that the enclaves have a much higher ratio of clinopyroxene to hornblende relative to the host granodiorite. These minerals and biotite also have slightly higher Mg/Mg + Fe ratios in the enclaves. This could be interpreted in terms of the 'restite' hypothesis (a) as indicating that the enclaves are derived from slightly more refractory, less hydrous, zones or pods in the source. These did not quite melt to a degree necessary for melt extraction and their complete physical disaggregation. In this model (e.g. Chen et al., 1990) the surrounding, more hydrous, regions of the source melted sufficiently to allow their physical disaggregation into a residue of individual restite crystals or small aggregates of restite crystals (later providing the ferromagnesian minerals and more calcic cores of plagioclase in the granodiorite), and a liquid extract (later crystallising as quartz, alkali feldspar and sodic plagioclase). The more refractory, coherent detached pods in the source became free to be mechanically entrained in the ascending liquid-restite mixture as melanocratic enclaves.

Because of the very long times required for complete solidification of large granitoid plutons, the magma globule hypothesis (c) is not necessarily incompatible with partial crystal-liquid equilibration and should not be discounted on the evidence available here. Partial mixing (mingling) of felsic and relatively mafic magmas may have occurred before both were completely solid, chiefly by mechanical mixing of felsic melt and exchange of crystals, and continued for a long time by diffusion at temperatures below the solidus. In the time available it seems possible that equilibrium or near-equilibrium could have been established for some mineral compositions and many elements (e.g. see Allen, 1991).

The generally rounded, ovoid shape of the enclaves, and the absence of angular corners or polygonal forms that could be interpreted as joint-bounded, seems most consistent with the magma globule hypothesis (c) but, particularly if they were not rigid brittle solids incapable of plastic deformation even at high temperatures, not necessarily incompatible with other origins.

Another possibly important petrographic observation is the acicular habit of apatite in the enclaves, which is thought to indicate rapid crystallisation from a magma (Wyllie *et al.*, 1962) and therefore also favours the magma globule hypothesis (c). If correct, this implies physical exchange of crystals from the globules to the host, as acicular apatite inclusions have also been observed in the host granodiorite. It is noteworthy that acicular apatite has been reported from I-type granitoids elsewhere, whilst S-type granitoids commonly contain larger prismatic apatites (e.g. Chappell, 1978; Hine *et al.*, 1983).

The available data do not allow the origin of the enclaves in the Upper Blessington Granodiorite to be confidently constrained. A brief survey of the international literature on microgranitoid enclaves reveals a wide range of views with no consensus as to their origin, in spite of some very detailed studies. Possibly they can be produced by several processes. Pessimistic views as to their significance and usefulness in studies of granite petrogenesis are given by Flinders and Clemens (1995) and Roberts and Clemens (1995).

Significance of the aplite

Normative quartz and alkali feldspar account for nearly 98% of the aplite, which can be thus be modelled in the haplogranite system by the composition *Q* 31.9%, *Ab* 39.5%, *Or* 28.6%. This lies close to the water-saturated ternary minimum at pressures of about 1 to 2 kb (Tuttle and Bowen, 1958). This suggests that the aplite may represent a crystal-free, near-minimum melt, and broadly supports the independent pressure estimate of Goscombe *et al.* (1992).

The aplite may represent a sample of the liquid fraction of the granitic magma that has freed itself of restite by crystal settling (although some compositional modification, probably by precipitation of plagioclase, must have occurred while the magma ascended from source depths, due to the shift in the position of the ternary minimum towards the quartz-othoclase join with decreasing pressure). Alternatively, it may merely represent a minor, late-stage segregation.

ECONOMIC SIGNIFICANCE

Blevin and Chappell (1992) observed "an extreme lack of significant magmatic-hydrothermal mineralisation associated with restite-fractionated granite suites in the Lachlan Fold Belt" of southeastern Australia, which can be regarded as including northeast Tasmania. This was attributed to the inability of restite separation to enrich ore elements more than a few times above their source concentrations, even if the elements partition into the melt; and to the lower temperatures of restite-fractionated suites, resulting in the availability of less heat to drive hydrothermal systems. This lack of mineralisation was considered to apply to both I- and S-type restite-fractionated suites.

It is interesting to plot the composition of the Upper Blessington granodiorite on the diagrams of Blevin and Chappell (1992, 1995) which utilise elements and element ratios such as SiO_2, total iron as FeO, Fe_2O_3/FeO, Rb and Rb/Sr in an attempt to characterise mineralised granitoids in the Lachlan Fold Belt and elsewhere by their degree of fractionation and oxidation state. Granitoids associated with tin and/or wolframite mineralisation are reduced to intermediate in their oxidation states (low to moderate Fe_2O_3/FeO) but are invariably more fractionated (higher SiO_2, Rb, Rb/Sr, lower FeO) than the Upper Blessington granodiorite. Some of the granitoids associated with scheelite skarn mineralisation are less fractionated and have values of these parameters approaching that of the Upper Blessington granodiorite; their Fe_2O_3/FeO is similar or slightly higher. In this context the absence of significant known carbonate horizons in the Mathinna Beds may be unfortunate. Granitoids related to copper-molybdenum and particularly copper-only mineralisation extend to some quite mafic compositions in melt-rich, crystal-fractionated suites (e.g. the Boggy Plain Supersuite described by Wyborn *et al.*, 1987), but they are invariably more oxidised than the Upper Blessington granodiorite. Blevin and Chappell (1995) noted that copper-mineralised granitoids in the Lachlan Fold Belt are more evolved and less oxidised than granitoids associated with major porphyry-copper mineralisation elsewhere.

This assessment is reinforced by the low values of tin (<4 ppm), tungsten (<10 ppm) and molybdenum (2 ppm) recorded in the granodiorite (Table 6). Copper is extremely low (<3 ppm), perhaps due to early separation of sulphide, but the higher value in the enclave (45 ppm) is moderately anomalous.

The potential for gold mineralisation related to the Upper Blessington granodiorite is difficult to evaluate, because gold metallogeny and its relationship to granitoids (if any) is not well understood. A possible empirical association with hornblende-biotite granodiorites has been suggested (e.g. Klominsky and Groves, 1970). In northeast Tasmania the spatial relationship between gold and granitoids is variable; there is no obvious relationship in the main Mangana–Mathinna–Alberton–Lyndhurst lineament, but small gold deposits occur in contact aureoles elsewhere, and at Golden Ridge (Double Event and New Carthage prospects) in the Lisle–Golconda area there is some gold-base metal mineralisation within granodiorite (-adamellite) (e.g. Twelvetrees, 1909; Reid, 1926; Bottrill, 1994; Roach, 1994; Turner *in* McClenaghan *et al.*, 1994).

According to Blevin and Chappell (1992), the relationship between granitoids and gold mineralisation in the Lachlan Fold Belt is also usually ambiguous. Nevertheless their data define a relatively unfractionated and relatively oxidised field for 'gold mineralised granites' in terms of total FeO, Fe_2O_3/FeO and Rb. The relatively reduced Upper Blessington granodiorite lies just outside this field (at lower Fe_2O_3/FeO), whilst most of the more oxidised granodiorites from the Lisle area fall within it (Roach, 1994).

It may be that there is a clear distinction in northeast Tasmania between mesothermal gold-only mineralisation, deposited from bisulphide complexes in cool dilute hydrothermal fluids of metamorphic origin, and gold-base metal mineralisation, deposited from hot chloride-rich saline fluids at least partly of magmatic origin. The slate-hosted deposits of the Mangana–Mathinna–Alberton–Lyndhurst trend clearly fall into the former category (Taheri and Bottrill, 1994), and possibly the only significance of the granitoids is as a heat source, or as another manifestation of a deeper-seated thermal event. The apparently granodiorite-related gold-base metal deposits at Golden Ridge and near Lisle may belong to the inferred latter category but insufficient data are available.

The recognition of the Upper Blessington Granodiorite as a relatively unfractionated (or merely restite fractionated) pluton explains the lack of historically recorded mineralisation in its vicinity and downgrades the potential for related magmatic-hydrothermal deposits in the area. The potential for related tin or wolframite mineralisation is negligible, and for scheelite and copper- molybdenum it is low. The potential for gold in the area is possibly moderate to high, but may be unrelated to the granodiorite.

This unpromising evaluation probably applies to most of the I-type Scottsdale Batholith, as its geochemical variation is mainly attributed to restite unmixing (M. P. McClenaghan, unpublished data). Exploration should attempt to identify fractionated and/or oxidised plutons or parts of plutons. It is intended to more fully examine the geochemistry and metallogeny of the Scottsdale Batholith, partly in the context of the ideas of Blevin and Chappell (1992, 1995), in a later report.

Sharples (1990) did not examine the Upper Blessington Granodiorite during a study of Tasmanian building stone resources, but rated other granodiorites in the Scottsdale Batholith as 'high' to 'medium prospectivity'.

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