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Opaque mineralogy and mafic mineral chemistry of I- and S-type granites of the Lachlan fold belt, southeast Australia*

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ABSTRACT

About one-quarter or 44000 km^2 of the Lachlan fold belt of southeast Australia is underlain by granite batholiths of Silurian-Devonian age. Recent work has recognized a major distinction between granites formed from igneous sources (I-type) and those formed from sedimentary sources (S-type). Lachlan I- and S-type granites are generally characterized by the opaque mineral assemblages magnetite + ilmenite + minor sulfide (pyrite > chalcopyrite > pyrrhotite) and ilmenite + sulfide (pyrrhotite > pyrite > chalcopyrite), respectively. There are, however, magnetite-free I-type and magnetite-bearing S-type granites. Texturally earlier opaque phases are generally magnetite + ilmenite in I-type and ilmenite + sulfides in S-type granites. Sulfide minerals, even when abundant (rarely) in I-type granites, are texturally late phases. On the basis of rock chemistry, opaque mineral assemblages, and mafic mineral chemistry, most Lachlan S-type granites formed at lower f_{O_2} conditions than most Lachlan I-type granites. The higher sulfide content of S-type granites and their reduced nature may reflect the sulfur and carbon content of their sedimentary source rocks. The plutonic opaque mineral assemblage is another useful I- and S-type discriminator; however, the Fe-Ti oxide assemblage alone is not.

Application of the magnetite- and ilmenite-series classification, developed from work on Japanese granites, has shown that I- and S-type granites may belong to either the magnetite or ilmenite series. However, the bulk of I-type granites are magnetite series, and the bulk of S-type granites are ilmenite series. The f_{O_2} in a granitic magma may be more important than the nature of the granitic source rocks in controlling the type of associated mineral deposits.

INTRODUCTION

Over the past 20 years, large-scale surveys of opaque minerals in granites have been mainly limited to the work on Japanese granites by Ishihara and coworkers (Tsusue and Ishihara, 1974; Ishihara, 1977, 1981), from which the descriptive magnetite- and ilmenite-series granite classification developed. Concurrently, during work on granites of the Lachlan fold belt, Chappell, White, and coworkers (Chappell and White, 1974; White et al., 1977b; Griffin et al., 1978; White and Chappell, 1983) developed the petrogenetic I- and S-type granite classification. The relationship between these two granite classifications has been a subject of some interest and speculation (Ishihara, 1978, 1981; Takahashi et al., 1980). This systematic survey of opaque mineral assemblages and mafic mineral chemistry, in the same specimens from which the I- and S-type granite classification was developed, was undertaken to clarify this situation. In addition, such a study of mafic silicates and opaque minerals can indicate relative oxidation states within granitic plutons (e.g., Czamanske and Wones, 1973; Mason, 1978) or between granite types (e.g., Czamanske et al., 1981; Wones, 1981). This study of 231 carefully selected granite and xenolith samples (see Fig. 1 and Table 1) was greatly facilitated by an extensive pre-existing body of geologic, petrologic, modal, and chemical data.

BACKGROUND

That portion of the Tasman fold belt in southeastern Australia bounded by the flat-lying Mesozoic and Cenozoic strata of the Murray, Great Artesian, and Sydney basins is known as the Lachlan fold belt. Paleozoic sedimentary rocks in the belt are intruded by Silurian to Devonian granite batholiths that occupy about one-quarter (44000 km^2) of the belt (White et al., 1974). Felsic volcanic rocks, presumably the extrusive equivalents of the granites, are an important component in the Silurian-Devonian sequences. Chappell and White (1974; White and Chappell, 1977, 1983; Chappell, 1978) have proposed a genetic subdivision of the granites—based on many geologic, mineralogic, chemical, and isotopic criteria—into those derived from igneous source rocks (I-type) and those derived from sedimentary source rocks

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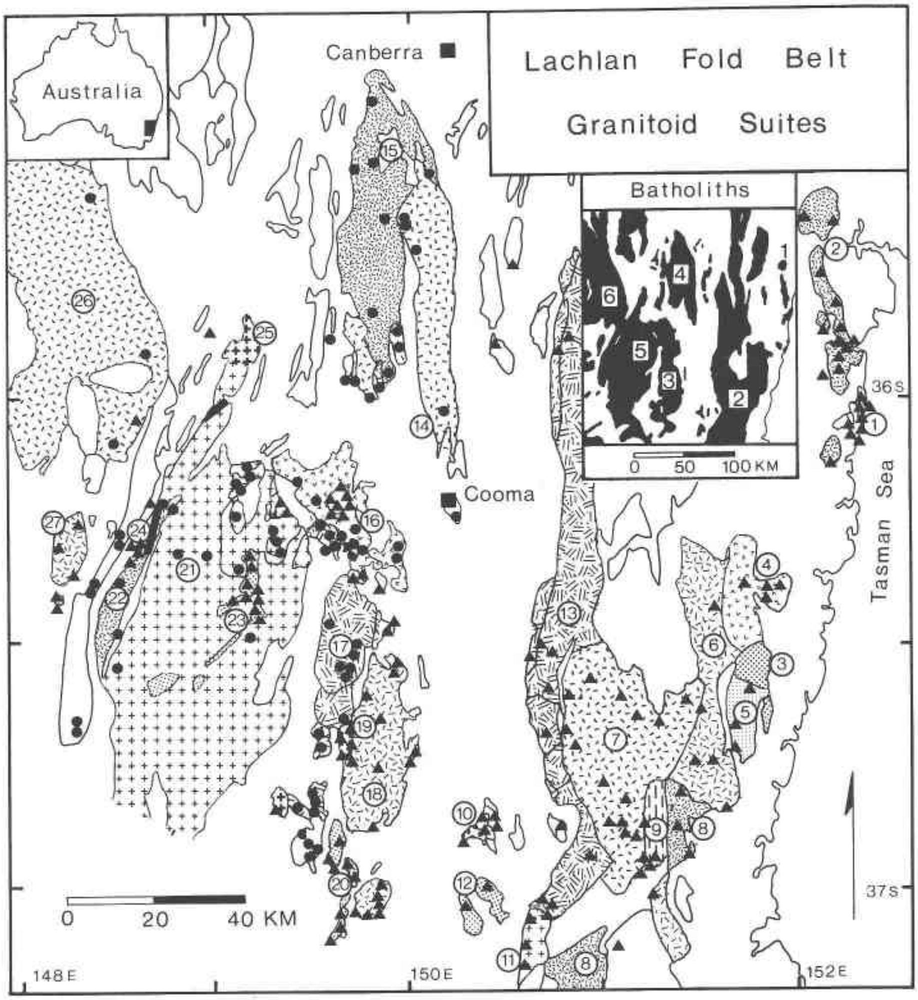

Fig. 1. Location of different I- and S-type granitoid suites and opaque mineral samples (I-type = filled triangles; S-type = filled circles) in part of the Lachlan fold belt. The main batholiths are numbered in the insert on the upper right: (1) Moruya, (2) Bega, (3) Berridale, (4) Murrumbidgee, (5) Kosciusko, (6) Maragle. The following main suites (designated I- or S-type in parentheses) are shown with different patterns and numbered in circles: (1) Bingie Bingie (I), (2) Moruya (I), (3) Mumbulla (I), (4) Cobargo (I), (5) Brogo (I), (6) Kameruka (I), (7) Bemboka (I), (8) Candelo (I), (9) Why Worry (I), (10) Kelvin (I), (11) Tonghi (I), (12) Flat Rock (I), (13) Glenbog (I), (14) Clear Range (I), (15) Shannons Flat (S), (16) Cootralantra (S), (17) Dalgety (S), (18) Buckleys Lake (I), (19) Finister (I), (20) Currowong (I), (21) Bullenbulong (S), (22) The Ghost (S), (23) Jindabyne (I), (24) Gang Gang (I), (25) Boggy Plains (I), (26) Green Hills (S), (27) Khancoban (I). (Based on sources given in Table 1 and unpublished data of B. W. Chappell.)

(S-type). A few pertinent features are that amphibole and accessory primary titanite are restricted to I-type granites. Cordierite, often altered, is of widespread occurrence in S-type granites. Apatite occurs as small acicular crystals in the mafic minerals of I-type granites and as discrete prismatic crystals in S-type granites. The oxidation state of Fe is relatively low in S-type granites (Flood and Shaw, 1975; White et al., 1977b).

The distribution of both I- and S-type granites in the Lachlan fold belt is apparently controlled by a geologic (lower crustal?) feature following a line east of Canberra and Cooma that extends to the south through the Berridale batholith (Fig. 1). No S-type granites are known to the east of this line. S-type granites are dominant to the west, but I-type granites do occur sporadically. Within the Lachlan fold belt, samples were examined from the Moruya, Bega, Berridale, Murrumbidgee, Kosciusko, and Maragle batholiths (Fig. 1 and Table 1). The granitoids have been subdivided, on the basis of geochemical and geologic data, into intrusive suites, the differences between which are thought to reflect differences in their respective source materials.

The restite model of White and Chappell (1977) has been central to various studies on the Lachlan I- and S-type granites (e.g., Compston and Chappell, 1979). Most granites are interpreted to be mixtures of crystallized melt and recrystallized refractory material (restite) that was not melted when the magma formed by partial melting. Most inclusions (microgranitoid enclaves), anhedral mafic mineral aggregates (microxenoliths), and the cores of mantled plagioclase crystals are interpreted as recognizable restite components of granites. An alternative inter-

TABLE 1. Aspects of studied Lachlan fold belt batholiths

Batholiths	Size (km²)	Granite type (%)	Types of samples*	References
Moruya	250	100 I-type	18 G; 1 X	Griffen et al. (1978)
Bega	7700	100 I-type	55 G; 3 X	Chappell and White (1976); Beams (1979, 1980)
Murrumbidgee	1400	99.9 S-type	19 G	Snelling (1960); Joyce (1973a, 1973b)
Berridale	1530	50 I-type 50 S-type	36 G; 6 X 18 G; 6 X	Chappell and White (1976); Williams et al. (1976); White et al. (1977b); White and Chappell (1981)
Kosciusko	4000	10 I-type 90 S-type	25 G 17 G	White et al. (1977b); Wyborn (1977); Hine et al. (1978)
Maragle	3000	10 I-type 90 S-type	14 G 8 G	Wyborn (1977); Wyborn and Chappell (1979)

* Studied for opaque minerals; G = granite sample, and X = xenolith sample.

pretation, proposed by Vernon (1983, 1984), is that the microgranitoid enclaves represent globules of more mafic magma that have mingled and quenched in the host granite magma. Vernon (1984) concluded that microstructural evidence for restite in granites is meager. The subject continues to be controversial, for unequivocal evidence for one of these interpretations versus the others is difficult to obtain.

PETROGRAPHIC AND MINERALOGIC DESCRIPTIONS OF THE OPAQUE MINERALS

The textural features of the opaque minerals described in the following section can be generally classed as "earlier" or "later." Phases that can be identified as being paragenetically "later" are mainly the products of the superimposed processes of replacement, exsolution, oxidation, silicate mineral reactions, and alteration. "Earlier" opaque minerals, which comprise the bulk, by volume, of the opaque minerals present in granites, may reflect direct crystallization from a melt, incorporation of restite or source material, and/or mafic silicate mineral reactions or compositional changes within a magma. The main textural features of the opaque minerals are presented in Figures 2, 3, and 4.

Magnetite

Magnetite generally occurs (1) as inclusions in amphibole and biotite aggregates and in plagioclase cores and (2) as separate grains or aggregates (Fig. 2a). Furthermore, it commonly is associated with ilmenite grains and contains acicular apatite inclusions. Small magnetite inclusions occurring in quartz and plagioclase rims may represent a later generation of magnetite than that contained in mafic silicates. In non–minimum melt granites, e.g., the Jindabyne suite, magnetite lacks fine apatite inclusions and occurs as euhedral grains included in, and as anhedral grains between, quartz and plagioclase grains, rather than in mafic silicate aggregates. In some mafic I-type granites, magnetite forms fine-grained aggregates and also symplectitic intergrowths in the centers of large amphibole clots. Similar magnetite, occurring in amphibole but not in its dendritelike clinopyroxene core, indicates that such magnetite is a product of pyroxene replacement by amphibole.

Ilmenite oxyexsolution lamellae in magnetite are common, and magnetite often has associated grains or partial rims of ilmenite, a texture termed "external grain exsolution" by Buddington and Lindsley (1964). Though ilmenite exsolution lamellae generally occur along magnetite {111} planes (Fig. 2b), ilmenite exsolved along {100} planes (Fig. 2c) was noted in an S-type granite. In this instance, that ilmenite originally exsolved as ülvospinel. Spinel exsolved on magnetite {100} planes (observed only in a few mafic samples) is generally small, erratically distributed in the host grain, and associated with ilmenite exsolution (Fig. 2c).

Magnetite replacement by biotite (Fig. 2d) has been observed in both I- and S-type granites. The presence of unaffected ilmenite exsolution lamellae in optically continuous biotite indicates that the alteration was post–ilmenite oxyexsolution. A second type of alteration, martitization, features irregular hematite lamellae along magnetite {111} planes (Fig. 2e) or alteration rims around magnetite (Fig. 2f). Such alteration occurs mainly in samples that are quite oxidized, as indicated by hematite exsolution in, and titanite overgrowth on and replacement of, ilmenite. Therefore, the alteration is a deuteric process, not a near-surface weathering effect.

Ilmenite

Texturally early ilmenite includes a portion of the ilmenite associated with magnetite grains and ilmenite that occurs separately as anhedral and subrounded inclusions in mafic silicates (Fig. 3a). Texturally later ilmenite includes that formed during oxyexsolution from magnetite (Figs. 2b, 2c) and ilmenite plus rutile laths along biotite cleavages or between biotite grains. Ilmenite exsolution from biotite is more common in S-type granites, frequently being the only opaque mineral present. Later ilmenite is also formed by chlorite or muscovite replacement of biotite. Muscovite alteration has been observed in foliated S-type granites where a biotite-rich area grades laterally within 4 mm into an area of fine-grained muscovite with interstitial ilmenite. An ilmenite-producing reaction extensively developed in the Murrumbidgee batholith S-type granites is that of biotite apparently breaking down to produce ilmenite plus albite and minor K-feldspar (Fig. 3b). Some mafic samples contain fine-grained,

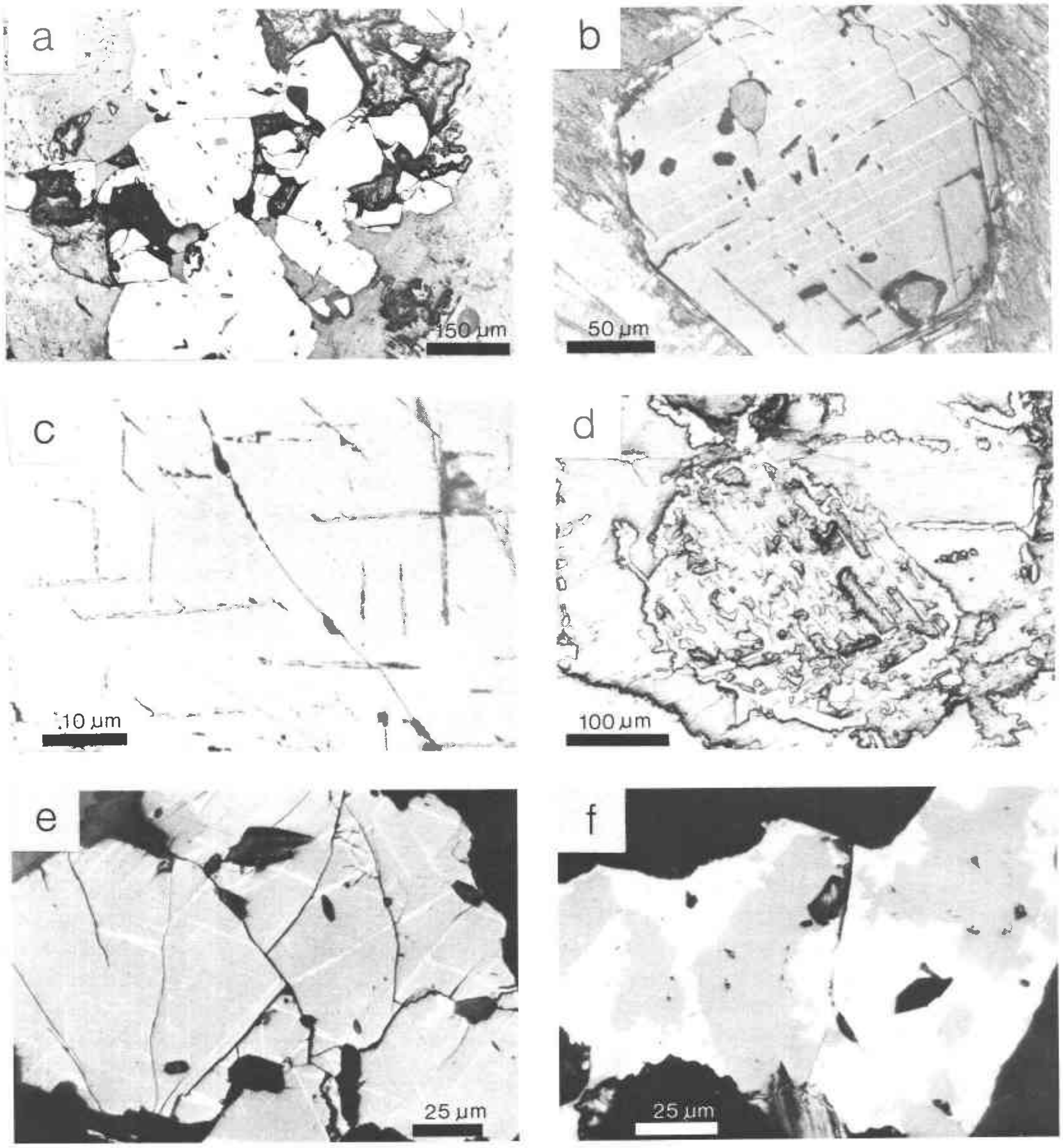

Fig. 2. Abbreviations for Figs. 2, 3, and 4: PRL = plane-polarized reflected light; PTL = plane-polarized transmitted light; XTL = cross-polarized transmitted light; XRL = cross-polarized reflected light; OI = oil immersion.

Magnetite features: (**a**) Aggregate of euhedral to subhedral magnetite grains surrounded by plagioclase and minor biotite (within magnetite are apatite inclusions); I-type, KB-49, PRL. (**b**) Subhedral magnetite with ilmenite oxyexsolution lamellae mainly along one {111} plane; some apatite inclusions are present in the magnetite, I-type, AB-106, partly XRL, OI. (**c**) Ilmenite exsolution lamellae oriented on {100} planes of magnetite indicate that it was exsolved as ülvospinel and subsequently oxidized; the fine black granules at the edges of the ilmenite lamellae are thought to be spinel; S-type, BB-2, PRL. (**d**) Ilmenite lamellae along two presumed {111} planes indicate the earlier presence of a magnetite grain that has been replaced by biotite; I-type, AB-21, PRL. (**e**) An aggregate of magnetite grains containing hematite oxidation lamellae that are thicker and more abundant toward grain edges; the aggregate is bounded by titanite on one side; I-type, BB-110, PRL, OI. (**f**) Magnetite grain largely altered to hematite; the hematite has irregular but sharp contacts with magnetite; I-type, AB-130, PRL, OI.

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aligned, euhedral ilmenite laths included in the cores of dark green amphibole (Fig. 3c). Such laths may have exsolved from a more Ti-rich amphibole or pyroxene. Hematite exsolution lamellae in ilmenite parallel to {0001} (Figs. 3e, 3f) occur only in some I-type granites.

Alteration of ilmenite includes rimming and replacement by titanite (Figs. 3d, 3e), patches of fine-grained hematite plus rutile alteration in ilmenite containing hematite exsolution lamellae (Fig. 3f), and grain-boundary and fracture-related rutile alteration. Altered ilmenites are quite common in I-type granites, whereas in S-type granites, ilmenite is generally fresh, but, if altered, it is to rutile without hematite. These ilmenite alterations are interpreted to result from magmatic or subsolidus pro-

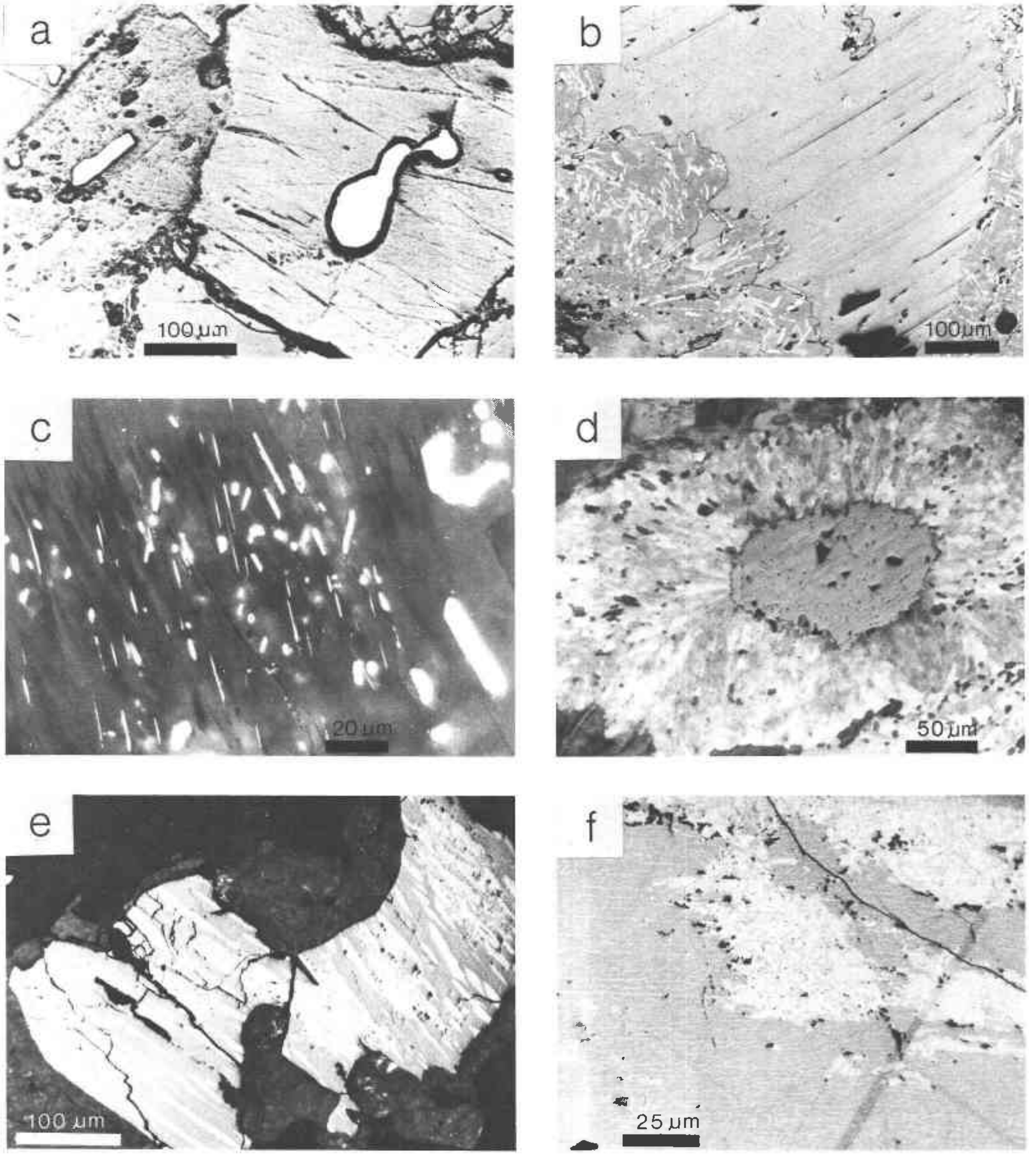

Fig. 3. Ilmenite features: (**a**) Anhedral subrounded ilmenite inclusions in biotite, typical mode of occurrence of ilmenite in S-type granites; KB-45, PRL, OI. (**b**) Biotite surrounded by abundant ilmenite laths in quartz and feldspar; the biotite is embayed and corroded; S-type, MB-15, PRL. (**c**) Amphibole containing fine-grained ilmenite laths in its core; the ilmenites are oriented parallel to the *c* axis of the amphibole and may be due to exsolution; I-type, MG-23, PRL, OI. (**d**) Corroded ilmenite grain with a radiating rim of titanite, possibly formed by inward replacement of ilmenite rather than as an outward overgrowth rim; I-type, CB-61, partly XRL, OI. (**e**) Ilmenite grains containing hematite exsolution lamellae included in a large grain of titanite; I-type, MG-23, PRL, OI. (**f**) Part of a large ilmenite grain containing hematite exsolution lamellae; two twin planes cut across the grain. The ilmenite contains patches of alteration to hematite and rutile; I-type, KB-28, PRL. For key to abbreviations, see Fig. 2.

cesses, not near-surface weathering. Differences in ilmenite alteration in I- and S-type granites and the association in I-type granites between alteration and other indications of oxidizing conditions support this conclusion.

Sulfide minerals

In I-type granites, sulfide minerals (mainly pyrite and lesser chalcopyrite) generally make up less than a few percent of the opaque phases and occur as scattered inclusions in mafic silicates and Fe-Ti oxides (Fig. 4a). In I-type granites, if sulfides are a major phase, they are texturally late, apparently subsolidus phases that occur as dendritelike aggregates veining and rimming mafic minerals (Fig. 4b) or at grain boundaries of silicate minerals. In S-type granites, sulfide minerals are texturally early phases, like ilmenite, and occur as separate grains included mainly in biotite (Figs. 4c, 4d, and 4e) and plagioclase cores. Pyrrhotite, which is more prevalent than pyrite in

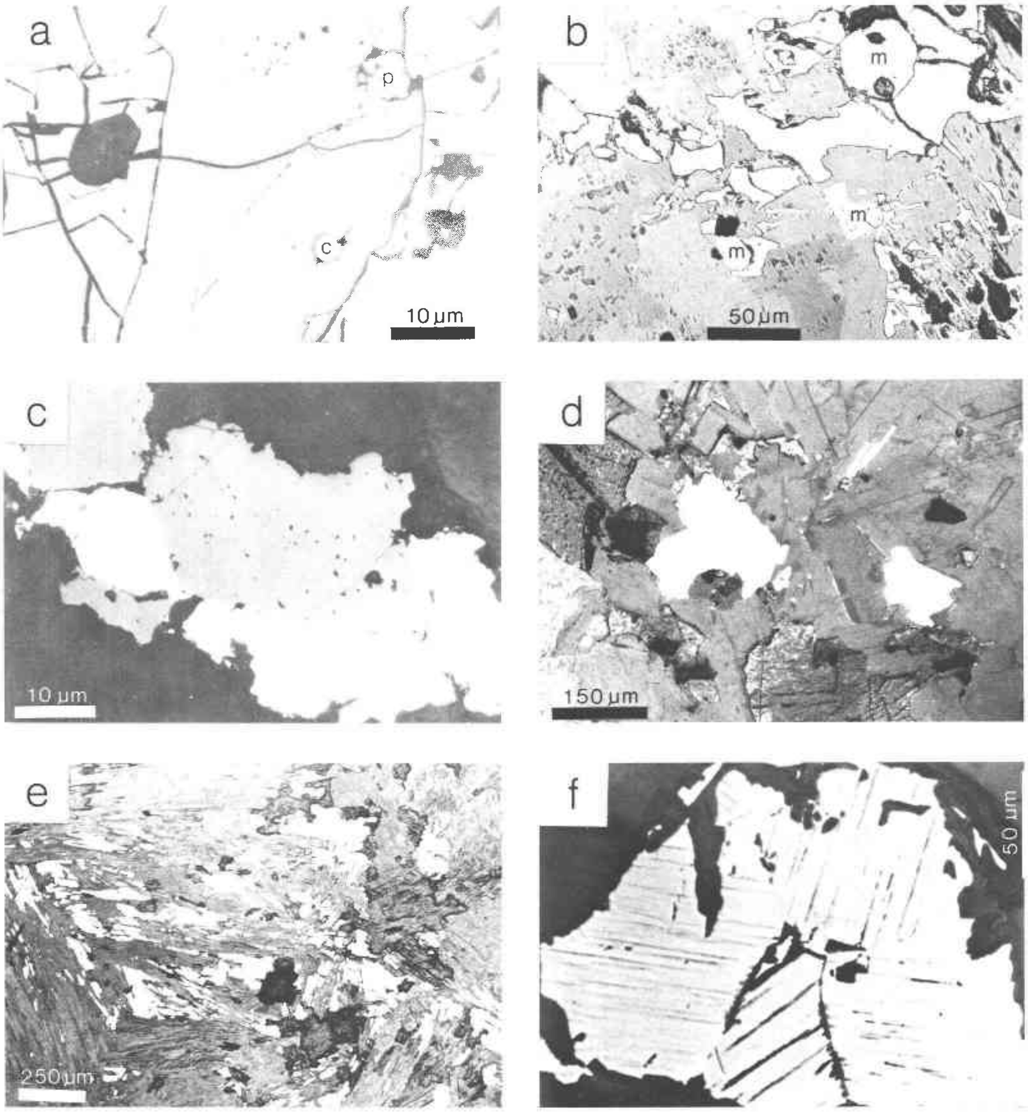

Fig. 4. Sulfide features: (**a**) A composite magnetite-ilmenite grain; the ilmenite contains both pyrite (p) and chalcopyrite (c) inclusions; I-type, BB-10, PRL, OI. (**b**) Pyrite rimming magnetite (m) and replacing amphibole in a veining dendritelike form; I-type, AB-17, PRL. (**c**) Composite ilmenite-pyrite-chalcopyrite aggregate within a biotite aggregate. Chalcopyrite occurs as an interstitial filling between pyrite and ilmenite grains; the sulfide does not appear to replace the ilmenite; S-type, BB-83, PRL, OI. (**d**) Pyrite grains in a biotite aggregate; between some biotite grains there is ilmenite that has exsolved from biotite; BB-36, PRL. (**e**) Aggregate of sillimanite and partly interstitial pyrrhotite in a S-type xenolith; BB-146, PRL. (**f**) Aggregate of pyrrhotite grains with alteration along cleavage partings; S-type, CB-35, PRL. For key to abbreviations, see Fig. 2.

S-type granites, occurs as monomineralic aggregates with other sulfides or with ilmenite. In some samples, pyrite has iron oxide rims and limonite forms pseudomorphs after pyrite; these alterations are thought to be due to near-surface weathering. Pyrrhotite has been noted with a bleaching-type alteration at grain edges and along cleavage partings (Fig. 4f).

Differences in opaque minerals between I- and S-type granites

A fundamental difference between I- and S-type granites is the greater opaque mineral abundance in I-type granites (Fig. 5). I- and S-type granites are generally characterized by the magnetite + ilmenite + minor sulfide assemblage and the ilmenite + sulfide assemblage, respectively (Figs. 6 and 7). I-type granites lacking magnetite are more common than S-type granites containing magnetite. In S-type granites, sulfides are texturally early phases with pyrrhotite being more abundant than pyrite, whereas in I-type granites, sulfides are texturally late phases with pyrite being more abundant (Fig. 6). Within different intrusive suites (for locations, see Fig. 1), there is a general consistency of opaque mineral assemblages. The S-type granites that contain magnetite belong to the

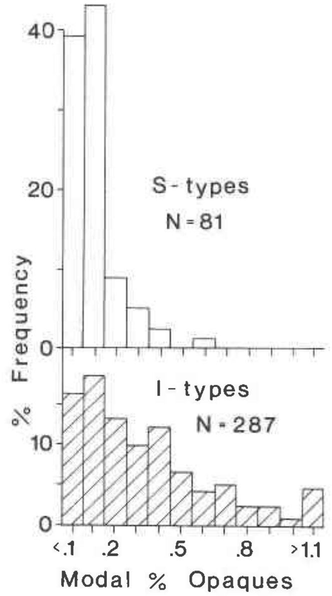

Fig. 5. Histograms of the modal percentage of opaque minerals in S- and I-type granites of the Lachlan fold belt. Based on all available unpublished modal data of B. W. Chappell.

Shannons Flat and Dalgety suites. I-type granites containing mainly ilmenite and sulfides belong to the Mumbulla, Glenbog, Finister, and Gang Gang suites. Most magnetite-free I-type granites within the Maragle batholith are gneissic granites. Whole-rock Fe ratios [$100Fe^{3+}/(Fe^{3+} + Fe^{2+})$] reflect these differences in opaque mineral assemblages (Fig. 8). Although there is considerable overlap, magnetite-bearing S-type granites are more oxidized than the average S-type granite [$100Fe^{3+}/(Fe^{3+} + Fe^{2+}) = 16$], and magnetite-poor I-type granites are mainly more reduced than the average I-type granite [$100Fe^{3+}/(Fe^{3+} + Fe^{2+}) = 30$]. Within individual suites, the magnetite-poor samples are more reduced than the magnetite-bearing samples (Fig. 8), the main exception being the Glenbog suite. Glenbog samples contain common pseudomorphs of biotite plus ilmenite after magnetite (see Fig. 2d), so they were formerly magnetite-bearing.

Differences in opaque mineral assemblages between I- and S-type granites may, like other characteristics of these granite types, image their respective source rocks. Flood and Shaw (1975) have suggested that the reduced character of S-type granites reflects the presence in their metasedimentary source rocks of organically derived carbonaceous material. Shannons Flat and Dalgety, the most silicic S-type granite suites, could be magnetite-bearing because they are restite-deficient suites or because they were derived from more oxidized, possibly graphite-poorer source rocks than the other S-type suites. Similarly, the sulfide-bearing nature of most S-type granites and their slightly higher sulfur content than I-type granites may reflect higher sulfur content in their sedimentary source rocks.

MAFIC MINERAL CHEMISTRY

Mafic mineral chemistry was examined to help delineate differences in intensive variables between I- and S-type granites in a manner similar to other recent studies on intrusive rocks (Czamanske and Mihálik, 1972; Czamanske and Wones, 1973; Czamanske et al., 1977, 1981; Mason, 1978; Wones, 1981). Intrusive suites were selected, on the basis of their opaque mineral assemblages, to represent the range in oxidation state in Lachlan granites. Of the I-type suites, Moruya, a minimum melt suite, is the most oxidized on the basis of hematite exsolution in, and titanite overgrowth rims on, ilmenite. Jindabyne, a non–minimum melt suite, is the next most oxidized on

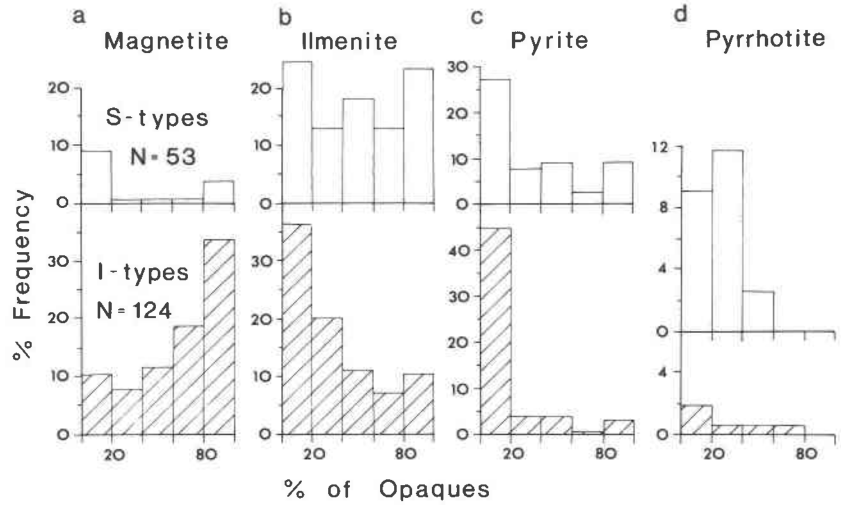

Fig. 6. Histograms of the visually estimated percentages (i.e., not point counted) of magnetite, ilmenite, pyrite, and pyrrhotite in S-type (top histograms) and I-type (lower histograms) granites and xenoliths. Only a portion of the samples plotted in Fig. 5 was studied.

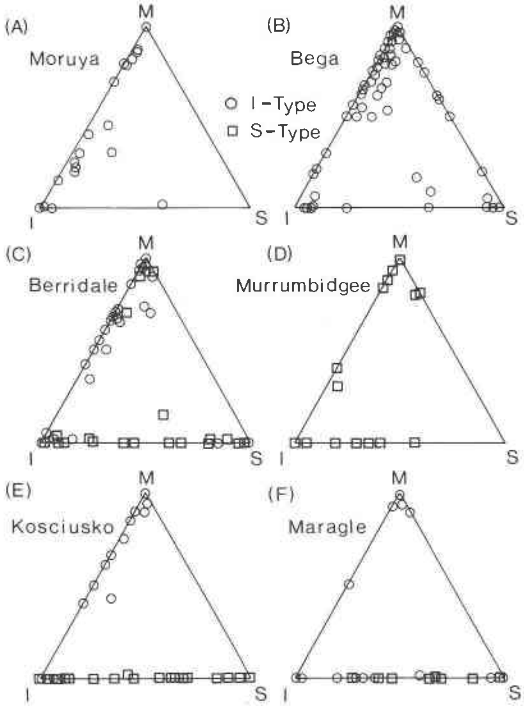

Fig. 7. Triangular diagrams for opaque mineral assemblages in I- and S-type granites of different batholiths of the Lachlan fold belt; ilmenite (I), magnetite (M), and total sulfides (S).

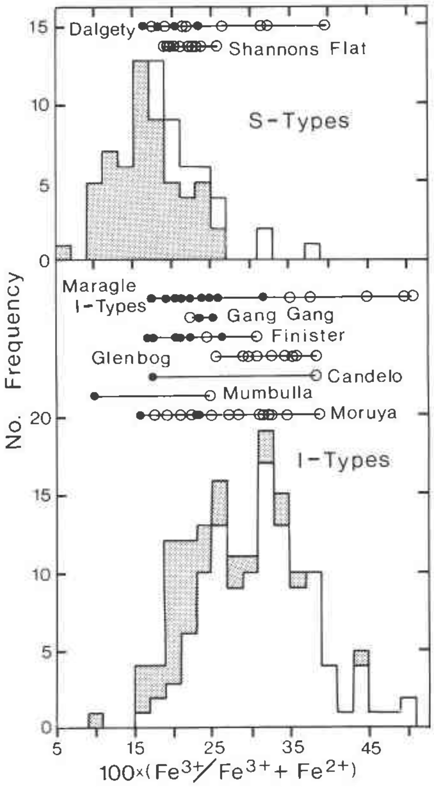

Fig. 8. Histograms of whole-rock $100Fe^{3+}/(Fe^{3+} + Fe^{2+})$ for studied I- and S-type granite samples. In the upper histogram for S-type granites, the shaded area is for samples lacking magnetite and the unshaded areas are for magnetite-bearing samples. Above the histogram are plotted samples from the two magnetite-bearing S-type suites (Dalgety and Shannons Flat); open and closed circles represent samples that contain and lack magnetite, respectively. In the lower histogram for I-type granites, the shaded and unshaded areas represent samples containing less than and greater than 10% magnetite, respectively. Plotted above the histogram are suites with low magnetite contents; filled and open circles correspond to samples containing less than and greater than 10% magnetite, respectively. Magnetite-bearing S-type granites are more oxidized, and magnetite-poor I-type granites are more reduced, than the mean of their respective groups.

the basis of abundant magnetite but lack of other oxidized features, and Finister is the least oxidized, for it is low in opaque phases and is almost magnetite-free. Of the S-type suites, the Shannons Flat and Dalgety suites, which contain magnetite, are thought to be more oxidized than the Cootralantra and Clear Range suites that lack it. Data on 125 ilmenite (446 analyses), 75 magnetite (271 analyses), 128 biotite (536 analyses), and 40 amphibole (206 analyses) grains from 56 samples were obtained by energy-dispersive methods on the Technische Physische Dienst (TPD) electron microprobe at the Australian National University (ANU) (see Reed and Ware, 1975). Subsequently, all acceptable analyses on each grain were averaged and structural formulae calculated. Additional analyses were also made of some sulfide minerals (68) and altered Fe-Ti oxide minerals (236). For the sake of brevity, only average mineral compositions from the most mafic and felsic granites in each suite are presented in Tables 2, 3, and 4, and mineral compositional variations with respect to whole-rock silica content for the suites are summarized in Tables 5 and 6. Descriptions and locations of the studied Lachlan granites and all the individual microprobe analyses have been placed on deposit.[1] For comparison purposes, data from the Finnmarka Complex, a suite for which an oxidizing trend has been documented (Czamanske and Wones, 1973), is included in Tables 5 and 6. A brief summary of the main mafic mineral and chemical features is followed by a discussion of chemical interrelationships between minerals and other implications of the data.

Opaque minerals

Magnetite. As the analyzed magnetites are almost pure Fe_3O_4, inclusion of representative analyses was considered unnecessary. They contain only small amounts of Ti, Al, Mg, and Cr; the highest ülvospinel content is 3.25 mol% with most values being less than 1 mol%. Magnetites in S-type granites and the one analysis from the Finister suite tend to be slightly more enriched in ülvospi-

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[1] The deposited data may be ordered as Document AM-88-367 from the Business Office, Mineralogical Society of America, 1625 I Street, N.W., Suite 414, Washington, D.C. 20006, U.S.A. Please remit $5.00 in advance for the microfiche.

TABLE 2. Representative ilmenite compositions from Lachlan fold belt granite suites

Intrusive suite:	Moruya		Jindabyne		Finister		Shannons Flat		Dalgety		Clear Range		Cootralantra
Sample no.:	34735	34733	31863	31860	27519	30213	20510	20515	27481	27475	20543	20546	27522
Rock SiO_2:	52.3	74.9	60.2	66.7	64.1	66.5	71.9	72.3	68.2	73.5	66.7	68.9	67.6
No. of analyses:	13	6	3	6	4	12	12	15	8	11	12	10	12
TiO_2	46.52	52.82	44.83	50.07	50.75	51.36	49.09	52.17	52.18	48.18	52.72	52.90	53.06
FeO	50.05	30.84	47.64	43.88	44.28	44.77	44.02	42.82	41.71	46.19	42.09	42.10	41.57
MnO	1.77	16.17	5.71	5.22	3.92	3.41	6.18	4.43	5.66	4.46	5.10	4.57	5.60
MgO	0.12	0.03	N.D.	0.03	N.D.	0.04	0.03	N.D.	0.05	0.03	0.16	0.17	0.06
$FeTiO_3$	84.84	64.93	73.67	84.22	88.76	90.31	80.09	90.06	87.03	82.38	88.38	88.50	87.12
Fe_2O_3	10.89	—	13.99	4.45	2.78	2.23	6.55	0.42	0.64	7.90	0.14	—	—
$MnTiO_3$	3.82	34.48	12.34	11.22	8.46	7.31	13.25	9.52	12.14	9.60	10.88	9.73	11.89
$MgTiO_3$	0.46	0.11	—	0.11	—	0.15	0.11	—	0.19	0.11	0.60	0.64	0.22

Note: Al_2O_3, V_2O_3, and CaO contents less than 0.2 wt%. Calculations according to Anderson (1968) except mol% R_2O_3 end members recalculated to 100%; N.D. = not detected.

nel and V + Cr relative to magnetites from the Moruya and Jindabyne suites (Fig. 9 and Table 5). Magnetite in symplectitic intergrowths is enriched in Cr and V relative to other magnetite in the same samples; other magnetite textural types are not distinguishable. Magnetite altered to hematite contains slightly higher Si and Al than unaltered magnetite.

Ilmenite. The composition of ilmenite, the most ubiquitous opaque mineral, varies considerably in the components $FeTiO_3$, Fe_2O_3, and $MnTiO_3$ (Fig. 9, Tables 2 and 5). Ilmenite in the magnetite-free S-type suites contains little or no Fe_2O_3 and has relatively low $MnTiO_3$ and high $FeTiO_3$ contents, whereas in the magnetite-bearing suites, Fe_2O_3 and $MnTiO_3$ contents are higher and $FeTiO_3$ contents correspondingly lower. Within I-type suites, average $MnTiO_3$ and Fe_2O_3 contents of ilmenite decrease and $FeTiO_3$ contents increase in the order Moruya → Jindabyne → Finister. Ilmenite enrichment in

TABLE 3. Representative electron-microprobe analyses and structural formulae for biotites from Lachlan fold belt granite suites

Intrusive suite:	Moruya		Jindabyne		Finister		Shannons Flat*		Dalgety		Clear Range*		Cootralantra	
Sample no.:	34735	34733	31863	31865	27519	30213	20510	20523	27555	27475	20543	20546	27501	27522
Rock SiO_2:	52.3	74.9	60.2	67.2	64.1	66.5	71.9	73.3	67.8	73.5	66.7	68.9	65.9	67.6
No. of analyses:	4	6	6	9	8	8	8	8	8	12	16	8	12	8
SiO_2	36.59	33.85	36.59	35.84	36.46	35.52	35.35	36.03	35.31	35.76	35.58	35.90	35.99	35.37
TiO_2	4.00	3.16	2.96	2.61	2.74	2.68	3.04	3.76	3.42	3.62	2.48	2.94	0.88	3.31
Al_2O_3	14.14	17.18	15.01	15.79	14.41	14.63	16.70	15.18	16.22	15.16	16.15	18.20	18.24	16.99
Fe_2O_3	—	—	—	—	2.25	2.54	1.98	1.86	2.06	2.36	1.42	2.66	0.88	0.89
FeO	19.16	26.38	17.68	20.62	18.37	20.68	20.41	20.37	16.76	19.18	17.94	17.33	18.34	18.42
MnO	N.D.	0.85	0.08	0.38	0.13	0.22	0.28	0.18	0.25	0.18	0.20	0.12	0.16	0.12
MgO	12.39	4.60	12.85	10.59	11.29	9.60	8.24	8.76	10.67	9.21	10.83	8.81	11.36	9.88
CaO	0.05	0.02	0.08	0.04	0.02	0.05	0.02	—	0.06	0.06	0.05	N.D.	0.02	N.D.
K_2O	9.52	9.44	9.62	9.90	9.71	9.44	9.90	9.81	9.44	9.35	9.82	10.00	9.95	9.90
Na_2O	N.D.	0.08	0.03	N.D.	N.D.	0.04	0.11	0.03	0.16	0.20	N.D.	0.02	0.07	0.06
Cl	0.06	0.10	0.08	0.16	0.23	0.34	0.10	0.18	0.44	0.26	0.10	0.15	0.13	0.14
Total	96.57	95.66	94.98	95.93	95.61	95.74	96.13	96.16	94.79	95.34	94.57	96.13	96.02	95.08
Si	5.559	5.374	5.574	5.505	5.587	5.514	5.436	5.536	5.427	5.518	5.486	5.427	5.446	5.428
Al	2.441	2.626	2.426	2.495	2.413	2.486	2.564	2.464	2.573	2.482	2.514	2.573	2.554	2.572
Al	0.090	0.588	0.268	0.363	0.189	0.191	0.462	0.285	0.365	0.275	0.421	0.670	0.699	0.500
Ti	0.457	0.377	0.339	0.301	0.316	0.313	0.352	0.434	0.395	0.420	0.288	0.334	0.100	0.382
Fe^{3+}	—	—	—	—	0.259	0.297	0.229	0.215	0.238	0.274	0.165	0.303	0.100	0.103
Fe^{2+}	2.434	3.502	2.252	2.649	2.354	2.685	2.625	2.617	2.154	2.475	2.313	2.191	2.321	2.364
Mn	—	0.114	0.010	0.049	0.017	0.029	0.036	0.023	0.033	0.024	0.026	0.015	0.021	0.016
Mg	2.806	1.089	2.918	2.425	2.579	2.222	1.889	2.007	2.445	2.119	2.489	1.986	2.563	2.260
$\Sigma(M_1 + M_2)$	5.787	5.670	5.787	5.787	5.714	5.737	5.593	5.581	5.630	5.587	5.702	5.499	5.804	5.625
Ca	0.008	0.003	0.013	0.007	0.003	0.008	0.003	—	0.010	0.010	0.008	—	0.003	—
Na	—	0.025	0.009	—	—	0.012	0.033	0.009	0.048	0.060	—	0.006	0.021	0.018
K	1.845	1.912	1.869	1.940	1.898	1.870	1.942	1.923	1.851	1.841	1.932	1.929	1.921	1.938
$\Sigma(A)$	1.853	1.940	1.891	1.947	1.901	1.890	1.978	1.932	1.909	1.911	1.940	1.935	1.945	1.956
Fe/(Fe + Mg)	0.465	0.763	0.436	0.522	0.503	0.573	0.602	0.585	0.495	0.565	0.499	0.557	0.486	0.522

Note: N.D. = not detected.

* Proportions of Fe^{3+} vs. Fe^{2+} based on wet-chemical analyses of mineral separates from Joyce (1973a); other Fe^{3+} data from Tetley (1978).

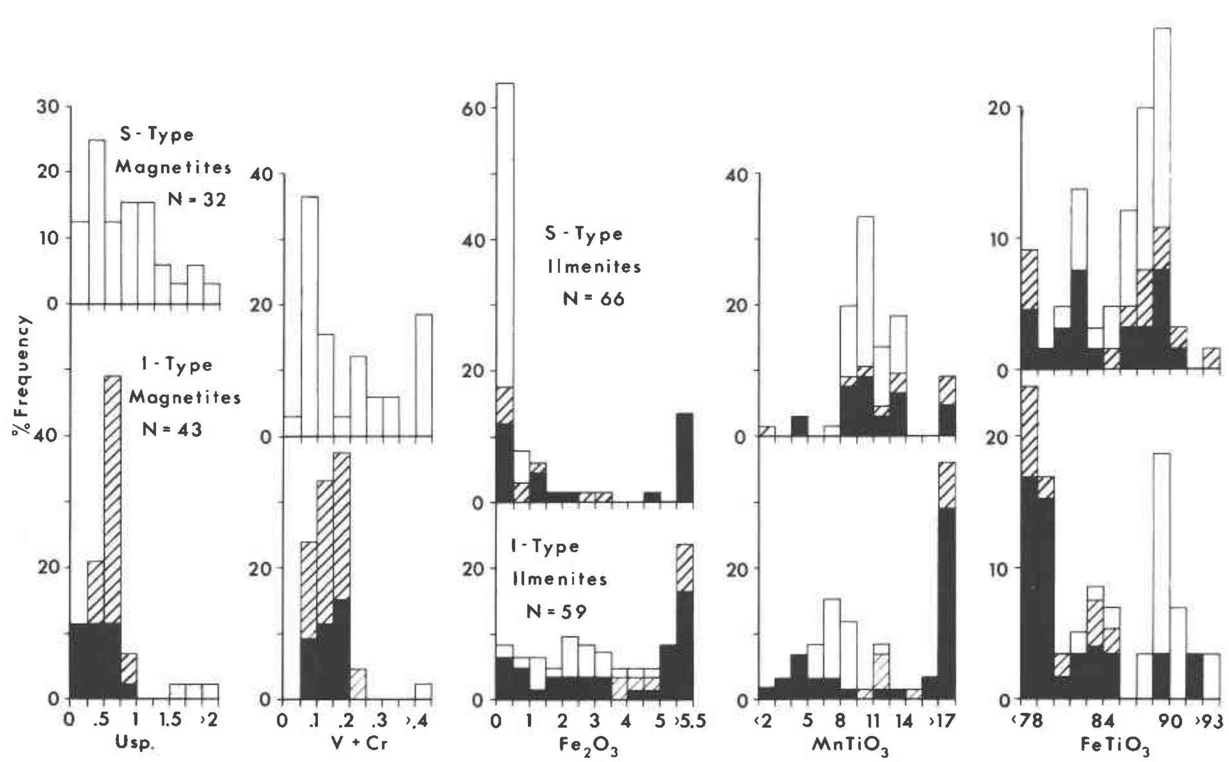

Fig. 9. Histograms of some features of Fe-Ti oxide mineral chemistry. S-type granites are shown in the top group of histograms; for ilmenites, shaded portions are from magnetite-bearing S-type granites, cross-hatched portions are from Dalgety and Shannons Flat samples in which magnetite has not been identified, and unpatterned portions are from magnetite-free S-type granites. I-type granites are shown in the bottom group of histograms; shaded portions are from the Moruya suite, cross-hatched portions are from Jindabyne samples, and unpatterned portions are from the Finister suite. *N* = number of grains.

TABLE 4. Representative electron-microprobe analyses and structural formulae for amphiboles from Lachlan fold belt granite suites

Intrusive suite:	Moruya		Jindabyne		Finister	
Sample no.:	34735	34728	31863	34366	27519	30213
Rock SiO_2:	52.3	67.2	60.2	65.4	64.1	66.5
No. of analyses:	33	9	13	9	11	10
SiO_2	45.39	46.66	46.79	47.67	48.49	45.75
TiO_2	2.10	0.88	1.00	0.56	0.67	1.02
Al_2O_3	8.71	7.18	7.98	6.82	6.08	7.86
FeO	15.08	18.08	15.44	16.26	16.96	19.68
MnO	0.26	0.62	0.56	0.66	0.50	0.42
MgO	12.53	11.30	12.99	12.64	12.22	10.14
CaO	12.16	11.56	11.15	11.15	11.20	10.93
K_2O	0.64	0.58	0.36	0.60	0.44	0.60
Na_2O	N.D.*	1.11	0.86	0.94	0.78	0.97
Cl	0.04	0.06	0.12	0.13	0.04	0.08
Total	96.91	98.03	97.25	97.43	97.38	97.45
Si	6.767	6.984	6.945	7.097	7.214	6.928
Al	1.233	1.016	1.055	0.903	0.786	1.072
Al	0.297	0.251	0.341	0.294	0.280	0.330
Ti	0.235	0.099	0.112	0.063	0.075	0.116
Mg	2.785	2.521	2.874	2.806	2.710	2.289
Fe^{2+}	1.683	2.129	1.673	1.838	1.935	2.265
Fe^{2+}	0.197	0.134	0.244	0.187	0.175	0.227
Mn	0.033	0.079	0.070	0.083	0.063	0.054
Ca	1.770	1.787	1.686	1.730	1.762	1.719
Ca	0.172	0.067	0.087	0.049	0.024	0.054
Na	—	0.322	0.249	0.271	0.225	0.285
K	0.122	0.111	0.068	0.114	0.084	0.116
Σ(A)	0.294	0.500	0.403	0.434	0.332	0.455
Fe/(Fe + Mg)	0.403	0.473	0.400	0.419	0.438	0.521

* N.D. = not detected.

$MnTiO_3$ component is greatest (23 to 33 mol%) for the most siliceous samples of the Moruya and Shannons Flat suites. Although there is some variability in composition between individual ilmenite grains in a sample, no evidence for chemical differences between different textural types of ilmenite was noted. In the rare instances where exsolutions were sufficiently coarse, exsolutions of ilmenite from biotite and from magnetite were found to be chemically indistinguishable from earlier ilmenite in the same samples.

Alteration products of ilmenite are generally so fine-grained as to be beyond the resolution of the microprobe. Relative to fresh grains, analyses of different points on I-type ilmenites altered to rutile + hematite (Fig. 3f) indicate a large increase in Si and Al, a decrease of 80% in the amount of Mn present, and variation between points in Ti and Fe concentrations. Alteration of ilmenite to rutile alone is characterized by almost complete loss of Fe and Mn, a change that is gradational from unaltered domains of the ilmenite grain. Ilmenite alteration to rutile in S-type granites is similar, except contacts between fresh ilmenite and rutile may be sharp.

Sulfide minerals. Sulfide minerals were not extensively analyzed. For pyrrhotite in S-type granites, the mole fraction of FeS in the system FeS-S_2 was found to range from 0.939 to 1 and minor (<0.5%) amounts of Ni, Cu, and Zn are present. Pyrite in S-type granites was found to contain traces (<0.5%) of Ni, Zn, and greater (0.5 to 2.5%)

TABLE 5. Variations in Fe-Ti oxide and biotite chemistry

		I-type granites			Magnetite-bearing S-type granites		Magnetite-free S-type granites		
	Intrusive suite:	Moruya	Jindabyne	Finister	Shannons Flat	Dalgety	Clear Range	Cootralantra	Finnmarka*
	No. of samples:	12	9	7	5	9	5	9	6
	Rock SiO_2 range:	52.31–74.90	60.18–66.79	64.11–66.53	70.95–75.69	66.10–73.48	66.28–68.71	56.8–67.82	56.92–74.26
Magnetite	Ülvospinel	0.38 ± 0.16 ir. dec. tr.	0.84 ± 0.58 no tr.	3.28 one grain	0.84 ± 0.51 inc. tr. (0.26–1.45)	0.79 ± 0.41 ir. inc. tr.	—	—	0.998 ± 0.463 dec. tr.
	Cr + V	0.131 ± 0.044 dec. tr. (0.183–0.065)	0.143 ± 0.042 ir. dec. tr.	0.937 one grain	0.170 ± 0.075 inc. tr. (0.067–0.227)	0.204 ± 0.168 ir. inc. tr.	—	—	0.0287 ± 0.031 dec. tr.
Ilmenite	$FeTiO_3$	78.28 ± 7.20 str. ir. dec. tr.	77.55 ± 4.72 ir. inc. tr.	89.00 ± 1.75 no tr.	79.13 ± 8.32 dec. tr.	84.29 ± 4.80 ir. dec. tr.	87.57 ± 1.36 sl. inc. tr.	86.56 ± 3.11 no tr.	59.70 ± 27.90 str. dec. tr.
	Fe_2O_3	5.24 ± 4.48 str. ir. dec. tr. (12.96–0.08)	7.47 ± 4.46 ir. dec. tr. (14.08–4.39)	2.44 ± 0.57 sl. ir. dec. tr.	2.54 ± 3.51 no tr.	3.68 ± 3.58 no tr.	0.10 ± 0.14 no tr.	0.50 ± 1.07 no tr.	5.10 ± 0.79 sl. dec. tr.
	$MnTiO_3$	15.90 ± 8.99 str. ir. inc. tr. (3.80–33.26)	14.69 ± 3.58 no tr.	7.87 ± 1.47 sl. ir. dec. tr.	17.18 ± 10.25 inc. tr.	11.02 ± 5.82 no tr.	11.10 ± 1.51 ir. dec. tr.	11.10 ± 1.56 no tr.	35.00 ± 28.76 str. inc. tr. (7.40–64.80)
Biotite	Si	5.423 ± 0.075 str. dec. tr. (5.456–5.277)	5.431 ± 0.045 ir. dec. tr.	5.518 ± 0.049 no tr.	5.443 ± 0.089 ir dec. tr.	5.434 ± 0.046 no tr.	5.430 ± 0.031 dec. tr.	5.437 ± 0.033 no tr.	5.930 ± 0.27 str. inc. tr. (5.598–6.237)
	^{VI}Al	0.146 ± 0.174 ir. inc. tr.	0.144 ± 0.106 ir. inc. tr.	0.224 ± 0.073 no tr.	0.424 ± 0.098 no tr.	0.353 ± 0.151 no tr.	0.561 ± 0.104 ir. inc. tr.	0.490 ± 0.154 no tr.	0.022 ± 0.020 inc. tr. (0.000–0.063)
	Ti	0.411 ± 0.053 ir. dec. tr.	0.331 ± 0.60 ir. dec. tr.	0.272 ± 0.059 ir. dec. tr.	0.354 ± 0.051 no tr.	0.385 ± 0.044 no tr.	0.347 ± 0.056 sl. inc. tr.	0.360 ± 0.114 no tr.	0.311 ± 0.155 str. dec. tr.
	Mn	0.045 ± 0.033 str. inc. tr. (0.000–0.113)	0.041 ± 0.013 inc. tr.	0.021 ± 0.011 ir. inc. tr.	0.041 ± 0.032 no tr.	0.026 ± 0.007 sl. dec. tr.	0.022 ± 0.004 no tr.	0.020 ± 0.006 no tr.	0.202 ± 0.112 str. inc. tr. (0.033–0.321)
	Fe^{2+} total	2.871 ± 0.386 str. inc. tr. (2.463–3.514)	2.605 ± 0.190 ir. inc. tr. (2.290–2.677)	2.793 ± 0.162 ir. sl. inc. tr.	2.953 ± 0.187 no tr.	2.712 ± 0.235 ir. sl. inc. tr.	2.540 ± 0.106 ir. sl. inc. tr.	2.446 ± 0.127 ir. sl. inc. tr.	1.982 ± 0.781 str. dec. tr. (3.335–1.351)
	Mg	2.136 ± 0.515 str. dec. tr. (2.752–1.068)	2.492 ± 0.231 ir. dec. tr. (2.862–2.379)	2.475 ± 0.230 no tr.	1.863 ± 0.236 ir. dec. tr.	2.191 ± 0.154 no tr.	2.140 ± 0.206 ir. dec. tr.	2.357 ± 0.229 ir. dec. tr.	3.221 ± 0.788 str. inc. tr. (1.845–3.898)
	100Fe/(Fe + Mg)	57.59 ± 9.15 str. inc. tr. (47.23–76.69)	51.24 ± 4.16 ir. inc. tr.	53.06 ± 3.59 no tr.	61.35 ± 4.54 no tr.	55.25 ± 3.66 no tr.	54.32 ± 2.96 inc. tr.	50.99 ± 3.42 no tr.	38.10 ± 15.06 str. dec. tr. (64.38–25.74)
	Σ Octahedral site	5.562 ± 0.071 no tr.	5.613 ± 0.042 no tr.	5.801 ± 0.063 inc. then dec. tr.	5.642 ± 0.041 no tr.	5.650 ± 0.044 no tr.	5.623 ± 0.081 ir. dec. tr.	5.661 ± 0.074 inc. then dec. tr.	5.707 ± 0.032 sl. inc. tr.
	Σ X site	1.902 ± 0.042 sl. inc. tr.	1.891 ± 0.020 sl. inc. tr.	1.880 ± 0.037 sl. inc. tr.	1.933 ± 0.049 dec. tr.	1.913 ± 0.019 no tr.	1.952 ± 0.015 ir. dec. tr.	1.931 ± 0.036 no tr.	1.890 ± 0.027 sl. inc. tr.

Note: Given are the mean ± 1 standard deviation in atoms and the trend exhibited by the data in relationship to increasing whole-rock SiO_2; if there is a notable trend, the range is also given enclosed in brackets. Abbreviations: ir = irregular; st. = strong; sl. = slight; inc. = increasing; dec. = decreasing; tr. = trend.

* Based on data of Czamanske and Mihálik (1972) for Fe-Ti oxides and Czamanske and Wones (1973) for biotite.

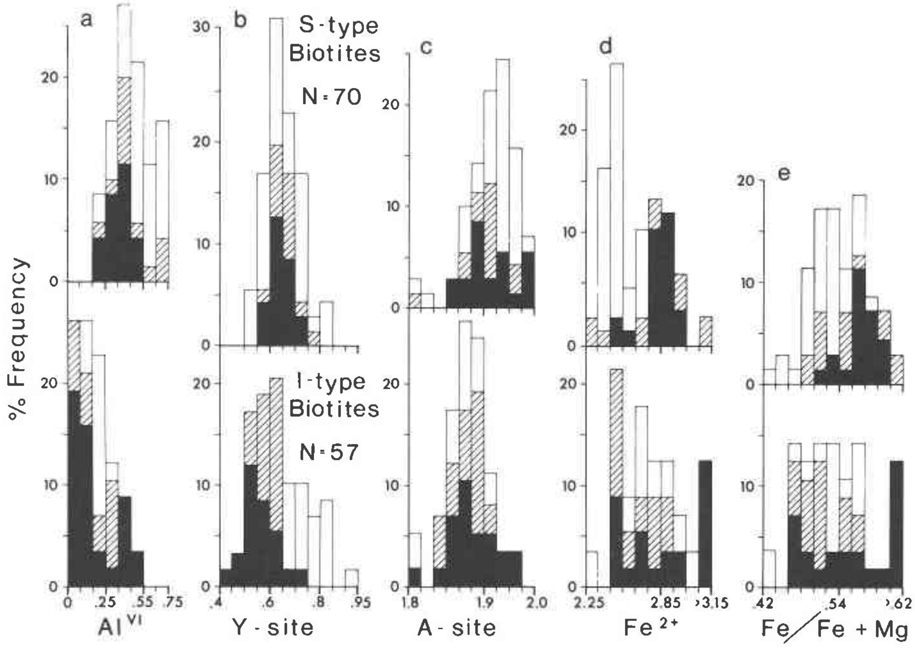

Fig. 10. Histograms of some features of biotite chemistry. S-type granites are shown in the top grouping of histograms; shading types for different suites as in Fig. 9. *N* = number of grains.

amounts of Co. One chalcopyrite grain contained 6% Zn, but all others lacked Zn; Ni and Co were not detected.

Mafic silicates

Biotite. A distinctive feature of biotites in S-type granites is their "foxy" red color, in contrast to the light brown to dark brown or black color of biotite in I-type granites (White et al., 1977b). Biotites in S-type granites contain appreciable amounts of ^{VI}Al and low Fe^{3+} (Tables 3 and 5, Fig. 10), features attributed to their coexistence with muscovite and/or other Al-rich minerals (garnet, sillimanite) and the reduced nature [low 100(Fe^{3+})/(Fe^{3+} + Fe^{2+})] of the host rock (Chappell, 1966; Joyce, 1973a). Biotite ^{VI}Al content does not correlate well with whether biotite occurs alone or coexists with amphibole or muscovite, and S-type granites have somewhat higher biotite ^{VI}Al/^{IV}Al (Fig. 11). Biotites in S-type granites exhibit a small range in total Fe calculated as Fe^{2+} and Fe/(Fe + Mg) in contrast to the greater range for these values in I-type granites, even within individual suites. Within the Moruya, Jindabyne, and Clear Range suites, biotite Fe/(Fe + Mg) increases with increasing host-rock silica content, whereas there is little variation in the other suites (Tables 3 and 5).

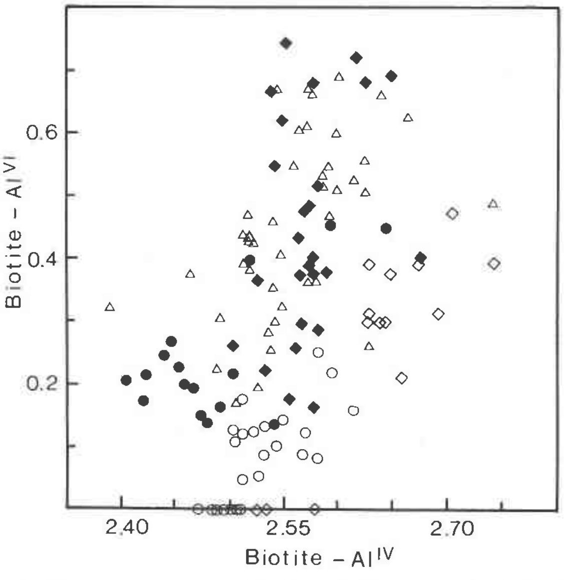

Fig. 11. Plot of ^{IV}Al vs. ^{VI}Al for biotites coexisting with (○) amphibole, (●) amphibole in Finister suite, (◇) biotite alone in I-types, (△) biotite alone in S-types, (◆) muscovite in S-types.

Mason (1978) documented two contrasting types of zoning from core to rim in biotite and amphibole crystals from intrusive rocks of the Western Highlands of Papua New Guinea: increasing Fe/(Fe + Mg) with increasing ^{VI}Al and decreasing Fe/(Fe + Mg) with increasing ^{VI}Al. These trends were interpreted as indicating melt evolution to more reducing conditions and melt evolution to more oxidizing conditions, respectively. Though most biotites in the Lachlan granites were found to show some zoning, zoning in both ^{VI}Al and Fe/(Fe + Mg) was detected in only 6 of the 19 samples found to contain zoned biotites. These 6 samples were from the Shannons Flat (2), Clear Range (1), Jindabyne (2), and Cootralantra (1) suites. Consistent differences from core to rim were a decrease in Ti and in total Fe calculated as Fe^{2+} relative to Mg [decreasing Fe/(Fe + Mg)] accompanied by an increase in ${}^{VI}Al$. Other biotites decreased in ${}^{VI}Al$ and Ti from core to rim with only slight irregular variation in Fe/(Fe + Mg).

Amphibole. Amphibole, which occurs only in relatively mafic I-type granites, was found not to exhibit distinct chemical differences between different suites (Table 4). The main variation in amphibole chemistry with increasing rock SiO_2 (Tables 4 and 6) is an increase in total Fe calculated as Fe^{2+}, accompanied by a decrease in Mg [increasing Fe/(Fe + Mg)] for all suites. There is also an increase in ${}^{IV}Al$ and Mn with increasing rock SiO_2 for Moruya amphiboles but the opposite trend for Jindabyne and Finister amphiboles. The analyses show a decrease in average ${}^{IV}Al$ and Mg and an increase in mean Si, ${}^{VI}Al$, Fe^{2+}, and Fe/(Fe + Mg) of amphiboles in the order Moruya → Jindabyne → Finister (Tables 4 and 6).

Chemical zoning in amphibole, as summarized in the previous section on biotite, can be related to changes in the oxidation state of granitic magmas (Mason, 1978). Such zoning is present in each of the I-type suites; however, it is typically not regular within grains or between different grains in the same sample. A consistent zoning feature is decreasing Ti content toward amphibole rims, but zoning in terms of total Fe calculated as Fe^{2+} and ${}^{IV}Al$, suggested to be important by Mason (1978), is less common. Some samples from the Moruya suite and a sample from the Bingie Bingie suite were found to have zoning trends of decreasing total Fe and ${}^{VI}Al$ from core to rim (Fig. 12). Jindabyne amphiboles were found to be unzoned or irregularly zoned in Fe^{2+} and ${}^{IV}Al$. Finister suite amphiboles varied considerably in core-to-rim zoning trends that include decreasing ${}^{IV}Al$ and little variation in Fe^{2+}, decreasing ${}^{IV}Al$ and increasing Fe^{2+}, and increasing ${}^{IV}Al$ and Fe^{2+}, then decreasing ${}^{IV}Al$ with constant Fe^{2+}.

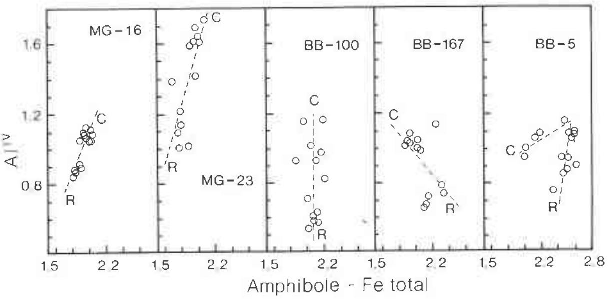

Fig. 12. Zoning of ${}^{IV}Al$ vs. total Fe as Fe^{2+} in amphibole from the Moruya (MG-16), Bingie Bingie (MG-23), and Finister (BB-100, 167, 5) suites. Point analysis (O), grain core (C) and rim (R) positions, and visually estimated trends for the data (dashed lines) are plotted.

f_{O_2} conditions during crystallization of I- and S-type granites

Unfortunately, although opaque minerals and mafic silicates in granitic rocks may reflect the original magma and also the source region, they may also change significantly during the history of a given magma. A number of recent papers (Burnham and Ohmoto, 1980; Wones, 1981) have discussed and quantified in general terms the differences in intensive parameters between I- and S-type granites. For this reason and as subsolidus recrystallization makes quantitative reconstruction of intensive parameters difficult, a detailed discussion of this subject is considered unwarranted. Some features that do indicate the relative oxidation state of these two granite types are as follows:

1. The oxidation state of Fe is relatively low in S-type versus I-type granites (Fig. 8) (Flood and Shaw, 1975; White et al., 1977b; Chappell, 1978), a conclusion that is substantiated by the opaque mineral assemblages in the granites (Figs. 6 to 7).

2. Titanite is a relatively common accessory mineral in I-type granites but absent, except as a subsolidus alteration phase, in S-type granites. Where it has been observed in studied samples, notably the Moruya suite, it commonly forms reaction rims around ilmenites, which contain hematite exsolutions and hematite + rutile altera-

TABLE 6. Variations in amphibole chemistry in some Lachlan fold belt I-type granite suites

Intrusive suite:	Moruya	Jindabyne	Finister	Finnmarka*
No. of samples:	6	4	5	2
Rock SiO_2 range:	52.31–67.18	60.18–65.43	64.11–66.53	56.92–62.96
${}^{IV}Al$	1.041 ± 0.212 ir. inc. tr.	0.986 ± 0.191 sl. ir. dec. tr.	0.906 ± 0.122 dec. tr.	0.894 ± 0.282 str. dec. tr.
${}^{VI}Al$	0.116 ± 0.065 no tr.	0.199 ± 0.022 sl. dec. tr.	0.240 ± 0.041 sl. dec. tr.	0.062 ± 0.037 inc. tr.
Ti	0.124 ± 0.056 ir. dec. tr.	0.066 ± 0.030 dec. tr.	0.087 ± 0.023 ir. inc. tr.	0.134 ± 0.057 dec. tr.
Fe	2.031 ± 0.214 ir. inc. tr.	2.104 ± 0.154 ir. inc. tr.	2.218 ± 0.173 ir. inc. tr.	2.141 ± 0.781 str. dec. tr.
Mg	2.747 ± 0.255 ir. dec. tr.	2.799 ± 0.220 sl. dec. tr.	2.612 ± 0.201 ir. dec. tr.	2.713 ± 0.695 str. inc. tr.
Mn	0.055 ± 0.016 ir. sl. inc. tr.	0.101 ± 0.034 ir. dec. tr.	0.050 ± 0.013 ir. sl. dec. tr.	0.037 ± 0.042 sl. inc. tr.
100Fe/(Fe + Mg)	43.34 ± 4.94 ir. inc. tr.	42.92 ± 3.33 ir. inc. tr.	46.25 ± 3.96 ir. inc. tr.	41.74 ± 15.19 str. dec. tr.

Note: Given are the mean ± 1 standard deviation in atoms and the trend exhibited by the data in relationship to increasing whole-rock SiO_2. Abbreviations: ir. = irregular; inc. = increasing; tr. = trend; sl. = slight; dec. = decreasing; str. = strong.

* From data of Czamanske and Wones (1973).

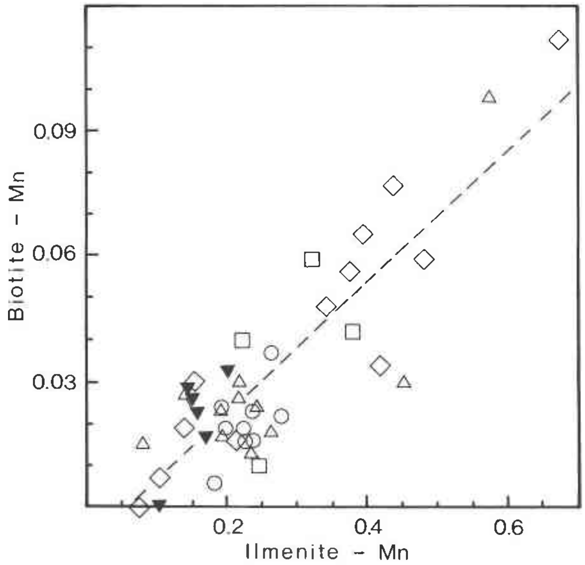

Fig. 13. Plot of Mn content of biotite vs. Mn content of ilmenite with calculated regression line; each point represents a rock sample. Suite symbols: (◇) Moruya; (□) Jindabyne; (▼) Finister; (△) magnetite-bearing S-types; (○) magnetite-free S-types.

tion; these samples also contain magnetite with hematite alteration. Similar features described from the Finnmarka complex (Czamanske and Wones, 1973) have been interpreted as indicating relatively oxidized conditions.

3. Based on experimental work of Buddington and Lindsley (1964), compositions of Fe-Ti oxides have been widely employed to give a quantitative measure of f_{O_2} and *T*. Unfortunately, analyzed magnetites have re-equilibrated at low temperatures and are exceptionally low in ülvospinel. The consistent partitioning of Mn between ilmenite and biotite (Fig. 13), analogous to that found for the Pliny Range intrusive complex (Czamanske et al., 1977), suggests that ilmenite compositions may reflect magmatic f_{O_2} conditions better than magnetite compositions. With increasing f_{O_2}, ilmenite becomes more enriched in Fe_2O_3 component (Buddington and Lindsley, 1964) and may become very enriched in $MnTiO_3$ (Czamanske and Mihálik, 1972). Calculation of the mole fraction $Fe_2O_3/(Fe_2O_3 + FeTiO_3)$ in ilmenites, assuming $MnTiO_3$ to be inert, indicates that ilmenite ranges from a more oxidized Ilm_{78} (Moruya suite), through Ilm_{84} (Jindabyne suite), Ilm_{96} (Finister suite), and Ilm_{91} (magnetite-bearing S-types), to a more reduced Ilm_{99} (magnetite-free S-types).

4. Particular biotite and amphibole compositional variations in the Finnmarka complex (Czamanske and Wones, 1973), in Japanese granitoid rocks (Czamanske et al., 1981), and within individual grains or samples of mineralized and unmineralized intrusive suites (Mason, 1978) have been suggested as indictive of suite or magma evolution to more oxidizing conditions. In a general way, lower Fe^{3+} content of biotite separates from S-type granites of the Berridale batholith (Tetley, 1978), Murrumbidgee batholith (Joyce, 1973a), and the New England batholith (Chappell, 1966) indicate the more reduced nature of these granites. Biotite microprobe analyses of this study indicate somewhat higher Fe/(Fe + Mg) values for S-type versus I-type granites (Fig. 10), but there is considerable overlap. Within studied S- and I-type granite suites, biotite exhibits a trend of increasing Fe/(Fe + Mg) with increasing host-rock silica content (Tables 3 and 5). This trend is considered usual in "calc-alkaline" rock suites (Nockolds, 1947; Larsen and Draisen, 1950) and has been suggested to indicate evolution to more reducing conditions. Consistent trends of increasing ^{VI}Al and decreasing Fe/(Fe + Mg) from core to rim in biotites from the Shannons Flat, Clear Range, Cootralantra, and Jindabyne suites are the compositional trends considered by Mason (1978) as indicative of melt evolution to more oxidizing conditions. These trends may be subsolidus features, possibly indicating biotite re-equilibration with oxidized deuteric fluids. Amphibole, though of restricted distribution in studied samples, exhibits the same reducing trend as biotite, that is, increasing Fe/(Fe + Mg) with increasing host-rock silica (Tables 4 and 6). Within individual samples, zoning of Fe^{2+} and ^{VI}Al in amphiboles, although somewhat irregular, exhibits trends in the Moruya and Bingie Bingie suites that suggest relatively high initial f_{O_2} in the melt and evolution to more oxidizing conditions. Trends in the Jindabyne and Finister suites suggest relatively low initial f_{O_2} in the melt. Such an interpretation of the amphibole zoning is consistent with other features of these suites described above.

The data collected in this study are consistent with the conclusion of Wones (1981) that the quartz-fayalite-magnetite (QFM) buffer can probably be taken as the dividing line between oxidized magnetite-bearing granites and reduced ilmenite-bearing granites. Most I-type granites formed under f_{O_2} conditions greater than QFM, though a wide range of f_{O_2} conditions is indicated by the existence of magnetite-free I-type granites. Most S-type granites formed under f_{O_2} conditions lower than QFM though magnetite-bearing S-type probably formed under conditions approximating QFM.

Granite classifications and associated mineral deposits

The magnetite- and ilmenite-series classification of Japanese granites (Ishihara, 1977, 1978, 1981) is a descriptive twofold division based on the accessory minerals magnetite and ilmenite. Recent comparisons of this petrologic scheme with the genetic I- and S-type granite classification (Takahashi et al., 1980; Ishihara, 1981) have concluded that the magnetite series in Japan can be correlated with I-type granites and that the ilmenite series in Japan is composed of both I- and S-type granites. This study has indicated that in the Lachlan fold belt, however, I-type granites as well as S-type granites include both magnetite-series and ilmenite-series granites. Nevertheless, the majority of S-type granites belong to the ilmenite series, and the majority of I-type granites belong to the magnetite series. It should be noted, however, that the trends documented in this study for Lachlan granites of increasing Fe/(Fe + Mg) with increasing host-rock silica for both biotite and amphibole are the same as those documented by Czamanske et al. (1981) for ilmenite-series suites in Japan. In contrast, magnetite-series suites in Japan were found to be characterized by trends of decreasing Fe/(Fe + Mg) with increasing host-rock silica. This study and also that of Bowden et al. (1984) indicate that petrologic granite classification schemes based on specific minerals, such as the magnetite- and ilmenite-series scheme of Ishihara (1977) are less useful than other types of petrologic and chemical classifications.

The suggestion has been made that particular types of ore deposits are associated with I- and S-type granites (Chappell and White, 1974; White et al., 1977a) and with magnetite- and ilmenite-series granites (Ishihara, 1977, 1978, 1981). Tin deposits are considered to be associated with S-type and ilmenite-series granites and molybdenum deposits and porphyry copper deposits with I-type and magnetite-series granites. The association of tin deposits with S-type and ilmenite-series granites has been attibuted, in part, to the higher Sn content of sedimentary source rocks. Burnham (1979) has attributed porphyry copper deposits, in part, to the higher Cu abundance in I-type sources, such as metamorphosed oceanic basalt or lower-crustal amphibolites. Because of the potential of Sn to be accommodated in titanite and magnetite, common restite phases in I-type granites, White et al. (1977a) suggested that a minimum melt from an igneous source should be low in Sn. Similarly, Ishihara (1978) recognized the high Sn content of titanite and magnetite and suggested that Sn in magnetite-series granites is present as Sn^{4+}, which substitutes for Ti^{4+} and Fe^{3+} in these minerals, whereas in the more reduced ilmenite-series granites, Sn is present as Sn^{2+}, which is concentrated in the melt phase. The texturally early (restite?) and ubiquitous sulfide phases in S-type granites may help explain the less common occurrence of base-metal deposits with this granite type. Chalcophile elements (Pb, Zn, Cu, Mo, Co, Ni) are partitioned into early-formed sulfides and are not concentrated in the melt or late-stage fluid phases. From discussions of Ishihara (1981), it is apparent that some of the Sn-bearing ilmenite-series granites in Japan are I-type. This and recent summaries of current theories on the factors controlling origin and concentration of metals in magmas (Burnham, 1979; Burnham and Ohmoto, 1980) strongly suggest that oxygen fugacity of the magma may be more important than nature of the source rock in controlling differences in metal associations between granites.

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