GRANITIC SERIES AND THEIR ECONOMIC GEOLOGY

DISSERTATION

Submitted in partial Fulfilment of the
Requirements for the Degree of
MASTER OF SCIENCE (EXPLORATION GEOLOGY)
of Rhodes University

by

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January 1993

To my beloved wife

Soraia

"There are Granites and Granites."

H. H. Read

Abstract

The granitic rocks are subdivided into four series: tholeiitic, alkaline, calc-alkaline and mobilizates. These series can be formed from melting of mantle material (M-type granites) or from crustal rocks. There are granitic rocks formed from the mixing of these two magmas types. The rocks formed from crustal anatexis are subdivided into those formed from igneous rocks (I-type granites) and those formed from meta-sedimentary rocks (S-type granites). The former has similar characteristics to the mantle-derived granitoids. The mineral deposits related to igneous or mantle derived magma usually are Cu-Au, Cu, Cu-Mo, Mo porphyries and have high oxygen fugacity and magnetic susceptibility (magnetite series). The Sn-W deposits usually are related to magma derived from meta-sedimentary or igneous rocks derived magma with low oxygen fugacity and magnetic susceptibility (ilmenite series). According to the tectonic setting, the granitoids rocks are classified as: Andino type, West Pacific type, Hercyno type, Caledonian type and Anorogenic (A-type granites).

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1. Introduction

The knowledge of granitic rocks has increased considerably in the last 30 years . After the "granite controversy," and the suggestion of the igneous rocks nomenclature by the IUGS Subcommission on the Systematics of Igneous Rocks, many advances in the understanding of origin and formation were achieved. Lameyre and Bowden (1982) classify the granitic series mainly according their evolution in the quartz-alkali feldspar-plagioclase diagram. However, this type of classification does not take into account the source rocks of the granitoids. Diverse authors suggest classifications based on the source of the magma i. e. mantle and/or continental crust (White and Chappell, 1983), tectonic setting Pitcher (1979), depth of emplacement (Buddington, 1959), and magnetic susceptibility (Ishihara, 1977).

The aim of this dissertation is to evaluate the granitic series and the mineralization related to it. The first sections review the modern nomenclature, chemical composition and the chemical classification of the granitoids, and the granitic series classification.

The following sections describe those granitic series defined by their tectonic setting, depth of emplacement and magmatic origin. These classifications are denominated of specialized granitic series, because they do not define a petrochemical trend, but an association with some specific characteristic. The mineralizations associated with the granitic series are reviewed in the last sections.

1. Granitic series, classifications and composition

Granitoids are clssified using different characteristics. These different classifications consider the tectonic setting and the original source of the granitic melt (sedimentary or igneous). This section aims to describe the various classifications and the chemical evolution of the respective granitoids.

2. Classification of Granites

Granitic rock is defined, in broad terms as a rock containing more than 20% but less than 45% volume of quartz and a low colour index. It usually consists of two feldspars in varied proportions. The granitic rocks are classified according to different proportions of feldspar and quartz. Figures 1a and 1b illustrate this classification. The traditional way to classify granitoids is by using a triangular diagram with quartz (Q), alkaline feldspar (A) and plagioclase (P) as end members.

3. Composition of the Granites

The most common mafic minerals usually present in granitoids are biotite and hornblende. Hornblende is the most common amphibole. Peralkaline granites contain riebeckite, arfvedsonite or other sodic amphiboles. The other common accessory minerals are apatite, zircon, Fe-Ti oxides, epidote, sphene, pyrite, tourmaline, fluorite, monazite, xenotime and almandine. Hughes (1982) points out that granites which have muscovite and/or almandine garnet, and cordierite, never contain sodic amphiboles like riebeckite-arfvedsonite. The most common pyroxene occurring in granitoids is augite. Granite containing orthopyroxene is known as charnockite and is associated with very high grade metamorphism. Trondhjemites are leucotonalites containing

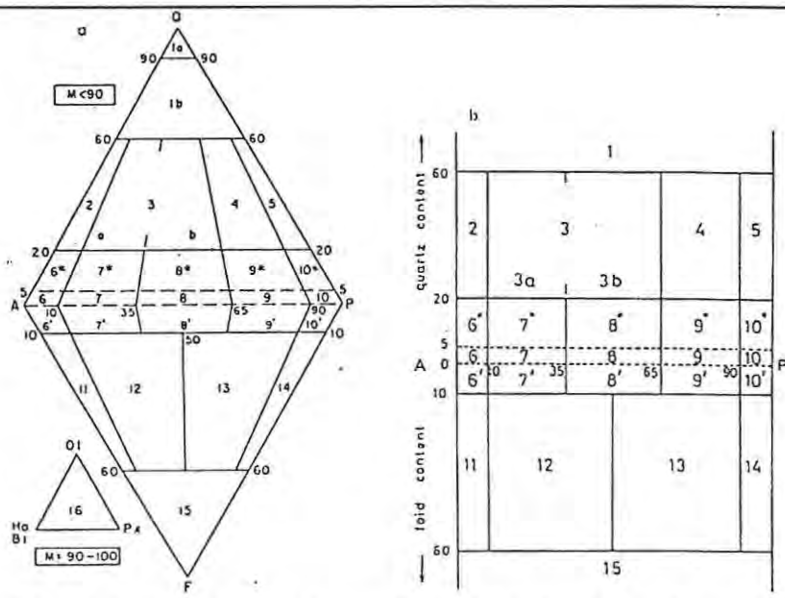


Fig. 1a. General classification and nomenclature of plutonic rocks according to mineral content (in vol. %).
$Q + A + P = 100$, or $A + P + F = 100$.
1a, quartzolite (silexite); 1b, quartz-rich granitoids; 2, alkali-feldspar granite; 3, granite; 4, granodiorite; 5, tonalite, 6*, quartz alkali-feldspar syenite; 7*, quartz syenite; 8*, quartz monzonite; 9*, quartz monzodiorite/quartz monzogabbro; 10*, quartz diorite/quartz gabbro/quartz anorthosite; 6, alkali-feldspar syenite; 7, syenite; 8, monzonite; 9, monzodiorite/monzogabbro; 10, diorite/gabbro/anorthosite; 6', foid-bearing alkali-feldspar syenite; 7', foid-bearing syenite; 8', foid-bearing monzonite; 9', foid-bearing monzodiorite/monzogabbro; 10', foid-bearing diorite/gabbro; 11, foid syenite; 12, foid monzosyenite (syn. foid plagisyenite); 13, foid monzodiorite/foid monzogabbro (essexite = nepheline monzodiorite/monzogabbro); 14, foid diorite/foid gabbro (theralite = nepheline gabbro, teschenite = analcime gabbro); 15, foidolites; 16, ultramafic plutonic rocks (ultramafitolites).
b. Possible classification of plutonic rocks by using quartz and foid contents as actually present in the rocks. On the left margin: quartz and foid contents as given by the modes; from left to right: feldspar ratio f.r. = $P/(A + P)$.

oligoclase instead of andesine. Alaskite is an alkali feldspar granite with a very low colour index.

Granitic rocks have similar chemical and modal compositions, but with variations in the feldspar composition. Tonalites and alkali feldspar granites form the two end members of these. Tables I and II display the mean modal composition as well as trace element content of granites of the calc-alkaline complex of New England, USA, and the Rosses Complex of Donegal in northwestern Ireland. Middlemost (1985) considers them to represent the typical composition for granitic rocks.

Table I Chemical composition of selected granitic rocks (%) (after Middlemost, 1985).

	1	2	3	4	5	6	7
SiO_2	75.26	72.64	71.30	68.65	66.09	61.52	71.72
TiO_2	0.26	0.26	0.31	0.54	0.54	0.73	0.22
Al_2	10.48	14.04	14.32	14.55	15.73	16.48	15.98
Fe_2	2.42	0.87	1.21	1.23	1.38	1.83	0.49
FeO	1.32	0.96	1.64	2.70	2.73	3.82	0.88
MnO	0.10	0.03	0.05	0.08	0.08	0.08	0.03
MgO	0.35	0.38	0.71	1.14	1.74	2.80	0.53
CaO	0.57	1.39	1.84	2.68	3.83	5.42	2.83
Na_2O	4.04	3.32	3.68	3.47	3.75	3.63	5.56
K_2O	4.66	5.48	4.07	4.00	2.73	2.07	1.21
H_2O^+	0.48	0.34	0.64	0.59	0.85	1.04	0.53
H_2O^-	0.08	0.06	0.13	0.14	0.19	0.20	0.01
P_2O_5	0.08	0.09	0.12	0.19	0.18	0.25	0.06
CO_2	0.01	0.07	0.05	0.09	0.08	0.14	0.02
Total	100.11	99.93	100.07	100.05	99.90	100.01	100.07

1. Chemical composition of a riebeckite-aegirine granite from Liruei, Younger Granite Province of Northern Nigeria (after Jacobson et al. 1958: 17, No.2). The rock also contains 0.18 per cent ZrO_2, 0.06 per cent Cl and 0.09 per cent F.
2. Chemical composition of US Geological Survey Standard G-1 granite from Westerly, Rhode Island, USA (after Fleischer 1969: 65, No. 3a).
3. Mean chemical composition of granite (after Le Maitre, 1976a: 606) (total number of analyses 2485).
4. Mean chemical composition of granite (variety adamelite) (after Le Maitre 1976a: 608) (total number of analyses 135; sample based towards rocks from Australia).
5. Mean chemical composition of granodiorite (after Le Maitre 1976a: 609) (total number of analyses 885).
6. Mean chemical composition of tonalite (after Le Maitre 1976a: 612) (total number of analyses 97).
7. Chemical composition of trondhjemite from the type-area of Trondhjeim-Oppdal. Norway (after Barker & Millard 1979: 523, No. N-2); quarry 2 Km east of Stϕren. Rock also contains 0.02 per cent F.

Granitic rocks form 85% to 88% of the volume of intrusive rocks in the Earth's crust. Of the 85% volume, granodiorite constitute 34%, granites and monzogranites (adamelites) constitute 44% and tonalites constitute 8% (Brownlow, 1979).

The chemical composition of granitoids is defined by Streckeisen (1973) as very broad, although most granites have similar compositions to rhyolite and dacites. Granites which contain more alkali feldspar than plagioclase are similar to rhyolite while granites which contain more plagioclase than alkali feldspar are similar to dacite. Other chemical

Table II Average content of trace elements in granitoids (after Middlemost, 1985).

	p.p.m		*p.p.m.*		*p.p.m.*
Li	24	Sr	250	Eu	1.3
Be	3	Y	13	Gd	5
B	1.5	Zr	210	Tb	0.6
N	8	Nb	20	Dv	2.5
F	700	Mo	7	Ho	0.5
Cl	≈70	Ru	<0.4	Er	2
Sc	3	Rh	<0.005	Tm	0.2
Ti	1500	Pd	0.0025	Y	1
V	16	Ag	0.04	Lu	0.2
Cr	22	Cd	0.06	Hf	6
Mn	230	In	0.025	Ta	1.6
Co	2.4	Sn	4	W	<0.8
Ni	1.5	Sb	0.4	Re	0.00056
Cu	13	Cs	1.5	Os	0.00006
Zn	45	Ba	1200	Pt	<0.01
Ga	18	La	100	Au	0.005
Ge	1	Ce	170	Hg	0.245
As	0.8	Pr	17	Tl	1.3
Br	0.13	Nd	55	Pb	49
Rb	220	Sm	9	Th	52
				U	4

characteristics of the granitic rocks are:

- TiO_2, Al_2O_3, MgO and CaO exhibit a progressive decrease and SiO_2 and K_2O an increase in the suite tonalite-granodiorite-granite-alkali feldspar granite respectively. There are many exceptions to this pattern including mesocratic granites, leucogranodiorite and tonalites (Middlemost, 1985).

- The normative mineralogy displays a progressive increase in the amount of quartz and orthoclase ith a commensurable decrease in anorthite, pyroxene and Fe-Ti oxides. The albite remains constant.

3.1. Chemical evolution of the granitoids

The evolution of granitoids is very dependent on the composition of the magma source, the reaction of the magma with the country rocks, tectonic setting, time of crystallization, depth of emplacement, and the fractionation processes involved during the crystallization.

The composition and the temperature of the magma controls the generation of the mineral assemblage. The high/low melting point constituents ratios progressively decrease from quartz-diorite, tonalite, granodiorite to leucocratic granites. The study of their variation in a given igneous complex can provide information on the petrogenesis and magmatic source of the granitic rocks. Certain factors have to be considered in this kind of analysis including the possible presence of xenoliths and that the granitic magma may contain restitic crystals not melted during the anatexis.

The variation of isotopic ratios and contents may indicate a possible contmination by the country rocks (Clarke and Halliday, 1980). Ikeda (1978) suggests that the composition of the Japanese granites displays a close relationship with the geochemistry of the country rocks. If there is an absence of xenoliths and the granite shows a constant pattern of the isotopic ratios, then it may be explained by magmatic differentiation rather than contamination by country rocks. The mechanisms of magmatic differentiation can vary. Gravitational differentiation or crystal settling is uncommon in acid magmatic processes, and it is indicated by the occurrence of rare acid intrusions displaying igneous layering (Hall, 1987).

The high viscosity of granitic magmas indicates their capacity to carry crystals and heavy xenoliths and that convection currents within an acid magma chamber are improbable. Nakada (1983) explains that the increase of phenocryst content in successive rhyolite and dacites is the product of crystal settling in the magma chamber. However, Hildreth (1981) suggests that the compositional zoning in rhyolites which contain a very low amount of phenocryst are the result of liquid fractionation rather than crystal settling. One of the characteristic features magmatic differentiation is the concentric compositional zonation of granitoid plutons (Hall, 1987). This process of differentiation can be explained by several mechanisms:

- Differentiation where crystallization occurs inward and minerals formed at lower temperatures concentrate near the nucleus of the intrusion,
- contamination of the margins of the pluton,
- primary differentiation during anatexis where variable composition may represent diverse stages of partial melting of the source rocks,
- Wyllie (1972) points out that a tonalite formed under crustal conditions cannot be totally liquid but will be a crystal mush enriched in residual crystals. He also shows that anatectic liquid starts as a granite and evolves to granodiorite with a corresponding increase in the proportion of mafic phases.

The proportion of felsic minerals in granitoids is dependent on water content in the magma. The water content also influences the melting temperature of the source rock in that the higher the water content, the lower will be the temperature necessary to form granitic magmas (Whitney, 1988; Willie, 1977).

The calc-alkaline granitoids are much more common than the peralkaline granites. Peralkaline granitoids occur as volumetrically minor intrusions in continental margin and island arc environments. The peralkaline granitoids, i.e. rhyolite, occur in Hokkaido (Japan), Papua New Guinea, and New Zealand. Nevertheless, the main occurrences are in anorogenic tectonic environments and the best known examples are the Younger Granites of Nigeria (Bonin, 1986). The oceanic islands contain some examples of anorogenic granitic magmatism like those in Iceland, the Azores and Ascension Island. However, the oceanic granitoids are plagiogranites of the tholeiitic series while the continental anorogenic granitoids are of the alkaline series.

Middlemost (1985) points out that usually magmas derived from the mantle unaffected by contamination crystallize magnetite-free rocks. He also suggests those magnetite-bearing granitoids might be formed by a differential loss of H_2 or assimilation of oxidized supra-crustal rocks. Middlemost (op. cit.) further considers that the attempts to link the I-type/S-type granites with magnetite/ilmenite series are unsuccessful because of the great shifts in the oxygen fugacity which may occur during the crystallization of granitic magmas. The granitic rocks may vary geochemically due to the magma source, the existence of contamination, oxygen fugacity (fO_2) or the water content in the magma.

The most notable features affected are the isotopic composition, proportion of high-T melting to low-T melting components, the alumina saturation, and accessory mineral content, like ilmenite or magnetite.

3.2. Isotopic Composition

The isotopic composition of granitic rocks places constraints on the possible origin of each intrusion. However, it is not always possible to be certain of the main source of granitic magma. The initial $^{87}Sr/^{86}Sr$ ratio of granites usually indicates the possible magmatic source. From the Archean to the present time there is a general increase in the initial Sr ratios of the granioids (figure 2).

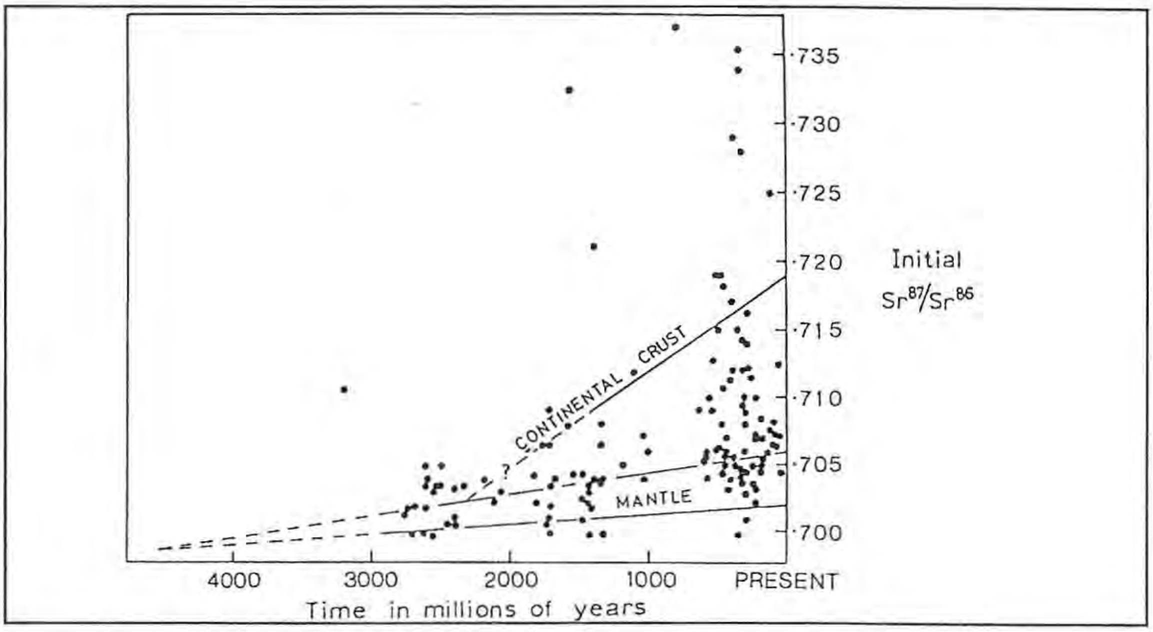


Figure 2 Plot of initial $^{87}Sr/^{86}Sr$ ratios of granites against their ages (after Faure and Powell, 1972; in Hall, 1987).

Source rocks of the granitic magma also have to be considered. Dasch (1969) points out that some greywackes of volcanoclastic origins have $^{87}Sr/^{86}Sr$ ratios as low as basalt, and seafloor sediments can provide metasomatic fluids with very high strontium isotopic ratios. These fluids could interact with oceanic basalt shifting the initial isotopic ratios.

The Nd isotopic data also have a similar pattern to strontium ratios. Allégre and Othman (1980) point out that those granites with initial $^{87}Sr/^{86}Sr$ ratios of 0.704 or less yield positive values of neodymium isotopes (ϵNd) while those with negative ϵNd values (-15 to 0) have high initial $^{87}Sr/^{86}Sr$.

The only stable isotope which yields meaningful information concerning the identification of magmatic source are those of oxygen. Taylor (1980) suggest that many granitic provinces bear a positive correlation between $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ ratios (figure 3).

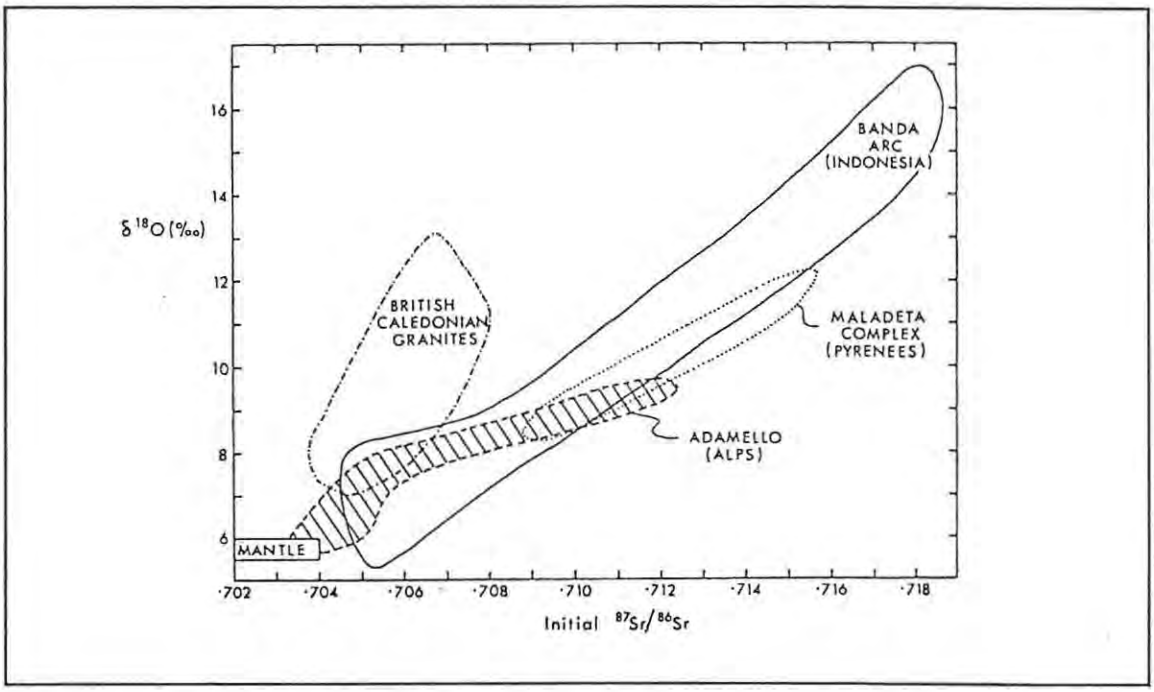


Figure 3 Variation of $\delta^{18}O$ for various igneous suites (after Taylor, 1980).

Contamination of the granitic magma by sedimentary and/or igneous rocks magmas can alter the initial contents of $\delta^{18}O$ and strontium isotopic ratios (Clarke and Halliday, 1980). The use of zircons to obtain U/Pb ratios or Pb/Pb ratios may be problematic, mainly because zircons may be partly of restitic origin.

The isotopic composition of peralkaline granitoids varies from values indicating a crustal source such as the Young Granites of Nigeria, to those very similar to the present basalts (Hall, 1987). Although the origin of the Younger Granites of Nigeria is not established conclusively. Some authors consider that the mantle is either the source of magma or heat the source for magmatic differentiation or crustal anatexis (Kinnaird and Bowden, 1987; Bonin, 1986). The calc-alkaline granitoids are depleted of some elements like Zr, Nd, V and rare earth elements (REE), when compared with the peralkaline granitoids (Bonin, op. cit.).

4. Chemical classification of granitoids

Shand (1951) identifies a chemical classification of igneous rocks using alumina saturation in relation to alkalis (Na_2O + K2O) (table III).

Table III Shand's chemical classification based on the alumina saturation.

Peraluminous	Metaluminous	Subaluminous	Peralkaline
$Al_2O_3/(Na_2O+CaO)>1$	$Al_2O_3/(Na_2O+CaO)<1\geq Al_2O/(Na_2O+K_2O)$	$Al_2O/(Na_2O+K_2O) \approx 1$	$Al_2O/(Na_2O+K_2O) <1$
corundum normative	anorthite normative	low Al bearing normative minerals	acmite normative
usually muscovite, andalusite, almandine, cordierite.	biotite, hornblende	olivine, hypersthene	aegirine, riebeckite

Peacock (1931) divides igneous rocks into four groups based on alkali-lime index as follows:

Rock Series	Alkali-lime index
Alkali	<51
Alkali-calcic	51-56
Calcic-alkali	56-61
Calcic	>61

5. Granitic series

Brownlow (1979) recognizes two magma types responsible for the generation of the most volumetrically significant granitic batholiths. These are a calc-alkaline suite and an alkaline suite. Some of the characteristics recognised by Brownlow (op. cit.) include the following:

- Calc-alkaline suites are generated in the shallow mantle edge above lateral compressive zones of ocean crust destruction;
- Alkaline suites result from anorogenic, tensional environments whose magma source lie within deeper mantle zones;
- The calc-alkaline series predominates throughout most of earth's history;
- the alkaline suite became a relevant product of intraplate magmatism in mid-Proterozoic times (1500-2000Ma).

Brownlow (op. cit.) suggests that the dominant igneous intrusive rock types in the continental crust are tonalites. The cordillera-type batholiths are formed by a large number of granitic intrusions of calc-alkaline affinity.

Granitoids of Archean age are mainly of tonalite-trondhjemite composition and usually display gneissic foliations. These tonalites show intrusion by granites (sensu stricto of the Streckeisen's classification) which usually contain megacrysts of potassium feldspar.

Lameyre and Bowden (1982) suggested that granitic rocks could be subdivided into four major granitoid series using the Streckeisen QAP diagrams:

- Calc-alkaline series;
- Alkaline series;
- Tholeiitic series;
- Mobilizates and related rocks.

5.1. Calc-alkaline granitoids series and its variants

Lameyre and Bowden (1982) classify granitoid rocks of the calc-alkaline series into three subdivisions conforming to the evolutionary path of the feldspar and consequently, the proportion of potassium. The subdivision of the calc-alkaline series is denominated as follows:

- calc-alkaline series with low K, or trondhjemitic;
- medium K, or granodioritic,;
- high K series, or monzonitic.

Arth et al. (1978) identify a gabbro-diorite-tonalite-trondhjemite suite in the Uusikaupunki-Kalanti area of south-west Finland. The rocks of this area vary between hornblendite to hornblende gabbro, biotite hornblende-tonalite and finally trondhjemite and present no gaps in the composition . Furthermore, major and trace element variations show a similar development of the modal composition. Arth et al. (op. cit.) point out that the major features of the petrochemical evolution are the decreasing content of K_2O and REE and an increase of Na_2O content from the intermediate to silicic compositions. Lameyre and Bowden (1982) prefer calling this series the calc-alkaline trondhjemitic or low K, calc-alkaline series.

Some examples of the calc-alkaline granodioritic are the batholith of Sierra Nevada (U.S.A.) and the majority of the granitoids in Chile and Peru (Lameyre and Bowden, op. cit.). The same authors point out that these rocks follow a classical path of evolution with the most granitoids plotting in the QAP diagram between the plagioclase corner and the granite composition field. This suggests a process of plagioclase fractionation.

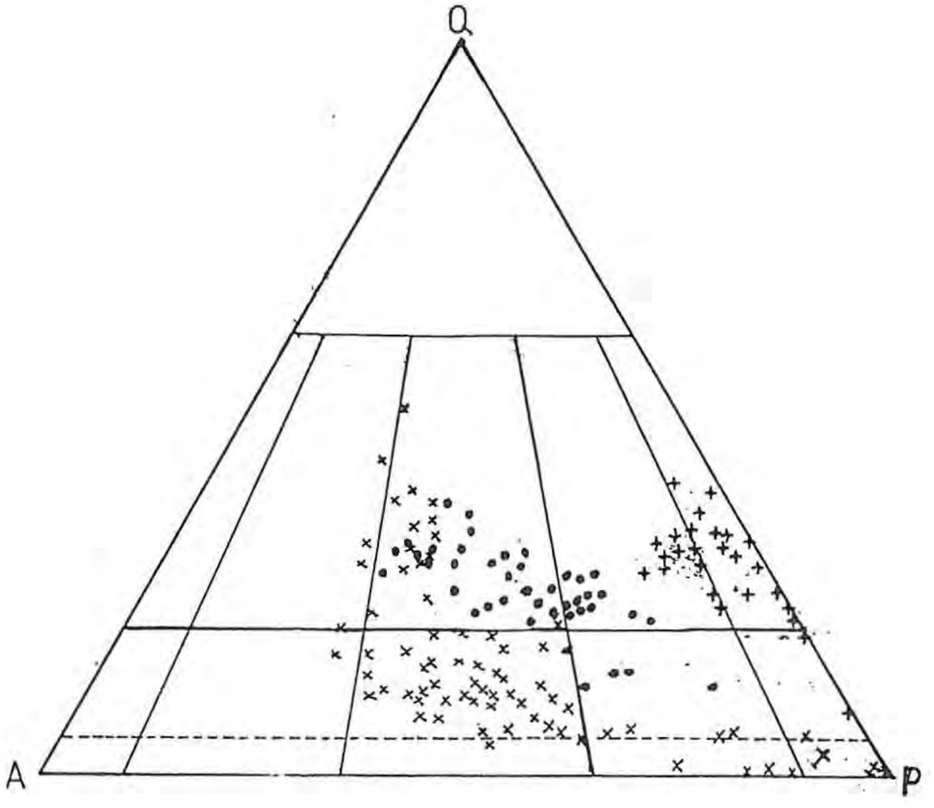


Figure 4 Calc-alkaline granodioritic (points, data from Sierra Nevada, U.S.), trondhjemitic (crosses, data from SW Finland), and monzonitic (data from Corsica and Ballons Massif) x's in the QAP diagram (modified after Lameyre and Bowden, 1982).

The last of the calc-alkaline subdivision is the calc-alkaline monzonitic series (high-K, calc-alkaline series) (Lameyre and Bowden, op. cit.). Orsini (1976; in Lameyre and Bowden, 1982) label some granitic rocks of the Variscan orogeny as of the subalkaline series. Pagel and Leterrier (1980) suggest that rocks of this series have similarities with the shoshonitic association (Morrison, 1980) and are characterized by high K_2O/Na_2O ratios, Ba, Sr, U and Th contents. The characteristic petrographic sequence is gabbro, monzogabbro, monzonite, quartz monzonite and monzogranite.

Figure 4 displays the modal composition of the calc-alkaline subdivisions: trondhjemitic, granodioritic and monzonitic series. The three series have distinct evolutions in the QAP diagram. The granodioritic series data is from Bateman et al. (1962; in Lameyre and Bowden, 1982). The monzonitic series is from Corsican granitoids and the Ballons Massif in France (Pagel and Leterrier, 1980).

Figure 5 shows the evolutionary trend of the calc-alkaline series from the trondhjemitic to monzonitic series. Lameyre and Bowden (op. cit.) suggest that the trend shown by the calc-alkaline series is related to the geotectonic evolution and the chronology of the formation and emplacement of the granitoids. The evolutionary trend, therefore, is from an earlier low-K magmatism to a late high-K magmatism.

5.2.Alkaline granitoid series

The alkaline series is comprised of post-orogenic and anorogenic granitoids like the alkaline granites of Corsica and the Younger Granites of Nigeria and Niger, respectively. This series consists of gabbro, monzonite, syenite and alkali feldspar granite (Lameyre and Bowden, op. cit.). In the continental crust, the alkaline series granitoids evolve from

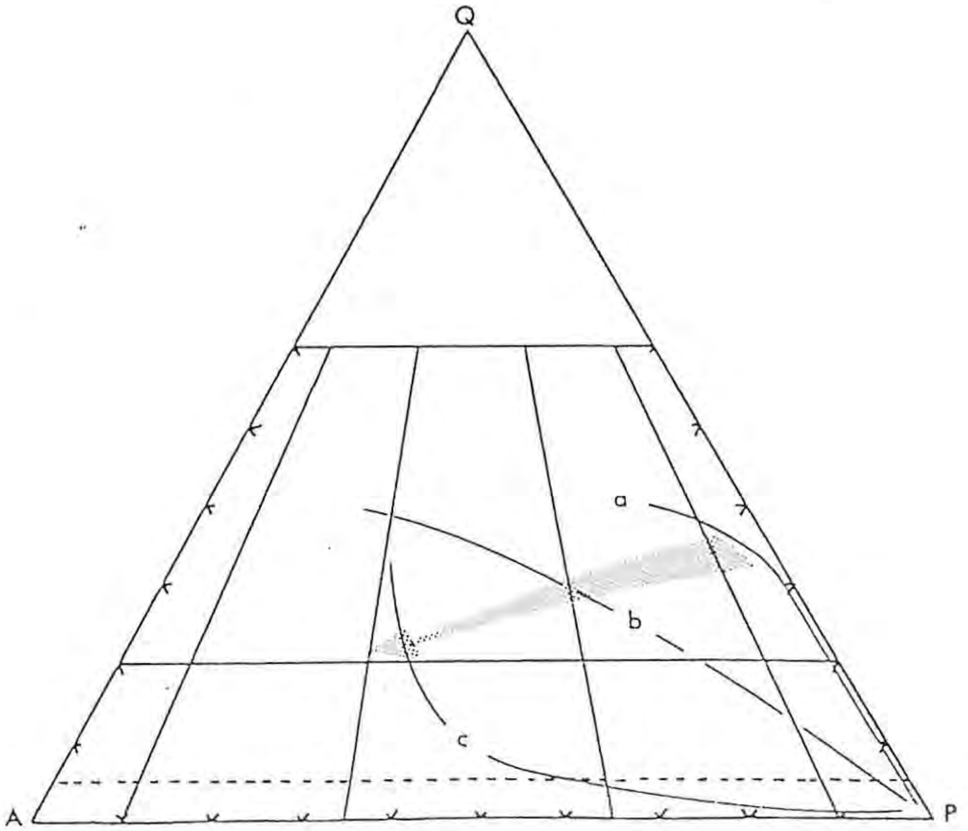


Figure 5 Schematic representation of the evolution in space and time (shaded arrow) of the calc-alkaline divisions: a=trondhjemitic, b=granodioritic, and c=monzonitic (after Lameyre and Bowden, 1982).

gabbros to syenite containing a slightly enhanced quartz content. The alkaline series granitoids containing more than 15 modal % of quartz are only formed from syenitic compositions.

Figure 6 shows the field of alkaline series and tholeiitic series and their evolutionary trend in the QAP diagram. The final evolution product of the alkaline series occupies the field of the syenogranite and alkali feldspar granite, or the alkaline and peralkaline granitoids.

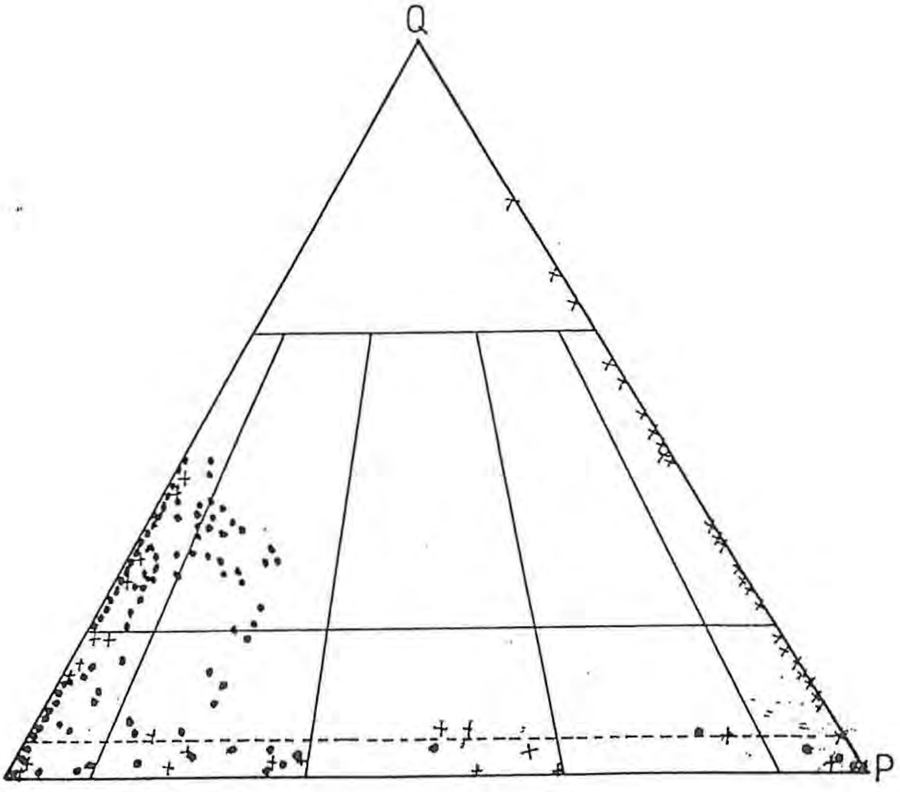


Figure 6 Alkaline and tholeiitic granitoids series. Dots= granitoids from Corsica; crosses= anorogenic granitoids from Niger and Nigeria; x's tholeiitic series (modified after Lameyre and Bowden, 1982).

5.3. Tholeiitic granitoid series

The tholeiitic series occupies the quartz-plagioclase border. However, there are K-rich members of this series in island arcs and continental platforms (Coleman and Peterman, 1975; Lameyre and Bowden, 1982). Lameyre and Bowden (op. cit.) point out that the modal composition of the end members of this series, when the anorthite composition reach An_{05}, shift from the QP boundary to the QA periphery. Trondhjemites related to this series do not have associated granodiorite as the trondhjemites of the calc-alkaline series do.

5.4. Mobilizates and related granitoids

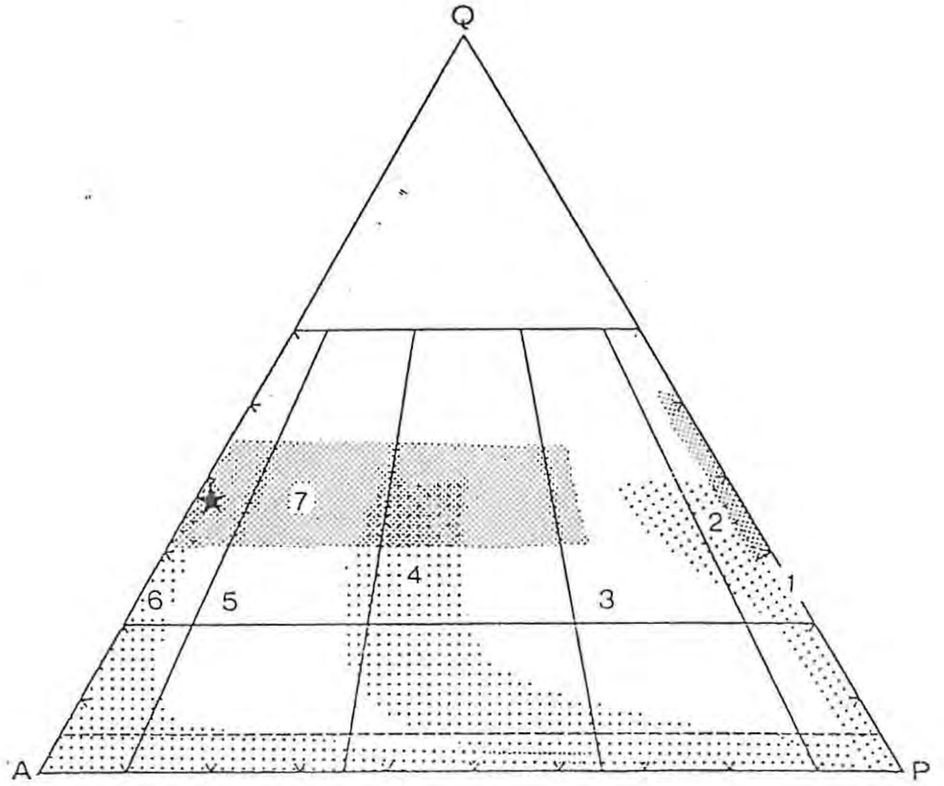
The granitoids of this series are formed under crustal conditions and usually show metasedimentary xenoliths although meta-igneous enclaves are not excluded (Lameyre and Bowden, 1982; Lameyre, 1987). The granitoid members of this series may be classified as I-type and S-type granitoids (Chappell and White, 1974) according to the composition of the source rocks.

The composition of the mobilizate rocks can vary but they are generally, rich in quartz. The group most commonly consists of the leucogranites (including alaskite and leuco-granodiorite) (Lameyre and Bowden, op. cit.).

The field occupied by the mobilizate granitoids is shown in the figure 7 together with the fields of the other granitic series. Mobilizate granitoids overlap the fields occupied by the other series.

5.5. General evolution and summary of the granitic series

Granitic series have a general evolutionary trend which can be analyzed with the QAP modal diagram demonstrated by Lameyre and Bowden (1982). This is summarised in figure 7, which displays the fields of the tholeiitic, calc-alkaline, alkaline and mobilizate granitic series.



The fields of each series are:1=tholeiitic;2=calc-alkaline trondhjemitic(lowK);3=calc-alkaline granodioritic(mediumK); 4=calc-alkaline monzonitic (high K);5=aluminous granitoids found in alkaline provinces; 6=alkaline & peralkaline granitoids;7=mobilizates granitoids formed by crustal fusion;black star=median minimum composition.

Figure 7 Summary of the field occupied by the granitic series in the QAP diagram (after Lameyre and Bowden, 1982).

6. Specialization of the Granitic Series

This chapter will cover the specialization to which the granitic rocks are subject. The term specializations refers to those series defined by characteristics like the magma origin or the tectonic setting of the granitoids.

The granitic series are subdivided according to diverse parameters like the tectonic setting, geochemistry, age and form of emplacement. Buddington (1959) classifies the U. S. granitoids according to the depth of their emplacement.

There are diverse classifications based in the tectonic setting in which granitoids are formed. Pitcher (1979 and 1982) classifies the granitoids into four groups according to their tectonic setting. Pitcher (1982) also classifies the granitoids into those with a mantle magmatic origin, the anorogenic granitoids, the granitoids formed from anatexis of meta-sedimentary rocks and two subdivisions of the I-type granitoids according to their tectonic setting.

Chappell and White (1974) divide the granitoids of the Lachlan Fold Belt based on the different source rocks. These source rocks can be sedimentary or igneous in character. The authors consider that the source of heat and melting are related to ultrametamorphic conditions at deep levels within the crust. Magma generated by anatexis of meta-sediments and igneous rocks produce S-type and I-type granitoids, respectively.

After the Chappell and White (op. cit.) study many other researchers have contributed to the understanding of the specialization of the granitic series (Loiselle and Wones 1979, Pitcher 1979 and 1982, and Ishihara 1977). Loisele and Wones (1979) were the first to classify anorogenic granites (A-type). Pitcher (1979 and 1982) follow the I-type and S-type classification, but include tectonic setting as an additional element to the original classification. Anorogenic granites and those formed from mantle magmatism without the participation of continental crust are also included in the classification. Pitcher (1979, 1982) also provides a subdivision for M-type granitoids.

Ishihara (1977) suggests the division of the Japanese granitoids within a two fold classification according to magnetic susceptibility. Ishihara (1977) divides granitic rocks into the magnetite and ilmenite series. These are based on studies of the Inner Zone Batholith, south-western Japan. It has a size similar to the Sierra Nevada Batholith (western U. S. A.), although the Japanese example is formed by granodiorites and granites. Finally, Barbarin (1990) classifies the granitoids according to their petrogenetic affiliation and the tectonic setting of their generation and emplacement.

6.1.Crustal depth emplacement classification

Buddington (1959) classifies granitic rocks into three groups. The three subdivisions are identified as katazonal, mesozonal and epizonal granitoids. The author developed this classification based on the study and comparison of case histories of North American granites. Tables IV, V and VI display the principal characteristics of each group.

Katazonal granites are formed at the same depth and under the same physical conditions as migmatites. These granites may be formed by partial melting of high grade metamorphic rocks. Katazonal granites usually display some structural orientation. It is possible that the emplacement of the granitic melt is controlled by the orientation of the foliation in the palaeosome.

Table IV Overall structural features of granitic bodies (after Hughes, 1982)

Nomenclature of Buddington(1959)	Epizone granite	Mesozone granite		Katazone granite
Approximate depth of emplacement	(exact limits impossible as emplacement style depends on the temperature and rheidity of country rock which varies with depth according to the geothermal gradient which itself varies from place to place)			
	0 - 9 km	7 - 16 km		> 12 km
Intrusion style	"permissive"	"forceful"		rheid adjustment
				"granitization"
Overall structure	ring-dyke intrusions connected to overlying cauldron subsidence intrusions	diapirs		incipient diapirs of migmatite
				migmatite complexes in situ
Internal structure	generally homophanous (structureless)	igneous foliation common; the domain of "granite tectonics", ± superimposed regional deformation		tendency towards chaotic;loss of any pre-existing planar structure.
Contact relationship	chilled contact against hornfels	highly variable; chilling generally not obvious	phyllonite along fault contact	broad zone of regional\contact migmatite
			schist aureole	gradation in proportion of neosome material in regional migmatite complex
			narrow zone of contact migmatite	
Temperature difference between granite and country rock	extreme	variable increase with depth		very little
				nil
Probable physical state	liquid phenocryst	crystal mush,probably largely solid		solid with incipient silicate melt
Resolution of "space problem"	large-scale magmatic stoping	forceful pushing aside of flanks of diapir;incorporation of "pendants"or smaller "septa" in roof zone		large-scale plastic deformation of migmatite complex and country-rock envelope
				replacement and recrystallization

The mesozone granites have a higher contrast in temperature to the country rocks than the katazonal ones. The result of this contrast is the wide variety of structural contacts. Mesozonal granites may have foliations as a result of the parallelism of platy and/or tabular minerals like biotite or

Table V Petrological features of granitic bodies (after Hughes, 1982)

Nomenclature of Buddington(1959)	Epizone granite	Mesozone granite	Katazone granite
Nature of inclusions	inclusions rare;some angular "accidental"inclusions of country rock near contacts;cognate inclusions uncommon	inclusions common;rounded "cognate"inclusions of debatable origin,plus inclusions of country rock near upper contacts	inclusions numerous;representing the metamorphic component of migmatite
Common rock types	diorite to granite,including syenite and quartz-syenite;ideal granite composition include felsitic and granophyric textural varieties;high quartz contents common overall;seldom peraluminous;granitic and syenitic varieties commonly rich in Fe and\or peralkaline;pegmatites uncommon	diorite to granite,excluding syenite and quartz-syenite;low quartz content varieties common overall;ideal granite compositions rare; silicic varieties often peraluminous;pegmatites common;localized autometasomatism resulting in greisening,tourmalinization, and kaolinization	generally inhomogeneous,but locally homogeneous;bulk composition variable and difficult to determine;commonly peraluminous
Dark minerals	biotite and hornblende common throughout		
	fayalite,hedenbergite,aegirine and riebeckite often found in granitic and syenite compositions	muscovite common in granitic compositions;also pinite after cordierite,both reflecting a peraluminous condition	"metamorphic"minerals such as garnet,cordierite,and sillimanite common
Nature of alkali feldspar	mesoperthite	perthitic orthoclase or perthite microcline	microcline
	determination complicated by subsolidous exsolution and recrystallization		
Relationship to solvus at time of emplacement	hypersolvus	subsolvus	relatively low-temperature subsolvus equilibrium attained

feldspar. Igneous foliation or lineation are commonly seen near the contact of mesozonal granites and are usually parallel to the wall of the intrusion.

The contacts of epizone granite represent a large difference in temperature. Epizonal granites are usually devoid of any directional mineralogical structures although it may have vesiculated and drusy cavities. Some shallow, fine grained granitic rocks can undergo autobrecciation near the margins. This autobrecciation is referred to as protoclastic breccia.

Table VI Geological relationship, economic potential, and origin of granitic bodies (after Hughes, 1982).

Nomenclature of Buddington(1959)	Epizone granite	Mesozone granite	Katazone granite
Relationship,if any,to comagmatic volcanic rocks	indubitable in a majority of cases,and inferred in many of remainder:intrusive rocks linked to volcanism by occurrence of such distinctive subvolcanic features as cone sheets,diatremes,and near-surface crystallization of intrusive bodies of degassed magma, e.g., felsite.	very doubtful(but direct evidence usually lacking as the amount of erosion necessary to expose mesozone intrusions would have removed consanguineous volcanic rocks if ever present)	none
Relationship to regional metamorphism	"post-orogenic";generally more appropriately termed"anorogenic"(i.e. no genetic relationship what-soever to regional metamorphism)	"late-orogenic"	"syn-orogenic
Economic potential	porphyry copper type deposits;mineralized breccia pipes;pyrophyllite	kaolin,china clay;vein mineralization(Sn,W,Cu,etc.)	barren
		simple and complex pegmatites	
Origin (still controversial)	fractionation of mantle-derived melts ± some possible assimilation of crustal material;also some crust-derived melts	diapiric ascent of lower crustal material remobilized under katazonal conditions	crustal"granitization " processes

6.2.Tectonic setting classifications

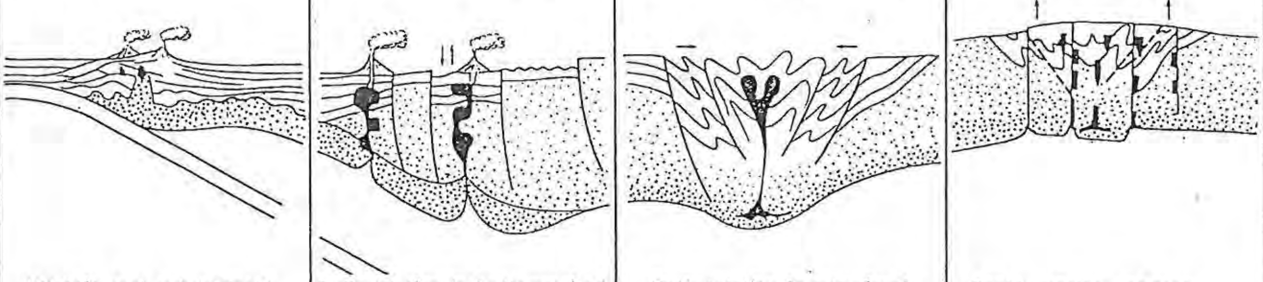
Middlemost (1985) distinguishes between orogenic and anorogenic granites, each of which is subdivided into four groups (Table VII). Most of the orogenic granites fall in the field of calc-alkaline series (Middlemost, op. cit.).

The orogenic granitic rocks normally display a regional pattern similar to the composition of the orogenic volcanic rocks and show compositional variation, across the width of the elongate compound batholiths on a regional scale. For example, the Sierra Nevada Batholith has quartz diorites, gabbros and tonalites to the west while the central part consists of granodiorite and granites. The eastern portion is made up of monzodiorites, monzonite, quartz monzonite and granites (Bateman, 1983).

Table VII Simplified model of the tectonic setting and nature of the granitic rocks of Earth (after Middlemost, 1985).

Orogenic Granitic Rocks			
Pacific-type	Cordilleran-type	Caledonian-type	Himalayan-type
Subduction beneath an oceanic island arc	Subduction of oceanic materials beneath a continental margin	Uplift and relaxation immediately after the closure of an ocean basin	Continent-continent collision
Small composite or zoned stocks	Huge composite batholiths	Discrete multiple intrusions	Large bodies of autochthonous granite,migmatite,and local stocks
Essentially evolved from a mantle-derived magma that usually belongs to either the island arc tholeiite or the calc-alkaline series.	Calc-alkalic parental magmas,plus assimilation of continental crustal materials.	Calc-alkalic parental magma plus anatexis of continental crustal materials.	Large-scale anatexis of continental crustal materials.
Tonalites	Tonalite, Granodiorite and Granites	Granodiorite and granite	Leucogranites and Granites
Plutonism is generally short-lived	Plutonism is episodic and extends over a long period	Plutonism is generally short-lived	Plutonism of moderate duration.
Anorogenic Granitic Rocks			
Barberton-type	Tholeiitic-type	Normal Alkalic-type	Hyperpotassic-type
Extensive melting and mobilisation of primitive proto-continental crust	Tholeiitic basalt magma emplaced into continental	Subvolcanic intrusions into continental areas of doming and rifting	Subvolcanic intrusions
Archaean grey gneiss complexes	Discrete stocks usually associated with a range of more mafic tholeiitic rocks	Composite stocks and ring dykes often associated with syenitic rocks	Composite stocks and ring dykes usually associated with quartz monzonite
Extensive anatexis and migmatite formation	Magmatic differentiation together with local assimilation of continental crustal materials	Magmatic differentiation of sodic alkalic basaltic magma, volume of silic magma augmented by assimilation	Magmatic differentiation of hyperpotassic alkalic magma
Trondhjemites and Tonalites	Granodiorite and Granites	Alkali-Feldspar Granites and Granites	Alkali-feldspar Granites and Granites
Plutonism characteristic of the Archaean prior to the cratonization of the crust	Local intraplate plutonism	Intraplate doming and rifting	Local intraplate plutonism

Pitcher (1982) suggests a classification consisting of five tectonic settings and associates them with the Chapell and White (1974) classification of I- and S-type granites (figure 8).



Pacific-type Oceanic island arc	Andinotype Continental-lip arc	Hercynotype Oblique continental collision	Caledonian-type Post-closure uplift
Volcanic and volcaniclastic aprons	Sedimentation in fault-margined furrows and liminal basins	Sedimentation in extensional basins	Rapid erosion, molasse
Basalts	Andesites in great volume	Rarely silicic lavas	Plateau-type basaltic volcanicity
Burial metamorphism	Burial metamorphism	Regional low pressure metamorphism	Strongly discordant aureoles
Gabbro, 'M' type plagiogranite in mature arcs	I-type tonalites (Cordilleran), gabbros	Migmatites, S-type granite	I-type biotite granite (Caledonian), appinitic gabbro and diorite
Small, zoned plutons	Disharmonious (Daly), linear, cauldron batholiths feeding volcanoes	Harmonious (Suess) diapir batholiths	Discordant plutons and distension diapirs
Open folding	Minimal shortening	Shortening	Tensional tectonics, major faulting, uplift

Figure 8 Schematic representation of the different tectonic setting and their related granitoids (after Pitcher, 1982).

Pitcher (1982) modifies the I- and S-type classifications by adding two other types and subdividing the I-type granite into two groups. The Pitcher M-type granites are essentially mantle derived and are generally formed in oceanic island-arc environments. The mineralization associated with this type is in the form of Cu-Au porphyries. According to Pitcher (1982) the most common granite type is the I-Cordilleran type. They occur at active continental margins and the mineralization associated with these is Cu-Mo porphyry. The other I-type is the Caledonian type which occurs in rapid post-closure uplift. The last in the Pitcher classification are the S-type (Chappel and White, 1974) and the A-type granitoids (Loisele and Wones, 1979). The S-type are granitic rocks formed from the melting of pelitic rocks.

Pearce et al. (1984) classify the granitic rocks according to the tectonic setting, into four main groups, viz., the ocean ridge granites (ORG), volcanic arc granites (VAG), within plate granites (WPG) and collision granites (COLG). Each group is subdivided into subgroups according to their precise tectonic setting and petrogenetic features. The authors used trace elements to discriminate between different tectonic environments. The elements used to differentiate between the tectonic settings are K, Rb, Sr, Y, Zr and Nb. Figure 9 displays the distribution of the tectonic series proposed by Pearce et al. (op. cit.). The co-ordinates of the discriminant boundaries are for the Rb-(Y+Nb) diagram; syn COLG/VAG = 2.80 to 55300; syn COLG/ WPG = 55300 to 400,200; VAG/WPG = 55300 to 51•5,8; VAG/ORG = 51•5,8 to 50,1; ORG/WPG = 51•5,8 to 2000,400; for the RB-(Yb-Ta) diagram: syn COLG/VAG = 0•5,140 to 6,2000; syn COLG/WPG= 6,200 to 50,2000; VAG/WPG = 6,2000 to 6.8; ORG/WPG = 6,8 to 200,400.

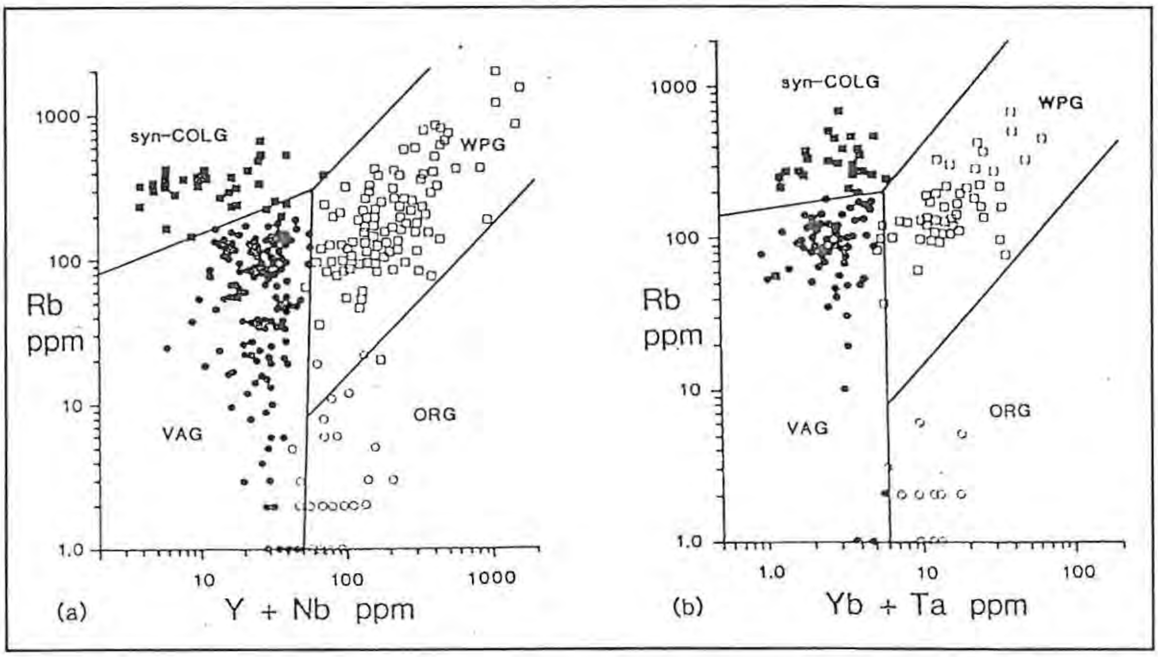


Figure 9 Discriminant diagrams for syn collision (syn-COL), volcanic arc (VAG), within plate (WPG), and normal and anomalous ocean ridge. (a) Rb-(Y+Nb) diagram and (B) Rb-(Yb+Ta) diagram (after Pearce et al., 1984).

The ocean ridge granites (ORG) are divided into four subgroups according to the tectonic setting and the geochemistry of the mantle magma. Initially, this group is divide into granitoids unrelated to subduction zones and those related to subduction zones. The geochemical characteristics of the parent mantle magmas are used to classify them as "normal" type mid-ocean ridge basalts (MORB) or the anomalous MORB (E- or T-type MORB) (Pearce et al., op. cit.). Petrographically, these granitoids are quartz diorites or tonalites and may be metaluminous or peraluminous. The four subdivisions are:

- "Normal" oceanic ridges i. e. the rocks yield geochemical features of normal MORB magmatism.
- Anomalous oceanic ridges i. e. related to T- or E-type MORB.
- Back arc basin ridges.
- Supra subduction zone (fore arc basin) ridge.

The volcanic arc granites (VAG) can vary in composition from tholeiitic to calc-alkaline to shoshonitic and their tectonic setting can be associated with either oceanic volcanic arcs or continental volcanic arc (Pearce et al., 1984). Petrological variations may occur within a particular tectonic region as for example, in Papua New Guinea and the Solomon Islands (Mason and McDonald, 1978). This group displays a petrological variation similar to the evolutionary path shown by the three subdivisions of the calc-alkaline series of Lameyre and Bowden (1982). Pearce et al. (op. cit.) recognize that the granitoids of this group can be classified as M-type or I-type. The authors subdivided this group into three subgroups:

- Oceanic, mainly tholeiitic arcs,
- Oceanic, mainly calc-alkaline arcs, and

- Active continental margin.

Within plate granites (WPG) are divided according to the nature of the crust into which they are intruded. These granitoids are divided into those emplaced in the continental crust and those emplaced within oceanic crust. Within continental crust granitoids are further subdivided according to the thickness of the crust into which they intrude. The majority of the granitoids emplaced in relatively thicker continental crust, are mainly classified as A-type granites (Loiselle and Wones, 1979). Those emplaced within thin continental crust, are considered as member of calc-alkaline series. The subdivisions of this main group are listed below:

- Intra-continental ring complexes and graben associated intrusions,
- Attenuated continental crust, and
- Oceanic islands.

Collision-related granites (COLG) are divided into three subdivisions according to the kind of collision involved (continent-continent, continent-arc, arc-arc) and to the temporal relationship (syn-tectonic, post-tectonic). The granitoids associated with this group can be classified as I-type or S-type (Chappell and White, 1974). The three subdivisions are:

- Continent-continent collision: syn-tectonic,
- Continent-continent collision: late or post-tectonic, and
- Continent-island arc collision: syn-tectonic.

6.3. S-type granites

Pelitic rocks are commonly peraluminous and have a low Na/K ratio. When these rocks are heated to temperatures of around 700-800°C and a certain amount of water is present, they will melt to form a granitic magma (Whitney, 1988 and 1989). This magma will bear the same geochemical characteristics as the source rock.

The S-type granites are characterized by a high initial $^{87}Sr/^{86}Sr$, probably due to the enrichment of Rb relative to Sr in the pelitic rocks (White and Chappell, 1977). S-type granites are also characterized by the xenolith type or minerals not completely absorbed during the anatexis (restites). The xenoliths are often of pelitic composition and the mineral restites are garnet, biotite, cordierite, sillimanite and other aluminosilicates. When the S-type granitoids are compared with I-types, the former display more compositional variations than the latter. Hine et al. (1977) compare the I-type with the S-type of the Kosciuscko Batholith, southern Lachlan Fold belt in Australia. The S-type granites of this batholith were emplaced as relatively homogeneous, large plutons and have lenticular quartz and mica aggregates forming a well defined foliation. Some characteristics of the S-type granitoids observed by Hine et al. (op. cit.) are:

- Petrographically most of the granitoids are granodiorites and monzogranites.
- Biotite is the most common mafic mineral and muscovite, in most of the cases, is a subsolidus phase.
- Cordierite and apatite are two common accessory minerals. The other accessory minerals are ilmenite, iron sulphide and rutile.
- There are two xenolith types: one is considered a restite from the source rock of the magma and consists of cordierite

bearing biotite gneiss and the other, enclaves of country rocks to the intrusion.

- The S-types display a Fe/Mg ratio ≈1 as in calc-alkaline rocks but the K_2O content is similar to alkaline granites.
- The high content of K is explained by enrichment relative to Na in the pelitic source rocks.
- The S-types have low Fe_2O_3/FeO indicating a low oxygen fugacity (fO_2), probably due to the presence of carbon or sulphur in the source rocks.
- As the S-type sources are more siliceous, the general SiO_2 content is more uniform and slightly higher than the I-type granitoids.
- Elements which are enriched in metapelites such as Cr, and Ni, have a relatively higher content in the S-type than in the I-types.

A summary of the general characteristics of the S-type granitoids are shown on the table 8 (White and Chappell, 1983).

Table VIII Geochemical characteristics of S-type granitoids (after White and Chappell, 1983).

PARAMETER	CHARACTERISTIC VALUE	EXPLANATION
SiO_2	Within range 65-74%	Derived from SiO_2-rich source
K_2O/Na_2O	High	K adsorbed by clays on weathering, whereas Na is removed
Ca and Sr	Low	Removed in weathering cycle
$\frac{Al_2O_3}{Na_2O+K_2O+CaO}$	High (>1.05) and increases as the rocks become more mafic	Weathering increases Al relative to Na+K+Ca
Fe^{3+}/Fe^{2+}	Low	Carbon common in sedimentary source rocks
Cr and Ni	High relative to I-type	Cr and Ni incorporated into clays during weathering
$\delta^{18}O$	High	Oxygen isotopes fractionate during production of clays during low temperature weathering
$^{87}Sr/^{86}Sr$	High (normally >0.708)	Rb concentrated relative to Sr during weathering and sedimentation

6.4. I-type granites

I-type granites are those formed from the melting of igneous rocks (Chappell and White 1974). White and Chappell (1977) suggest that to form a large volume of granitic magma it would be necessary to melt igneous rocks with an intermediate composition, rather than a basaltic composition. Meta-igneous rocks containing amphiboles, plagioclase and pyroxene may form magma when they are heated to high temperatures. The water released from the amphibole structure will dissolve into the magma and lower the temperature necessary to melt partially more meta-igneous rocks (White and Chappell, 1983). The dehydration of amphiboles and/or micas is one of the processes needed to form granulite rocks (Fyfe, 1973). From these assumptions, it is possible to explain the origin of mafic xenoliths.

Hine et al. (1977) points out that the most common I-type granitoids in the Kosciusko Batholith of southeast Australia are tonalites. The other I-type granitoids, in order of abundance, are granodiorite and gabbro. According to Hine et al. (op. cit.) the typical accessory mineral assemblage of the I-type granitoids are listed as:

Rock Types	Accessories
Gabbroic	apatite, zircon, K feldspar, magnetite
Tonalitic/ Granodioritic	magnetite, allanite, apatite, zircon.

Hine et al. (op. cit.) suggests that the development of allanite is due to the low Ti content. The high oxidation state favours the development of allanite instead of sphene. The same authors point out that the compositional range of these I-types is similar to the Al-rich basalts, andesites, dacites and rhyolites of continental margin areas. The Fe/Mg ratios are constant in all the batholiths.

The alumina index, after the applied correction for the calcium in apatite, is less than 1,1. The I-type granitoids are depleted in K when compared with S-type granitoids. The SiO_2 content has a range of 60% to 67%.

White and Chappell (1983) suggest that I-type granites of the Lachlan Belt are derived from partial melting of crustal igneous rocks rather than differentiation of ocean floor basalts or a peridotitic mantle. The mineral accessory minerals of I-type granitoids are biotite or hornblende. Magnetite is more common accessory mineral than ilmenite due to high fO_2 often occurring in I-type granitoids.

White and Chappell (1977) demonstrate the existence of two different I-type granitoids in the Lachlan Belt, based on the variation of P_2O_5. The same authors explain this variation by derivation from different melts. Phosphorus is insoluble in melts of quartz and feldspar. Magmas which do not contain restites and have contents of Cr, Ni, Mg and P relatively close to nil, are called minimum melts. White and Chappell (1983) point out that the mineralogical composition of the residues must be calcic-plagioclase, orthopyroxene and clinopyroxene in order to allow most of the interstitial water to be incorporated into the melt. The relative enrichment of P_2O_5 would indicate an origin from non-minimum melts. The P_2O_5 content in rocks formed from minimum melt display minimum variation with the silica content while rocks formed from non-minimum melts vary steadily with the silica content as shown in figures 10 and 11 (White and Chappell, 1977). The minimum melt residue probably will contain amphibole and biotite with F and Cl as substitutes of OH^-. Table 9 shows the main characteristics of the I-type granites.

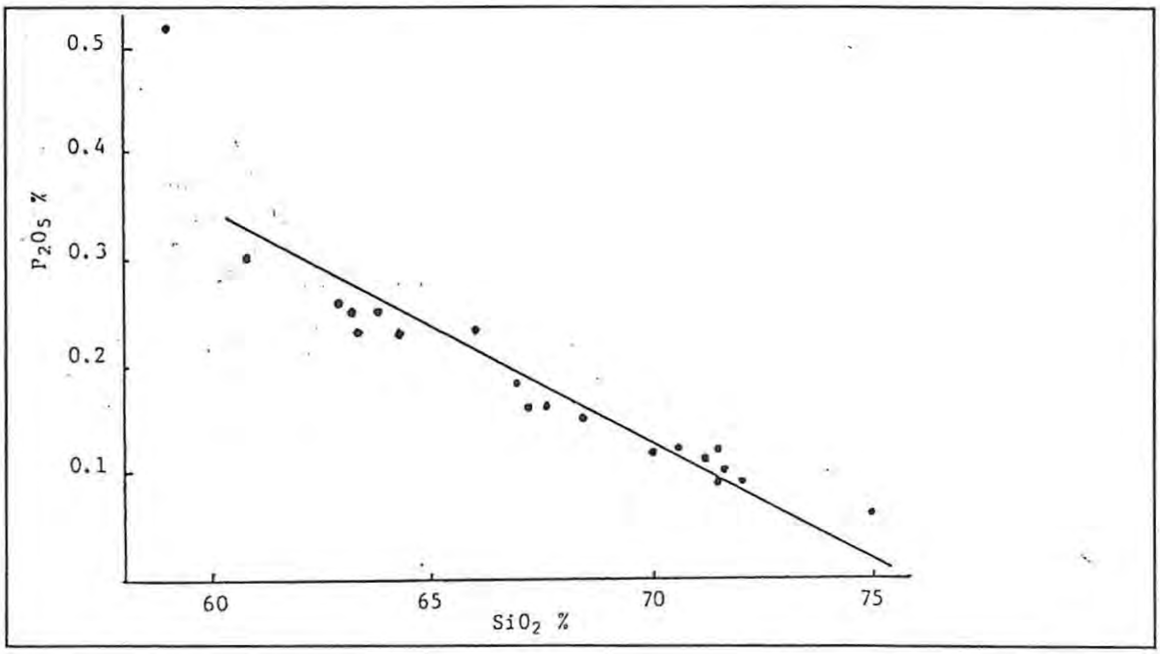


Figure 10 P_2O_5 vs SiO_2 variation diagram for various granitoids of the Moruya Suite formed from non-minimum melt (after White and Chappell, 1977).

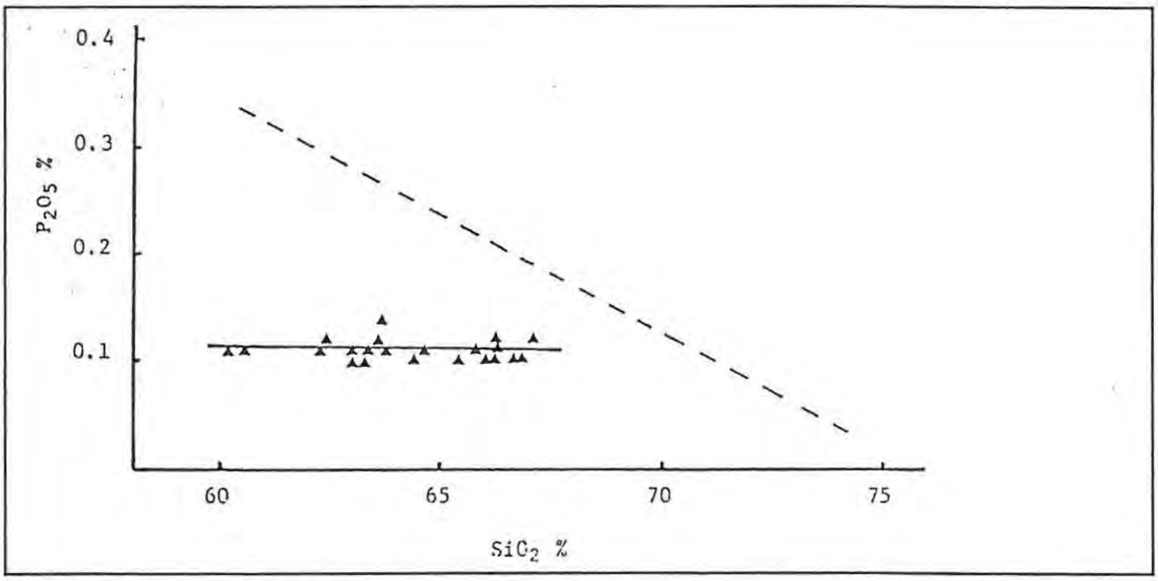


Figure 11 P_2O_5 vs SiO_2 variation diagram for I-type granitoids of the Jindabyne Suite of the Kosciusko Batholith formed from minimum melts (after White and Chappell, 1977).

Table IX Geochemical characteristics of I-type granitoids

PARAMETER	CHARACTERISTIC VALUE	EXPLANATION
SiO_2	Wide range 53-76%	Relatively mafic source rocks
K_2O/Na_2O	Low	Na has not been removed by weathering
K_2O/SiO_2	Variable	Derived from sources rocks of moderate and variable K-content
Ca	High in mafic rocks	High Ca in source; not removed by weathering
$\frac{Al_2O_3}{Na_2O+K_2O+CaO}$	Normally low	Only minimum temperature melts or fractionated I-type rocks may be peraluminous
Fe^{3+}/Fe^{2+}	Moderate	
Cr and Ni	Low	Source rocks relatively low in Cr and Ni, indicating prior fractionation
$\delta^{18}O$	Low	Primary igneous source rock
$^{87}Sr/^{86}Sr$	Generally low	Mantle-derived igneous source rocks. Some high values for granitoids derived from old source rocks with high Rb/Sr

6.5.Differences between I-type and S-type granites

The Kosciusko Batholith has some geochemical differences that cannot be explained by a model of melting of igneous or sedimentary rocks (Hine et al., 1978). These different characteristics are:.

- S-type granitoids have, on average, higher SiO_2 content than I-types;
- Fe, Mg, Ti, Sc, V, Cr, Co and Ni have a negative correlation with silica in S-types granitoids;
- Barium has a negative and a positive correlation with SiO_2 in the S-types and the I-types respectively;
- Rb, Th and U are enriched in the S-types when compared with I-types at similar SiO_2 contents;
- La, Ce, Nd and Y behave similarly;
- S-type granitoids display a strong negative correlation between Zn and SiO_2.
- A plot of Zr versus Ti may discriminate between the two

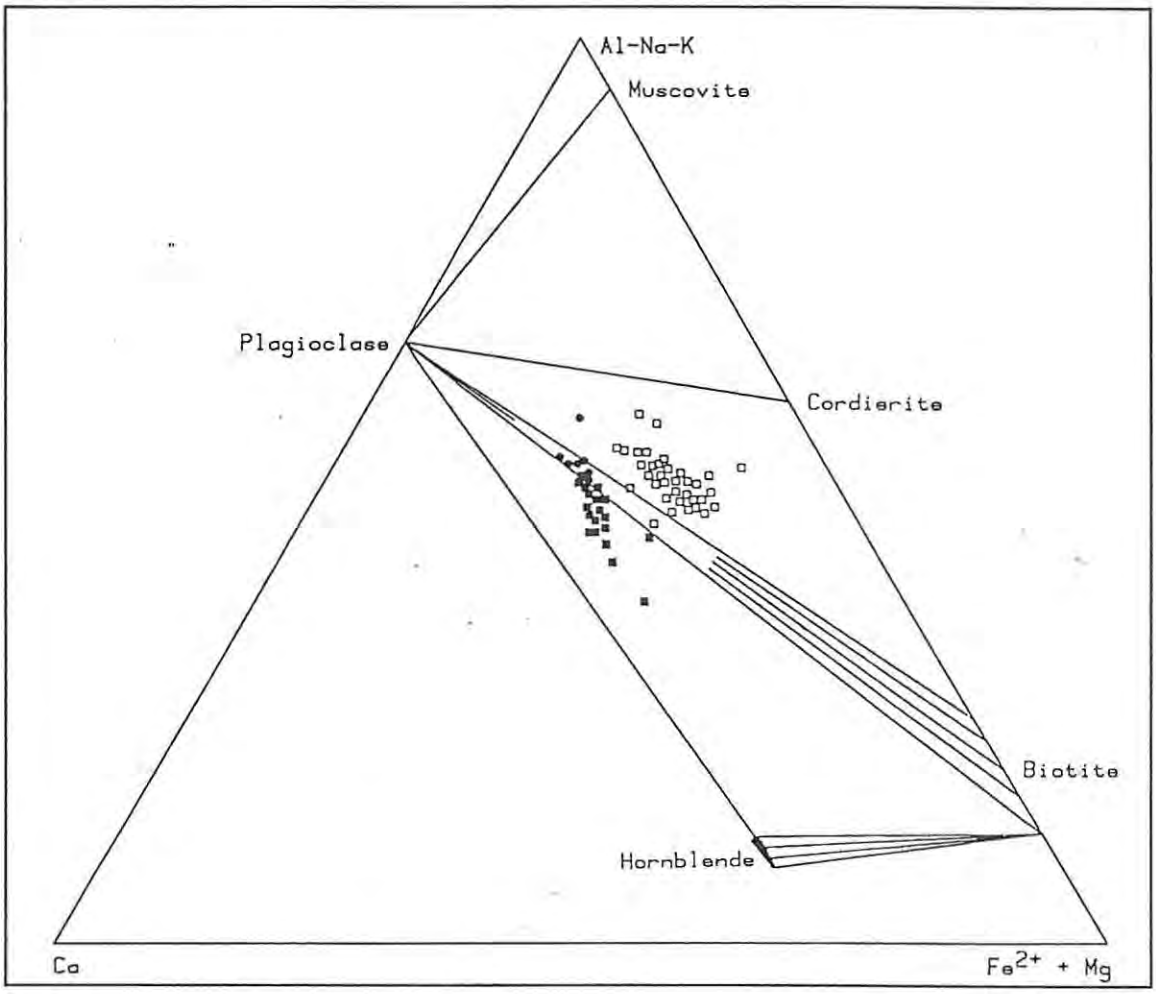


Figure 12 Compositional differences between the KosciusKo granitoids. Open squares are S-Types, filled squares are hornblende I-types, and filled circles are hornblende free I-type (after Hine et al., 1978).

granitoid types.

The different Na content and its relationship with Al, K and Ca will determine the differences in the mineralogy of the various granitoids (Hine et al., 1978) (figure 12).

White and Chappell (1983) point out that there is a tectonic lineament which separates the I-type granitoids of the eastern part of the Lachlan Fold belt, from the S-types in the western part of the belt. Furthermore, the S-type granites are formed in continental collision zones while the

I-type granitoids are formed in subduction zones. this is the case in south-east Asia, i. e. Malaysia, Thailand and Indonesia (Hutchinson, 1983; Suensilpong et al., 1983).

Figure 13 displays the spatial distribution of the S-type and I-type granitoids in south-east Asia. Cobbing et al. (1986) recognise four distinct granite provinces in south-east Asia, each one characterized by different mineralization styles as described below:

- The S-type granites of the Main Range are mainly of Triassic age and the mineralization occurs in endogenous greisen-vein swarms of cassiterite and wolframite.
- The eastern province contains magnetite-cassiterite skarns and also localized base-metal and antimony mineralization associated with I-type granitic plutons of Permo-Triassic age (Huntchison, 1983).
- The western province is formed by I-type and S-type granitoids of Cretaceous age and the mineralization occurs as greisen bordered vein swarms and pegmatites of cassiterite and wolframite.
- The North Thailand province is characterized by S-type granites associated with migmatitic terrain. The ore deposits in the North Thailand province are endogenous greisen vein, skarn replacement scheelite, and fluorite deposits which contain accessory cassiterite. Cobbing et al. (1986) suggest that the migmatite are contemporaneous with the S-type granitic plutons of Triassic age.

Cobbing et al. (op. cit.) classify the Main Range province granitoids as syn-collisional granites and the Eastern province as volcanic arc granitoids according to the tectonic classification suggested by Pearce et al. (1984).

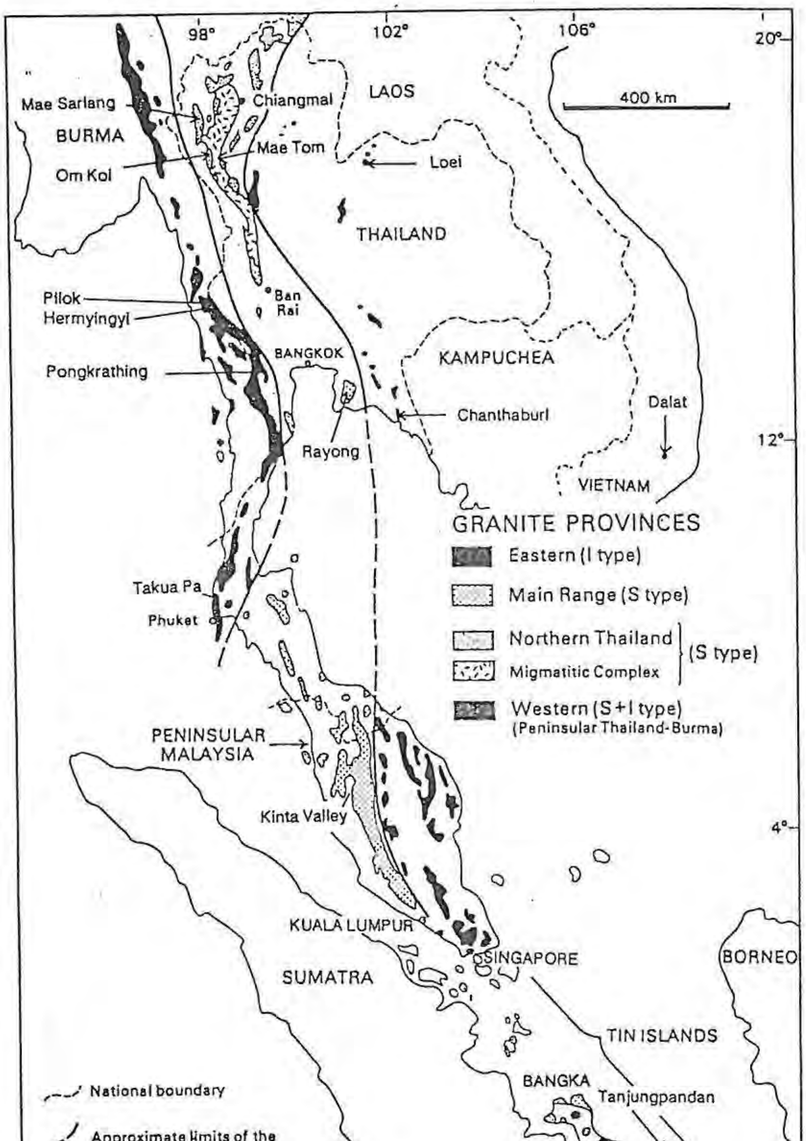


Figure 13 Spatial distribution of the granite provinces in the SE Asian tin belt (after Cobbing, 1986).

Chappell et al. (1988) suggest that the differences in composition, tectono history and metallogenic pattern in the Lachalan Fold Belt is not only because different tectonic processes but also the compositional heterogeneity of the lower crust. This heterogeneity delineate geological provinces. They defined the granitic provinces in the Lachlan Fold Belt according to the following characteristics:

- chemical compositions of provinces vary regionally;
- within the provinces the chemical compositions have a constant pattern;
- the existence of discrete tectonic terrains with different geological histories;
- distinction of granitoids in S- and I-type with further subdivision into petrological suites and supersuites;
- similar isotopic composition within a province, but different between provinces;
- I-type granites occur mainly in the eastern parts and S-type granites are mainly in the western parts of the Lachlan Fold Belt.

Chappell et al. (op. cit.) recognise ten granitic provinces and denominated them as: BaBT = Bathurst, BeBT = Bega, KBT = Kosciusko, WBT = Wagga, HBT = Howqua, MBT = Melbourne, SBT = Stawell, GSBT = Grampian-Stavely, BnBT = Bassian and TBT = Taswegia. Figure 14 displays the regional distribution of the granitic provinces. The Taswegia Terrane in western part of Tasmania and the Grampians-Stavaley Terrane in western Victoria, Australia, are considered by the authors as representative of granitic provinces that are associated tectonically with the other eight provinces of the Lachlan Fold Belt.

The distinct granitic provinces have contrasting metallogenic affinities. The Taswegia Terrane is highly mineralized with Sn, W, and base metal deposits and the Boggy Plain Supersuite

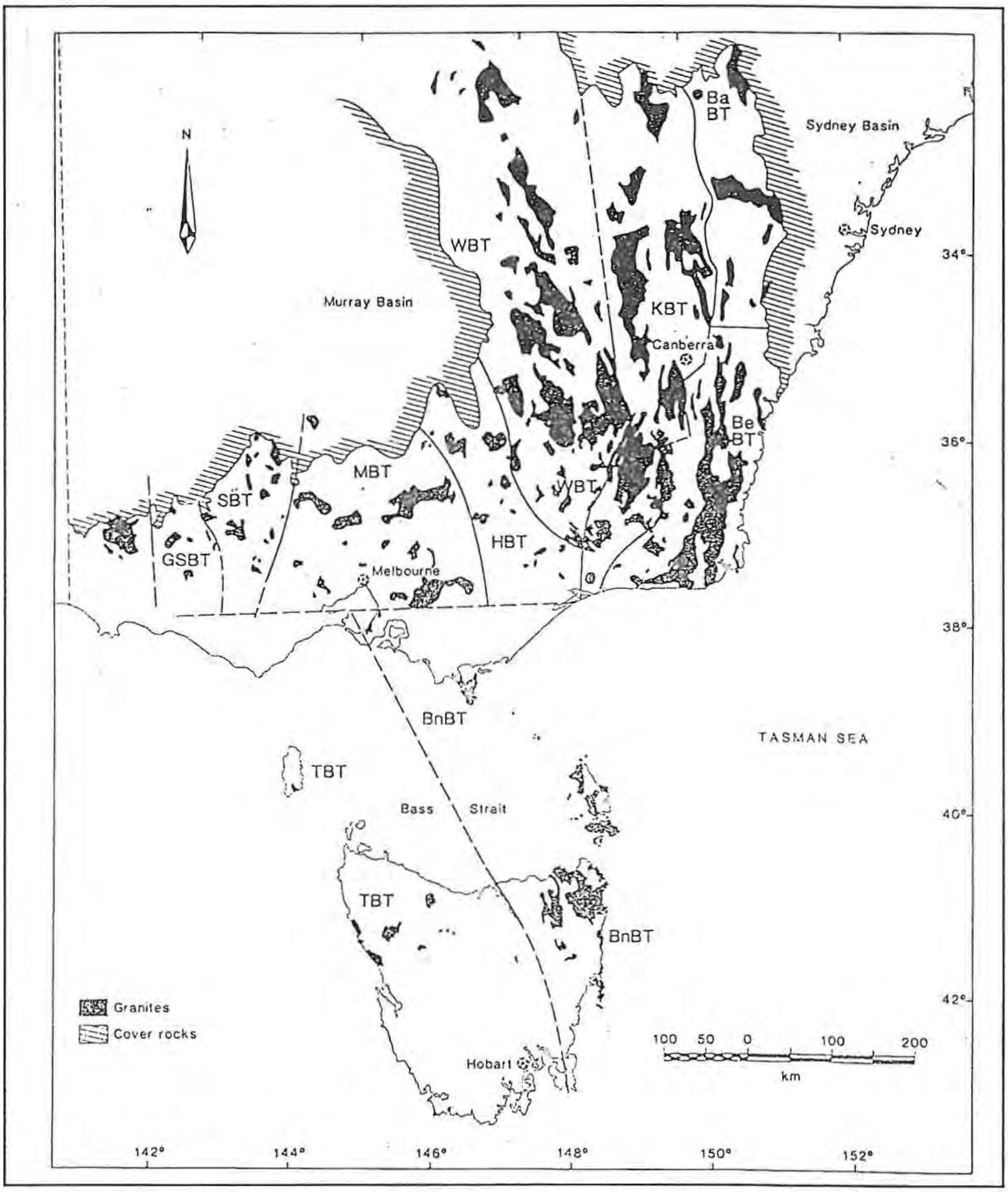


Figure 14 Map showing the distribution of the granitic provinces in the Lachalan Fold Belt. Full lines are the proposed boundaries between provinces and broken lines are the suggested location of such boundaries (after Chappell et al., 1988).

have associated Cu, Au and W mineralization (Chappell et al., 1988; Suppel and Scheibner, 1990; Ramsay and VandenBerg, 1990). They interpret the distinct regional geochemical pattern of the granitoids as product of regional compositional differences in the lower crust.

6.6. A-Type granites

A-type granitoids are formed in anorogenic environments and display distinct geochemical features (Loiselle and Wones, 1979). Those granites often have a composition similar of alkaline granites. Bonin (1986) claims that the origin of A-type granite lies in the mantle.

The granitoids which White and Chappell (1983) studied and defined as A-type are characterized by annite biotite, arfvedsonite amphibole and fluorite. Some textural features like miarolitic cavities and granophyric intergrowths indicate the epithermal conditions of the intrusion. A-type granitoids include the hypersolvus granites (Bonin, 1986).

Collins et al. (1982) point out that A-type granites are enriched in large and highly-charged cations like Ga, Nb, Sn, Zr and REE. They also claim that a high Ga/Al ratio is diagnostic and discriminate them from the I-type granitoids. The A-type rhyolite usually erupts as lava flow while the I-type and S-type rhyolites erupt as ash-flows or lava domes. This indicates that the viscosity of the A-type magma is low and that it is favourable for crystal settling and convection currents within the magma chamber (Collins et al., 1982).

The A-type granitoids in the Lachlan Belt are associated with some gabbroic rocks. Intermediate rocks are absent (White and Chappell, 1983). The A-type granites occur in the late stages of the magmatic history of a region. A-type granitic batholiths have a similar size to the I-type ones, and usually do not show compositional variation over vertical distances up to 450m (White and Chappell, 1983). This suggests that the production of A-type magmas is much deeper than epizonal settings.

The chemical analyses of average A-type granitoids display some characteristics dictated by the quartz-feldspar-liquid eutectic, like:

- high SiO_2, Na_2O, K_2O and
- low in Al_2O_3, MgO and P_2O_5.

This may be formed by partial malting of SiO_2 rich mafic rock or by extreme fractionation of basaltic magma. The A-type granitoids are enriched in Rb, Ba, Zr, Y, Nb, light REE, Ga and F which are incompatible with the major mineralogical phases of basalts (Bonin, 1986). Schilling et al. (1980) point out that tholeiitic melts may contain 200-500 ppm of fluorine. The incompatible elements in A-type magma are enriched in this kind of melt until the SiO_2 content reaches 74% (Turner et al., 1992; Whalen et al., 1987).

The I-type and S-type granitoids have an earlier accessory mineral saturation than the A-type ones. It is probably caused by the higher T, low water content and higher F content of the latter. Clemens et al. (1986) point out that the experimental data of the Water-gums granite (A-type) in the Lachlan Belt, demonstrate that the mineral assemblage can be reproduced only with temperatures above 900^0C and 2,2 to 4 wt.% of water.

White and Chappell (1983) favour a hypothesis that an anhydrous, F and Cl rich magma is the source of these granitoids. They also suggest that this anhydrous source was depleted in water to form a precursor I-type granitoid melt that evolved to produce A-type magmas as manifestations of late stage magmatic activity.

Collins et al. (1982) suggest that A-type granitoids would be the product of residual melts which previously formed the I-type granitoids. The residual source would be enriched in F, which might be within the biotite and hornblende structure substituting with the OH^- in their structure. Creaser et al. (1991) suggest that a residual source is unlikely to generate a partial melt with the appropriate major elements characteristics. The rock source could be a residual felsic granulite (Collins et al., op. cit.). Creaser et al. (op. cit.) suggest that the A-type granites can be derived from partial melting of crustal igneous rocks of tonalitic to granodioritic composition. They also indicate that those rocks do not need to undergo a previous melt generation and do not require granulite metamorphic facies for melt generation. Creaser et al. (op. cit.) based their concepts in the following:

- Source rocks of tonalite to granodiorite composition are geochemically more evolved than sources of I-type granites (the basaltic to tonalitic sources).
- Melts formed from vapour-absent partial melting of leucotonalites and granodiorite which are not metamorphosed to granulite facies, have a low water content.
- In modern environments of continental extension, the lower and middle crust have very high geothermal gradients. Calculated temperatures of 900^0 - 950^0C are ideal for the formation of A-type granites (Creaser et al., 1991; Ruttler and Wyllie, 1988).
- F partitions into the melt. A source with 400 to 800 ppm F will concentrate up to 3200ppm in the melt with partial melting of 25wt% (Clemens et al., 1986).
- The high content of Ba and Pb in A-type granites can be explained by the composition of the potassic phases, alkali feldspar and biotite. These minerals can have in their crystalline structure considerable amounts of Ba (both phases) and Pb (alkali-feldspar only). Ba and Pb may be

scavenged from the source rocks during the partial melting process.

- The high heat necessary to form melts from vapour-absent partial melting of tonalitic-granodioritic rocks (900 - 950^{0}C) may be explained by the dual association of A-type granites with mafic igneous rocks. The A-type granitoids would be formed from high temperature, mantle magmas which might intrude at lower and middle levels of the crust.

Turner et al. (1992) suggest that there is more than one mode of origin for A-type magmas. They suggest that the A-type granites of Padthaway Ridge, South Australia, are the product of fractionation of a basaltic parental magma.

Table X summarize the geochemical characteristics of the A-type granitoids.

Table X Geochemical characteristics of A-type granitoids (after, White and Chappell, 1983).

PARAMETER	CHARACTERISTIC VALUE	EXPLANATION
SiO_2	Usually high, often near 77%	Small degree of partial melting
Na_2O	High	Small degrees of partial melting
CaO	Low	Small degree of partial melting, Ca not compatible with melt structure
Ga/Al	High	Ga complexed in melt, plagioclase in residue
Y and REE	High except Eu	Complexed in melt, with much Eu remaining in anorthite
Nb and Sn	High	Complexed in melt
Zr	Normally high, particularly in more mafic varieties	Complexed in melt
F and Cl	High	Source rock is a residue from an earlier melt and is rich in F and Cl

6.7.M-Type Granites

Pitcher (1982) suggested that the granitoids formed in oceanic island arcs should be called M-type granitoids. This is because they are formed by mantle sources without or with the least possible contamination from crustal material. In the Aleutian arc there are zoned quartz diorite plutons with gabbros forming the periphery of the plutons. The quartz diorites are augite bearing (Perfit et al., 1980).

Perfit and Lawrence (1979) point out that Captain Bay pluton, in the Aleutian Islands, has variable initial strontium ratios. They suggest that this is inherited from the magmatic source. The initial $^{87}Sr/^{86}Sr$ ratios are very low (0.70377) and $\delta^{18}O \leq 6.0$ are the same as the volcanic rocks associated with the quartz diorites (Perfit et al., op. cit.). Pitcher (op. cit.) suggests that M-type granitoids are probably the product of fractional differentiation of similar Al-rich basaltic magma from which the volcanics where derived.

The M-type granitoids have similar geochemical features but more primitive compositions compared to the I-type granitoids (Pitcher, 1982). Whalen (1985) describes the Uaisilay plutonic complex of New Britain, in New Guinea, noticing the following characteristics are similar to those described by Pitcher (1982):

- plagiogranite subordinated to gabbro;
- hornblende, biotite and pyroxene as mafics;
- interstitial K-feldspar.

6.8.Magnetite series - Ilmenite series

Ishihara (1977) classifies the Japanese granitoids according to magnetic susceptibility, which is basically dependent on the presence or absence of magnetite. The state of oxidation controls the formation of magnetite and ilmenite rather than the chemical composition. The control of fO_2 in those granitoids is possibly the dissociation of H_2O in the hydrous magma for the magnetite-series, and the assimilation of crustal carbon for the ilmenite-series (Ishihara, 1981).

The ilmenite-magnetite series show spatial and temporal variations in the Circum-Pacific orogenic belt. Ishihara (1981) notices that the magnetite series is generally, younger than the ilmenite series and both vary their relative geographical positions to the continent coast. In Japan the magnetite series occurs near the marginal sea and the ilmenite series occurs toward the back-arc basin. In western American continent the ilmenite occurs close to the continental margin (Ishihara, op. cit.). Ishihara (op. cit.) proposes that the magnetite-ilmenite series classification can be extended to the anorogenic granites.

The magnetite series can be distinguished from the ilmenite series over the entire SiO_2 content range of the granitoids. The two series have distinct Fe_2O_3/FeO ratios which reflect the state of oxidation during granitoid crystallization (Ishihara, 1981). Figure 15 shows the modal opaque minerals (vol. %) versus the modal K-feldspar+quartz (vol %) and in figure 16, the modal opaque minerals (vol. %) is plotted versus the magnetic susceptibility.

The ilmenite series have up to 0,1 vol.% of opaque minerals and magnetic susceptibility of 1×10^{-4} emu/g. This values above discriminates between both series where lower values represent ilmenite series and higher values the magnetite series (Ishihara, 1981). The magnetite series has an opaque content as much as 5% in some quartz gabbros and magnetite usually makes up more than 90% of the opaque oxides (Ishihara, 1977). The other opaque minerals in the magnetite series are usually pyrite, ilmenite and rarely chalcopyrite. The ilmenite series generally has a low opaque mineral content. However, some gabbros can contain as much as 4% opaque minerals, other opaque minerals are pyrrhotite, arsenopyrite in tin granites of the Japanese tin-belt and rarely graphite (Terashima and Ishihara, 1976). Ishihara (1981) also points out that epidote and sphene are commonly associated with the magnetite series while monazite and garnet are usually associated with the ilmenite series.

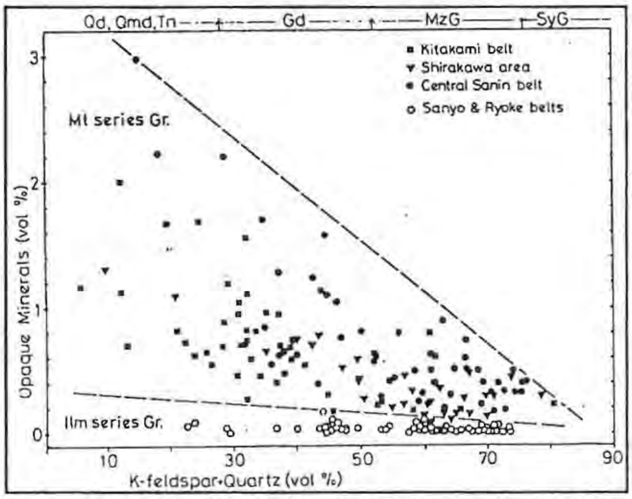


Figure 15 Modal opaque minerals vs K-feldspar+quartz for some japanese granitoids (after Ishihara, 1981).

The differences in fO_2 between the two series also influence the Fe/(Fe+Mg) ratios of biotite and amphiboles (Ishihara, 1977). The magnetite series has a lower ratio because it has a bigger opaque mineral content than the ilmenite series thus reducing the total Fe available to the ferromagnesian silicates. The Fe/(Fe+Mg) decreases with the increase in SiO_2 in the magnetite series. In the ilmenite series, the ratio increases with increasing SiO_2. Figure 17 shows the refraction index of the biotite in magnetite series granitoids. Ilmenite series have a higher refractive index than the magnetite series. This indicates that the refractive index of biotite is affected by its chemical composition which is influenced by fO_2 (Ishihara, op. cit.).

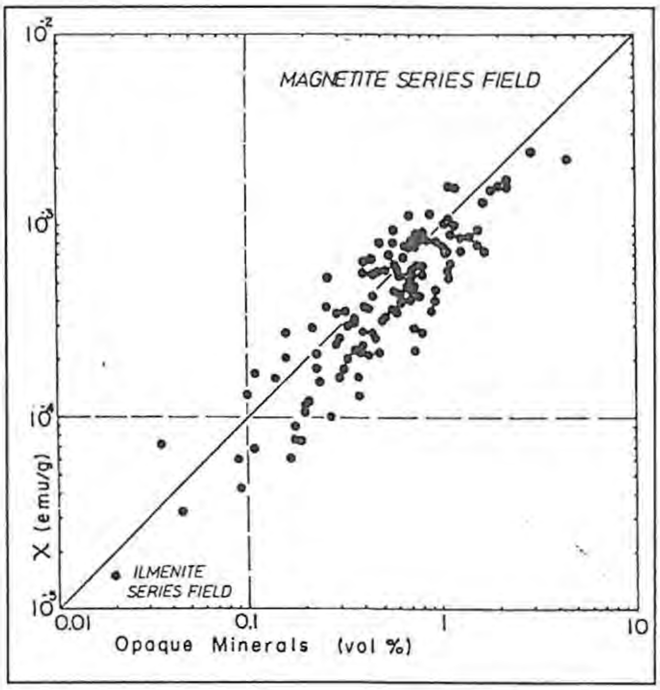


Figure 16 Modal opaque minerals vs magnetic susceptibility of some japanese granitoids (after Ishihara, 1981).

Tischendorf (1977) points out that the lithophile elements like F, Rb, Li, Pb, Sn and Be are enriched in tin granites. Ishihara (1981) claims that these elements have positive correlation with the differentiation index in magnetite series. The ilmenite series has a higher F content and a lower Cl content than magnetite series. The two series may be distinguished by the ratio F/Cl=3 i. e. >3 = ilmenite series (Ishihara and Terashima, 1977). Terashima and Ishihara (1980) suggest that the granitoids which contains minerals like fluorite, topaz and halite (in fluid inclusions) are related to tin, fluorite and base metal mineralization respectively.

Sassaki and Ishihara (1979) point out that the magnetite series have different δ^{34}S (+1 to +9°/$_{oo}$) to the ilmenite series δ^{34}S (-11 to + 1°/$_{oo}$). The same authors suggest that the differences of sulphur isotope data are due to their different magma source respectively. Sasaki and Ishihara (op. cit.) point out that the magnetite series have consistent values of S content while the ilmenite series S content vary. Sulphur in the magnetite series occurs in the oxidized forms and is concentrated in the aqueous phase while the ilmenite series contains sulphur in the reduced form that partitions into the silicate melt (Ishihara et al., 1988).

Ishihara (1978) considers that most of the Japanese granites are the product of one the magmatic processes listed below:

- mixing of mantle derived mafic magma with felsic magma derived from sialic crust;
- intermediate magma formed from igneous and sedimentary rocks in the lower crust.

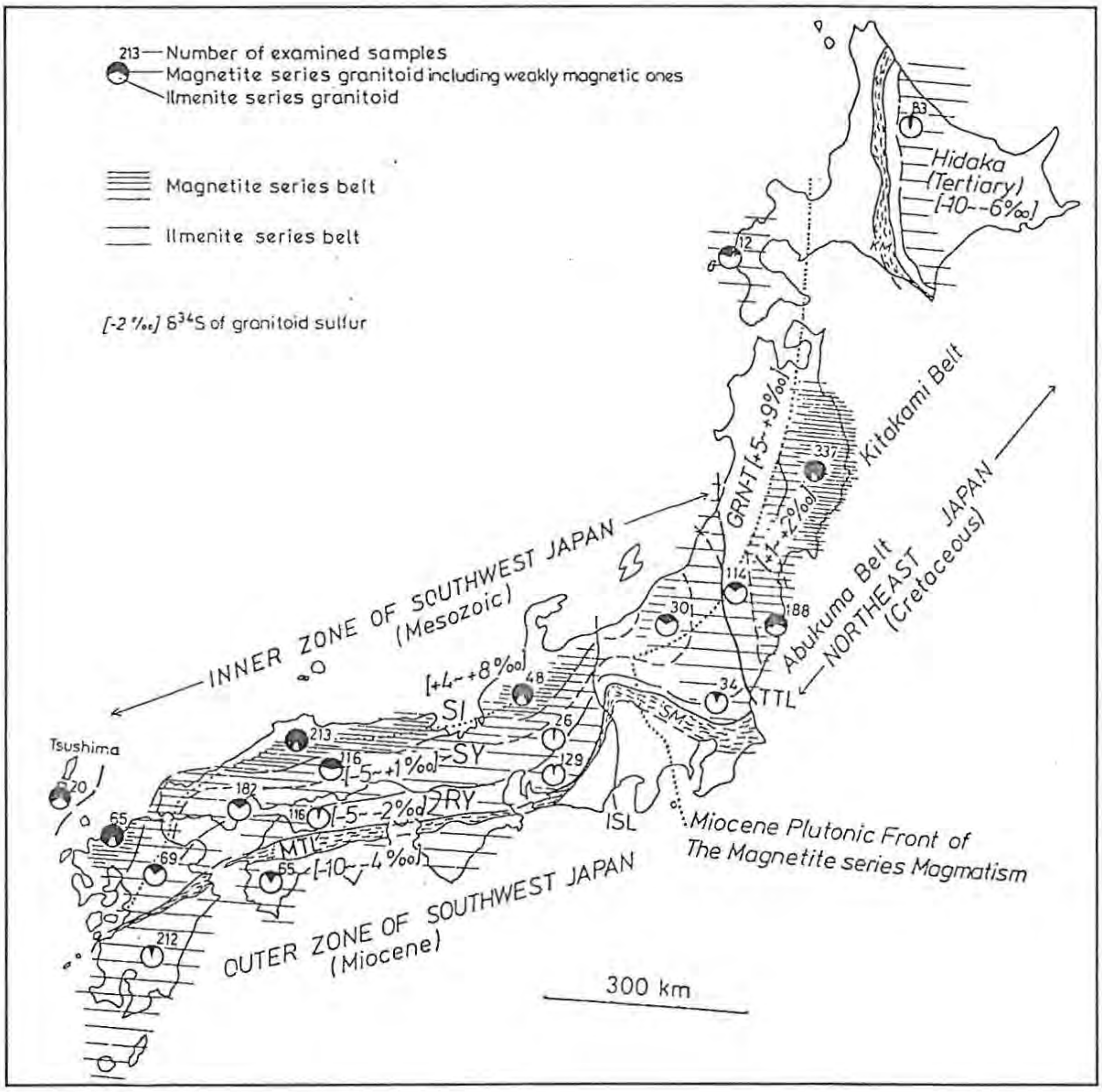


Figure 17 Distribution of the magnetite series and ilmenite series granitoids, and $\delta^{34}S$ data of the japanese granitoids (after Ishihara, 1981).

Ishihara (1978) suggests that a small portion of the Japanese granitoids are formed from carbon bearing meta-sediments. Shibata and Ishihara (1979) point out that the initial $^{87}Sr/^{86}Sr$ ratios of the Japanese granitoids vary between 0,7037 to 0,7124. Within this range there are two groups divided by the value 0,706. The low value group (< 0,706) is considered by Shibata and Ishihara (op. cit.) as the product of mantle derived magmas with some contamination by crustal rocks. The group with the high initial strontium ratio values (> 0,706) could have been formed by anatexis of crustal material. The magnetite series has on average lower initial $^{87}Sr/^{86}Sr$ ratios than the granitoids of the ilmenite series.

Figure 17 displays the spacial distribution of the magnetite series and the ilmenite series and their respective sulphur isotopic ratios. The magnetite series occurs mainly in the south-west and north-east of the Japanese islands while the ilmenite series dominate the other regions.

Magnetite series are younger than the ilmenite series (Ishihara, 1978). Figure 18 shows the age variation in the inner zone, Chugoku batholith, south-western Japan. The younger magnetite series granitoids contain Mo mineralization. The older granitoids of the weakly magnetic magnetite series and the ilmenite series contain W-Sn mineralizations (Ishihara, 1978). Ishihara (1981) points out that the older rocks

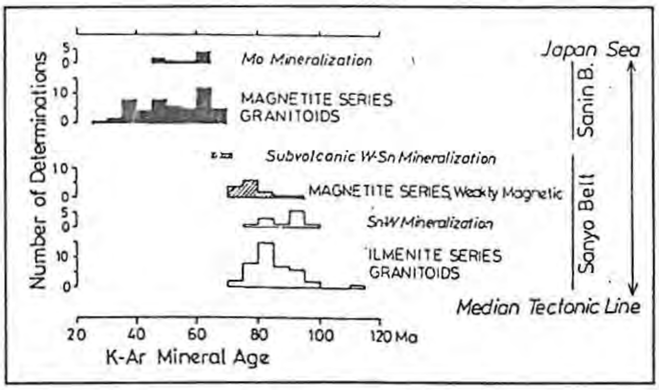


Figure 18 Histograms of K-Ar mineral ages of the Cretaceous-Palaeogene granitoids of the Chugoku batholith (after Ishihara, 1981).

(ilmenite series) are more felsic than the magnetite series, indicating that the ilmenite series is formed from an earlier magma. The magnetite series/ilmenite series ratio seems to increase from the Cretaceous onward (Ishihara, 1978).

Ishihara (1981) suggests that the eastern Asian continental margin and the Japanese Islands have similar patterns of occurrence of magnetite series-ilmenite series granitoids.

6.9.Petrogenetic classification of granitoids

Barbarin (1990) revised the twenty most common classifications of the granitic rocks. He suggests that the granitoids can be grouped according to the original petrogenetic source as either continental crust, mantle, or hybrid magmas. Subdivisions in the classification are based on tectonic setting of magma generation and emplacement.

Barbarin (op. cit) proposed that the granitoids are named primarily by the origin of the magma, viz., C-group, the exclusively crustal orogenic granitoids, H-group, a hybrid magma formed by mixing of crustal anatexis and mantle magma, and a T- or A- group, those formed exclusively by mantle magmatism. The T-group are the tholeiitic series granitoids (Lameyre and Bowden, 1982) and the A-group is the A-type granitoids (Loisele and Wones, 1979; Collins et al., 1982).

The crustal granitoids can be subdivided into three different types:

- C_{st} = crustal shearing and thrusting group, which are usually leucogranite and granites. They contain abundant tourmaline, muscovite and apatite with relatively minor biotite and garnet. They are peraluminous and have a low Ca content and the strontium isotope composition data have a very wide range. The $\delta^{18}O$ ($^{\circ}/_{\circ\circ}$) is +10 to +14.

- C_{CA} = crustal collisional autochthonous group, which generally consist of biotite-rich and alumina silicate bearing leucogranites to granodiorite with associated migmatite and abundant restites. They contain abundant biotite, cordierite, apatite, and frequent muscovite, zircon, monazite and garnet. The initial strontium isotopic ratios are higher than 0.715 and the $\delta^{18}O$ ($^{\circ}/_{\circ\circ}$) are +10 to +13.
- C_{CI} = crustal collisional intrusive group, which has similar characteristics to the C_{CA}. They are less peraluminous than the autochthonous variety and the initial $^{87}Sr/^{86}Sr$ ratios tend to be more primitive. They have a lower content of the muscovite, cordierite, garnet than C_{CA} granitoids. The bulk chemical composition is more potassic than the other crustal granitoids.

The mantle derived granitoids are members of the alkaline and tholeiitic series of the Lameyre and Bowden (1982) classification and could be classified as A-type and M-type granitoids of White and Chappell (1983) classification respectively. They are formed in anorogenic environments or in island arcs and have the following characteristics:

- A = alkaline group; they are formed in anorogenic environments associated with extensional tectonism. They consist mainly of alkali feldspar granites, syenogranites, and quartz syenite. Associated rocks are usually syenite, gabbros and alkaline lavas and rhyolite. Their mineralogy is characterized by the presence of alkali amphiboles and more rarely alkali pyroxene and abundant zircon, apatite and allanite. These above features are similar to the A-type granitoids described in the previous section.
- T_{OR} = tholeiitic oceanic ridge group is formed in an anorogenic environment but is compositionally distinct from the other anorogenic granites. These granitoids are primarily plagiogranites, and secondarily tonalites and trondjemites. The mineralogical composition is given by

abundant hornblende and pyroxene. It is also worthy to note the relative abundance of magnetite relative to the ilmenite content.

- T_{IA} = Tholeiitic island arc group; this group has similar characteristics to the continental arc calc-alkaline granitoids (H_{CA}).

Barbarin (op. cit.) divided the hybrid or mixed origin granitoids into two groups, viz., low K - high Ca, and high K - low Ca granitoids. The low K - high Ca has similar characteristics to T_{IA} and may be related to calc-alkaline trondhjemitic and granodioritic compositions. The high K, calc-alkaline granitoid are relatable to the calc-alkaline monzonitic of the Lameyre and Bowden (1982) classification. The two subdivision are:

- H_{LO} = hybrid late orogenic group; the composition of these granitoids consists of monzogranites, granodiorite and quartz diorites. They are commonly porphyritic. Their mineralogy consists of abundant biotite, zircon, allanite and sphene; the aluminous minerals like cordierite and sillimanite are absent. The granitoids of this group are emplaced during the earlier stages of post-orogenesis.
- H_{CA} = hybrid continental arc group; this group is formed by granodiorites, tonalites and gabbros. Granites sensu stricto, have a limited participation. The volcanics associated with the group, are andesite and dacite. They may contain a large proportion of mafic, mantle enclaves that may present evidence of magma mixing. The dominant mineral assemblage contains abundant amphibole, pyroxene and biotite. The typical trace minerals are apatite, zircon, sphene and allanite. The proportion of magnetite indicated by Barbarin (op. cit.) suggests that it is possible to correlate this group with the magnetite series proposed by Ishihara (1977, and 1981). The isotopic data like the initial strontium ratios (0.706 to 0.708) and $\delta^{18}O$ ($^{\circ}/_{\circ\circ}$) values (+5 to +10)

indicate an igneous source.

The petrogenetic classification is summarized in the table XI, where the origin and the tectonic setting of the various granitoid types are shown.

Table XI Petrogenetic classification of the granitoids (after Barbarin, 1990).

Origin	Granitoid Types		Tectonic Setting	
Crustal origin Peraluminous rocks	intrusive two mica leucogranites	C_{ST}	Collision or Post-collision zones	Orogenic granitoids
	peraluminous autochthonous granitoids	C_{CA}		
	peraluminous intrusive granitoids	C_{CI}		
Mixed origin Metaluminous or calc-alkaline rocks	potassic calc-alkaline granitoids (high K - low Ca)	H_{LO}		
	calc-alkaline granitoids (low K - high Ca)	H_{CA}	Subduction zones	
Mantle origin Tholeiitic, alkaline or peralkaline rocks	island arc tholeiitic granitoids	T_{IA}		
	midocean ridge tholeiitic granitoids	T_{OR}	Rifting or Doming zones	Anorogenic granitoids
	alkaline and peralkaline granitoids	A		

7. Economic geology of the granitic series

Lameyre et al. (1982) recognize the following ore associations (figure 19):

- massive sulphide deposits are associated with the tholeiitic and trondhjemitic series;
- Cu, Cu-Mo porphyries are related to the calc-alkaline trondhjemitic and granodioritic series but Mo porphyries are related to the calc-alkaline monzonitic or sub-alkaline series which are also rich in U and Th;
- Th, Y, REE, Zr and Mo are enriched in the alkaline series;
- and the W, Sn, Nb, U, Y and REE have economic mineralization in the mobilizate granitoids.

7.1. Economic geology of the magnetite and ilmenite series

Ishihara (1981) suggests that the proportion of magnetite to ilmenite within each series might be the essential factor controlling the distribution and zoning of associated mineralization. The same author made distinctions between three tectono-geographic regions:

- Magnetite series/ilmenite series terrains: inner zone of south-western Japan, south-eastern China and the southern Korean peninsula.
- Magnetite series terrains: Green Tuff belt and Chilean Andes.
- Ilmenite series terrains: Malay peninsula, outer zone of south-western Japan.

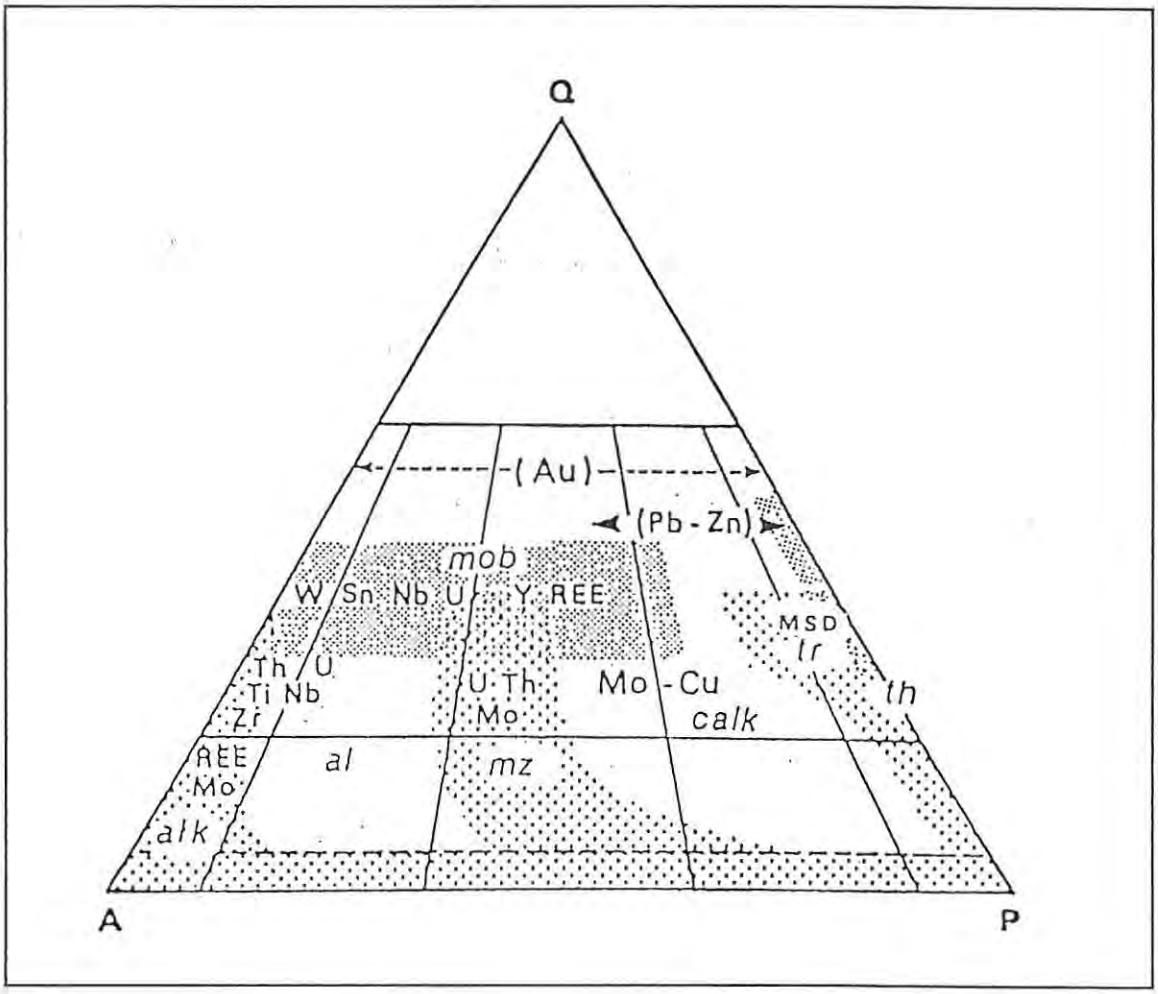


Figure 19 Fields of the granitic series and the associated mineralizations.th=tholeiitic; tr=trondhjemitic; calk= granodioritic; al= aluminous alkaline granitoids; mob= mobilizated; MSD= massive sulphide deposits, (after Lameyre, 1987).

7.1.1. Magnetite series and ilmenite series terrains

The Cretaceous magmatism in the inner zone of south-western Japan, the magnetite series of the Sanin belt, contains a Mo(Pb-Zn) province and the ilmenite series of the Sanyo belt, yields a W-Sn-Cu province. According to Shimazaki (1980) this indicates different fO_2 conditions within the granitic magmas with the liberation of ore-bearing solutions vital to the formation of the metallogenic provinces. Sn and W are associated with ilmenite series in the Miocene outer zone,

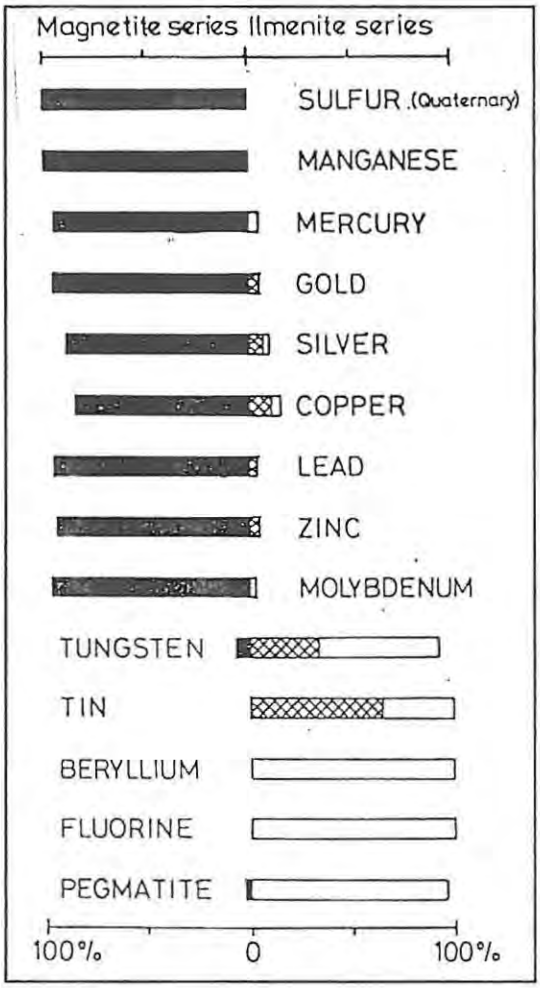


Figure 20 Proportion of the mineralizations in Japan as classified as magnetite series/ilmenite series. Solid part-magnetite series, shaded-weakly magnetic magnetite series, and open part-ilmenite series (after Ishihara, 1981).

south-western Japan and the magnetite series has associated Au and base metal sulphide mineralization in the Green Tuff belt, inner zone. Ishihara (1981) concludes from this pattern that major sulphide mineralization is associated with the magnetite series and Sn and W are related to the ilmenite series. Figure 20 displays the relative proportion of different mineralization to magnetite and ilmenite series in Japan.

In southeastern China the deposits of wolframite-quartz and tin, beryllium and Nb-Ta mineralizations are related to Jurassic granites of the ilmenite series (Ishihara, 1981). There is a further group of granites in southern China which has associated Cu-Mo porphyry and skarn deposits related to high level mafic to intermediate plutonism of the magnetite series (Ishihara, op. cit.).

7.1.2. Magnetite series terrains

Granitic terrains containing only the magnetite series or ilmenite series, do not display distinct zonation across the belt (Ishihara, 1981). Ishihara and Ulriksen (1980) point out that Jurassic and later granitoids of the central Andes seem to be members of the magnetite series. There is a zonation of the mineralization from the coast to the interior of Chile, i. e., Fe-Cu, Au-Mo, Cu-Pb-Zn-Ag and Sn(W-Ag), respectively (Sillitoe, 1976). Ishihara (1978) also notices that the Green Tuff belt in Japan does not show lateral variation. However, this has a variable base metal ratio in a north-south direction. The Quaternary sulphur and pyrite mineralizations have a concentration peak along the volcanic belt that decreases toward the Japan Sea (Ishihara, 1981). The sequence of mineralization from the volcanic arc toward the sea margin is Cu, Pb-Zn, and Au-Ag. This is thought to be due to the regional temperature gradients associated with granitic magma or ore solutions (Ishihara, op. cit.).

7.1.3. Ilmenite series terrains

The lower diversity of the mineralization associated with the ilmenite series than the magnetite series is due to the limited occurrences of sulphide ore deposits (Ishihara, 1981). The outer zone of south-western Japan is the most mineralized ilmenite series in Japan (Ishihara, 1978). Tin mineralization is related to the ilmenite series which can also be classified as I-type granites (Ishihara, 1978). Ishihara (1981) points out that base metal mineralization is more common in the I-type magnetite series than in the S-type, ilmenite series.

The granites of the Malay peninsula are considered to be ilmenite series rocks, although the eastern belt is a composite of S- and I-type granites. The main range is of S-type granitoids (Hutchinson, 1983). The two belts have some distinct characteristics (Hutchinson, op. cit.):

- the Main Range' tin deposits contain malayaite in pegmatite and skarns but it is absent in the eastern belt;
- Cornish-type stanniferous lodes and Sn-Fe oxide skarns are

usually present in the eastern belt and rarely in the main range;

- Main Range granitoids have the characteristics of mesozonal granites and the eastern belt is epizonal (see tables IV, V and VI);
- Rb\Sr ratios are high in the main range granites and low in the eastern belt;
- Eastern belt granitoids form a compositionally expanded calc-alkaline series (Hutchinson, op. cit.) and can be classified as an andino type according to Pitcher's (1979) classification.

The difference in the style of mineralization in the two Malay belts is due to the different pressures that prevail during the granitic magmatism and emplacement. In contrast the Japanese skarn deposits formed under fairly constant pressure (after sphalerite geobarometry) (Ishihara, 1981). The pressure and it had a minor influence on the formation of distinct Japanese ore provinces (Ishihara, op. cit.).

7.1.4. Mineralization associated with the magnetite and ilmenite series

The correlation between the commodities and the granitic series is considered by Ishihara (1981) to be reliable only for proximal type ore deposits. Problems with associating certain metals with particular series were related by Ishihara (op. cit.) as follow:

- a Japanese Mo deposit is hosted by a two mica granite, which might be an altered phase of fine-grained magnetite series granitoid;
- Sn-W mineralizations is associated with the above deposit but Sato and Akiyama (1980) consider it a product of a hidden ilmenite series granitic cupola;
- some of volcanic hosted deposits analogous to the granitic

series, are considered as product of magnetite series magmatism. However, the host rock does not yield the magnetic susceptibility to be classified as member of this series. Ishihara (1981) proposes that the loss of magnetic susceptibility is due a process of pyritization during the fixation of the mineralization;

- the $\delta^{34}S$ data of sulphide ore deposits is similar to the nearby granites;
- there are base metal sulphide deposits associated with the ilmenite series in Japan, although the ore volume of these deposits is relatively low.

Figure 21 displays the different magnetic susceptibility of different deposits. The deposits are grouped according to their mineralization style and types. The porphyry ore types have a higher magnetic susceptibility than the Sn and W deposits. However, Mo-porphyry deposits seem to have lower magnetic suscetipbility than cu-porphyry deposits. Some Mo-porphyries in the interior of the U. S. A. (Climax Mo deposit) contain Sn, W, Ta and fluorite mineralizations. They are formed from F-rich granitic magmas (Desborough and Sharp, 1978) eventhough these elements occur typically associated with the ilmenite series of the Japanese arc and in southeast Asia.

Plutonic-type Sn-W deposits are associated with granitic rocks of low magnetic susceptibility (Ishihara, 1977). This is indicative of low fO_2 during tin mineralization, but some Japanese sub-volcanic type Sn deposits are related to relatively more oxidized rocks (Ishihara, 1981).

Burnham and Ohmoto (1980) suggest that the tin deposits are formed under reducing conditions. Lehmann (1990) points out that hydrothermal depletion of magmatically tin-enriched rocks is effective only if realized in peraluminous, ilmenite-series granitic rocks, and with an fO_2 below the Ni-

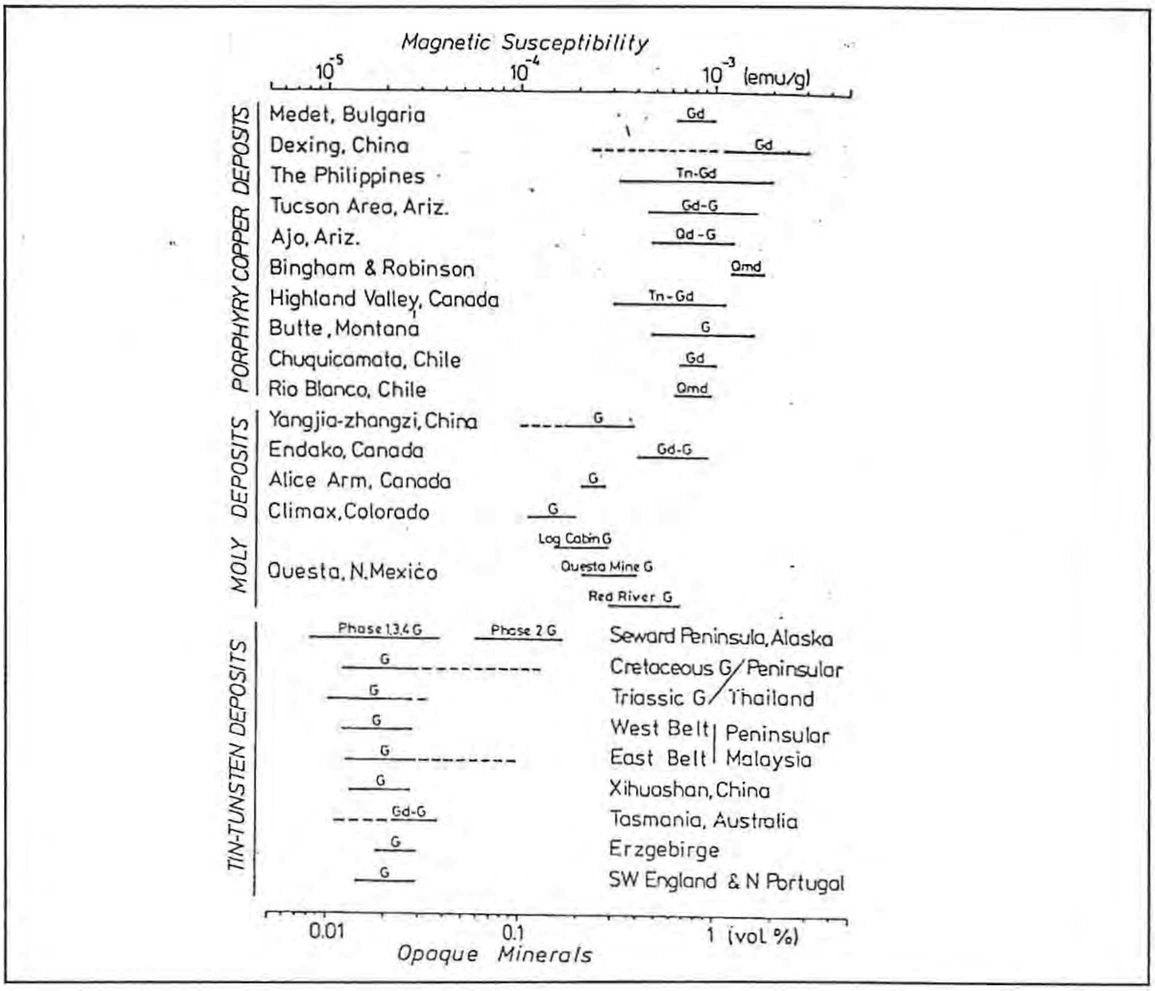


Figure 21 Magnetic susceptibility of granitoids related to ore deposits. Tn, tonalite; Qmd, quartz monzodiorite; Gd, granodiorite; G, granite, mostly monzogranite (after Ishihara, 1981).

NiO buffer. In the Bolivian Llallague tin deposit, pyrite predominates over pyrrhotite in the Sn-porphyry. However, at deeper levels pyrrhotite is the main sulphide phase. This is indicating that the mineralization was generated in reducing conditions, and pyrite was produced later by oxidizing meteoric water.

The association of W with the ilmenite series has been the major source of tungsten in southern China (Ishihara, 1981). This region produces most of the W consumed in the world. Skarn mineralization containing scheelite is commonly related to the magnetite series granitoids in the Kitakami belt (Ishihara, 1978). Although in the western U. S. A. W-skarn deposits with the highest grades are associated with the most reducing fluids or magmas (Keith et al., 1989). Tungsten deposits may be associated with both series. They seem to have a preference for ilmenite series rocks, at least in relation to higher grade ore deposits.

7.1.5. Magnetite and ilmenite series ore genesis

The two series occurs within distinct geotectonic settings. The ilmenite series appears in compressional environments as in the case of the Malay peninsula and south-western England. The magnetite series occurs in tensional environments such as the Green Tuff belt in Japan and the Chilean Andes (Ishihara, 1981). The ilmenite series, correlatable with S-type granitoids, have minor or no comagmatic volcanics associated (Ishihara, 1977). Ishihara (1981) suggests that the ilmenite series granitoids are emplaced at deeper levels than the magnetite series but the magmas of the former are formed at shallower depths. As the ilmenite series would have little chance for magmatic differentiation and concentration of ore elements, the granitoid composition and the metal contents in the ore deposits are dependent on the original composition of the granitoids (Ishihara, 1981). Table 12 displays some average contents of selected elements associated with the ilmenite series.

The δS^{34} data indicates that its source is crustal material. It also shows that the concentration of S in parts per million (ppm) is slightly higher than in the magnetite series. Ishihara (1978) points out that Na-rich granitoids (plagiogranites) formed and emplaced within oceanic crust have a very low average Sn content. The Japanese Sn deposits are associated with tin rich ilmenite series granitoids (see table 12) (Ishihara, 1978). A similar situation occurs in

Table XII Average contents of tin, fluorine, and sulphur, and average ratios of sulphur strontium isotopes of the ilmenite series granitoids (after Ishihara, 1981).

Province	Sn (ppm)	F (ppm)	S (ppm)	$\delta^{34}S_{\text{rock sulphur}}$ ($^{o}/_{oo}$)	$^{87}Sr/^{86}Sr$ initial
peninsular Thailand, W-Sn province	13.9	1.698	80	n.d.	0.7100
Sanyo belt, (Sn-)W province	4.0	917	80	-4.4	0.7081
outer zone, southwest Japan(W-)Sn province	4.0	803	389	-6.3	0.7075
Hidaka belt, barren province	2.6	363	407	-6.3	0.7046

the Malay peninsula where tin granites have in average 18 ppm Sn and barren granites 10 ppm Sn (Ishihara, 1981). According to Ishihara (1978) the Sn^{4+} will substitute for Ti^{4+} and Fe^{3+} in the rock forming minerals of the magnetite series. This might explain why some magnetite series granitoids are tin rich but do not develop economic mineralization.

Ishihara (1981) notices that tin deposits are related genetically to Sn-rich granitoids. However, the surrounding basement rocks of the Japanese granitoids have on average 1.5 ppm Sn while the Sn-rich granites have 4 ppm. The same author considers the possibility of a scavenging model during the magma generation, is improbable for the Japanese granitoids. He also notices that the sedimentary and metamorphic rocks have lower F contents than the granitoids (Ishihara, op. cit.).

The generation of tin-rich granitoids is thought to be the product of crustal material anatexis containing older tin granites (Tu et al., 1980). Tin-rich granites might have cassiterite, fluorite and topaz as rock forming minerals in the granitic cupolas. This can be explained by the high concentration of fluorine, which can form complexes with Sn and therefore, concentrate the metal during the late stages of magmatism (Ishihara, 1981). The relative proportion of Sn and F are different for distinct geotectonic setting. Figure 22 display the variation of Sn versus F in different tectonic setting, and tin rich and barren ilmenite series granitoids (Ishihara, 1981).

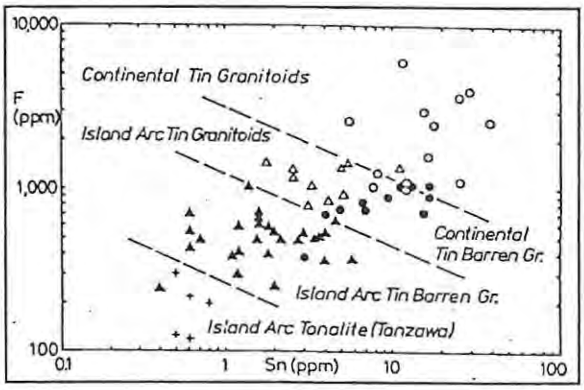


Figure 22 Sn vs F of the Mesozoic granitoids in Japan and Thailand. Continental examples=circle, island arc=triangle; open symbols are Sn-W mineralized granites, solid symbols barren granites; cross are M-type tonalites (after Ishihara, 1981).

Table 13 displays the average contents of some selected elements from the magnetite series granitoids. The data of initial Sr^{87}/Sr^{86} ratios and the other elements indicate a relative homogeneous source for the magnetite series magmas. The Cu data from Japanese rocks have distinct averages that can be related to different metallogenic provinces (Ishihara, 1981).

The Japanese metallogenic provinces have higher Cu contents than the surrounding country rocks, indicating that the source of the Cu for the mineralization was the granitoids rather than the host rocks (Ishihara, 1978 and 1981). The source of metals for base metals-rich granitoids is controversial. Sillitoe (1972) suggests that the source of Cu is the Cu-enriched oceanic sediments and basalt. Burnham (1979) points out that partial melting of oceanic basalt can generate a quartz diorite with as much as 400 ppm Cu. Doe (1978) points out that oceanic basalts have Cu/Pb ratio values of more than 100, although the Japanese Miocene mineralization province is Pb rich and it has a Cu/Pb ratio of 2. He also suggests that this indicates probable

Table XIII Average contents of copper and sulphur, and average ratios of sulphur and strontium isotopes of the magnetite series igneous rocks (after Ishihara, 1981).

Province	Cu(ppm	S(ppm)	$\delta^{34}S_{rock\ sulphur}$ (‰)	$^{87}Sr/^{88}Sr_o$
Kitakami belt, W-Cu province	37	123	1.5	0.7040
Green Tuff belt, Cu-Pb-Zn province	25	100	5.6	0.7048
Sanin belt, Mo(Pb-Zn) province	5	65	5.8	0.7054(west) 0.7090(east)
coastal Chile (andesite), Cu-Fe province	85	n.d.	5.5	0.7047
Green Tuff belt (basalts)	57	n.d.	n.d.	(0.7042)
Green Tuff belt (dacite and rhyolite)	5	n.d.	n.d.	(0.7044)

geochemical influence of the continental crust.

The source for the sulphur is probably the sea-water, incorporated during the subduction process (Sasaki and Ishihara, 1979). The sulphur dissolved in the melt exists in the aqueous phase as H_2S and SO_2. Their partition coefficients are controlled by the H_2O and O_2 fugacities with distinct fSO_2/fH_2S ratios for both the magnetite series and ilmenite series (Burnham and Ohmoto, 1979). The magnetite series has a larger fSO_2/fH_2S ratio than the ilmenite series.

Tsusue et al. (1981) point out that the apatite from W and F mineralized ilmenite series granitoids are F rich. They have also shown that the Japanese Mo province has a higher Cl content than the W-F ore province. The Cl content in apatite has a negative correlation with the differentiation index, while F in apatite has a positive correlation with the differentiation index (Tsusue et al., op. cit.). Terashima and Ishihara (1980) point out that Cl is concentrated in the fluid phase of granitoids associated with Pb-Zn mineralization.

7.2. Mineralization in A-type granitoids

Bowden and Kinnaird (1978) recognized several styles of mineralization associated with the A-type granitoids of the Younger Granites of Nigeria:

- late magmatic pegmatitic pods with quartz, topaz, beryl and feldspar;
- pervasive metasomatic disseminations with columbite or pyrochlore ±cassiterite;
- pre-joint and post-joint pegmatitic lenses with albite or microcline, genthelvite, uraninite, columbite and thorite;
- quartz rafts, stockworks, sheeted greisen veins and pervasively altered host rock with cassiterite, wolframite and sulphide;
- fissure fillings, veins or lodes with cassiterite, wolframite and sulphide;
- quartz veins with wolframite or scheelite, bismuth minerals, and sometimes abundant cassiterite and/or sulphide;
- mineralized margins of ring dykes, with cassiterite and sulphide.

Bowden and Kinnaird (op. cit.) also point out that the initial $^{87}Sr/^{86}Sr$ ratios of the mineralized granites in this province are always higher than 0.720. The origin of these tin-rich granites is controversial. Wright (1970) suggests that the Sn is only scavenged from the crust if it is dissolved in hyperalkaline magmas. However, in the Younger Granites of Nigeria, Sn is associated with peraluminous granites instead of hyperalkaline granitoids. This indicates that a crustal origin is disfavoured under these conditions (Kinnaird and Bowden, 1987). There is no specific association of any mineralization style with the different hydrothermal processes (Kinnaird, 1985). However, metasomatic processes can be related to different parts of a granitic intrusion (Kinnaird and Bowden, 1987):

- The roof zone is characterized by the association of Na, K or acid metasomatism with disseminated mineralization, sheeted vein systems and pegmatitic pods and veinlets.
- The marginal zone is characterized by greisenization, silicification with a complex paragenesis of sulphide and oxides in stockworks, sheeted veins, pegmatitic pods and wall rock alteration;
- The contact zone of alteration is up to 20m wide along the contact between the country rock and the granitic intrusion. The contact beneath a volcanic cover may contain minerals like genthevite, feldspar and pegmatitic quartz; if basement rocks are chloritized intensively, then the occurrence of massive sulphide is possible.
- The mineralization in country rock may be quartz veins and stringers or marginal greisen. The ore is usually wolframite or scheelite, and occasionally bismuth minerals and cassiterite.
- The ring dykes of granite porphyry which commonly accompany the anorogenic ring complexes may occur as disseminated mineralizations within the ring dyke, along joint planes and/or inner and outer margins of the dyke. It is generally economically insignificant and sporadic. The ore minerals are cassiterite with sphalerite, chalcopyrite and galena as major minerals of the sulphide assemblage.

Table 14 displays the styles of mineralization with their mineralogical assemblages. However, most of the tin production in Nigeria is from alluvial deposits.

The mineralogy of the younger Granites of Nigeria usually reflects the alteration of the granitoids by the residual fluids (Bowden, 1985). Bowden and Kinnaird (1984a) notice that various rock-forming minerals in the granitoids control the metasomatic creations:

- orthoclase altered to microcline;
- Li-Al micas are formed from K-feldspar or later, magmatic Fe-rich micas.

Kinnaird (1984) recognizes that the first hydrothermal process to occur was sodic metasomatism, followed by potassic, acid, silica and argillic alteration. Table 15 shows the general characteristics of the metasomatic processes. Sodic metasomatism acts mainly in the biotite and amphibole-bearing granites. It alters the perthitic feldspar to albite and is responsible for the enrichment of Nb-bearing ore minerals.

The potassic metasomatism transforms the original perthite or the albite produced in the earlier sodic metasomatism into microcline, and it can introduce cassiterite and wolframite. The acid metasomatism mineral assemblage is dependent on the previous alteration. Accessory cassiterite, oxides, sphalerite and other sulphides are always present.

With the liberation of silica resulting from the breakdown of feldspar, widespread silicification occurs (Kinnaird, 1985). The last metasomatic process to occur is the argillic, chloritic and zeolitic alterations, all of which are of local importance (Kinnaird, op. cit.). Intense metasomatism occurs only in granites which have cupolas with shallow outward dipping contacts where late magmatic fluids can be retained (Bowden and Kinnaird, 1984a).

All the metasomatic processes are characterized by modification of the Na/K and Th/V ratios, mobility of REE, changing ore assemblages and changes in trace element contents (Kinnaird et al., 1985). Kinnaird and Bowden (1987) point out that:

Table XIV Ore mineral assemblages related to styles of mineralisation (after Kinnaird and Bowden, 1987).

style	major	accessory minerals	ore assemblage
i) late magmatic pegmatitic pods	quartz-alkali feldspar	beryl, topaz	
ii) pervasive metasomatic disseminations	quartz albite quartz-microcline quartz-mica	thorite, xenotime, monazite, zircon zircon,	columbite, ilmenite, cassiterite pyrochlore cassiterite, wolframite, molybdenite cassiterite
iii) pre-joint and post-joint pegmatitic lenses	quartz-albite quartz-microcline	genthelvite, protolithionite, thorite, zinnawaldite or protolithionite, beryl, genthelvite	columbite uraninite, microlite
iv) quartz, rafts, stockworks, sheeted greisen veins and altered wallrock	quartz quartz-mica	genthelvite topaz, fluorite	cassiterite, haematite cassiterite,sphalerite, chalcopyrite
v) fissure filling veins or lodes	quartz-microcline-mica	monazite, thorite, xenotime, zircon	cassiterite, columbite, wolframite, rutile, sphalerite, molybdenite, stannite pyrite, arsenopyrite, chalcopyrite, pyrrhotite, bismuth minerals, galena
vi) irregular shaped replacement bodies	quartz-mica	fluorite, siderite, chlorite	cassiterite, wolframite bismuthinite, sphalerite, chalcopyrite, pyrite
vii) quartz veins	quartz	haematite	wolframite, cassiterite, bismuth minerals
viii) mineralised margins of ring dykes	quartz-microcline-mica	fluorite	sphalerite, chalcopyrite and galena with pyrite, pyrrhotite, stannite arsenopyrite, molybdenite and cassiterite

- sodic metasomatism produces an increase in Na, Fe and normative albite, and a decrease in K, Si and normative quartz. Enrichment of REE, especially in peralkaline granites, U and Li are also characteristic of sodic alterations;
- potassic metasomatism exchanges K for Na (Martin and Bowden, 1981), with normative orthoclase increasing at the expense of normative albite. During this process there is a general depletion in REE and most trace element except for Rb, Li, Sn and Zn;
- acid metasomatism: due to feldspar breakdown or by addition of Fe_2O_2 and SiO_2, there is a remarkable decrease in K^+ and Al_2O_3. Normative orthoclase and albite decreases while normative quartz increases. The biotite granites are depleted in Zr and Th, while Ce and Y are enriched in the granitoids when compared with rocks affected by potassic metasomatism;
- during silicification, all the other elements undergo depletion. Iron in some cases can accompany the silica and be relative enriched.

- During argillic alteration, the light REE and heavy REE are strongly and slightly depleted, respectively (Alderton, et al., 1979).

Most of the mineralization is not associated with any specific metasomatic process but there are some paragenetic sequences which can be related to some alteration processes (figure 23).

Table XVCharacteristic mineralogy assemblage for each alteration process (after Kinnard and Bowden, 1987)

Process	common texture	colour	style of mineralisation	characteristic feldspar	characteristic mica	ore minerals	others acessories
sodic metasomatism	saccharoidal	white or grey	disseminated process affecting the cupola zone	perthitic feldspar altered to rodered albite	pale coloured: in the compositional range li-annite-protolithionite - zinnwaldite - cryophyllite to trilithionite	pyroclore with monazite and molybdenite in peralkaline facies columbite with cassiterite rutile, thorite, ilmenite monazite ± uraninite ± sphalerite in peraluminous facies fergusonite in metaluminous facies	aegirine, amphiboles in range riebeckite to lithian arfvedsonite, villiaumite, cryolite, amblygonite, thomsenolite, astrophyllie, chevkinite, narsasukite and zircon in peralkaline facies zircon, fluorite, genthelvite and cryolite in peraluminous facies allanite and zircon in metaluminous facies
potassic metasomatism	miarolitic	pink or red	restricted to miarolitic cavities in contact zones, or to fissure margins	perthitic or albitised feldspar altered to intermediate or maximum microcline	chloritisation of original mica: new mica in the range annite-siderophyllite	cassiterite, monazite, molybdenite, wolframite ± sphalerite	amphibole in the range ferrorichterite to arfvedsonite in peralakline facies: zircon in both peralkaline and peraluminous facies
chloritic alteration	fine-grained	dark green, grey to black	at contact zones and within zones in unaltered biotite granite	destabilisation of feldspar to micaceous aggregates	chlorite ± sericite	sphalerite, cassiterite, chalcopyrite, monazite, pyrrhotite, stannite, pyrite, allanite	fluorite, zircon ± topaz
acid metasomatism	'granitic'	green or grey	may be a pervasive process in the cupola zone or occur in tabular zones, or infill fissures	destabilisation of feldspar into topaz/sericite or chlorite/sericite aggregates:	new mica in the compositional range siderophyllite - zinnwaldite	cassiterite, monazite, wolframite, rutile, molybdenite, thorite, sphalerite	zircon, quartz, topaz, sometimes fluorite, cryolite, siderite and genthelvite
silica metasomatism	quartzose	colourless or milky quartz	may be a pervasive process in the cupola zone or form veins	vestiges of feldspar altered to clay minerals or zeolites	no new mica	sphalerite, chalcopyrite, galena, cassiterite, wolframite, pyrite, pyrrhotite, stannite, molybdenite, cubanite, mackinawite, etc	quartz, haematite
argillic alteration	chalky	white or red-stained clays	restricted to cupola zones that have already been extensively sodic metasomatised	feldspar converted to kaolinite (or montmorillonite)	chlorite	haematite; supergene alteration of sphalerite, chalcopyrite and other sulphides to secondary ores.	epidote, siderite

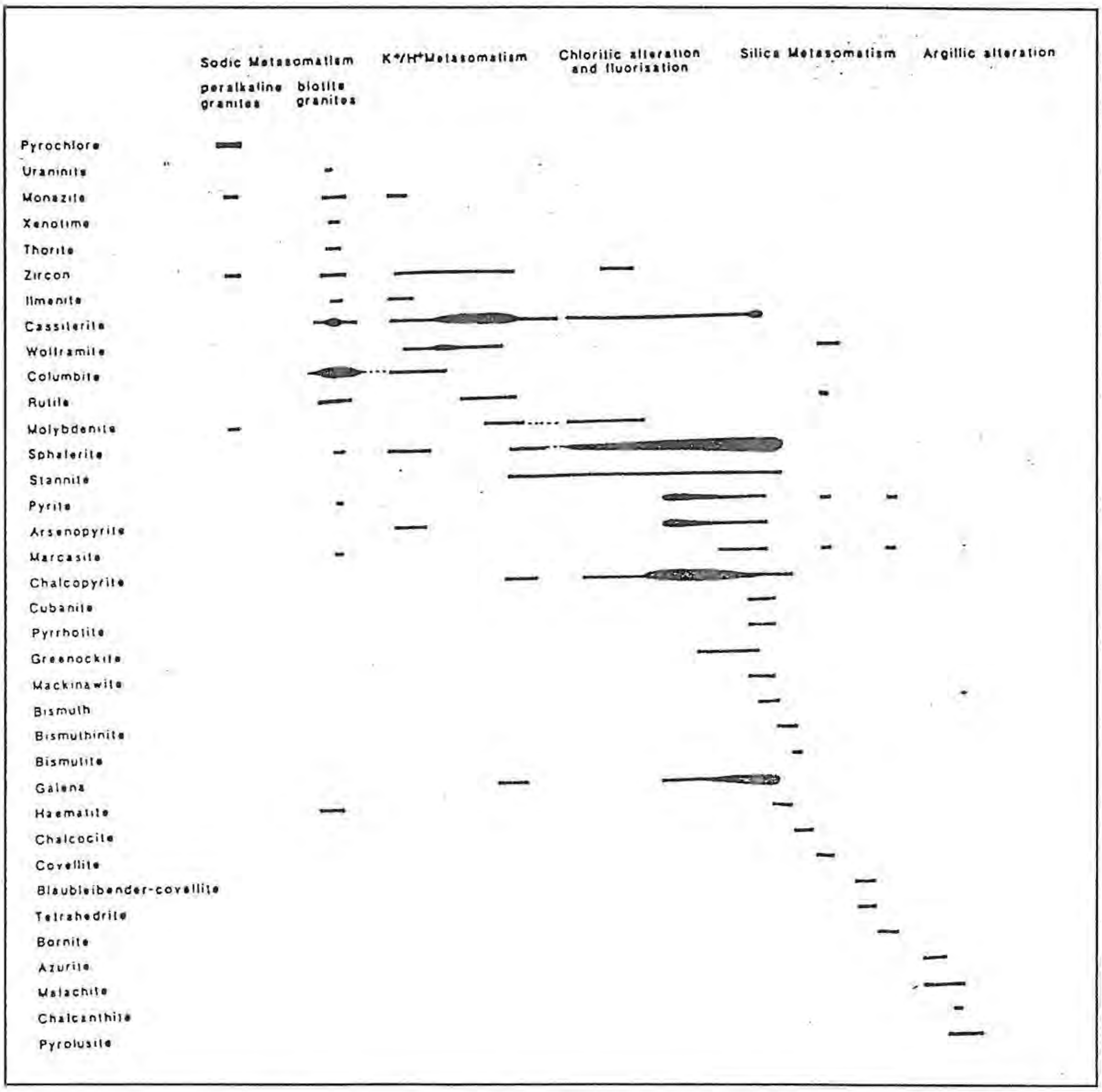


Figure 23 Schematic paragenetic ore sequence related the alteration stages (After Kinnaird, 1985)

Some trace elements may be used as indicators of possible mineralization. Elements like Rb are concentrated in the late magmatic fluids (Bowden and Kinnaird, 1978), and Sr which is depleted in the late stages, display higher sensitivity to hydrothermal alteration than K and Ca (Kinnaird, 1984). The K/Rb, Rb/Sr, and Ba/Rb ratios can indicate the presence of hydrothermal alteration (Kinnaird, op. cit.):

- K has a negative correlation to Rb. Bowden and Kinnaird (1984b) suggest that the trend toward lower values of K/Rb ratios in the Nigeria ring complexes is controlled by mineralized, albite rich fluids in a post magmatic phase.
- Rb/Sr ratios are higher in the biotite granites than in the hornblende bearing granites. The granitoids which have undergone microclinisation and greisenization, contain the highest Rb/Sr ratios (Bowden and Kinnaird, 1984b).
- The initial $^{87}Sr/^{86}Sr$ ratios are very variable in anorogenic granites. The Nigerian Younger granites have average ratios that vary between 0.702 and 0.7052 (Bremen et al., 1975), but the A-type granitoids of Corsica have ratios that vary between 0.703 and 0.709. The Gardar anorogenic province of South Greenland contain granitoids that have ratios of up to 0.713 (Bonin, 1986).

The wide range of the initial strontium isotopic ratios are explained as a product of interaction of the granitoids with late stage magmatic fluids. The late stage fluid processes enriched the most evolved liquids with Rb by also including leached elements from the country rocks (Bremen et al., 1975; Blaxland, 1976). However, Bowden and Kinnaird (1978) as referred to above claim that the mineralized granitoids of the Younger Granites of Nigeria have high initial $^{87}Sr/^{86}Sr$ ratios greater than 0.720 and do not require enrichment processes to explain their Sr-isotope geochemistry.

The REE behaviour in the A-type, Nigerian granitoids was suggested by Bowden and Kinnaird (1984b) to be as the following:

- REE distribution coefficients are similar to both mineral-fluid and mineral-liquid at T of 800-700°C;
- between 700° and 500°C the light REE and Eu are fractionated

toward the fluid but the heavy REE are fractionated toward the rock. The REE had subsolidous distributions associated with sodic metasomatism at T of 700° to 500°C.

- lower temperature metasomatic process enhances the REE content in the rock by precipitating REE bearing accessory minerals in greisen and altered wall rock;
- Zr/Hf ratio decreases during the hydrothermal alteration according to the T variation. Lower temperature produces lower ratios.
- In most of the metasomatic processes (excluding kaolinization) there is an overall increase in F/Cl ratio.

7.3. Economic geology of the M- and I-type granitoids

The most common and important ore deposits associated with M- and I-type granitoids are the porphyry deposits. They can be mineralized with Cu, Mo, and Au, in varied proportions. However, the Cu, Cu-Mo, Cu-Au, and Au-Cu associations are the most common pattern of mineralization. The other mineralization style associated with the above are Cu-W-(Mo) skarn deposits.

There are many examples of mineralization associated with I-type granitoids, viz., in the Andes Cordillera, in the western U. S., in Canada and in eastern Asia. The I-type granitoids of the Lachlan Fold Belt in Australia, contains molybdenum-gold mineralization associated with diverse plutons (Ramsay and VandenBerg, 1990). There are also some mineralizations associated with dyke swarms in the close of the Tabberabberan Orogeny. Their initial composition was dioritic and lamprophyric derived from a highly differentiated calc-alkaline magma (Tomlinson, 1990).

The early Devonian diorites and I-type granitoids are considered as the source of replacement and skarn mineralization in regions of New South Wales, for example at

Cadia and Brould (Suppel and Scheibner, 1990). Cu-Porphyry deposits occur associated with the Boggy Plain Supersuite, where dacite and rhyolites are extruded within the Molong Volcanic arc (Suppel and Scheibner, op. cit.). However, Wyborn et al. (1987) indicate that mineralization could be related to an adjacent granite.

Vidal (1985) indicates that the mineralization in the Andes Cordillera was formed during three stages:

- the first stage is related to an eugeosinclinal phase with volcanogenic and sedimentary deposits;
- the second is related to the intrusion of several granitoids during the Late Cretaceous with the generation of Cu veins, Cu-Mo-W contact metasomatic deposits, porphyry Cu-Mo occurrences and Au veins;
- the third phase is represented by the classical porphyry style of mineralization formed during the Upper Palaeocene.

The I-type granitoids of the Andes Cordillera contain Fe-Cu-Au-Ag-Mo-(W) mineralization, and some granitoids could be classified as M-type granitoids (Pitcher and Cobbing, 1985). Pitcher and Cobbing (op. cit.) point out that within the Coastal Batholith of Peru, the rocks with the most evolved composition are the poorest in ore minerals. Vidal (1985) indicates that the early gabbros of the Coastal Batholith of Peru contain the Fe-Cu-(Co), Cu mineralized veins, Cu-Mo porphyry and Cu- Mo-W skarn ores. Vidal (op. cit.) suggests that Au-Ag veins have their generation linked to the intrusion of granitoids during the Late Cretaceous in the Arequipa segment. He also pointed out that the other segments of the same suite are relatively barren. Vidal (op. cit.) describes the deposits related to the Coastal Batholith of Peru as:

- Amphibole-magnetite-chalcopyrite deposits related to the gabbroic rocks and characterized by apatite, sodic scapolite and sphene as accessory minerals. The deposits are found mostly within or along the contacts of gabbro-diorite plutons. They form sheets, veins and erratic disseminate lodes within zones altered by amphibolitization.

- Quartz-specularite-chalcopyrite deposits occur as groups of veins controlled by fractures. Usually, there are more than one episode of vein formation. The dominant mineralogy of the deposits located within the plutonic rocks is quartz-alkali feldspar-magnetite-tourmaline. However, the dominant mineral assemblage formed in the country rocks is quartz-specularite-pyrite-chalcopyrite. Au and Ag are recovered as by-products. This kind of deposit is associated with K-rich granitoids. The fluid inclusion evidence indicates that high T and high chlorine contents were involved in the formation of the veins. The deposits are generally small and uneconomic.
- Chalcopyrite-molybdenite-scheelite deposits are usually formed at the contact with hornfels roof pendants and within the wall rocks, some distance from the intrusive contact of the pluton. The variable composition of the country rock limestones influences the mineralogy of the skarns. When the deposits are very well developed the mineralization consist of Cu-Mo-W and Zn-Pb-Bi-Ag of secondary importance. The formation of the skarn is random. They are normally of small size. This irregular distribution pattern and the occasional mineralization imply that the fluids participating in the formation of the deposits were not an abundant and efficient means of metal transport.
- Quartz-calcite-auriferous pyrite deposits are related to one region called Palpa-Ocoña. The mineral assemblage consists of quartz-calcite-ankerite and the auriferous pyrite is characterized by sharp contacts and narrow alteration areas around veins. They usually display brecciation and mylonites which indicate multiple episodes of movement and vein formation. There is no relationship between any

specific plutonic suite and this kind of mineralization. The host rocks are mainly tonalite-granodiorite but there are deposits hosted by gabbros, monzodiorites, volcanic rocks and meta-sedimentary sequences. Usually, those deposits are located in or near the silicic portions of the batholith.

The M-type granitoid mineralization is generally a Cu-porphyry type with gold as co- or by-product. The composition of granitoids related to the mineralization vary and consist of calc-alkaline plutons and rocks of the tholeiitic series. Mason and McDonald (1978) point out that the granitoids in Papua New Guinea are classified as members of low-K, medium-K, and high-K calc-alkaline series. Examples of high-K and low-K calc-alkaline series are the Ok Tedi porphyry deposit and Koloula Igneous Complex, respectively. Sillitoe (1979) classifies the Ok Tedi deposit as members of shoshonitic series. The calc-alkaline plutons at the Koloula igneous complex can have two evolutionary path as in the case of the, Guadalcanal, Solomon islands granitoids (Chivas, 1978).

The two evolutionary trends are shown in figure 24. The trend which follows the QP margin of the diagram has features similar to trondhjemitic and/or tholeiitic series (Lameyre and Bowden, 1982). The other trend follows a similar evolutionary path to the normal K calc-alkaline series of Lameyre and Bowden (1982) classification. The low-K calc-alkaline series of the Papua New Guinea and Solomon Islands is referred to from now in the text as the trondhjemitic series. The choice of the name trondhjemitic instead of tholeiitic is in accordance with most of the authors when they referred to those rocks as calc-alkaline in the past. Nevertheless, Watmuff (1978) suggests that the low-K calc-alkaline series contain features of the tholeiitic series too.

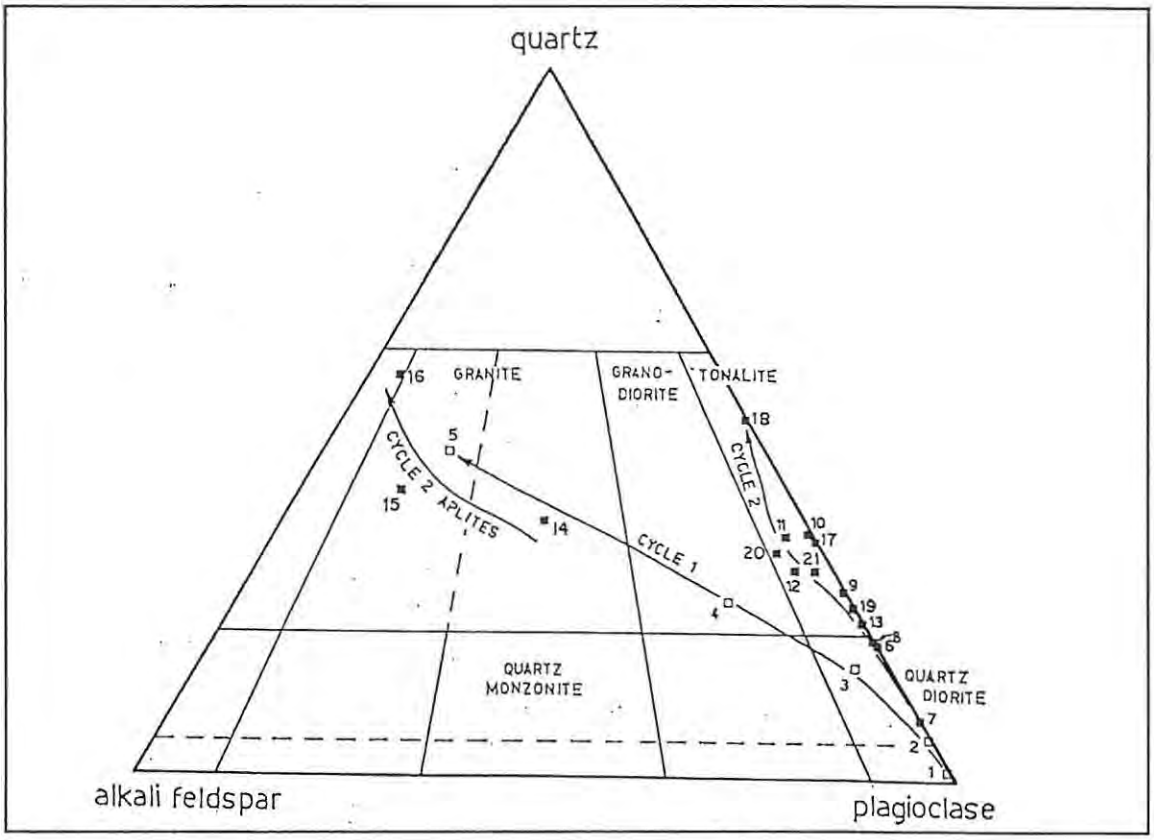


Figure 24 Modal composition of major rock types of the Koloula Igneous Complex, arrows indicate the differentiation trends for both intrusive cycles (after Chivas, 1978).

Chivas (1978) and Chivas and McDougall (1978) point out that the older rocks of the trondhjemitic series are leucogabbros which contain bodies of cumulate olivine-pyroxenite. The younger phases of intrusion are diorite, quartz-diorite, tonalite, trondhjemite, and aplite. The latter are the most evolved phase of the trondhjemitic series.

The normal K calc-alkaline series trend is older than the trondhjemitic series, and it consists of gabbro, diorite and granodiorite. There are also four episodes of andesitic intrusions.

The mineralization is related to two events of intrusive porphyritic tonalites and the source of the copper is considered to be the magmatic fluids (Chivas, 1978). The first event is related to the calc-alkaline series and associated, high temperature mineralizing fluids (500°-700°C). The second mineralization (trondhjemitic series) event was less saline and cooler (≈350°C). The introduction of copper mineralization is restricted to the potassic alteration in the first and second events but also associated with chloritic alteration during the second event (Chivas, 1978). However, Mason and McDonald (1978) suggest that the Cu mineralization in Papua New Guinea and the Solomon Islands is associated with the low-K calc-alkaline series and the medium-K calc-alkaline series is barren.

In contrast to Sillitoe (1979), Arnold and Griffin (1978) describe the rocks of the Star Mountains (including Ok Tedi) as high-K calc-alkaline rocks. Arnold and Griffin (op. cit.) indicate that the Star Mountains deposits are associated with intrusives in a foreland thrust-belt. This foreland thrust belt was developed in a shallow marine sequence formed along the tectonically stable northern edge of the Australian plate.

7.4. Economic geology of the S-type granites

The S-type granites are formed in collision-tectonic environments or in tectonic settings of crustal thickening (Pitcher, 1987). The most common mineralization associated with them are Sn, W, and U. The examples most famous for S-type granites are the Thailand-Malaysia tin belt, the Himalayan two-micas granites and the Hercynian orogeny of western Europe (Le Fort, 1987).

The S-type granitoids in the Lachlan Fold Belt contain generally, Sn-W mineralization and some rare gold mineralization. Some examples of Sn-W mineralization in this belt are the Early Silurian granitoids related to the Omeo metamorphic belt (Victoria, Australia) (Ramsay and VandenBerg, 1990), and the Ardlethan Tin deposits (New South Wales) (Paterson, 1990). Rare gold deposits are associated with S-type granitoids within the Lachlan Fold Belt in New South Wales. The most notable examples are the Harden and McMahons Reef deposits (Suppel and Scheibner, 1990).

Paterson (1990) describes the Ardlethan tin deposits as being hosted by the Mine Granite. It was intruded by a quartz-feldspar porphyry plug that hydrothermally brecciated the host rock and chloritized or tourmaline-topaz altered it. The tin mineralization occurs in the upper parts of the altered zone and the richest ore is associated with late tourmaline pipes. The cassiterite occurs mainly within the chloritized and sericitized zones. Chalcopyrite, pyrite and arsenopyrite are secondary minerals in the altered zone and in the black tourmaline pipes. The average grade is 0.5% Sn, 0.1% Cu and 0.05% Zn within the tourmaline pipes (Paterson, op. cit.).

The Himalayan, S-type granitoids were emplaced during the late tectonic stage. The geochemical pattern of major elements does not show sufficient variation to be considered important but the minor and trace elements have variable compositions. Le Fort (1987) interprets it as a product of the heavy minerals fractionation.

Le Fort (op. cit.) suggests the absence of the hydrothermal alteration and the higher concentration of tin and tungsten in the whole rock analyses than in the average granitoid rocks are evidence of a submagmatic origin to Sn and W mineralization. The same author also shows that the Himalayan granitoids are rich in tourmaline and therefore, enriched in B and F.

The source rocks of the S-type granites are considered to be shales and graywackes naturally enriched in metal contents. However, the average chemical composition of these source rocks do not have enhanced metallic contents. Le Fort (1987) suggests that the preferential melting of the minerals, like the micas and some accessory minerals, may provide sufficient Sn and W for the generation of a metal enriched magma. Lehmann (1990) points out that the sources of the Bolivian S-type tin granites are not tin rich. He based his observation on the fact that the least fractionated granitoids related to the tin granites have compositions similar to the average of the crust and the tin granites are the products of the differentiation processes that those granites had been through.

For S-type granites there is a pronounced positive correlation of Sn, and a negative correlation of Ti, Zr, Zn, Pb, Mg, Fe, and K/Rb ratios with the differentiation index (Stone, 1982). The enrichment of incompatible elements is also dependent on the intercumulus melt/solid ratios, where the lower ratios indicate that the incompatible elements are depleted in favour of the final liquid phases (McCarthy and Hasty, 1976). Manning and Henderson (1984) suggest that in an aqueous phase dominated by Cl and P, metals like W and Sn would be partitioned into the aqueous phase but if the system is controlled by F or B, those metals are partionated toward the melt.

The interaction of the S-type granites with country rocks can modify its evolutionary path. The magmas formed from meta-sedimentary rocks would yield reducing conditions. If there is any interaction of the magma with the country rocks, then the composition of the latter may alter the magma's reduction-oxidation conditions to more oxidising conditions. The formation of Sn deposits is dependent on reducing conditions (i. e. lower or equal fO_2 than the Ni-NiO buffer) and high temperatures (500-600°C) associated with high salinities (Lehmann, 1990). Under these conditions the hydrothermal fluids can transport very high concentrations of Sn (Lehmann, op. cit.). Le Fort (1987) points out some conditions to deplete the melt of Sn and W in favour of the hydrothermal fluids:

- High temperature for both elements;
- Higher pressures for W than to Sn;
- Lower fO_2 for Sn than W;
- Low pH for both metals;
- low F and CO_2 for W
- High Cl and no Ca for both elements.

The last condition set by Le Fort (op. cit.) of high Cl is not consistent with the generalized view that the tin granites are also rich in fluorine. The presence of fluorine is considered fundamental to the transport of Sn in the complex compounds (Tischendorf, 1977; Govett, 1983). Lehmann (1990) indicates that the tin granites are boron dominated systems rather than fluorine dominated systems, and that the latter system is characteristic of the magnetite series and I-type Mo rich granitoids.

The separation and the conditions related to separation of an aqueous phase during the crystallization will determine the possibility of ore deposit formation. The Pressure of water (vapour) (PH_2O) controls the formation of pegmatite or hydrothermal systems. If the PH_2O is high, then pegmatites can be formed. However, if it is low and F, B, and Li dominate the system, then the chances to form a hydrothermal system is greater (Manning, 1982).

The separation of an aqueous phase is ruled by some features such as the depth of emplacement, water content, and the temperature of the granitic magma. The depth of emplacement is controlled by the structural setting and the viscosity of the intruding magma. The latter depends on the water content. The formation temperature of the granitoid is a function of the depth of melting, the water content of the rock source when the anatexis takes place and the presence of halogens which can decrease the melting temperature.

The S-type granitoids are generally classified as katazonal or mesozonal granitoids. The ideal conditions of a high contrast in temperature and pressure with the country rocks are seldom achieved to form large deposits of economic value. Le Fort (1987) suggests that the heterogeneity of the geological conditions is the most beneficial to the precipitation of the mineralization, and he lists some favourable features like:

- temperature decrease;
- fO_2 increase for both metals;
- variation in pH;
- increase in Ca;
- increase of Fe and Mn for W;
- decrease in Cl content for both elements.

8. Aspects of Mineral Exploration

The development of mineral deposits related to specific granitic series is not only dependent on the granitic series, but the distinct tectonic setting, magmatic source and physio-chemical conditions that characterize the granitic series. The applicability of some of the above classifications for mineral exploration in pre-Mesozoic terrains, is doubtful.

The tectonic classifications were conceived from the study of post-Mesozoic orogenies. The other classifications (i. e. Chappell and White, 1974 and Pitcher, 1979) also are based on observations of younger orogenies. The advantage of using granitic series classification is the recognition of tectonic position, possible magmatic source, depth of emplacement or the oxidation conditions involved in granitoid formation.

Mitchell and Garson (1981) point out that the Cu-Mo-(Au) porphyry deposits are formed in magmatic arcs while the Mo porphyry type deposits are formed in back arc extensional basins. Recognition of tectonic environments may prove a useful exploration guide, however, the magmatic source or magnetic susceptibility classifications can be as better regional exploration tools. For example, the porphyry type deposits are related to I-type granitoids of magnetite series and emplaced under epizonal conditions, while the tin deposits in the Malay peninsula are associated with S-type granitoids of ilmenite series and emplaced under mesozonal conditions.

The I- and M-type granitoids have three kinds of mineralization associated with them i. e. porphyry type deposits, mineralized basic dykes and skarn deposits, in the Andes Cordillera (Vidal, 1985) and in Papua New Guinea (Mason and McDonald, 1978; Chivas, 1978). The compositions of the mineralized plutons vary and no distinctions can be drawn between these two granitoid types. Mason and McDonald (1978) and Chivas (1978) point out that porphyry deposits in Papua New Guinea are associated with the least differentiated portions of composite intrusions. Furthermore, Mason and McDonald (op. cit.) indicate that porphyries are related to high K calc-alkaline intrusions. Vidal (1985) describes the mineralization associated with the Coastal Batholith of Peru and suggests that the mineralization is associated with the least evolved portions of composite intrusions. Most porphyries deposits in the Andes Cordillera and Papua New Guinea are emplaced during the late stages of the orogeny i. e., they are not deformed (Mason and McDonald, op. cit.; Vidal, op. cit.).

These two granitoid types share similar geochemical characteristics and ore deposits type (White and Chappell, 1983). However, the oxygen fugacity is high and they can be classified as magnetite series (Ishihara, 1981). The high fO_2 provides conditions to form magnetite. Paterson (1990) suggests that the porphyry deposits in the Papua New Guinea regions have very high magnetic susceptibilities associated with them. The mineralizations are associated with high salinity (35 weight percent), chlorine rich fluids and variable temperatures (250°-700°C) (Nash, 1976). Whitney (1988) suggests that the Cl source is the altered subducted oceanic crust. The same author also suggests that fluorine leads to the formation of more silicic plutons related to the Mo-porphyry deposits. Whitney (op. cit.) indicates that the Mo porphyry deposits have a high differentiation index (≈90) and those stocks have undergone considerable differentiation under crustal conditions. Baldwin and Pearce (1982) point out that Y and MnO have very low concentration in mineralized porphyry plutons in the Chilean Andes and Y concentrations vary in different provinces. They also suggest that the use of the Y vs. MnO diagram in order to discriminate between mineralized and barren intrusions.

The S-type granitoids are formed in continental-island arc or continent-continent collision environment. This granitoid type is not associated usually with volcanism. They are mesozonal granitoids and were formed under reducing conditions. Ishihara (1981) suggests that the low oxygen fugacity is due to assimilation of or heritaged sedimentary carbon or sulphur. The origin of the metals is suggested as magmatic or submagmatic (Le Fort, 1987; Rossi et al., 1988; Lehmann, 1990). Rossi et al. (1988) point out some conditions necessary to form Sn and W ore deposits:

- pre-concentration of metals in a granite;
- magmatic liquid must be highly differentiated;
- REE pattern rather flat and a remarkable Eu anomaly;
- metals should be scavenged by magmatic late fluids from the melt, and that meteoric or metamorphic water have a restrict participation in the formation of ore deposits.

Rossi et al. (op. cit.) suggest that Sn and W have a hygromagmatophile behaviour that allows them to be concentrated by magmatic differentiation. They also consider that a granite with less than 72% silica and less than 10 ppm Sn will not be mineralized.

The mineralization related to A-type granitoids is characterized by diverse metasomatic alterations. Bowden (1985) points out that the characteristics of A-type granites are controlled by the separation of a fluid phase responsible for a limited sodic and potassic metasomatism. Furthermore, the acid metasomatism is responsible for important U-Nb and Zn-Sn mineralization. Acid metasomatism reacts with the early minerals to form greisen (Bowden and Kinnaird, 1984a). The A-type granitoid mineralization has similar features to the mineralization associated with carbonatites (Bowden, op.

cit.). These characteristics are the abundance of sphalerite, rare earth minerals, zircon, uranium, thorium, columbite and pyrochlore. There is no particular association of any metasomatic process with a specific mineralization type. Table XVI gives a partial resume of the association of some ore elements and minerals with metasomatic processes.

Table XVI Mineralization associated with post-magmatic metasomatism in alkaline granite ring complexes (after Bowden, 1985).

Element association	Principal minerals	Controlling metasomatism
Nb type	Pyrochlore-columbite	Sodic metasomatism
REE type	Monazite, xenotime, fergusonite	Sodic, redistributed by potassic and acid metasomatism
U-Th	Uraninite, thorianite, thorite	sodic, redistributed by potassic metasomatism
Be/Zn	Genthelvite, beryl, sphalerite	Sodic, redistributed by potassic and acid metasomatism
W-Sn	Cassiterite, wolframite	Sodic and potassic, redistributed by acid metasomatism
Mo-Cu	Molybdenite, chalcopyrite and related Cu minerals	Sodic, redistributed by potassic and acid metasomatism
Bi-Pb	Bismuthinite, galena	Potassic, redistributed by acid metasomatism

Takahashi et al. (1980) point out that the ilmenite series and magnetite series are not exactly correlatable with the I- and S-type granitoids respectively. They notice that in Japan the ilmenite series corresponds to both the I-and S-type granitoids while the magnetite series granites are equivalent to I-type granitoids. Ishihara (1977, 1978, 1981) indicates Mo, Cu, Pb, Zn, Au and Ag deposits are associated with the magnetite series and the Sn, W, Nb and Ta deposits are related to the ilmenite series. Figure 25 display the distribution of selected Sn, Mo and Cu deposits in a silica vs. Fe_2O_3/FeO diagram. The copper deposits have a fairly

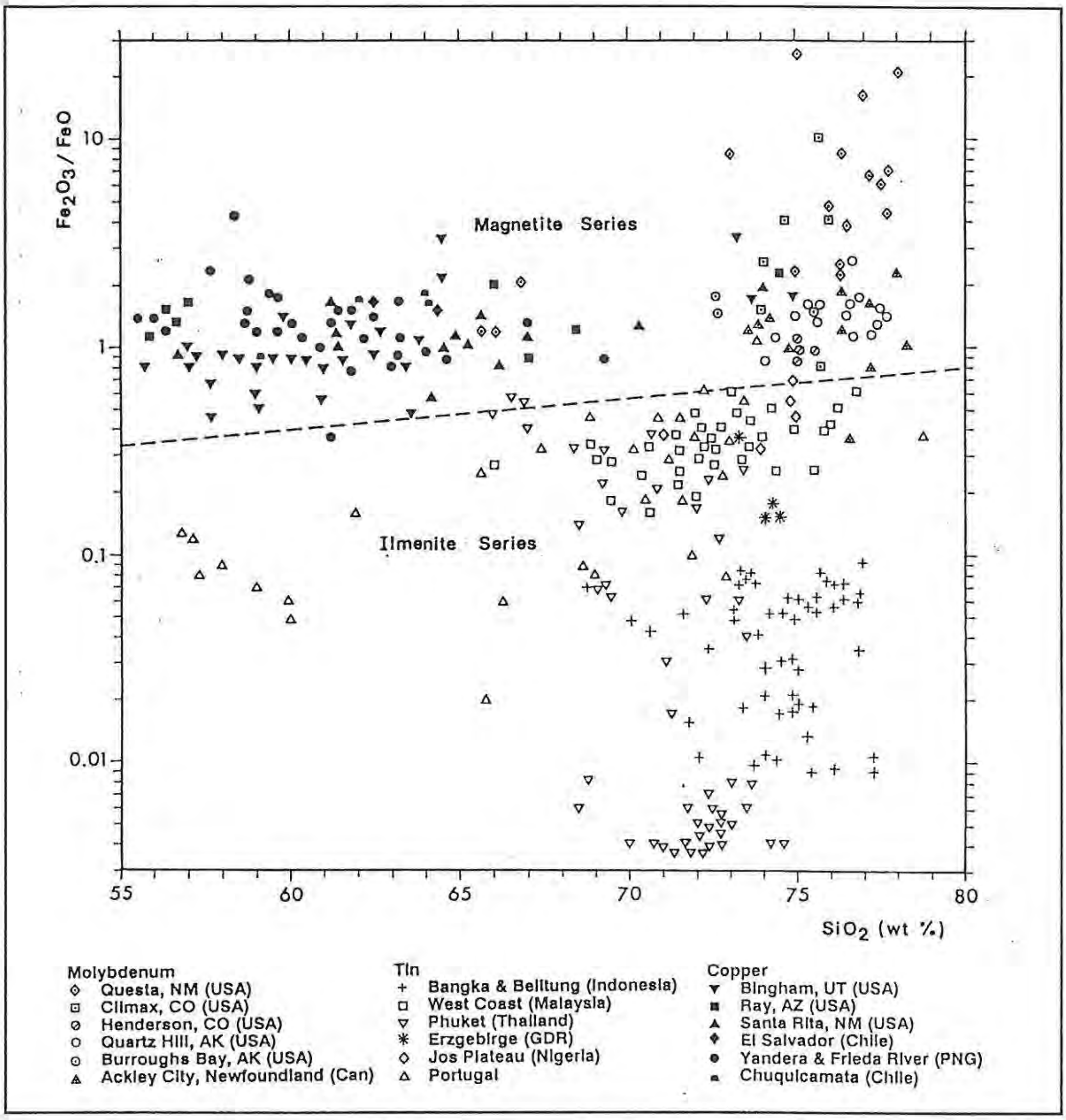


Figure 25 SiO_2 vs Fe_2O_3/FeO variation diagram for granitic rocks in association with Cu, Mo and Sn deposits (after Lehmann, 1990).

constant Fe_2O_3/FeO ratio relative to the silica variation. In contrast, the Mo and Sn mineralization paragenesis have much higher silica content than the Cu deposits and their iron ratios are variable. The line separating the magnetite series from the ilmenite series discriminates the Mo and Cu mineralization from the Sn deposits. Fe_2O_3/FeO ratio depends on the oxygen fugacity and the data shown in the figure 25 suggests that it plays a critical role in the formation of Sn and Mo mineralization (Lehmann, 1990). Lehmann (op. cit.) suggests that W has a in relation to intermediate to the behaviour of Mo and Sn, with respect to fO_2. Keith et al. (1989) indicate that the W skarn deposits in the U. S. are related to both series but the ilmenite series W-skarn deposits have bigger tonnage than those associated with magnetite series. Figure 26 shows the relationship of some deposits to oxygen fugacity. This indicates that at the relatively high fO_2 of Sn, W deposits cannot be formed. Mo and Cu porphyry deposits are formed are formed under higher fO_2 conditions than Sn-W deposits.

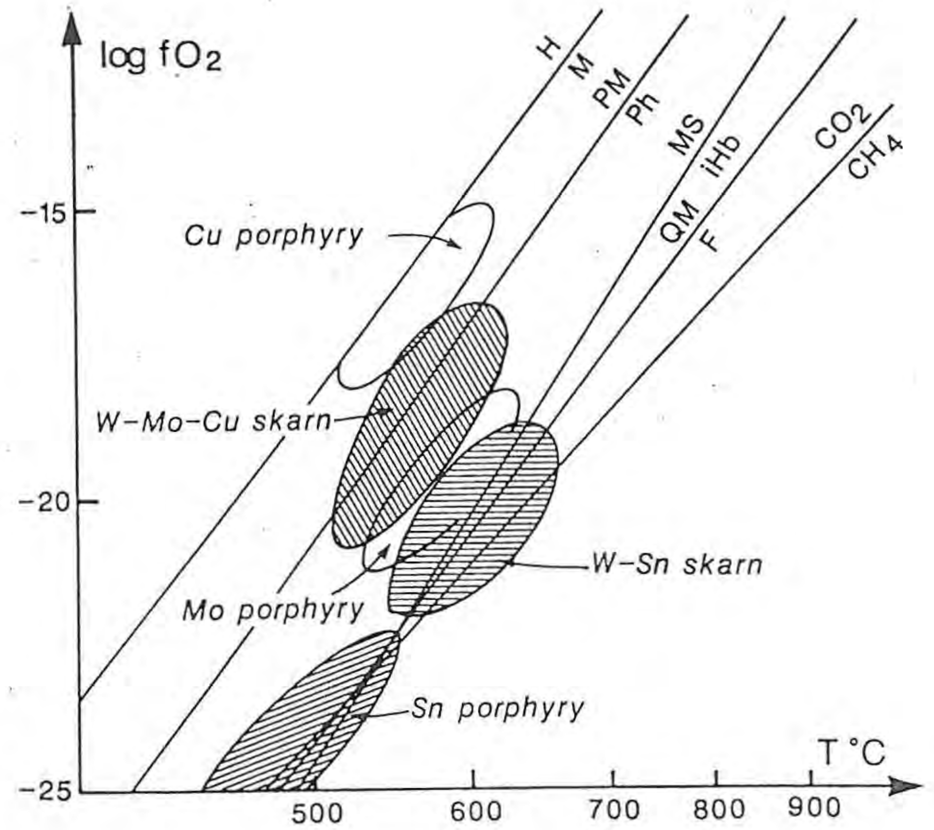


Figure 26 fO_2 vs temperature diagram showing the relation between some ore deposits and the simple buffer curves. F= fayalite,H=hematite,Hb=hornblende,I=ilmenite, M= magnetite, P=pyrite,Ph=pyrrhotite,Q=quartz,S=sphene(after Le Fort,1987).

9. Discussion and conclusion

Lameyre and Bowden (1982) demonstrate that there are four granitic series that plot evolutionary trends on a QAP diagram and that the calc-alkaline series can be subdivided into three groups according to potassium content.

The granitic series can be interpreted and classified according to their magmatic origin, tectonic setting and depth of emplacement. The granitic rocks can be generated from mantle derived and crustal derived magma. Barbarin (1990) suggests the existence of hybrid mantle and crustal magmas. Each magmatic origin can be related to a specific tectonic setting (Pitcher, 1979). There is no classification which can accommodate all the aspects involved in the generation and evolution of the granitic rocks. Some possible correlations and similarities between the respective granitic series classification are:

- Mantle magmas can be the source of M-, A-, I-type, and magnetite series granitoids;
- Crustal derived magmas can generate A-, I-, S-type, magnetite and ilmenite series granitoids;
- Mixing of mantle and crustal derived magmas can form A-, I-type, magnetite and ilmenite series granitoids;
- M-type is equivalent to the magnetite series while S-type is similar to the ilmenite series. A- and I-type granitoids can be either magnetite series or ilmenite series rocks.

Table XVII attempts to correlate the main classifications with one another.

The mineral deposits associated with granitic rocks are classified according to their relationship to the tectonic setting and the magma source. Porphyry-type deposits are characteristically developed over subduction zones.

Table XVII Comparison of the main classifications of granitic series

<table>
<tr><td>Authors</td><td colspan="5">Crustal</td><td colspan="2">Hybrid</td><td colspan="3">Mantle</td></tr>
<tr><td>Lameyre and Bowden (1982)</td><td colspan="5">Mobilizates</td><td colspan="2">Calc-alkaline series high, medium or low K</td><td colspan="2">Tholeiitic series</td><td>Alkaline series</td></tr>
<tr><td>Ishihara (1977)</td><td colspan="6">Ilmenite series</td><td colspan="3">Magnetite series</td><td></td></tr>
<tr><td>White and Chappell (1983)</td><td colspan="5">S-type</td><td colspan="2">I-type</td><td colspan="2">M-type</td><td>A-type</td></tr>
<tr><td>Pearce et al. (1984)</td><td colspan="6">COLG collision granites
Syn-tectonic/Post-tectonic</td><td colspan="2">VAG Volcanic arc granites</td><td>ORG</td><td>WPG within plate granites</td></tr>
<tr><td>Pitcher (1983 and 1987)</td><td colspan="3">Hercyno type</td><td colspan="3">Caledonian type</td><td>Andino type</td><td colspan="2">W-Pacific type</td><td>Nigeria Type</td></tr>
<tr><td>Barbarin (1990)</td><td>C_{ST}</td><td>C_{CA}</td><td colspan="2">C_{CI}</td><td colspan="2">H_{LO}</td><td>H_{CA}</td><td colspan="2">T</td><td>A</td></tr>
</table>

They are associated with M- or I-type granitoids. The subduction zone can be Andean type or west Pacific type. Continental collision may generate S-type granitoids. Tin-W and U mineralizations are associated with S-type granitoids.

The most important granitoid series for mineral exploration are the magnetite and ilmenite series classification. Figures 25 and 26 display the distribution of base metal deposits in relation to the Fe_2O_3/FeO ratios and oxygen fugacity, respectively. Tin, W, Nb, and Ta are associated with ilmenite series, S- and A-type granitoids. Molybdenum, Cu, Pb, Ag, and Au deposits are associated with magnetite series (Ishihara, 1981). Copper, Mo and Au mineralizations are associate with I- and M-type granitoids.

The granitoids series association with mineralization is dependent on certain features:

- granitic metallogenic provinces are a function of the magma source. Differences in the composition of the crust and mantle will reflect in the granitoids' metallic composition (Chappell et al., 1988).

- the oxidation state history of the granitic magma will contribute to the metal concentration in late stage fluids or in the crystalline phase.
- depth of the granitic emplacement controls the temperature and pressure contrast necessary for precipitation of ore elements.

Acknowledgments

I would like to thank the academic staff of the Rhodes University Geology Department, particularly Prof. J. M. Moore for his support and supervision along the course. I also would like To thank to the Geology Department for the Graduate Assistantship offered me.

I am indebted to my fellow colleagues and friends Cornwell Gapara, Gordon Dwyer and Brian Coxon for their nice companionship and supportive friendship during this year.

I also would like to thank Henry Holland, Johann Stiefenhofer, Otto Kritzinger and again Brain Coxon for proof-reading of my dissertation.

Finally, I would like to express my most sincere gratitude to my wife Soraia for her total support and encouragement throughout all these years.

References

Alderton, D. H. M., Pearce, J. A. and Potts, P. J., 1979. rare earth elemnet mobility during granite alteration: evidence from southwest England. *Earth Planet. Sci.* Lett., vol 49, p. 149-165.

Allègre, C. J. and Othman, D. B., 1980. Nd - Sr isotopic relationship in granitoid rocks and continental crust development. a chemical approach to orogenesis. *Nature*, vol. 286, p. 335-342.

Arnold, G. O. and Griffin, T. J., 1978. Intrusions and pophyry copper prospects of the Star Mountains, Papua New Guinea. *Econ. Geol.*, vol. 73, p. 785-795.

Arth, J. G., Barker, F., Peterman, Z. E. and Friedman, I., 1978. Geochemistry of the gabbro-diorite-tonalite-trondhjemite suite of southwest Finland and its implications for the origin of the tonalitic and trondhjemitic magmas. *Jour. Petrol.*, vol. 19, p. 289-316.

Baldwin, J. A. and Pearce, J.A., 1982. Discrimination of productive and nonproductive porphyritic intrusion in chilean Andes. *Econ. Geol.*, vol. 77, p. 664-674.

Barbarin, B., 1990. Granitoids: main petrogenetic classification in relation to origin and tectonic setting. *Geol. Journ.*, vol. 25, p. 227-238.

Bateman, P. C., 1983. A summary of critical relations in the central part of the Sierra Nevada batholith, California, U. S. A. In Circum-Pacific plutonic terranes, ed. roddick, J. A., *Geol. Soc. Am. Memoir*, no. 159, p. 241-254.

Blaxland, A. B., 1976, Rb-Sr isotopic evidence for the age and origin of the Ivigut granite and associated cryolite body, South Greenland. *Eco. Geol.*, vol. 71, p. 864-869.

Bonin, B., 1986. *Ring complex granites and anorogenic magmatism*. North Oxford Academic, 189 p.

Bowden, P., 1985. The geochemistry and mineralization of alkaline ring complexes in Africa. *Jour. Afric. Earth Sci.*, vol 3, p. 17-39.

Bowden, P. and Kinnaird, J. A., 1978. Younger Granites of Nigeria - a zinc-rich tin province. *Trans. section B. Inst. Min. Metall.*, vol. 87. 66-69.

Bowden, P. and Kinnaird, J. A., 1984a. Petrological and geochemical criteria for the indentification of (potential) ore bearing Nigerian granitoids. *Proc. 27th Int. Geol. Cong., Moscow*, vol. 9, p. 85-119. Vnu Science Press, Utrecht, The Netherlands.

Bowden, P. and Kinnaird, J. A., 1984b. The petrology and geochemistry of alkaline granites from Nigeria. *Phys. Earth Plan. Inter.*, vol. 35, p. 199-211.

Bremen, O. van, Hutchinson, J. and Bowden, P., 1975. Age and origin of the Nigerian Mesozoic granites: a Rb-Sr isotopic study. *Cont. Mineral. Petrol.*, vol. 50, p. 157-172.

Brownlow, A. H., 1979. *Geochemistry*. Prentice Hall, N. J., 498 p.

Buddington, A. F., 1959. Granite emplacement with special reference to North America, *Geol. Soc. America., Bulletin*, vol. 70, p. 671-747.

Burnham, C. W., 1979. Magmas and hydrothermal fluids. In Barnes, H. J., ed., *Geochemistry of hydrothermal ore deposits*, 2nd ed., New York, John Wiley and Sons, p. 71-136.

Burnham, C. W. and Ohmoto, H., 1980. Late stage processes of felsic magmatism. In Ishihara, S. and Takenouchi, S., eds., *Granitic magmatism and related mineralization. Min. Geol. Spec. Issue*, no. 8, p. 1-11.

Chappell, B. W. and White, A. J., 1974. Two contrasting granite types. *Pacific Geol.*, vol. 8, p. 173-174.

Chappell, B. W., White, A. J. R. and Hine, R., 1988. Granite provinces and basement terranes in Lachlan Fold Belt, southeastern Australia. *Austr. J. Earth Sci.*, vol. 35, p. 505-521.

Chivas, A. R., 1978. Porphyry copper mineralization at the Koloula Igneous Complex, Guadalcanal, Solomon Island. *Econ. Geol.*, vol. 73, p. 645-677.

Chivas, A. R. and McDougall, I., 1978. Geochronology of the Koloula Porphyry Copper prospect, Guadalcanal, Solomon Islands. *Econ. Geol.*, vol. 73, p. 678-689.

Clark, D. B. and Halliday, A. N., 1980. strontium isotope geology of the South Mountain batholilh, Nova Scotia. *Geochim. Cosmochim Acta*, vol. 44, p. 1045-1058.

Clemens, J. D., Holloway, J. R. and White, A. J. R., 1986. Origin of an A type granite: experimental constraints, *Am. Mineral.*, vol. 71, p. 317-324.

Cobbing, E. J., Mallick, D. I. J., Pitfield, P. E. and Teoh, L. H., 1986. The granites of the southeast Asian tin belt. *Jour. Geol. Soc. London*, vol. 143, p. 537-550.

Coleman, R. G. and Peterman, U. Z. E., 1975. Oceanic plagiogranite. *J. Geophys. Res.*, vol. 80, p. 1099-1108.

Collins, W. J., Beams, S. D., White, A. J. R. and Chappell, B. W., 1982. Nature and origin of A-type granites with particular reference to southeastern Australia. *Contrib. Mineral. Petrol.*, vol. 80, p. 189-200.

Creaser, R. A., Price, R. C. and Wormald, R. J., 1991. A-type granites revisited: assessment of a residual-source model. *Geology*, vol. 19, p. 163-166.

Dasch, E. J., 1969. Strotium isotopes in weathering profiles, deep sea and sedimentary rocks. *Geochim. Cosmochin. Acta*, vol. 33, p. 1521-1552.

Desdobourgh, G. A. and Sharp, W. N., 1978. Tantalum, uranium, and scandium in heavy accessory oxides, Clymax molybdenum mine, Climax, Colorado. *Econ. Geol.*, vol. 73, p. 1749-1751.

Doe, B. R., 1978. The status of lead isotope studies of Japan. *Min. Geol.*, vol. 28, 277-279.

Fyfe, W. S., 1973. The generation of batholiths. *Tectonophysics*, vol. 17, p. 273-283.

Govett, G. J. S., 1983, *Rock Geochemistry in mineral exploration*. Elsevier, New York, p. 461.

Hall, A., 1987. *Igneous Petrology*. Longman Sci. and Techn. UK., p. 573.

Hildreth, W., 1981. Gradients in silicic magma chambers: implications for lithospheric magmatism. *Journal Geophys. Res.*, vol. 86 (B.11), p. 10153-10192.

Hine, R., Williams, I. S., Chappell, B. W. and White, A. J. R., 1978. Contrasts between I and S type granitoids of the Koiciusko batholith. *J. Geol. Soc. Australia*, vol. 25, p. 219-234.

Hughes, C. J., 1982. *Igneous Petrology*. Developments in petrology, number 7. Elsevier Sci. Publ. Amsterdam., p. 551.

Hutchison, C. S., 1983. Multiple Mesozoic Sn-W-Sb granitoids of southeast Asia. In: *Circum-pacific plutonic terranes*, ed. Roddick, J. A. Geol. Soc. of Amer., mem. no. 159, p. 35-60.

Ikeda, Y., 1978. Intimate correlation in composition between granitic rocks and their country rocks in Japan. *J. Geol.*, vol. 86, p. 261-268.

Ishihara, S., 1977. The magnetite series and ilmenite series granitic rocks. *Min. Geol.*, vol. 27, p. 293-305.

Ishihara, S., 1978. Metallogenisis in the japanese island-are system. *J. Geol. Soc. London*, vol. 135, p. 389-406.

Ishihara, S., 1981. The Granitoid series and mineralization. *Econ. Geol.*, vol. 75th aniversary, p. 458-484.

Ishihara, S., Sasaki, A. and Terashima, S., 1988. Sulphur in granitoids and its role for mineralization. *Proceedings of the 7th quadrennial IAGOD symposium*, p. 573-581.

Ishihara, S. and Ulriksen, C. E., 1980. The magnetite series and ilmenite series in Chile. *Min. Geol.*, vol. 30, p. 183-190.

Ishihara, S. and Terashima, S., 1977. Chlorine and fluorine contents of granitoids as indicators for base metal and tin mineralizations. *Min. Geol.*, vol. 27, p. 191-199, (in Japanese with English summary).

Keith, J. D., van Middelaar, W., Clark, A. H. and Hodgson, C. J., 1989. Granitoid textures, compositions and volatile fugacities associated with the formation of tugsten-dominated skarn deposits. In: Whitney, J. A. and Naldret A. J., eds. *Reviews in Economic Geology*, vol. 4, p. 235-251.

Kinnaird, J., 1984. Hydrothermal alteration and mineralization of the alkaline anorogenic ring complexes of Nigeria. *Jour. Afric. Earth Sci.*, vol 3, p. 229-251.

Kinnaird, J., 1985. Hydrothermal alteration and mineralization of the alkaline anorogenic ring complexes of Nigeria. *Jour. Afr. Earth Sci.*, vol. 3, p. 229-251.

Kinnaird, J., Batchelor, R. A., Whitley, J. E. and MacKenzie, A. B., 1985. Geochemistry, mineralization and hydrotheramal alteration of the Nigerian High Heat Production Granites. In: *High Heat Production (HHP) Granites, Hydrothermal circulation and Ore Genesis*. IMM London, p. 169-195.

Kinnaird, J. and Bowden, P., 1987. The geology, petrogenisis and economic geology of Alkaline Ring Complexes. *Course notes presented in Windhoek for Geol. Soc. S. Afr.*, 190 p.

Kwak, T. A. P., 1987. *W-Sn skarn deposits and related metamorphic skarns and granitoids*. Eselvier, Amsterdam. 459 p.

Lameyre, J., 1987. Granites and evolution of the crust. *Reb. Bras. Geociências*, vol. 17, no. 4, p.349-359.

Lameyre, J. and Bowden, P., 1982. Plutonic rock type series discrimination of various granitoid series and related rocks. *Journal Volc. Geothermal Res.*, number 14, p. 169-186.

Lameyre, J., Block, R., Bonin, B., Bowden, P. and Giret, A., 1982. The granitic terms of converging plutonic type series and associated mineralizations. *Geology of granites and their metallogenic relations*. In symposium Nanjing, China.

Le Fort, P., 1987. Mineralization of Sn, W, Mo and collision plutonism. *Rev. Bras. Geoc.*, vol. 17, no. 4, p. 551-554.

Lehmann, B., 1990. *Metallogeny of tin. Lecture notes in Earth Sciences*. Eds. Bhattacharji, S., Friedman, G. M., Neugebauer, H. J. and Seilacher, A.. Springer Verlag, Berlin, p 211.

Loiselle, M. C. and Wones, D. R., 1979. Characteristics and origin of amarogenics granites. *Geol. Soc. American, Bulletin*, abstr. prog., vol. 92, p. 468.

McCarthy, T. S. and Hasty, R. A., 1976. Trace element distribution patterns and their relationship to the crystalization of granitic melts. *Geoch. Cosmoch. Acta*, vol. 40, p. 1351-1358.

Manning, D. A. C., 1982. Chemical and morphological variation in tourmalines from the Hub Kapong batholith of peninsular Thailand. *Min. Mag.*, vol. 45, p. 139-147.

Manning, D. A. C. and Henderson, P., 1984. The behaviour of tungsten in granitic melt-vapour systems. *Contrib. Miner. Petrol.*, vol. 86, p. 286-293.

Martin, R. F. and Bowden, P., 1981. Peraluminous granites produced by rock-fluid interaction in the Ririwai nonrogenic ring complex, Nigeria: mineralogical evidence. *Can. Min.*, vol 19, p. 65-82.

Mason, D. R., 1978. Compositional variation in ferromagnesian minerals from prophyry copper-generating and barren intrusions of the western highlands, Papua New Guinea. *Econ. Geol.*, vol. 73, p. 878-890.

Mason, D. R. and MacDonald, 1978. Intrusive rocks and porphyry copper-occurances of the Papua, New Guinea-Salomon Islands regiaons a recognaissance study. *Econ. Geol.*, vol. 73, p. 857-890.

Middlemost, E. A. K., 1985. *Magmas and magmatic rocks; an introduction to igneous petrology.* Logman Sci. and Techn., 266 p.

Mitchell, A. H. G. and Garson, M. S., 1981. *Mineral deposits and global tectonic settings.* Academic Press, London, New York. 405p.

Morrison, G. W., 1980. Characteristics and tectonic setting of the shoshonite rock association. *Lithos* 13, p. 97-108.

Nakada, S., 1983. Zoned magma chamber of the Osuzuama acid rocks, southwest Japan. *J. Petr.*, vol. 24, p. 471-494.

Nash, J. T., 1976. Fluid inclusion petrology data from porphyry copper deposits and application to exploration. *U S Geol. Survey, Prof. Paper*, number 907 D, p. 16.

Pagel, M. and Leterrier, J., 1980. The subalkaline potassic magmatism of the Ballons massif (Southern Vosges, France): shoshonitic affinity. *Lithos*, vol. p. 1-10.

Paterson, R. G., 1990. Ardlethan Tin deposits. In: *Geology of the mineral deposits of Australia and Papua New Guinea*, ed. Hughes, F. E. Australsian Institute of Mining and Metallurgy: Melbourne. Vol. 2, p. 1357-1364.

Peacock, M. A., 1931. Classification of Igneous rock series. *J. Geol.*, vol. 39, p. 54-67.

Pearce, J. A., Harris, N. B. W. and Tindle, A. G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Jour. Petrol.*, vol. 25, p. 956-983.

Perfit, M. R., Brueckner, H., Lawrence, J. R. and Kay, R. W., 1980. Trace element and isotope variations in a zoned pluton and associated volcanic rocks, Unalasks Island, Alaska: a model fro fractionation in the Aleutian calc-alkaline suite. *Contr. Mineral. Petrol.*, vol. 73, p. 69-87.

Perfit, M. R. and Lawrence, J. R., 1979. Oxygen isotope evidence for meteoric water interaction with the Captains Bay pluton, Aleutian Island. *Earth Planet. Sci. Lett.*, vol. 45, p. 16-22.

Pitcher, W. S., 1979. The nature, ascent and emplacement of granitic magmas. *Journal Geol. Soc. London*, vol. 136, p. 627-662.

Pitcher, W. S., 1982. Granite type and tectonic environment. In Hsu, K. J. (eds), *Mountain Buiding Processes*. New York, Academic Press, p. 19-40.

Pitcher, W. S., 1987. Granites and yet more granites forty years on. *Geologische Rundschau*, vol. 76, p. 51-79.

Pitcher, W. S. and Cobbing, E. J., 1985. Epilogue. In: Pitcher, W. S., Atherton, M. P., Cobing, E. J. and Beckinsale, R. D., eds., *Magmatism at a plate edge: The Peruvian Andes*. Blakie Halsted Press, p. 285-289.

Ramsay, W. R. H. and VandenBerg, A. H. M., 1990. Lachlan Fold Belt in Victoria: regional geology and mineralization. In: *Geology of the mineral deposits of Australia and Papua New Guinea*, ed. Hughes, F. E. Australsian Institute of Mining and Metallurgy: Melbourne. Vol. 2, p. 1269-1273.

Rossi, Ph., Cocherie, A., Meyer, G., Fouillac, A. M. and Autran, A., 1988. Metallogenic W and Sn granites: genesis and main distinguish features. *In: Minerals deposits within the European Community*, Boissonnas, J. and Omenetto, P., eds., p. 3-28

Ruttler, M. J. and Wyllie, P. J., 1988. Melting of vapour - absent tonalite at 10kbar to simulate dehydration melting in the deep crust. *Nature*, vol. 331, p. 159-160.

Sasaki, A. and Ishihara, S., 1979. Sulfur isotopic composition of the magnetite and ilmenite series granitoids in Japan. *Contr. Min. Petrol.*, vol. 68, p. 105-107.

Sato, N. and Akiyama, Y., 1980. Structural control of the Akenobe tin-polymetalic deposits, Southwest Japan. In. Ishihara, S. and Takenouchi, T., Granite magmatism and related mineralization. *Min. Geol., Spec. Issue*, number 8, p. 189-196.

Schilling, J. G., Bergeron, M. B. and Evans, R., 1980. Halogens in the mantle beneath the North Atlantic. *Philos. Trans. R. Soc. London.*, vol. 297, p. 147-178.

Shand, S. J., 1951. *Eruptive Rocks*. 4thed., John Wiley and Sons Inc., New York, p. 488.

Shibata, K. and Ishihara, S., 1979. Initial Sr^{87}/Sr^{86} rations of plutonic rocks from Japan. *Contr. Min. Petrol.*, vol. 70, p. 381-390.

Shimazaki, H., 1980. Characteristics of skarn deposits and related acid magmatism in japan. *Econ. Geol.*, vol. 75, p. 173-183.

Silitoe, R. H., 1972. A plate tectonic model for the origin of porphyry copper deposits. *Eco. Geol.*, vol. 76, p. 184-197.

Sillitoe, R. H., 1976. Andean mineralization: a model for the metallogeny of convergent plate margins. *Geol. Assoc. Canada Spec. Paper*, no. 14, p. 59-100.

Sillitoe, R. H., 1979. Some thoughts on gold-rich porphyry copper deposits. *Mineraliun Deposita*, vol. 14, p. 161-174.

Stone, M., 1982. The behaviour of Tin and some other trace elements during granite differentiation, west Cornwall, England. In Evans, A. M. ed., *Metallization associated with acid magamtism*, J. Wiley & Sons ltd., p. 339-355.

Streckeisen, A., 1973. Classification and nomenclature of plutonic rocks. *Geol. Rundsch.*, vol. 63, p. 773-786.

Streckeisen, A., 1976. To each plutonic rocks its proper name. *Earth Sci. Rev.*, vol. 12, p. 1 -33.

Suensilpong, S., Putthapiban, P. and Mantajit, N., 1983. Some aspects of tin granites and its relationship to tectonic setting. In: *Circum-pacific plutonic terranes*, ed. Roddick, J. A. Geol. Soc. of Amer., mem. no. 159, p. 77-86.

Suppel, D. W. and Scheibner, E., 1990. Lachlan Fold Belt in New south wales: regional geology and mineral deposits. In: *Geology of the mineral deposits of Australia and Papua New Guinea*, ed. Hughes, F. E. Australsian Institute of Mining and Metallurgy: Melbourne. Vol. 2, p. 1321-1327.

Takahashi, M., Aramaki, S. and Ishihara, S., 1980. Magnetite series / Ilmenite series vs. I- type / S-type granitoids, in Ishihara, S. and Takemouchi, S.,, eds., Granitic Magmatism and related mineralization, *Min. Geol., Special Issue, number 8*, p. 13-28.

Taylor, R.P. and Fryer, B. J., 1983. Rare earth element Litho geochemistry of granitoid mineral deposits. *CIM Bull.*, vol. 76, no. 860, p. 74-84.

Terashima, S. and Ishihara, S., 1976. Contents of arsenic in granitoids and their relation to mineralization. *Min. Geol.*, vol. 26, p. 327-339.

Terashima, S. and Ishihara, S., 1980. Anomalous chlorine contents o Miocene granitoids from Tsushina, Japan. *Japanese Assoc. Miner. Petrol. Eco. Geol. Jour.*, vol. 75, p. 62-67.

Tischendorf, G., 1977. Geochemical and petrographic characters of silicic magmatic rocks associated with rare-element mineralization. In Stemprok, M. and others, eds., *Metallization associated with acid magmatism. Prage*, Csechoslovakia Geol. Sur., vol. 2, p. 41-96.

Tomlinson, K. M., 1990. Cohen's reef gold deposit, Walhalla. In: *Geology of the mineral deposits of Australia and Papua New Guinea*, ed. Hughes, F. E. Australsian Institute of Mining and Metallurgy: Melbourne. Vol. 2, p. 1269-1273.

Tsusue, A., Nedachi, M. and Haschimoto, K., 1981. Geochemistry of apatites in the granitic rocks of the molybdenum, tungsten and barren provinces of southewest Japan. *Journal Geochem. Explor.*, vol. 15, p. 285-294.

Tu, K. C., Wang, Z. G. and Yu, X. Y., 1980. Genesis of granitic rocks in South China and related mineralization. In. Ishihara, S. and Takenouchi, T., Granite magmatism and related mineralization. *Min. Geol., Spec. Issue*, number 8, p. 189-196.

Turner, S. P., Foden, J. D. and Morrison, R. S., 1992. Derivation of some A-type magmas by fractionation of basaltic magma: An example from the Pathaway Ridge, South Australia. *Lithos*, vol. 28, p. 151-179.

Vidal, C. E., 1985. Metallogenisis associated with the Coastal Batholith of Peru: a review. In: Pitcher, W. S., Atherton, M. P., Cobing, E. J. and Beckinsale, R. D., eds., *Magmatism at a plate edge: The Peruvian Andes*, p. 243-249.

Watmuff, G., 1978. Geology and alteration-mineralization zoning in the central portion of the Yandera Porphyry Copper prospect, Papua New Guinea. *Econ. Geol.*, vol. 73, p. 829-856.

Whalen, J. B., 1985. Geochemistry of an island-arc plutonic suite: the Uasilau - Yau Yau Intrusive Complex. New Britain, Papua New Guinea. *Jour. Petrl.*, vol. 26, p. 603-632.

Whalen, J. B., Currie, K. L. and Chappell, B. W., 1987. A-type granites geochemical characteristics, discrimination and petrogenesis. *Contrib. Mineral. Petrol.*, vol. 95, p. 407-419.

White, A. J. R. and Chappell, B. W., 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics*, vol. 43, p. 7-22.

White, A. J. R. and Chappell, B. W., 1983. Granitoids types and their distribution in the Lachalan Fold Belt, southeastern Australia. In: *Circum-pacific plutonic terranes*, ed. Roddick, J. A. Geol. Soc. of Amer., mem. no. 159, p. 21-34.

Whitney, J. A., 1988. The origin of granite: The role and source of water in the evolution of granitic magmas: *Geolgical Society of America, Bulletin*, vol. 100, p. 1886-1897.

Whitney, J. A., 1989. Origin and evolution ofsilicic magmas. In: Whitney, J. A. and Naldret A. J., eds. *Reviews in Economic Geology*, vol. 4, p. 183-201.

Wright, J. B., 1970. Origin of the Younger Granites of Northern Nigeria, by P. Bowden. *Contr. Mineral. Petr.*, vol. 29, p. 76-78.

Wyborn, D., Turner, B. S. and Chappell, B. W., 1987. The Boggy Plain Supersuite: a distinctive belt of I-type igneous rocks of potential significance in the Lachlan Fold Belt. *Austr. J. Earth Sci.*, vol. 34, p. 21-43.

Wyllie, P. J., 1977. Crustal anatexisi an experimental review. *Tectonophysics*, vol. 43, p. 41-71.