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The granitic rocks associated with cassiterite–pyrrhotite mineralisation

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CONTENTS

Introduction

In western Tasmania, a number of large stocks of granitic composition have intruded all sedimentary units from the Older Precambrian (Whyte Schist) to the Lower Devonian (Bell Shale). These stocks, generally multiple intrusions, post-date folding but have been faulted in places (e.g. Heemskirk, Pieman Heads). Carey (1953) and Solomon (1965) have suggested that they are intruded along large anticlinal structures and Solomon (1965) shows a possible anticlinal zone with alignment of the Heemskirk, Meredith and Housetop granites. The granite masses are relatively small and are generally elliptical in outline with arcuate boundaries against the country rocks, the largest being the Meredith Granite with a surface area of approximately 120 square miles. The granites have the features of typical post-kinematic high-level plutons.

The present study is concerned with the Meredith Granite, the Pine Hill complex and the Mt Bischoff complex and a comparison with the Heemskirk Granite which has been described (e.g. Brooks and Compston, 1965; Brooks, 1966; Heier and Brooks, 1966; Green, 1966*a*, *b*). Both the Meredith and Heemskirk granites exhibit discordant, intrusive contacts in detail although the Heemskirk Granite is roughly concordant with the regional structure. Re-orientation of the country rocks by the granites is shown by a large swing in the strike of rocks to subparallel and dip steeply away from the contacts on the northern flank of the Meredith Granite, and apparent doming of the Eldon Group on the southern flank.

The Pine Hill complex occurs some two miles south of Renison Bell and comprises a complex intrusion of adamellites, which are largely altered to quartz-tourmaline (schorl) rocks. Associated quartz-feldspar porphyry dykes are greisenised.

The intrusion, which occurs at the hinge zone of a northwest-trending anticline, has been considered by Ward (1909) to be a complex of dykes and by Blissett (1962) to be a complex sill.

At Mt Bischoff, quartz porphyries occur as a series of anastomosing dykes and sills which are probably emplaced in tensional fractures in the hinge zone of the Bischoff Anticlinorium (Groves and Solomon, 1964). There is no direct evidence that the porphyries are related to the Meredith Granite although this has been suggested by most authors (e.g. Groves and Solomon, 1964).

The granite masses appear to be penecontemporaneous (Table 1, Evernden and Richards, 1962; McDougall and Leggo, 1965; Brooks and Compston, 1965; Brooks, 1966). The Heemskirk, Meredith and Pieman granites have Rb-Sr ages between 353 and 357 8 million years which would correspond to an Upper Devonian age using the Phanerozoic Time Scale of Harland *et al.* (1964). The Rb-Sr ages of porphyries from Renison Bell and Mt Bischoff (355 4 and 349 4 million years) are not significantly different from the ages of the granites and suggest a close relationship between the intrusions. K-Ar dating of the Granite Tor mass gives a compatible figure, although K-Ar and Rb-Sr ages for the Hampshire Hills Granite (362 and 375 10 million years) are somewhat older.

The major part of the Tabberabberan folding appears to be pre-late Middle Devonian (Burns and Banks, *in:* Banks, 1962, p.185), supporting the earlier suggestion that the granites are post-kinematic (e.g. Solomon, 1962, p.334). McDougall and Leggo (1965) have suggested that generation of granitic magma may be initiated during the main folding phase but that the time-scale of movement of the granitic magma from the source to the loci of intrusion may be longer than the duration of the folding phase.

Tin deposits are associated with all the granitic masses investigated in this study. Tin deposits are particularly abundant in the Heemskirk Granite, in quartz-tourmaline veins, in greisenised granite and associated alluvial gravels. Tin deposits are much less abundant in the Meredith Granite, the only economic lode deposit being the South Bischoff mine in greisenised granite, although alluvial deposits are widespread (e.g. Stanley River, Wombat Flat, Pine Creek etc.). The Mt Lindsay mine occurs within the contact aureole on the southern flank. Tin deposits are associated with the Pine Hill complex (e.g. Penzance Workings) and the Renison Bell pyrrhotite-cassiterite ore bodies occur within the radius of extension of the greisenised dykes. The spatial association of pyrrhotite -cassiterite ores and granitic rocks is best demonstrated at Mt Bischoff, where they are intimately associated, the widespread association of pyrrhotite and cassiterite in the topazised dykes indicating a genetic relationship.

It appears probable that similar ores (e.g. at Cleveland, Razorback) are also associated with similar hidden granitic rocks. The spatial association of the majority of the lead-zinc deposits (e.g. Zeehan and Waratah fields) with these granitic rocks indicates a possible genetic relationship with the granites and indirectly with the tin ores. Similarly, deposits not directly associated with granitic rocks (e.g. Dundas, Magnet) may be associated with hidden masses of similar granitic rocks.

Table 1

Summary of isotopic dating of granitic rocks, West Coast, Tasmania.

Granite mass	*Rock type*	*Age (m.y.) (Initial Sr^{87}/Sr^{86})*	*Method*	*Reference*
Heemskirk	Granite?	338	K-Ar	Evernden and Richards (1962)
Heemskirk	Red and white adamellites	340 5	K-Ar	McDougall and Leggo (1965)
Heemskirk	White granite, A series	353 3 (0.734 0.002)	Rb-Sr	Brooks and Compston (1965)
Heemskirk	White granite	357 7	Rb-Sr	Brooks and Compston (1965)
Heemskirk	Red granite	354 3 (0.705 0.720)	Rb-Sr	Brooks and Compston (1965)
Pieman	Granite?	356 9 (0.7354 0.0018)	Rb-Sr	Brooks (1966)
Meredith	Micro-adamellite	350	K-Ar	McDougall and Leggo (1965)
Meredith	Porphyritic adamellite	353 7 (0.7155 0.0015)	Rb-Sr	Brooks (1966)
Renison Bell	Greisenised porphyry	354 4 (~0.700)	Rb-Sr	Brooks (1966)
Mt Bischoff	Quartz-orthoclase porphyry	349 4 (~0.700)	Rb-Sr	Brooks (1966)
Granite Tor	Granite	355 6	K-Ar	McDougall and Leggo (1965)
Housetop	Adamellite	362	K-Ar	McDougall and Leggo (1965)
Housetop	Adamellite	375 10 (0.710 0.002)	Rb-Sr	McDougall and Leggo (1965)

Summary of structure, petrography and metamorphism

A detailed study of the structure, petrography and contact metamorphism associated with the granitic rocks has shown the following features:

(a) The Meredith Granite is composed predominantly of fine even-grained adamellite and porphyritic grey adamellite which are compositionally similar. They comprise quartz, acid andesine and orthoclase-microperthite with subordinate biotite, and minor muscovite, hornblende, apatite, zircon and sphene. Orthoclase phenocrysts up to 60 mm in length are common in the porphyritic adamellite. The adamellites are intruded by aplite and sodaclase microgranite, comprising a granular intergrowth of quartz, potash-feldspar and albite, which in places contains abundant tourmaline nodules. The components of the Meredith Granite are petrographically similar to those described from the Heemskirk Granite (Green, 1966*a*).

The Pine Hill complex comprises predominantly sodaclase adamellites, in places porphyritic, comprising quartz, perthitic potash-feldspar (= 0.71–0.74) and albite with minor biotite, muscovite and tourmaline. They are similar to the micrograntes of the Meredith Granite. Quartz-feldspar porphyry dykes intrude these micro-adamellites and comprise large euhedral potash feldspar phenocrysts (= 0.62–0.64) with subordinate albite, quartz and biotite phenocrysts in a fine groundmass of quartz and feldspar.

The porphyries at Mt Bischoff are texturally similar to the porphyries at Pine Hill but comprise euhedral orthoclase and quartz phenocrysts with no plagioclase in a fine felsitic groundmass.

(b) The contact aureoles of the granites are up to 2.5 km wide in plan and are predominantly of the hornblende-hornfels facies and locally of the pyroxene-hornfels facies of metamorphism. The occurrence of sillimanite in the immediate contact zone of the Meredith Granite in the Stanley River area indicates a minimum temperature of approximately 650°C at 8 km depth, this temperature increasing with decreasing depth.

Using this temperature as a minimum initial contact temperature, a minimum initial temperature of the magma of 850°C is indicated if appropriate values of the geothermal gradient and diffusivities and thermal conductivities of the rock involved are substituted in the equations of Jaeger (1959). Temperatures of crystallisation of feldspars (Barth, 1962) are approximately 650° to 700°C for the Meredith Granite and similar values are indicated in the Heemskirk Granite by estimates of feldspar compositions (Brooks and Compston, 1965).

(c) The granitic rocks have the features of typical post-kinematic high-level plutons, including the persistence of monoclinic potash feldspar. The maximum possible thickness of cover was some 8 km and was probably between one and five kilometres.

(d) The granitic rocks have equivalent radiometric ages of approximately 350 m.y. which is Upper Devonian and post-main Tabberabberan folding phase.

(e) The position of the exposed area of the Heemskirk Granite may be a relatively higher level than the exposed area of the Meredith Granite. This is indicated by the unusually high proportion of mineralisation within the Heemskirk Granite relative to the Meredith Granite, and the cupola-type environment suggested by Brooks and Compston (1965) and Heier and Brooks (1966) to explain the high initial Sr^{87}/Sr^{86} ratios of the granites.

(f) The complex at Pine Hill appears to be the roof of a small cupola, structurally similar to the protuberance at Aberfoyle, which may be a relatively small upward projection of a larger granite stock. Extensive quartz-feldspar porphyry dykes are associated with this intrusive mass. At Mt Bischoff, a series of porphyry dykes and sills probably occupy a series of tensional fractures above a hidden cupola similar to that at Pine Hill. The position of the Mt Bischoff and Pine Hill complexes appears structurally controlled, both occurring in the hinge zone of large anticlinal folds.

(g) Contamination of the granitic magmas appears rare or absent, although Brooks and Compston (1965) suggest some contamination of the white granite series of the Heemskirk Granite by the country rocks on the occurrence of numerous xenoliths and the high initial Sr^{87}/Sr^{86} ratio.

(h) High concentrations of boron, fluorine, sulphur and water in the roof zones of the intruding magma are indicated by the almost ubiquitous occurrence of tourmaline, topaz, axinite and sulphides in the contact aureoles of exposed granites and above possible hidden bodies (e.g. Colebrook Hill, Exe River, etc.).

(i) Greisenisation, tourmalisation or topazisation of the high level granitic intrusions is common and may be divided by comparison with a well-defined period of jointing into a pre-joint and post-joint phase at Mt Bischoff and Pine Hill.

The features described above are consistent with the granitic rocks exposed being successively higher relative levels of intrusion of a large granitic mass or a group of compositionally similar granitic masses. The roof of the Meredith Granite is considered to be largely removed while the Heemskirk Granite is probably the roof area of a larger granite body. The Pine Hill complex is probably the roof of a small cupola-like projection from a stock-like mass similar to the Heemskirk Granite, and the porphyry complex at Mt Bischoff represents the small intrusions above a cupola-like body similar to Pine Hill. Similar small buried projections may produce metamorphic and metasomatic effects similar to those at Colebrook Hill.

If the later differentiates of a fractionating magma occur successively closer to the roof of a granite intrusion, then it should be possible to test the validity of the hypothesis outlined above. This has been attempted by employing a series of major and trace element analyses of the granitic rocks involved. The interpretation is important in the understanding of the pyrrhotite-cassiterite ore bodies not directly related to granite activity (e.g. Cleveland, Razorback). If the hypothesis is valid, further deposits may be located by detailed examination of alteration phenomena, possibly related to contact metamorphism, and/or geophysical techniques (e.g. gravity) to delineate possible granite cupolas.

Geochemistry of granitic rocks

Introduction

Study of the granites is made difficult by the inaccessibility of much of the Meredith Granite, which makes systematic sample collection virtually impossible. The extreme alteration of the rocks at Pine Hill and Mt Bischoff also makes sampling difficult.

Analytical methods

The analyses of major and trace elements of the granitic rocks in are given in Groves (1968). These analyses were carried out by the author with the exception of major elements in specimens 1408, 64-36, 64-39, 3063-4, 1390, 1392, and 1471-1474 which were analysed at the Department of Mines assay laboratories.

Rock powders were obtained by crushing 10 to 50 pounds of rock and grinding in a vibratory swing mill with chromium-steel grinding discs. Analyses of all elements except Na and H_2O were carried out by x-ray fluorescent spectroscopy using the methods of Norrish and Hutton (1964). Sodium was determined by flame photometry. Trace elements were also determined by x-ray fluorescent spectroscopy using artificial kaolin-based standards and W_1 was determined as a check of the accuracy of the determinations. The matrix corrections were applied to the determination of most trace elements using the 'Compton Scattering' method of Reynolds (1963).

Approximately one half of the determinations were done in duplicate. Precision of the data, expressed as relative deviation (C) was calculated from all duplicate determinations according to the formula:

$$C = \quad d^2/n-1$$

where *d* is the percentage deviation of each observation from the arithmetic mean of each pair of duplicates and *n* is the number of duplicate pairs. The precision of the results, given as C%, is shown in Table 2 together with the detection limit and the X-ray spectral lines used in the determination of the elements.

Table 2

Precision of measurement of trace elements.

Element	*Precision (C%)*	*Detection Limit (ppm)*	*Spectral line*
Ba	6.5	10	L_{2}
Cu	8.5	1	K_{1}
Li	2	4	= 671.1Å
Ni	7	2	K_{1}
Pb	6.5	2	K_{1}
Rb	2	1	K_{1}
Sn	8.5	1	K_{1}
Sr	2	1	K_{1}
U	13	3	L_{1}
Zn	10	1	K_{1}

Major Elements

Major element analyses are shown in Groves (1968). The average composition of the granites in shown in Table 3. Several major features are evident from these analyses.

It is evident that the fine-grained grey adamellite and the porphyritic adamellite of the Meredith Granite are chemically similar, thus substantiating the earlier work by Groves (1963) and Groves and Solomon (1964) who suggested that they were mineralogically similar on the basis of modal analyses. This also supports the field evidence of Waterhouse (1914) that the two types appeared gradational. The sodaclase microgranites are more fractionated, with respect to SiO_2, than the adamellites and are chemically similar to the sodaclase adamellites of Pine Hill. The adamellites of the Heemskirk Granite are far more fractionated with respect to SiO_2 than the adamellites of the Meredith Granite, supporting the hypothesis of Brooks and Compston (1965) that the Heemskirk mass was a highly differentiated, high level, cupola-like body.

The SiO_2 contents of the Heemskirk Granite are similar to those of granites from Rossarden and Royal George (Ben Lomond Granite) which are also high level bodies (Blissett, 1959; Beattie, 1967) and may also have anomalously high Sr^{87}/Sr^{86} ratios (McDougall and Leggo, 1965). The unaltered quartz-feldspar porphyry from Pine

Table 3

Average compositions of granitic rocks from the Meredith Granite, Heemskirk Granite, Pine Hill and Mt Bischoff

	Meredith Granite			Heemskirk Granite		Pine Hill Complex		Mt Bischoff
		Porphyritic	Sodaclase	Red	White	Sodaclase		
	Adamellite	adamellite	microgranite	granite	granite	adamellite	Porphyry	Porphyry
	(3)	(5)	(2)	(7)	(7)	(3)	(2)	(5)
SiO_2	72.2	73.3	74.35	75.52	74.44	73.9	72.7	75.3
TiO_2	0.36	0.27	0.13	0.19	0.21	0.06	0.01	0.02
Al_2O_3	14.10	13.40	13.50	12.73	13.44	14.75	14.95	14.25
Fe_2O_3				0.61	0.20			
FeO				1.13	1.66			
equiv. FeO	2.00	2.07	2.03			1.61	3.67	1.95
MnO	0.02	0.05	0.02	0.04	0.05	0.02	0.09	0.06
MgO	0.85	0.65	0.8	0.25	0.18	0.6	0.65	0.6
CaO	0.81	0.76	0.17	0.60	0.83	0.13	1.09	0.20
Na_2O	3.1	3.2	3.6	2.93	2.77	3.2	0.55	0.14
K_2O	4.7	4.8	4.15	5.23	5.00	4.6	4.0	4.9|
P_2O_5	0.04	0.04	0.01	0.05	0.11	0.02	0.04	0.09
H_2O^+	0.79	0.58	0.70	0.54	0.55	1.00	1.32	1.62
H_2O^-	0.38	0.18	0.28	0.25	0.14	0.21	0.12	0.23
F	<0.2	<0.2	<0.2			<0.2	0.8	<0.2
Total	99.36	99.30	99.74	100.07	99.58	100.10	99.79	99.36
Ba	552	396	83			88	190	149
Cu	9	6	4			7	5	4
Li	42	45	48			120	54	93
Ni	3?	5	4				10	5
Pb	33	27	25				27	32
Rb	218	243	327	358	399	754	784	906
Sn	3	5	4			27	59	72
Sr	80	47	14	35	38	8	6	3
Th	21	19	18	49.2	24.1	32	43	11
U	9	9	19	12.4	18.0	23	32	13
Zn	54	28	22			25	92	122
K/Rb	188	166	119	142	106	52	49	56
Th/U	2.3	2.9	1.0	4.0	1.3	1.7	1.4	0.8

Hill shows a similar fractionation to the Mt Bischoff porphyries but, as predicted from the petrography, contains significantly more Na_2O and CaO than the Mt Bischoff rocks.

It is evident from Figure 1 that there is a sympathetic variation of FeO and MgO for all the granite types, MgO increasing with increasing FeO. The adamellites of the Meredith Granite have higher FeO and correspondingly higher MgO than the adamellites of the Heemskirk Granite, and appear to be enriched in MgO. The rocks from Mt Bischoff and Pine Hill also appear to be slightly enriched in MgO relative to the Heemskirk Granite. It is interesting that the porphyries, which exhibit many similarities with leucogranites of the Snowy Mountains (Kolbe and Taylor, 1966), do not show the typical low concentrations of FeO and MgO shown by these rocks.

The relationship between the major alkalies is indicated in the plot of molecular quotients (100) of K_2O and Na_2O (fig. 1). The adamellites from the Meredith Granite, Heemskirk Granite and Pine Hill complex plot close to the line of equimolar proportions of K_2O and Na_2O with a tendency to plot on the K_2O-rich side of this line. The alkali oxides also show an inverse relationship and appear to plot about a line with the form $K_2O + Na_2O$ = constant (approx. 10). Superimposed on this major trend there is a tendency for total alkali oxides to increase slightly with increasing Na_2O, this being a common phenomenon in granitic rocks (Exley and Stone, 1966). The inverse relationship of Na_2O and K_2O has been used as evidence for internal metasomatism (Battey, 1955; Stone, 1961). However as Exley and Stone (1966) indicate, such conclusions based on alkali data are open to criticism. The total alkali content is generally governed by the feldspar content which is approximately a constant, one feldspar diminishing as the other increases. Thus there is a tendency for K_2O to vary inversely with Na_2O irrespective of the process causing variation.

The position of the porphyries from Mt Bischoff and Pine Hill on the alkali diagram is unusual and forms an entirely separate field to the adamellites. The porphyries have a similar range in K_2O to the adamellites but have extremely

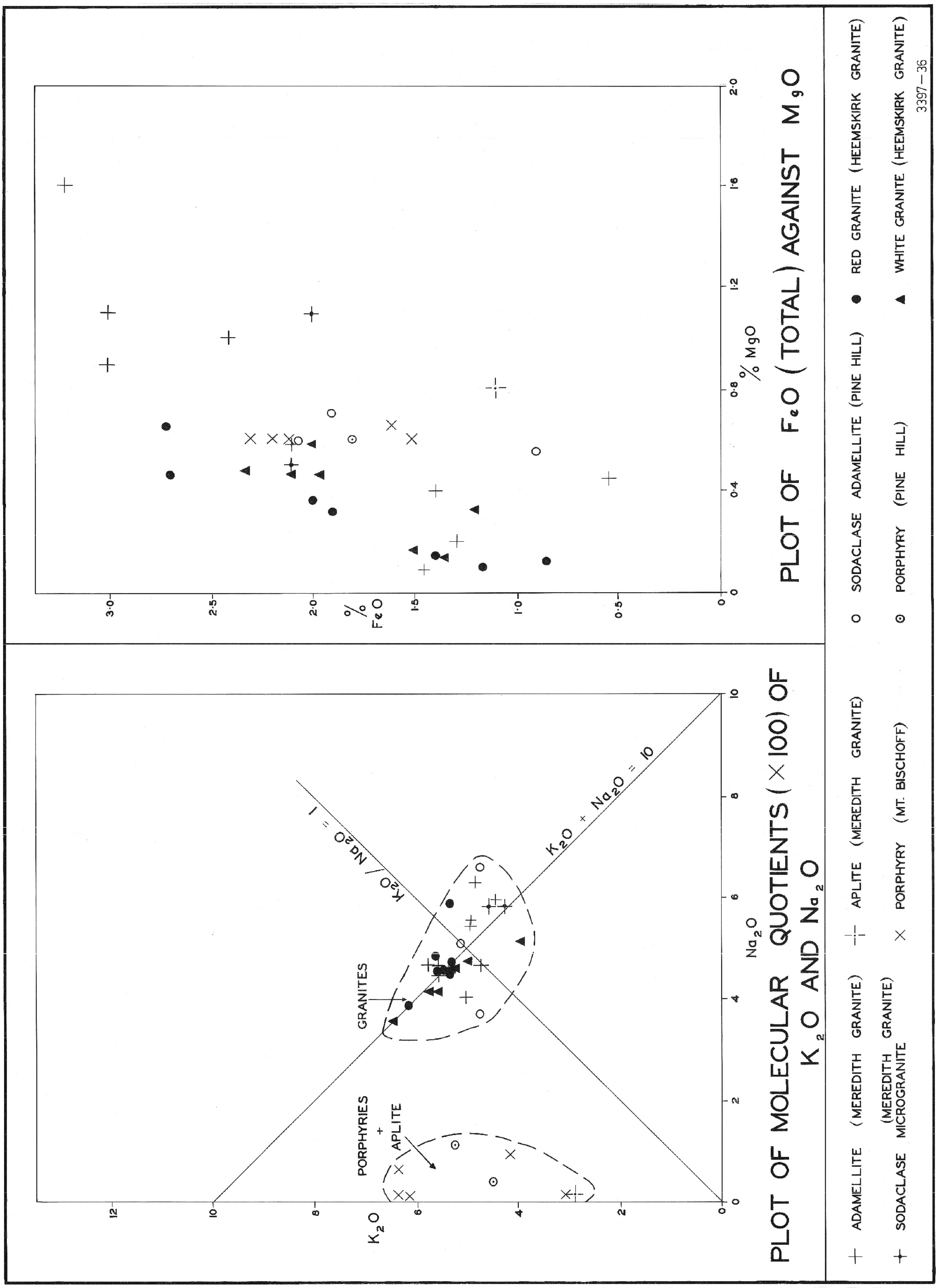

PLOT OF MOLECULAR QUOTIENTS (× 100) OF K₂O AND Na₂O
K₂O
Na₂O
K₂O / Na₂O = 1
K₂O + Na₂O = 10
GRANITES
PORPHYRIES + APLITE
PLOT OF FeO (TOTAL) AGAINST MgO
% FeO
% MgO
ADAMELLITE (MEREDITH GRANITE)
SODACLASE MICROGRANITE (MEREDITH GRANITE)
APLITE (MEREDITH GRANITE)
PORPHYRY (MT. BISCHOFF)
SODACLASE ADAMELLITE (PINE HILL)
PORPHYRY (PINE HILL)
RED GRANITE (HEEMSKIRK GRANITE)
WHITE GRANITE (HEEMSKIRK GRANITE)
3397–36

Figure I

low Na_2O values and there appears to be no correlation between K_2O and Na_2O in the limited range of values obtained. Similar enrichment of K_2O with exclusion of Na_2O has been recorded in some late stage intrusions of fine granite and elvans from the Carnmenellis Granite from southwest England (Ghosh, 1934). The relationship between the alkalies explains the anomalous behaviour of K found by Brooks and Compston (1965), the K in the white granites decreasing with increasing SiO_2, the reverse of trends shown by the red granites and general trends in granites described by Nockolds and Allen (1953). It can be seen that Na has the reverse relationship in each of the granite types, thus maintaining the inverse relationship indicated in Figure 1.

The sympathetic variation of FeO–MgO and the inverse relationship of K_2O and Na_2O indicates that the most valid graphical representation of chemical variation in the granitic rocks would be obtained by plotting Niggli values, calculated for groups of chemically similar oxides rather than single oxides. Values of al, alk, fm and c have been plotted against Si for all the granitic rocks (fig. 2) and smoothed variation curves are given in Figure 3.

The adamellites and microgranites of the Meredith Granite plot in the Si range of 329 to 452 and the Niggli values form smooth curves with al and alk increasing and fm and c decreasing with increasing Si. These trends are similar to trends shown by other granitic rocks with a similar range in Si (e.g. Van Moort, 1966, p.190). The adamellites of the Heemskirk Granite are more fractionated with respect to Si, values ranging from 408 to 522. The white and red granites plot on significantly different trends, the white granites generally having higher al and c values, and lower alk and fm values than the red granites. Both granite trends have similar slopes which are also similar to the slopes of the Meredith Granite trends. The adamellites and porphyries of the Pine Hill complex have a similar range of Si values to the adamellites of the Heemskirk Granite. However the slopes of alk, fm and c are reversed, alk decreasing sharply and fm and c increasing slightly with increasing Si. The al values are consistently higher and the slope of the al trend is less than that of the Heemskirk and Meredith trends. The Mt Bischoff porphyries, which show the greatest fractionation with respect to Si, reflect similar trends to the Pine Hill rocks with overall higher al and decreasing alk, and increasing fm with increasing Si.

Discussion

The variation diagrams of major elements are inconclusive in interpreting the relationship between the occurrences of granitic rocks. The fractionation with respect to Si is consistent with successive differentiation and higher relative level of intrusion from Meredith Granite–Heemskirk Granite–Pine Hill complex–Mt Bischoff complex and is also consistent with respect to the inter-relation of microgranites to adamellites in the Meredith Granite, and porphyries to micro-adamellites in the Pine Hill complex.

The results generally show that the granites do not belong to a simple differentiation series, if smooth variation is indicative of this process, and that the Heemskirk Granite may lie on a different trend to the Pine Hill and Mt Bischoff rocks. The deficiency in alkalies and the excess of alumina in the Pine Hill and Mt Bischoff rocks appears to be the prominent feature of their chemical separation from the Heemskirk Granite. This may in part be due to partial alteration of the potash feldspars (at least in the Mt Bischoff porphyries) to kaolin with the subsequent relative increase in alumina and decrease in alkalies. However it is unlikely that this contributes sufficient difference to account for the deviation of the two trends.

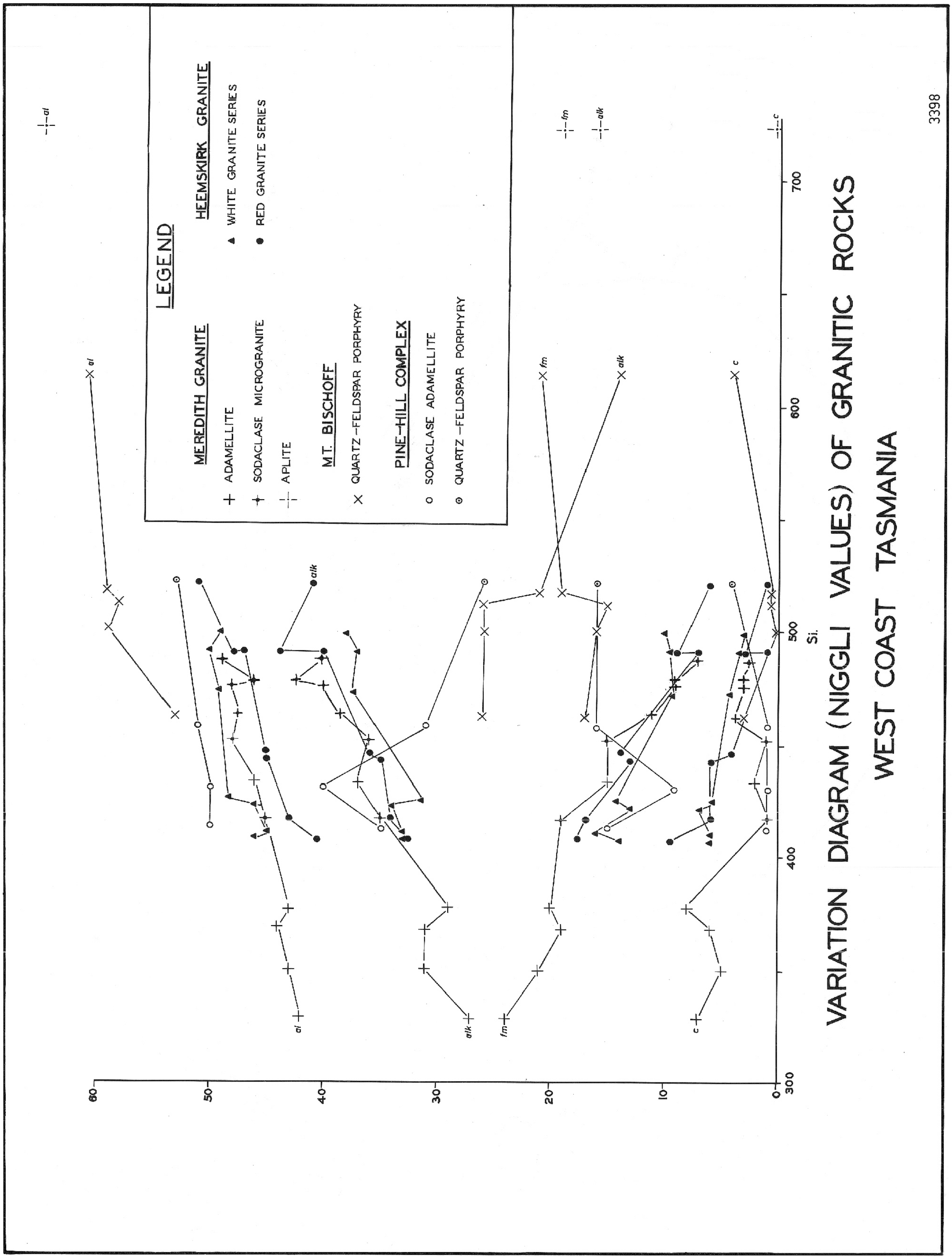
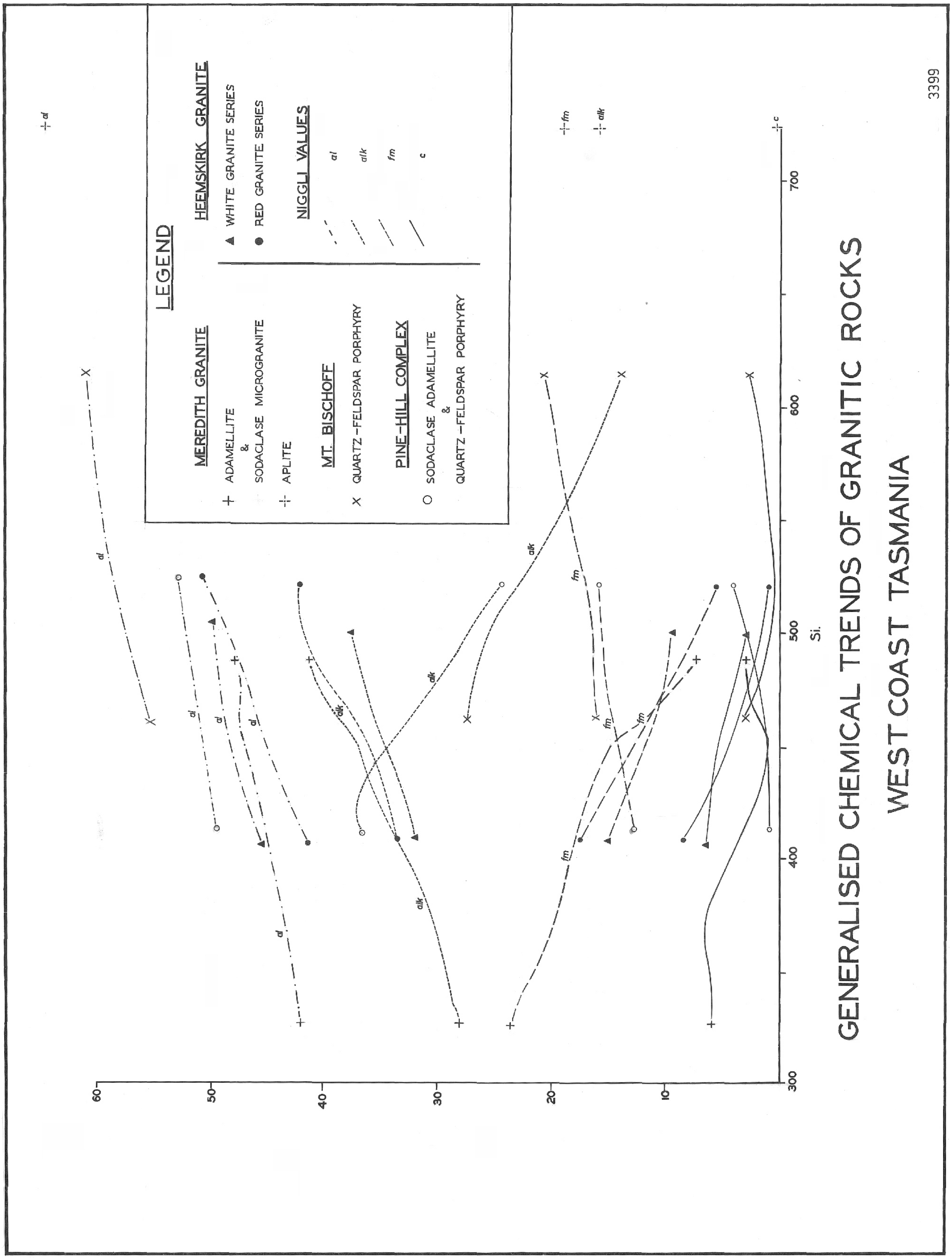

LEGEND
MEREDITH GRANITE
ADAMELLITE
SODACLASE MICROGRANITE
APLITE
MT. BISCHOFF
QUARTZ-FELDSPAR PORPHYRY
PINE-HILL COMPLEX
SODACLASE ADAMELLITE
QUARTZ-FELDSPAR PORPHYRY
HEEMSKIRK GRANITE
WHITE GRANITE SERIES
RED GRANITE SERIES
al
alk
fm
c
Si.
300
400
500
600
700
0
10
20
30
40
50
60
VARIATION DIAGRAM (NIGGLI VALUES) OF GRANITIC ROCKS
WEST COAST TASMANIA
3398

Figure 2



GENERALISED CHEMICAL TRENDS OF GRANITIC ROCKS
WEST COAST TASMANIA
LEGEND
MEREDITH GRANITE
+ ADAMELLITE & SODACLASE MICROGRANITE
APLITE
MT. BISCHOFF
X QUARTZ-FELDSPAR PORPHYRY
PINE-HILL COMPLEX
O SODACLASE ADAMELLITE & QUARTZ-FELDSPAR PORPHYRY
HEEMSKIRK GRANITE
▲ WHITE GRANITE SERIES
● RED GRANITE SERIES
NIGGLI VALUES
al
alk
fm
c
Si.
300
400
500
600
700
0
10
20
30
40
50
60
3399

Figure 3

Trace Elements

The average trace element compositions for the various granite types are given in Table 3. An investigation of K/Rb and Th/U ratios in the Heemskirk Granite has previously been presented by Heier and Brooks (1966) and a detailed investigation of trace elements in the Snowy Mountains granites has been described by Kolbe and Taylor (1966). This investigation is interesting in that it provides information on granites from the central part of the Lachlan Geosyncline which includes Tasmania as a southern extension.

The trace element results tend to confirm that the porphyries are related to the granites and not to basic magmas, as has been shown for the Snowy Mountains granites by Kolbe and Taylor (1966). A plot of Mg against Ni (fig. 4) contrasts with similar plots for granophyric rocks from the Skaergaard and Bushveld complexes (Wager and Mitchell, 1951; Liebenberg, 1961). The porphyries generally have a lower or equivalent Ni concentration to the basic differentiates but have a higher Mg concentration. They do not exhibit the extremely low concentrations of Ni described by Kolbe and Taylor (1966), but this may be partly due to contamination during preparation of the rocks for analysis. Other differences are the lower concentrations of ferromagnesian elements such as Cu, Ti and Mn than the basic differentiates, which retain a characteristic trace element distribution dependent on the composition of the basic parent magmas. In conclusion it appears extremely unlikely that the porphyries are differentiates of a basic magma.

The Behaviour of Rb, Sr, Ba, Li, Cu, Pb, Zn and Sn

Rubidium

The Rb values of the Meredith Granite (average 292 ppm) are similar to values for low Ca-granites (Turekian and Wedepohl, 1961) but the other values indicate strong enrichment. The K/Rb ratio has been found to be a particularly useful index of geological processes (Taylor, 1965). It has been demonstrated that enrichment of Rb relative to K is commonly due to magmatic differentiation, and several authors have shown that the K/Rb ratio decreases with increasing differentiation (e.g. Taylor and Heier, 1958; Demin and Khitarov, 1958; Volkov and Savinova, 1959). An interesting deviation is described by Butler *et al.* (1962) who showed a progressive decrease in the K/Rb ratio for the Liruei complex and an irregular behaviour in the Amo complex of northern Nigeria. Bowler (1959) has demonstrated that the high level granites in southwest England have abnormally high K/Rb ratios.

A plot of K against Rb for the Tasmanian granitic rocks is shown in Figure 4. The rocks of the Meredith Granite show a consistent K/Rb ratio of approximately 200 which is slightly lower than the approximate overall average for most types of continental crust (Taylor, 1965), and is equivalent to values for the gneissic granites and granodiorites of the Snowy Mountains granites (Kolbe and Taylor, 1966). The microgranites and aplites show a slight enrichment in Rb with respect to K. The rocks of the Heemskirk Granite have K/Rb ratios ranging from 55 to 165 with an average around 120, indicating strong differentiation. Similar ratios (53–208) have been recorded by Beattie (1967) for the granite at Royal George (East Tasmania) which is also a high level intrusion, with a tendency for lower K/Rb ratios in the microgranites. The ratio is also equivalent to the K/Rb ratio in the leucogranites of the Snowy Mountains granites. The rocks of the Pine Hill and Mt Bischoff dyke complexes have significantly lower K/Rb ratios, averaging 70, with some porphyries from Pine Hill giving K/Rb ratios as low as 50. These results indicate extremely strong fractionation of an initial acid magma.

The evidence from the K/Rb ratios indicates that they are consistent with the granitic rocks being successive differentiates from a single or similar magmas, the least fractionated being the Meredith Granite and the most fractionated the Pine Hill and Mt Bischoff complexes, with the Heemskirk showing intermediate differentiation.

Strontium–barium

The Ca-Sr and Ba-Sr relationships are shown for the granitic rocks in Figure 4. Unfortunately Ba has not been determined for the Heemskirk Granite. The rocks of the Meredith Granite have lower Ba and Sr values than average low Ca-granites (Turekian and Wedepohl, 1961).

In general the results indicate decreasing Sr from the Meredith Granite, Heemskirk Granite to the Pine Hill and Mt Bischoff porphyry complexes; i.e. a similar sequence to the increase in K/Rb ratios. This is consistent with progressive differentiation, owing to the capture of Sr in early formed K-minerals and subsequent depletion in the late stages of the differentiation sequence. Nockolds and Mitchell (1948) and Heier and Taylor (1959) indicated that Sr substitutes for K, with coupled substitution of Si^{4+} for Al^{3+}, more readily than Ca and that the Sr/Ca ratio is ten times greater in K-feldspar than in co-existing plagioclase. Decrease in Sr is also demonstrated by Kolbe and Taylor (1966) for the leucogranites of the Snowy Mountains granites.

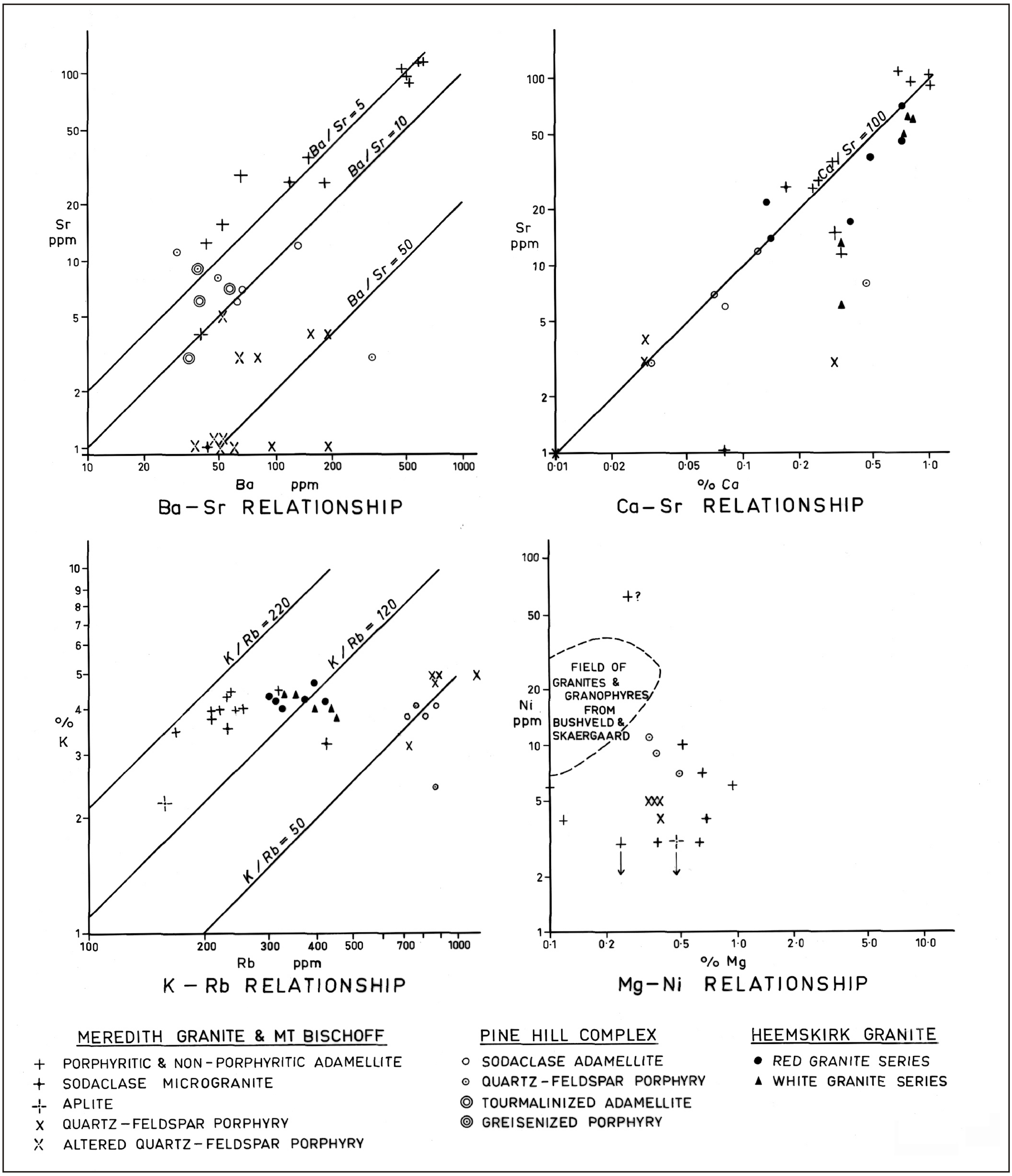


Figure 4

Trace element relationships, granitic rocks, western Tasmania

The Ca/Sr ratio for most of the Tasmanian rocks is consistent at approximately 100 but is somewhat greater for the rocks of the Heemskirk Granite and for one porphyry from both Mt Bischoff and Pine Hill, these possibly containing minor calcite which would increase the ratio. The Ca/Sr ratios and their behaviour is similar to that of the Snowy Mountains granites although Sr values are generally lower in the Mt Bischoff and Pine Hill porphyries than any values recorded for the leucogranites.

Nockolds and Allen (1953) indicated that Ba^{2+} substitutes for K^{+}, with a coupled substitution of Al^{3+} for Si^{4+}, and behaves according to the classical capture theory, readily entering early formed potash-minerals, and thus becoming depleted in the late differentiates. It is evident that the rocks of the Meredith Granite have the highest Ba content (185–595 ppm) with depletion in the microgranites and aplite (40–121 ppm) and strong decrease in the

Pine Hill micro-adamellites and porphyries (50–133 ppm, with one anomalous result of 329 ppm). The Mt Bischoff porphyries have anomalously high Ba contents (81–192 ppm), which may in part be due to their higher K content. The Ba/Sr ratios are irregular in distribution but show an overall increase from the Meredith Granite (approximately 5) to the Pine Hill complex (approximately 10) to the Mt Bischoff complex (approximately 50). This is contrary to successive differentiation according to Heier and Taylor (1959), who suggest that the Ba/Sr ratio decreases during fractionation in feldspars, but is similar to the results of Kolbe and Taylor (1966). They showed a range in Ba/Sr ratios for granodiorites and gneissic granites of approximately 2.0 to 5.5 whereas the leucogranites have ratios from 2.5 to 13.0 with an average of 6.0 (i.e. similar to the Pine Hill complex).

Lithium

Li constitutes some 30 ppm in the adamellites of the Meredith Granite, which is about the average abundance of Li in granitic rocks (Turekian and Wedepohl, 1961). In the microgranite the concentration is 48 ppm and in the aplite 225 ppm. In the rocks of the Pine Hill complex it varies from 24 to 299 ppm and appears to be more abundant in rocks containing abundant mica. The Mt Bischoff porphyries are enriched in Li, the range being 45 to 111 ppm, although three of the four analyses are above 100 ppm. Taylor (1965) concluded that concentrations of Li greater than 100 ppm in granites are indicative of extreme fractionation and imply that the rock is a late stage, high level product. Bowden (1966) recorded high lithium contents in tin-bearing biotite granites from northern Nigeria and suggested that the high values were introduced by late magmatic and post-magmatic processes. At Mt Bischoff and Pine Hill the porphyries with high Li values do not appear to be strongly greisenised and the Li contents probably indicate strong fractionation.

Copper, zinc and lead

Copper values in all granitic rocks analysed are remarkably consistent, without exception below 10 ppm, and generally ranging between 4 and 6 ppm. These concentrations are slightly below the average abundance of Cu in granites (Taylor, 1965). Zinc values are rather variable and are generally higher in the porphyries at Mt Bischoff and Pine Hill. The average value for the adamellites of the Meredith Granite is 47 ppm, which is approximately the average abundance in granites. The distribution of zinc values is difficult to discuss because knowledge of the geochemical distribution is unknown. Tauson and Kravchenko (1956) indicated that it occurs mainly as minute grains of sphalerite with minor substitution in biotites and feldspars. Lead has been determined only in a limited number of analyses because of the interference of As in the determinations by x-ray fluorescent spectroscopy. Pb occurs at a relatively constant concentration, slightly greater than the average abundance in granites. The Pb/Sr ratio increases markedly from the adamellites of the Meredith Granite (average 0.3) to the Pine Hill porphyries (average 3.8) and the Mt Bischoff porphyries (average 10.7). Taylor (1965) indicated that such an increase is consistent with fractionation of a magma. The distribution of Pb, like Zn, is uncertain due to the possibility of formation of the sulphide phase (Tauson and Kravchenko, 1956).

Tin

The distribution of tin is of primary importance from an economic viewpoint. It has generally been found that granites enclosing tin deposits have greater tin concentrations than unmineralised granites (e.g. Butler, 1953; Goldschmidt, 1954; Shibata *et al*., 1960). The average values of tin concentration in silica rocks are between 3 and 4 ppm (Onishi and Sandell, 1957; Hamaguchi *et al*., 1964) and values up to 800 ppm have been recorded for greisens (Goldschmidt, 1954). Values for unaltered biotite granites are generally lower, approximately 15 to 30 ppm (Barsukov, 1957). Ivanova (1963) found that the tin content of biotite granites enclosing tin deposits (16–32 ppm) is higher than that for other granites (<5 ppm) and that the tin concentration (60–110 ppm) increases with increasing late or post-magmatic alteration. The association of tin with biotite is well known, concentrations up to 4500 ppm equivalent SnO_2 being recorded (Ahrens and Liebenberg, 1950).

The granitic rocks of the Meredith Granite have low concentrations of Sn, averaging 3 ppm and ranging from 1 to 4 ppm. These are similar concentrations to those recorded from the Snowy Mountains granites (Kolbe and Taylor, 1966) and are similar to concentrations in tin-bearing granites at Royal George on the east coast of Tasmania (Beattie, 1967). These concentrations are approximately equivalent or slightly lower than the average concentration of Sn in silicic rocks. The Sn values are higher in the Pine Hill complex, ranging from 3 to 14 ppm and up to 16 ppm in the greisens. At Mt Bischoff, the unaltered porphyries are enriched and contain between 7 and 16 ppm Sn.

The relatively low values obtained in this investigation are unusual, but may be explained using predictions based on the known geochemistry of tin. Rankama and Sahana (1950) suggested that Sn occurs in magmas as Sn^{2+} and Sn^{4+}

ions. Ringwood (1955) suggested that Sn^{2+} ions are more likely to substitute for Na^{+} than Ca^{2+} and this is substantiated by the occurrence of more Sn in albite than in anorthite, although the concentrations are small (Hellwege, 1956). Nockolds (1966), on the basis of effective ionic radii, bond lengths to oxygen and bonding energies, suggested that Sn^{2+} should prefer to substitute for Fe^{2+} rather than Ca. Borchert and Djebek (1960) recorded high Sn values in olivines and postulated that Sn^{2+} is substituting for Fe^{2+}. Ringwood has also suggested that the high ionic potential of Sn^{4+} will favour the formation of an $(SnO_4)^{4-}$ complex which is not generally accepted into silicate lattices because of size difficulties and hence will tend to concentrate in residual melts. Ringwood also indicated that Sn^{4+} can act as a free ion and substitute in silicates rich in Fe^{2+} and Mg^{2+} ions and Taylor (1965) suggested that it substitutes for Ti in biotites and sphene.

Two origins have been suggested based on these assumptions. Barsukov (1958) found no evidence for cassiterite in Sn-rich biotites but found that it occurred along cleavage planes in muscovite in some post-magmatic deposits. He suggested that the Sn substitutes in the biotite structure and that cassiterite is formed by expulsion of Sn from the biotite during muscovitisation of the biotite concomitant with albitisation of the granite. This would explain the high Sn content of biotite in areas of cassiterite-bearing greisens (e.g. Ivanova, 1963). Rattigan (1960), MacDonald (1965) and others have concluded essentially the reverse relationship; that the tin deposits are associated with granites that contain low concentrations of the elements for which Sn substitutes in silicates. The Sn therefore concentrates in the residual magma and forms discrete tin deposits during a late stage of granite emplacement. Rattigan (l960) records that tin deposits of this origin are associated with granites with high K + Na/Ca + Mg ratios, this being consistent with the composition of the Tasmanian granites.

The latter hypothesis could explain the relatively low concentrations of Sn in the granitic rocks investigated in spite of the occurrence of tin deposits within and spatially associated with them. It is possible that, in general, both processes may operate dependent on the crystallisation history and late-magmatic processes operating in the granite magma.

Conclusions

Features consistent with successive magmatic differentiation of a single or similar magmas to produce the granitic rocks investigated (i.e. from the Meredith Granite as the least fractionated to the Mt Bischoff porphyries as the most fractionated) are summarised below.

(a) Increasing fractionation with respect to Si, the porphyries at Mt Bischoff being the most fractionated.

(b) Successive decrease in K/Rb ratios from 200 in the adamellites from the Meredith Granite to an average of 70 for porphyries from Pine Hill and Mt Bischoff.

(c) Successive decrease in Sr values, although Ca/Sr ratios remain essentially constant, the porphyries again having the lowest Sr concentrations.

(d) The occurrence of Li values greater than 100 ppm in the porphyries at Pine Hill and Mt Bischoff, indicating extreme fractionation.

(e) Increase in Sn concentrations in the porphyries.

Evidence inconsistent with this hypothesis is:

(a) The apparent bifurcation of chemical trends in the variation diagram of major oxides.

(b) The increase in Ba/Sr ratios, which generally decrease with increasing fractionation (Heier and Taylor, 1959).

The overall evidence indicates that the hypothesis of successive differentiation of a single or similar magmas, intruded at successively higher relative levels, is not generally inconsistent with the chemical data, and in fact is remarkably consistent in certain aspects. The bifurcation of chemical trends is probably real but may be accentuated by increasing alumina and decreasing alkalies produced by kaolinisation of the potash feldspars, both at Mt Bischoff and Pine Hill. The overall increase in Ba/Sr ratios is reasonably consistent with ratios for leucogranites given by Kolbe and Taylor (1966), which are generally greater than for granodiorites and gneissic granite.

References

AHRENS, L. H.; LIEBENBERG, W. R. 1950. Tin and indium in mica, as determined spectrochemically. *Amer. Min.* 35:571–578.

BANKS, M. R. 1962. Silurian and Devonian systems, *in:* SPRY, A.; BANKS, M. R. (ed.). The geology of Tasmania. *J. Geol. Soc. Aust.* 9:177–187.

BARSUKOV, V. L. 1957. The geochemistry of tin. *Geochemistry* 1:41–52.

BARSUKOV, V. L. 1958. New data on the geochemistry of tin, *in: Symposium de Exploration Geochemica*. 29–40. 20th International Geological Congress Mexico.

BARTH, T. F. W. 1962. The feldspar geological thermometer. *Norsk. Geol. Tidssk.* 42:330–339.

BATTEY, M. H. 1955. Alkali metasomatism and the petrology of some keratophyres. *Geol. Mag.* 92:104–126.

BEATTIE, R. D. 1967. *The geology of the Royal George area*. B.Sc. (Hons) Thesis, University of Tasmania.

BLISSETT, A. H. 1959. The geology of the Rossarden–Storeys Creek district. *Bull. geol. Surv. Tasm.* 46.

BLISSETT, A. H. 1962. One Mile Geological Map Series. K/55-5-50. Zeehan. *Explan. Rep. geol. Surv. Tasm.*

BORCHERT, H.; DJEBEK, J. 1960. Zur geochemie des zinns. *Chemie der Erde* 20:137–154.

BOWDEN, P. 1966. Lithium in younger granites of northern Nigeria. *Geochim. et Cosmochim. Acta* 30:555–564.

BOWLER, C. M. L. 1959. *The distribution of the five alkali elements and fluorine in some granite and associated aureoles from the south-west of England*. Ph.D. Thesis, University of Bristol.

BROOKS, C. 1966. The rubidium-strontium ages of some Tasmanian igneous rocks. *J. geol. Soc. Aust.* 13:457–469.

BROOKS, C.; COMPSTON, W. 1965. The age and initial Sr^{87}/Sr^{86} of the Heemskirk Granite, western Tasmania. *J. Geophys. Research* 70:6249–6262.

BUTLER, J. R. 1953. The geochemistry and petrology of rock weathering (I) the Lizard area, Cornwall. *Geochim. et Cosmochim. Acta.* 4:157–178.

BUTLER, J. R.; BOWDEN, P.; SMITH, A. Z. 1962. K/Rb ratios in the evolution of the younger granites of northern Nigeria. *Geochim. et Cosmochim. Acta* 26:89–100.

CAREY, S. W. 1953. The geological structure of Tasmania in relation to mineralization. *Publ. 5th. emp. min. metall. Congr.* 1:1108–1128.

DEMIN, A. M.; KHITAROV, D. N. 1958. Geochemistry of potassium, rubidium and thallium in application to problems in petrology. *Geochemistry* 1958:721–734.

EVERNDEN, J. F.; RICHARDS, J. R. 1962. Potassium-argon ages in eastern Australia. *J. geol. Soc. Aust.* 9:1–49.

EXLEY, C. S.; STONE, M. 1966. The granitic rocks of south-west England, *in:* HOSKING, K. F. G.; SHRIMPTON, G. J. (ed.). *Present views on some aspects of the geology of Cornwall and Devon.* 131–184. Royal Geological Society of Cornwall : Truro.

GHOSH, P. K. 1934. The Carnmenellis Granite: its petrology, metamorphism and tectonics. *Quart. J. geol. Soc. Lond.* 90:240–276.

GOLDSCHMIDT, V. M. 1954. *Geochemistry*. Clarendon Press : Oxford.

GREEN, T. H. 1966*a*. The geology of the Trial Harbour district. *Pap. Proc. R. Soc. Tasm.* 100:1–20.

GREEN, T. H. 1966*b*. Thermal metamorphism in the Trial Harbour district, Tasmania. *J. geol. Soc. Aust.* 13:405–418.

GROVES, D. I. 1963. *Geology of the Mt Bischoff area*. B.Sc. (Hons) Thesis, University of Tasmania.

GROVES, D. I. 1968. *The cassiterite–sulphide deposits of western Tasmania*. Ph.D. thesis, University of Tasmania.

GROVES, D. I.; SOLOMON, M. 1964. The geology of the Mt Bischoff district. *Pap. Proc. R. Soc. Tasm*. 98:1–22.

HAMAGUCHI, H.; KURODA, R.; OKUMA, N.; *et al.* 1964. The geochemistry of tin. *Geochim. et Cosmochim. Acta.* 28:1039–1053.

HARLAND, W. B.; SMITH, A. G.; WILCOCK, B. 1964. The Phanerozoic time-scale: A symposium. *Spec. Publ. geol. Soc. London*. 1.

HEIER, K. S.; BROOKS, C. 1966. Geochemistry and the genesis of the Heemskirk granite, west Tasmania. *Geochim. et Cosmochim. Acta* 30:633–643.

HEIER, K. S.; TAYLOR, S. R. 1959. Distribution of Ca, Sr and Ba in southern Norwegian pre-Cambrian alkali feldspars. *Geochim. et Cosmochim. Acta* 17:286–304.

HELLWEGE, H. 1956. Zur vorkommen des zinns als spurenelement in mineralien. *Hamb. Beitr. angew. Miner.* 1:73–136.

IVANOVA, G. F. 1963. Content of tin, tungsten and molybdenum in granites enclosing tin-tungsten deposits. *Geochemistry* 1963:492–500.

JAEGER, J. C. 1959. Temperatures outside a cooling intrusive sheet. *Am. J. Sci.* 257:44–54.

KOLBE, P.; TAYLOR, S. R. 1966. Geochemical investigation of the granitic rocks of the Snowy Mountains area, New South Wales. *J. geol. Soc. Aust.* 13:1–25.

LIEBENBERG, C. J. 1960. The trace elements of the rocks of the Bushveld igneous complex. *Publs Univ. Pretoria* 12.

LIEBENBERG, C. J. 1961. The trace elements of the rocks of the Bushveld igneous complex. Part II. The different rock types. *Publs Univ. Pretoria* 13.

MACDONALD, S. 1965. Tin ore potential of the South Island, New Zealand. *N.Z. J. Geol. Geophys.* 8:440–453.

MCDOUGALL, I.; LEGGO, P. J. 1965. Isotopic age determinations on granitic rocks from Tasmania. *J. geol. Soc. Aust.* 12:295–332.

NOCKOLDS, S. E. 1966. The behaviour of some elements during fractional crystallization of magma. *Geochim. et Cosmochim. Acta* 30:267–278.

NOCKOLDS, S. R.; ALLEN, R. 1953. The geochemistry of some igneous rock series. *Geochim. et Cosmochim. Acta* 4:105–142.

NOCKOLDS, S. R.; MITCHELL, R. L. 1948. The geochemistry of some Caledonian plutonic rocks. A study in the relationship between the major and trace elements of igneous rocks and their minerals. *Trans. R. Soc. Edinburgh* 61:533–575.

NORRISH, K.; HUTTON, J. T. 1964. Preparation of samples for analysis by x-ray fluorescent spectroscopy. *Rep. Div. Soils C.S.I.R.O. Aust.* 3/64.

ONISHI, H.; SANDELL, E. B. 1957. Meteoritic and terrestrial abundance of tin. *Geochim. et Cosmochim. Acta* 12:262–270.

RANKAMA, K.; SAHAMA, T. G. 1950. *Geochemistry*. University of Chicago Press.

RATTIGAN, J. H. 1960. Residual characteristics of crystallates genetically associated with ore deposits. *Econ. Geol.* 55:1272–1284.

REYNOLDS, R. C. 1963. Matrix corrections in trace element analysis by x-ray fluorescence. Estimation of the mass absorption by Compton scattering. *Amer. Min.* 48:1133–1143.

RINGWOOD, A. E. 1955. The principles governing trace element distribution during magmatic crystallization. Part I: The influence of electronegativity. *Geochim. et Cosmochim. Acta* 7:189–202.

SHIBATA, H.; OKADA, S.; ISHIKAWA, H. 1960. Chemical composition of Japanese granitic rocks in regard to petrographic provinces. VIII: Trace elements. *Sci. Rep. Tokyo Kyoiku Diagaku* (C) 7:217–270.

SOLOMON, M. 1962. The tectonic history of Tasmania, *in:* SPRY, A.; BANKS, M. R. (ed.). The geology of Tasmania. *J. Geol. Soc. Aust.* 9:311–339.

SOLOMON, M. 1965. Geology and mineralization of Tasmania. *Publ. 8th commonw. min. metall. Congr.* 1:464–477.

STONE, M. 1961. Genesis of the granites of south-west England. *Abstr. Proc. Conf. Geol. Geomorph. SW England*. 4:5–7. Royal Geological Society of Cornwall.

TAUSON, L. V.; KRAVCHENKO, L. A. 1956. Characteristics of lead and zinc distribution in minerals of the Caledonian granitoids of the Susamyr Batholith in central Tian-Shan. *Geochemisty International* 1956:78–88.

TAYLOR, S. R. 1965. The application of trace element data to problems in petrology. *Phys. Chem. Earth* 6:133–213.

TAYLOR, S. R.; HEIER, K. S. 1958. Alkali elements in potash feldspar from the pre-Cambrian of southern Norway. *Geochim. et Cosmochim. Acta*. 13:293–302.

TUREKIAN, K. K.; WEDEPOHL, W. H. 1961. Distribution of the elements in some major units of the Earth's crust. *Bull. geol. Soc. Am.* 72:175–192.

VAN MOORT, J. C. 1966. Les roches cristallophylliennes des Cévennes et les roches plutoniques du Mont Lozere. *Ann. Fac. Sci. Univ. Clermont* 31.

VOLVOV, V. P.; SAVINOVA, E. N. 1959. Distribution of rubidium and the K/Rb ratio in the rocks of the Lovozero alkaline massif. *Geochemistry* 6:635–642.

WAGER, L. R.; MITCHELL, R. L. 1951. The distribution of trace elements during strong fractionation of basic magma — a further study of the Skaergaard intrusion, East Greenland. *Geochim. et Cosmochim. Acta* 1:129–208.

WARD, L. K. 1909. The tin field of North Dundas. *Bull. geol. Surv. Tasm*. 6.

WATERHOUSE, L. L. 1914. The Stanley River tin field. *Bull. geol. Surv. Tasm.* 15.