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Petrology and Geochemistry of Acid Igneous Rocks of Northeast Queensland

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ABSTRACT

Acid igneous rocks of northeast Queensland range in age from Precambrian to Permian. The Precambrian to Devonian Forsayth and Robin Hood Granites and the Siluro-Devonian Dumbano Granite and Dido Granodiorite form deep-level intrusions and have generally unfractionated compositions, with relatively high K/Rb and low K/Na ratios. The only significant mineralization associated with them is gold. The Proterozoic Esmeralda Granite and Croydon Volcanics and the extensively mineralized Upper Palaeozoic high-level granitic rocks and their associated volcanics are mostly highly fractionated, with high K_2O*, Rb, Y, Th, U, and in some cases Li and Be contents, and low K/Rb ratios. The Esmeralda Granite and Croydon Volcanics are considered to have been derived by anatexis of K-rich sialic crustal rocks, but isotopic and chemical data suggest that the Upper Palaeozoic acid magmas originated by anatexis of Rb-poor deep crustal material, possibly caused by rising basaltic or andesitic magmas derived by melting of subducted oceanic crust. Granitic rocks with associated tin mineralization, including the Esmeralda Granite and several of the more fractionated Upper Palaeozoic granitic rocks are enriched in volatile elements such as Li, Be, B and F. Sn contents are significantly higher than those of non-stanniferous granites, but lower than values reported for many Sn-granites elsewhere. No correlation of granite geochemistry with Pb/Zn or Cu mineralization was found.*

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INTRODUCTION

In 1970 the Bureau of Mineral Resources began a geochemical investigation of the acid igneous rocks of northeast Queensland. Its main purpose was to investigate possible correlations between the geochemistry of the granitic rocks and the type of associated mineralization in order to discover possible geochemical criteria of general use in delineating areas of potential mineralization. In other words, is it possible by analysing samples of a particular intrusion to get some indication of the type of mineralization likely to be associated with it? Although numerous papers have been written on this subject, the results have, in many cases, been inconclusive, or, at best, of only limited application (e.g. see reviews by Barsukov, 1967; Tauson, 1967; Krauskopf, 1967). An attempt was also made to relate mineralization to such factors as petrography, tectonic environment, and so on.

The area chosen for the investigation covers a large part of northeast Queensland, including the Georgetown Inlier and most of the Hodgkinson Basin between Cape Melville in the north and Ingham in the south—a total area of about 140 000 km^2 (Pl. 1). The map area includes the Cape Melville, Cooktown, Mossman, Cairns, Atherton, Innisfail, Georgetown, Einasleigh, Ingham, Gilberton, and Clarke River 1:250 000 Sheet areas and parts of the Red River and Croydon Sheets. The general geology of the area has been described by de Keyser & Wolff (1964), White (1965), de Keyser & Lucas (1968), and Blake (1972). A wide variety of both intrusive and extrusive acid igneous rocks, ranging in age from Precambrian to Permian, is present in the area. The extensive Upper Palaeozoic igneous rocks of the Georgetown Inlier have been described in detail by Branch (1966). Associated with the granitic rocks is a variety of economic mineralization, including gold, tin, copper, lead, zinc, silver, molybdenum, tungsten, bismuth, antimony, fluorite, and minor uranium and tantalum. The region has been an important mining area for almost a century: the gold deposits of the Palmer, Etheridge, Hodgkinson, and other goldfields and the tin and other deposits of the Herberton and Chillagoe districts have been the largest producers. Present-day production is confined to relatively few, mostly small mines and prospects, the most important being the alluvial tin deposits near Mount Garnet (Solomon et al., 1972a, b).

A total of 562 samples, mostly of acid igneous rocks, was analysed for a large number of major and trace elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P, H_2O, CO_2, Li, Be, F, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Sn, Ba, La, Ce, Pb, Th, and U). Other elements of economic interest (e.g. Au, Ag, Mo, W, and Bi) were not determined because suitable techniques of sufficient sensitivity were not then available in the BMR laboratories. About 75 percent of samples were of Upper Palaeozoic igneous rocks, which are the most abundant in the area. The remaining samples were of Precambrian to Devonian age. Eighteen biotite samples, mostly from the Upper Palaeozoic granitic rocks, were analysed for Fe, Mg, Li, Cr, Cu, Zn, Sn, and Pb.

GEOLOGY AND PETROGRAPHY

The acid igneous rocks of the area range in age from Precambrian to Permian. They intrude the Precambrian metamorphics and sediments of the Georgetown Inlier as well as the Middle Palaeozoic sediments of the Hodgkinson Basin, a part of the Tasman Geosyncline, and cover a total area of about 42 000 km^2. The approximate ages of the main granitic rocks (mostly after Black, 1973, 1974), together with the associated economic mineralization, are given in Table 1.

The oldest granitic rocks form part of the Forsayth Batholith, which occupies much of the central and southern parts of the Georgetown Inlier. Five varieties, all considered to be of Precambrian age, were recognized in the Forsayth Batholith: the Forsayth, Robin Hood, McKinnons Creek, and Dumbano Granites and the Dido Granodiorite (White, 1961, 1965). The Dumbano Granite and Dido Granodiorite were subsequently shown to be of Siluro-Devonian age, but at least part of the Forsayth Granite is Precambrian (Richards et al., 1966). The Esmeralda Granite and associated Croydon Volcanics are also of Precambrian age, although these were originally correlated with the Upper Palaeozoic acid igneous rocks (Branch, 1966).

The nomenclature used for igneous rocks in this Bulletin is largely based on that of Hatch, Wells, & Wells (1961). The terms *granite, adamellite, granodiorite,* and *trondhjemite* are used for coarse-grained rocks containing more than 20 percent of quartz. In granite, alkali feldspar forms more than two-thirds of the

TABLE 1. MAJOR GRANITIC ROCKS OF NORTHEAST QUEENSLAND, SHOWING APPROXIMATE AGES AND ECONOMIC MINERALIZATION ASSOCIATED WITH EACH UNIT (Mineralization of only minor importance is shown in brackets).

	Approximate Age	*Associated Mineralization*
Esmeralda Granite	Precambrian	Au, Sn, (Pb, Ag, Cu)
Forsayth Granite	Precambrian to Devonian?	Au (Pb, Ag, Cu, Ta)
Robin Hood Granite	Precambrian to Devonian?	Au (Cu, Pb, Ag, Zn, U)
Dumbano Granite	Siluro-Devonian	—
Dido Granodiorite	Siluro-Devonian	—
Nymbool Granite	Late Carboniferous	—
Ixe Microgranodiorite	Late Carboniferous	—
Elizabeth Creek Granite	Late Carboniferous to Permo-Carboniferous	Sn, Mo, W, Pb, Cu, F (Au, Bi, Ag, Sb)
Hammonds Creek Granodiorite	Permo-Carboniferous*	—
Bakerville Granodiorite	Permo-Carboniferous	—
Herbert River Granite	Permo-Carboniferous	(Cu, Pb, W)
Almaden Granite	Permo-Carboniferous	Cu, Pb, Ag, Zn (Bi)
Unnamed Granitic Rocks of Ingham and Innisfail Sheet areas	Permo-Carboniferous	Sn, W (Bi, Mo, Pb, Zn, Au, Ag)
Hales Siding Granite		—
Atlanta Granite		—
Tully Granite Complex	Permo-Carboniferous to Early Permian	Au (Sn)
Kalunga Granodiorite	Early Permian	—
Watsonville Granite	Early Permian	—
Mareeba Granite	Early Permian	Sn, W, Cu, Au (Mo, Zn, Bi)
Cannibal Creek Granite	Early Permian?	?Sn
Puckley Granite	Early Permian	?(Au, Sn, Cu, W)
Trevethan Granite	Late Permian	—
Finlayson Granite	Late Permian	Sn (W, Mo, Pb, Cu)
Altanmoui Granite	Late Permian?	(Au, Sn, W, Sb, Cu)

* i.e., near the Permo-Carboniferous boundary.

N.B. The Upper Palaeozoic granitic rocks range in age from about 325 m.y. for the Ixe Microgranodiorite and part of the Elizabeth Creek Granite (Black, 1974) to about 260 m.y. for the Trevethan and Finlayson Granites. The latter age is based on K-Ar dates given by Richards et al. (1966), with an upward correction of 6 percent to permit more meaningful comparison with Rb-Sr data (see Black & Richards, 1972a).

total feldspar; in adamellite, between one-third and two-thirds; in granodiorite, between one-tenth and one-third; and in trondhjemite, less than one-tenth. Rocks with a grainsize between 0.05 and 1 mm are referred to as microgranite, microadamellite, etc. The fine-grained equivalents of granite, adamellite, and granodiorite are *rhyolite. rhyodacite,* and *dacite,* respectively; they are commonly porphyritic, and feldspar proportions were estimated, where possible, from both the phenocrysts and the groundmass. Where the groundmass was too fine-grained, reference was made to the chemical analysis to aid classification. Intermediate rocks with little or no alkali feldspar are referred to as *diorite,* of which *andesite* is the fine-grained equivalent. *Quartz diorite* is used for rocks containing up to 10 percent quartz and *tonalite* for rocks with 10 to 20 percent quartz. Harker (1954, p. 62) states that tonalites form a connecting link between the quartz diorites and the granitic rocks. Petrographic data and sample localities for all analysed rocks are given in Sheraton & Labonne (1974). Sample localities are also shown in Plate 1*.

Esmeralda Granite

The Esmeralda Granite forms a large batholith about 80 km long and 5 to 15 km wide along the western side of the Croydon Cauldron Subsidence Area. A number of smaller

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* In Plate 1 only the last few digits of the BMR registered number are used. To obtain the full number prefix numbers from 0001 to 0421 with 6859, from 1000 to 1290 with 7057. Numbers in the range W1 to W155 should be prefixed by 6749 (e.g. W14 = 67490014), and those in the form MG20 or DB18B by 6849 (e.g. MG20 = 68490020, DB181A = 68490181A).

intrusions lie on the eastern side of the cauldron. The total area covered by the granite is more than 650 km^2.

The granite is mostly uniform in texture and medium to coarse-grained, although finer-grained varieties near the contacts probably represent chilled margins. It is typically a grey biotite adamellite which grades into biotite granite; Branch (1966) has noted the occurrence of subordinate granodiorite. Pegmatites and aplite veins are rare, but greisen lodes are found in many localities.

The Esmeralda Granite intrudes Precambrian sediments and metamorphics as well as the Croydon Volcanics. Xenoliths of mica schist and gneiss occur near the contacts and are present even where the roof is formed of Croydon Volcanics, which suggests that the roof of the granite corresponds closely to the base of the volcanic pile (Branch, 1966, p. 95). The volcanics were extensively recrystallized by the intrusion of the granite, but other metamorphic effects were slight. The contact between the Esmeralda Granite and Croydon Volcanics at Stanhills Battery is sharp, but shows a thin zone of mylonite, cut by veins of granite. Branch (1966) estimated that the Esmeralda batholith was intruded under a volcanic cover only about 300 to 600 m thick.

In the Croydon area, the granite contains lenses of graphitic granite up to 3 km long by 250 m wide. They contain abundant xenoliths of graphite and graphitic siltstone which grade into greisenized granite. Branch (1966, p. 96) considered that they represent beds of carbonaceous siltstone, similar to those in the Etheridge Formation to the east of the cauldron, which were brecciated *in situ* and intruded by granite in the roof of the batholith.

The Esmeralda Granite was correlated by Branch with the Upper Palaeozoic Elizabeth Creek Granite, but Rb-Sr dating has shown that both the Esmeralda Granite and Croydon Volcanics have a similar Precambrian age. The granite has been dated at about 1411 m.y. (Webb, 1971; Black, 1973).

Petrography. The Esmeralda Granite is a medium to coarse-grained biotite adamellite which grades into biotite granite. It is generally even-grained, but porphyritic varieties occur locally. Finer-grained types (e.g. 70571057-60) probably represent a chilled margin. The texture is usually allotriomorphic granular, grading to hypidiomorphic granular in some of the adamellites.

Quartz (25-35%) is anhedral and commonly fractured. Microcline perthite (25-50%) is the usual alkali feldspar and many crystals are surrounded by micrographic intergrowths, particularly in the finer-grained rocks. Much of it is poikilitic and margins are usually corroded adjacent to grains of plagioclase. Alkali feldspar is more abundant than plagioclase in all except the more basic adamellites. Plagioclase (10-40%) is mostly oligoclase, some zoned, with an average composition near An_{26}. It is almost invariably extensively altered to sericite, saussurite, etc., whereas much of the alkali feldspar is relatively fresh. Biotite (3-10%) is pleochroic from pale greenish yellow to dark reddish brown and is usually partly chloritized. Relict hornblende occurs in two samples (70571059, 1073). Muscovite is commonly present, although much of it is secondary and replaces feldspar; a few specimens contain up to 2 percent.

Tourmaline is a common accessory mineral in the contact zones. Almandine-rich garnet occurs in a few samples, mostly of adamellite, and is most abundant on the eastern side of the cauldron, near Langlo Homestead. The garnet is usually irregular in shape and occurs in association with biotite, zircon, and opaque minerals. It is only slightly zoned and may show some replacement by chlorite. A typical analysis is given in Table 2. Other accessory minerals include apatite, epidote, zircon, opaque minerals, and, less commonly, fluorite, cassiterite, and pyrite. Graphite occurs in a few specimens (70571060, 1062).

Greisenization is common in the Stanhills area. Several of the analysed granites from this area are slightly greisenized (e.g. 70571064-6), with strongly altered feldspars, bleached biotite, and prominent tourmaline and fluorite.

Economic mineralization. Gold, tin, silver-lead, and copper minerals are associated with the Esmeralda Granite, though only gold has been produced in quantity.

Gold and tin are restricted to the granites and volcanics in the western part of the area, where tin lodes occur near Stanhills and Mount Cassiterite. Gold has been mined in the Croydon and Esmeralda areas.

The Snake Creek mine, at the southern end of the granite intrusions on the eastern side of the area, has been worked for silver-lead and a little copper in metasomatized rhyodacite. Copper has also been mined in the Mount Little area (White, 1965; Branch, 1966).

TABLE 2. COMPOSITION OF GARNETS FROM THE ESMERALDA GRANITE AND CROYDON VOLCANICS

	Croydon Volcanics				*Esmeralda Granite*
Component %	*1*	*2*	*3*	*4*	*5*
Almandine	86.3	86.8	92.7	89.2	88.4
Spessartine	8.5	8.3	4.7	7.3	4.7
Grossularite	3.8	3.7	2.1	2.0	3.5
Pyrope	1.4	1.4	0.5	1.5	3.4

Analyses were carried out by D. J. Pritchard, using a Jeol JXA-3A electron microprobe.

1. 70571050. 3. 70571063. 5. 70571087.
2. 70571061. 4. 70571068.

Croydon Volcanics

The Croydon Cauldron Subsidence Area, on the western side of the Georgetown Inlier, occupies nearly 6000 km^2; of this the Croydon Volcanics occupy more than 3000 km^2 and are intruded by the Esmeralda Granite, which is thought to be comagmatic. The cauldron is bounded by a series of intersecting rectilinear faults, which parallel major faults in the Precambrian basement flanking the cauldron. This suggested to Branch (1966, p. 35) that the boundary faults of the cauldron were controlled by major fractures in the basement, rejuvenated under tension, and that viscous rhyodacite was extruded from vents and fissures along them. The eruption of thick welded tuff sheets was then accompanied by subsidence of the cauldron block.

Branch (1966, p. 36) gives the following stratigraphic succession:

Thickness (m)	
120	Grey-green rhyodacite welded tuff sheet
150	Grey rhyodacite welded tuff sheet
60	Grey rhyolite and rhyodacite flows
15+	White siltstone (near Wallabadah Outstation).

Rhyodacite flows are generally restricted to the marginal parts of the cauldron. The higher flows are amygdaloidal and flow banding is poorly developed. The welded tuff sheets are usually recrystallized, particularly near intrusions of the Esmeralda Granite. Eutaxitic textures are poorly preserved and most of the units are massive. Many of the rocks contain graphite pellets, which are thought to have been derived from beds of carbonaceous siltstone assimilated at depth. In order to investigate this hypothesis, four samples of the Stockyard Creek Siltstone Member of the Etheridge Formation were analysed. The Proterozoic Etheridge Formation is intruded by the Esmeralda Granite, and crops out to the east of the Croydon cauldron (White, 1965).

Although correlated with the Upper Palaeozoic rocks of the Georgetown Inlier by Branch, the Croydon Volcanics have since been shown to be Precambrian in age. A Rb-Sr age of 1429 ± 75 m.y. was obtained (Webb, 1971). This is statistically indistinguishable from the age obtained for the Esmeralda Granite and is thus compatible with the observed field relations.

Petrography. In hand specimen the Croydon Volcanics are very homogeneous; they range from dark grey porphyritic rhyodacite to rhyolite. Many samples contain about twice as much alkali feldspar as plagioclase and thus fall on the borderline between rhyodacite and rhyolite. Phenocrysts typically make up between 15 and 30 percent of the rock and include quartz, white alkali feldspar, and white or pale greenish plagioclase. Quartz forms the most abundant phenocrysts (usually about 50-60%) and is commonly embayed, bipyramidal β-quartz. The resorption is probably due to the decrease in load pressure during rise of the magma within the crust, feldspar replacing quartz as the liquidus phase in rhyodacitic compositions at lower pressures (Green & Ringwood, 1968a). Alkali feldspar (25-35% of phenocrysts) includes high-temperature varieties such as sanidine (70571045), but microcline is much more common, particularly in the extensively recrystallized rocks near contacts with the Esmeralda Granite. The alkali feldspar is usually kaolinized and micrographic intergrowths are common. Plagioclase phenocrysts (10-25%) are corroded and invariably sericitized or saussuritized.

In all samples, the groundmass is devitrified, and it usually contains a higher proportion of alkali feldspar than the phenocrysts. It is aphanitic to cryptocrystalline and often partly spherulitic. It is so recrystallized that little evidence of the assumed pyroclastic origin of many of the samples has survived: only sample 70571048 contains recognizable relict pumice fragments. In several specimens, however, the feldspar phenocrysts tend to be oriented with their long axes parallel to the base of the sheet, presumably because of compaction (Branch, 1966).

The main mafic mineral is biotite, which is invariably partly chloritized. Almandine-rich garnet is present in a number of samples (70571050, 1061, 1063, 1068). It forms subhedral crystals, up to 0.5 mm in diameter, which are free of inclusions and show little or no zoning. The garnet appears to be a primary phase and probably crystallized directly from the magma at considerable depths (Green & Ringwood, 1968b). Partial analyses are given in Table 2. Minor constituents include sericite, calcite, graphite, epidote, apatite, sphene, opaque minerals, and, less commonly, fluorite and tourmaline.

As contacts with the Esmeralda Granite are approached, the grainsize increases and the margins of the phenocrysts become corroded (e.g. 70571056, 1061, 1063, 1071, 1082). Within a few metres of the contact the rock grades into microgranite. Many of the quartz phenocrysts are fractured and show undulose extinction, and micrographic textures are common. Microcline is the only alkali feldspar in these contact rocks. Fluorite and tourmaline appear to be associated with the contact zones and are particularly abundant in mineralized areas, as for example, north of Croydon (70571045-7) and at Stanhills (70571068).

Forsayth Granite

The Forsayth Granite crops out over more than 4000 km^2. It intrudes the Einasleigh and Robertson River metamorphics and the Etheridge Formation and is intruded by the Dumbano Granite. Many of the granitic rocks have features characteristic of late or synkinematic, relatively deep-level (catazonal or mesozonal) intrusions (Buddington, 1959). Thus, porphyroblastic and foliated rocks are common, and the metamorphic grade of the country rocks is mostly greenschist to amphibolite facies.

A wide variety of rock types is present, ranging from tonalite to granite, although adamellite and granodiorite are the most abundant, at least in the sampled areas. It is proposed that the Forsayth Granite be renamed the 'Georgetown Granite Complex' and the name Forsayth Granite reserved for the granites and adamellites of the Forsayth area (J. H. C. Bain, pers. comm.). In the latter area, the granite can be divided into two main varieties: one rather melanocratic and commonly strongly porphyritic, and the other relatively leucocratic and generally even-grained.

The melanocratic variety is typically a dark grey, medium to coarse-grained biotite adamellite (samples 68590020, 70571116, 1120, 1194-5), but grades into granodiorite (70571113) and granite (70571117). It contains white euhedral phenocrysts of alkali feldspar up to 4 cm long, although the proportion of phenocrysts varies greatly, even within the same outcrop. The groundmass is generally rich in biotite. Xenoliths, mostly metasedimentary, and biotite-rich mafic schlieren are locally abundant and a foliation is frequently developed, particularly near contacts with other granitic rocks. The foliation is defined by both alkali feldspar phenocrysts and biotite crystals, and xenoliths are aligned parallel to it.

The pale grey leucocratic variety grades from biotite adamellite to granite (68590101, 0103, 70571111, 1115, 1118, 1196-8), and is particularly abundant south of Forsayth. It is generally more homogeneous than the melanocratic type and in most cases appears to intrude it, although the melanocratic type contains occasional xenoliths of leucocratic granite. Pegmatitic and aplitic veins and segregations occur locally.

Every gradation between the two main varieties appears to exist. Much of the area southeast of Forsayth is underlain by slightly porphyritic adamellite or granite, intermediate between them (68590017, 0021, 70571110, 1112, 1114, 1119, 1121, 1199, 1233). In other areas the two types are complexly interfingered. Other rock types in the Forsayth area include a pink granite or adamellite, ranging from even-grained and leucocratic to porphyritic. Both this pink granite and numerous pink pegmatites intrude the melanocratic type, described above, which itself tends to assume a pink colouration near the contacts (J. H. C. Bain, pers. comm.).

Most of these rock types are more or less foliated, the foliation being generally parallel to intrusive contacts, although locally it cuts across them. It is thus a post-magmatic feature, as are the large porphyroblasts of alkali feldspar. The porphyroblastic origin is most apparent at contact zones, where feldspar porphyroblasts cut across the contact between porphyritic adamellite and leucocratic veins. It is possible, however, that a platy flow foliation is present in some localities (White, 1965).

Fine to medium-grained non-porphyritic biotite-rich rocks occur southwest of Forsayth, near the contact with the Etheridge Formation. They appear to grade into less siliceous rock types (quartz diorite, etc.).

Granodiorites are particularly abundant on both sides of the Newcastle Range, east of Georgetown (68590417, 70571226, 1232) and west of Eveleigh homestead (68590019, 70571222-5). The small intrusions southeast of Forest Home homestead, which were included with the Esmeralda Granite by White (1965), are granodioritic in composition (68590016, 70571102) and may be isolated stocks of Forsayth Granite. The intrusion 10 km west-southwest of Green Hills Outstation is a similar grey medium-grained granodiorite, although it was correlated with the Prestwood Microgranite by White (1965).

It seems likely, in view of the wide range of rock types present in the Forsayth Granite, that there have been several phases of intrusion, possibly extending over a considerable period of time. The available geochronological data are not inconsistent with such an interpretation. Richards et al. (1966) concluded that the Forsayth Granite (including the mass near Forest Home homestead) is probably at least 1200 m.y. old, but lost argon during later events, the last of which occurred during the Devonian, 384 ± 11 m.y. ago. This loss of argon may have accompanied the deformation that affected much of the Forsayth Granite and that may have partly resulted from the intrusion of the Devonian granites (see Richards et al., 1966, p. 8). On the other hand, it seems possible that some of the rocks classified as Forsayth Granite could be of Devonian age and related to the Dumbano Granite or Dido Granodiorite. In other words, some of the Devonian ages obtained by Richards et al. (1966) could be real. Rb-Sr age determination has suggested that at least two intrusive events occurred during the Precambrian. A sample from the Forsayth area has given an age of 1490 m.y. and one from west of Georgetown yielded a minimum age of about 1500 m.y.; an age of about 1250 m.y. is suggested for the masses near Forest Home homestead (Black, 1973 and pers. comm.). The intrusion near Dargalong, about 13 km southwest of Chillagoe, has given a Siluro-Devonian age (Black, 1973).

Petrography. The more acid rocks (granites and adamellites) are generally medium to coarse-grained; many are foliated and many porphyritic. The texture is normally allotriomorphic granular, but grades into hypidiomorphic granular. Quartz forms aggregates of small grains, and many of the grains show undulose extinction. Larger grains have serrated boundaries. Alkali feldspar is almost invariably microcline and is usually perthitic. It forms large tabular poikilitic phenocrysts as well as smaller anhedral grains. The plagioclase is subhedral and generally altered to sericite or saussurite. It ranges from oligoclase to sodic andesine and is usually zoned, except in the most acid rocks. The grains are corroded or form myrmekitic intergrowths close to microcline. Brown or reddish brown biotite (up to 10%) is present in all samples and is commonly associated with muscovite, epidote, zircon, and opaque minerals. Muscovite (up to 4%) occurs in most specimens, although only in trace amounts in some. The intrusion near Dargalong (70571034-5) is particularly rich in muscovite, which in some cases appears to partly replace biotite. Accessory minerals include epidote, zircon, apatite, allanite, sphene, opaque minerals, and occasionally garnet and fluorite. The granites are relatively poor in accessories.

The granodiorites are medium to coarse-grained, with a hypidiomorphic granular texture. They are less commonly foliated, but are usually slightly porphyritic. The euhedral zoned crystals of oligoclase-andesine are commonly altered to sericite, saussurite, and calcite. Alkali feldspar is usually microcline, although orthoclase is present in one sample (70571232), and forms anhedral interstitial crystals. Biotite (up to 15%) is the usual ferromagnesian mineral; hornblende is rare. Muscovite is common, but rarely exceeds 1 percent of the rock. Epidote is a prominent secondary mineral and in some cases apparently pseudomorphs hornblende. Accessory minerals include allanite, apatite, sphene, zircon, and opaque minerals.

The tonalite (68590100, 70571169) from north of Kidston contains less quartz (15-20%) than the granodiorites and contains about 3 percent of hornblende and 3 percent of epidote, as well as abundant biotite. Alkali feldspar is rare or absent. These rocks bear a closer resemblance to the Dido Granodiorite than to the typical Forsayth Granite.

Economic mineralization. The most important mineralization associated with the Forsayth Granite is gold; the principal areas are the Etheridge, Oaks, and Gilbert goldfields. The Etheridge goldfield is the most important, having yielded about 20 200 kg of gold since 1877, although there is no production at the present time (White, 1965). A little lead and silver has also been obtained from the gold lodes of the Etheridge goldfield, and the Eveleigh mine has been worked for lead and silver.

Copper mineralization has been located near the contacts with Precambrian metamorphics, but is of little importance. Small quantities of tantalum have been obtained from an albite pegmatite dyke at Grants Gully, 19 km west of Forsayth (White, 1965).

Robin Hood Granite

The Robin Hood Granite crops out over an area of about 900 km^2, forming a southern extension to the Forsayth Granite. Like the Forsayth Granite, it includes a variety of rock types ranging from granite to granodiorite. According to White (1965), it is typically a pink or grey medium to coarse-grained biotite adamellite or granite, commonly with quartz phenocrysts. The most widespread type in the Robin Hood homestead area is a grey medium-grained granodiorite, with abundant quartz phenocrysts (J. H. C. Bain, pers. comm.). Pink leucocratic muscovite and biotite-muscovite adamellite and granite, which occur as small masses in much of the area mapped as Robin Hood Granite, are considered by Bain to be older than the granodiorites, and possibly related to the Robertson River Metamorphics. These leucocratic rocks, which are associated with abundant muscovite pegmatites, have been renamed the Digger Creek Granite.

K-Ar dating has given similar results to those obtained for the Forsayth Granite and has suggested an age of at least 1200 m.y. for part of the Robin Hood Granite, with subsequent loss of argon (Richards et al., 1966). The argon loss possibly accompanied the local shearing, which may have been caused by the intrusion of nearby Palaeozoic granitic rocks. Rb-Sr dating has indicated a Siluro-Devonian age for the granodiorites, however (L. P. Black, pers. comm.).

Petrography. The adamellites (68590416, 70571124) and granites (68590018A,B, 70571125, 1128) are grey to pink and generally medium to coarse-grained. The pink varieties (70571124-5, 1128) are leucocratic, and almost devoid of biotite, although up to 3 percent of muscovite is present. The other samples contain 1 to 2 percent of partly chloritized biotite. Quartz is usually granulated, particularly along grain boundaries, and commonly shows undulose extinction. Alkali feldspar is microcline perthite. Oligoclase (An_{24-28}) is partly sericitized. Myrmekite is common between grains of plagioclase and microcline, and plagioclase commonly has corroded margins. Accessory minerals include sphene, apatite, zircon, opaque minerals, and less commonly garnet and fluorite. The granodiorites (70571122-3, 1126) are coarse-grained and contain both biotite (4-5%) and hornblende (2-3%). Much of the hornblende is pseudomorphed by biotite, chlorite, and epidote, and the biotite is slightly chloritized. Quartz, slightly perthitic microcline, and euhedral zoned andesine are the other major constituents.

Economic mineralization. The Percyville goldfield contains gold in complex copper, lead, silver, and zinc ores. The gold reefs are either in Robin Hood Granite or in Einasleigh Metamorphics intruded by the granite, although in some mines rhyolite dykes, probably of Late Palaeozoic age, were the main mineralizers (White, 1965). Uranium mineralization occurs at Timkins Uranium prospect, 8 km east-northeast of Percyville. The mineralization occupies small fractures in a quartz reef intruding Robin Hood Granite, but is of little economic significance (White, 1965).

Dumbano Granite

The Dumbano Granite forms at least three separate intrusions in the southern part of the Georgetown Inlier, where it is exposed over a total area of about 2000 km^2. It crops out in the area around Clarke Hills, Wando Vale, and Reedy Springs homesteads to the south of the Broken River Embayment, and to the west of Lyndhurst homestead, as well as forming much of the downfaulted blocks of the Bagstowe and Lochaber Ring Complexes.

The Dumbano Granite is typically a light grey to pink, medium-grained biotite adamellite, with pink feldspar phenocrysts (White, 1965). A body of pink leucocratic adamellite and granite occurs in the Bagstowe area and includes varieties that are rather similar in hand specimen to some of the Upper Palaeozoic granitic rocks of the area. The biotite trondhjemite near Butlers Knob bears some resemblance to the Dido Granodiorite.

The Dumbano Granite intrudes the Forsayth Granite (White, 1965) and is intruded by Upper Palaeozoic acid igneous rocks of the Bagstowe and Lochaber Ring Complexes. K-Ar dating has indicated a Devonian age, 380 ± 8 m.y., for the Dumbano Granite (Richards et al., 1966), whereas Rb-Sr mineral ages are 400 and 417 m.y. (Black, 1973).

Petrography. The more acid rocks (granite to adamellite) are generally medium-grained; some are foliated and a few are porphyritic. The texture is allotriomorphic granular. Quartz (23-35%) occurs as aggregates of small crystals, many of which show strain effects. Alkali feldspar (25-65%) forms anhedral crystals of slightly perthitic microcline or, less commonly, orthoclase, and is usually kaolinized. A few specimens (notably 70571180) contain occasional large euhedral poikilitic phenocrysts of pink alkali feldspar. Plagioclase (10-40%) is oligoclase or zoned oligoclase-andesine, which is commonly sericitized or saussuritized, particularly in the cores of the crystals. Myrmekitic intergrowths are common between grains of alkali feldspar and plagioclase. The brown biotite (up to 3%) is slightly chloritized and locally deformed. The more leucocratic rocks (70571129, 1131-2, 1138-9) contain only a trace of relict chloritized biotite. Muscovite is present in some samples. Accessory minerals include epidote, sphene, apatite, allanite, opaque minerals, and occasionally garnet.

The granodiorites (68590124, 0208, 70571182) are medium to coarse-grained and hypidiomorphic granular. Biotite (up to 3%) is the main ferromagnesian mineral. The trondhjemites (70571166-8) contain quartz (25-30%), zoned andesine (An_{32-38}) (60%), kaolinized microcline (up to 5%), and biotite (4-5%). Epidote is a prominent alteration product and forms up to 3 percent of the rock. The quartz diorite (70571162) contains less quartz (about 5%) and more biotite and epidote than the trondhjemite. A little muscovite is present in most of these rocks, which are notable for the absence of hornblende. Accessory minerals include sphene, allanite, apatite, and opaque minerals.

Dido Granodiorite

The Dido Granodiorite, like the Dumbano Granite, crops out in the southern part of the Georgetown Inlier, where it extends over an area of about 1250 km^2. It is generally more basic than the other pre-Carboniferous granitic rocks and consists largely of grey medium to coarse-grained and often foliated hornblende-biotite tonalite. It differs from the Dumbano Granite particularly in the abundance of hornblende. It was referred to as trondhjemite by White (1965), but the rocks are rather melanocratic for true trondhjemites, as they generally contain less than 20 percent quartz and about 10 percent mafic minerals. A few specimens (e.g. 70571188-9) do approach trondhjemite in composition. The tonalites were collected from the western side of the main intrusion, northeast of Lyndhurst homestead. Other rock types include hornblende-biotite-quartz diorite near the centre of the body, along Phantom Creek, and olivine gabbro which crops out a little farther east. The relationships of these various units are not known.

The Dido Granodiorite intrudes a variety of Precambrian metamorphic rocks. It has been dated by K-Ar methods at 405 ± 21 m.y., that is, slightly older than the Dumbano Granite (Richards et al., 1966). Rb-Sr ages of 404 and 407 m.y. have been obtained on biotites from the Dido Granodiorite (Black, 1973).

Both the Dumbano Granite and the Dido Granodiorite include a range of rock types, however, and there could be some overlap in age between the two groups.

No economic mineralization is known to be associated with the Dido Granodiorite.

Petrography The hornblende-biotite tonalite is medium to coarse-grained, with a hypidiomorphic granular texture, and is commonly foliated. Quartz (15-20%) is anhedral, poikilitic, and generally strained and granulated. Plagioclase (65-70%) forms euhedral to subhedral laths of zoned andesine or andesine-oligoclase (An_{29-42}). It is usually sericitized or saussuritized and occasionally partly replaced by carbonate. Myrmekite is common along grain margins. Microcline, where present, never exceeds 5 percent. The hornblende (up to 7%) is pleochroic from pale yellow to dark green, and is commonly partly pseudomorphed by biotite or epidote. The brown biotite (5-10%) is usually slightly chloritized, and in places deformed; it is associated with epidote and opaque minerals. In the more foliated rocks the biotite flakes show a preferred orientation. Epidote is particularly abundant in many of the samples and forms as much as 3 percent of the rock. Much of it appears to have been derived by alteration of hornblende or plagioclase by the action of hydrothermal solutions, possibly during deformation. The abundant accessory minerals include allanite, sphene, apatite, and opaque minerals; other minor constituents are muscovite and calcite.

The quartz diorites (70571174, 1177-8) are fairly similar to the tonalites, but contain less quartz (5-10%) and more abundant ferromagnesian minerals (15-20% hornblende and 5-10% biotite). Plagioclase is more calcic (An_{36-50}) and has sericitized cores. Relict clinopyroxene is present in some samples.

The single olivine gabbro sample (70571173) consists mainly of labradorite, olivine, and pyroxene. The olivine is partly serpentinized, and the hypersthene and clinopyroxene are largely replaced by secondary amphibole and chlorite. Traces of magnetite, spinel, quartz, and epidote are also present. An aplite (70571186A) is noteworthy for the presence of small subhedral crystals of garnet.

Upper Palaeozoic Igneous Rocks

Upper Palaeozoic igneous rocks occupy an area of about 30 000 km^2 in the Georgetown Inlier and Hodgkinson Basin and include extensive acid volcanics and associated granitic intrusions. The volcanic rocks consist mainly of rhyodacite welded tuff sheets with subordinate rhyolite, dacite, andesite, and basalt. The intrusive rocks are predominantly adamellite, but granite and granodiorite are also fairly common, and more basic types, including diorite and gabbro, also occur. Most of the extrusive and many of the intrusive rocks occur in eleven cauldron subsidence areas together with six associated ring complexes within, or immediately adjacent to, the Georgetown Inlier. The development of these structures has been described by Branch (1966, 1967). Such volcano-plutonic formations are characteristic of miogeosynclines and adjacent semi-stable platforms (Ustiyev, 1965; Hamilton & Myers, 1967). Dykes, mostly of acid composition, but also including intermediate and basic varieties, are common in the inlier and are probably related to the extrusive rocks. Five major dyke swarms can be distinguished. Most of the granitic rocks of the Hodgkinson Basin form simple stocks and batholiths.

Cumberland Range Cauldron Subsidence Area

The volcanic and granitic rocks which crop out in the Cumberland Range, south of Prestwood homestead, were considered to be the remnants of a deeply eroded cauldron subsidence area with a total area of about 550 km^2 (Branch, 1966). The structure has not been mapped in detail and most of the geological boundaries on the map have been photo-interpreted.

Two main units were distinguished by Branch (1966, p. 58)—the Cumberland Range Volcanics and the Prestwood Microgranite. The volcanics of the northeastern part of the Cumberland Range include pink and grey rhyodacite welded tuffs overlying arkose and shale interbedded with rhyodacite flows. The volcanics unconformably overlie Precambrian Forsayth Granite and are intruded by the Prestwood Microgranite. The microgranite is typically a pink porphyritic biotite microadamellite, which was considered to be related to the Elizabeth Creek Granite by Branch. Sampling in the area has revealed the presence of rock types not recorded by Branch. Specimens from the outcrops of Prestwood Microgranite a few kilometres south and east of Prestwood homestead are pink porphyritic microadamellite (68590025, 70571105-6), as is a single sample (70571097) from the ring dyke on the western side of the cauldron. Two samples (70571103-4) from the small body about 2 km east of Prestwood homestead are pale grey porphyritic hornblende-biotite microgranodiorite. The intrusions south of Green Hills Outstation are much less extensive than is apparent from the map and consist mainly of grey porphyritic dacite with abundant phenocrysts of quartz and white plagioclase (70571091-4). They are somewhat similar to the porphyritic hornblende-biotite microgranodiorite. Two samples from the dykes in the northeastern part of the cauldron are of dacitic composition.

The products of at least two different magma types are thus present within the intrusions mapped as Prestwood Microgranite: the microadamellites/rhyodacites and the microgranodiorites/dacites.

Petrography. The typical Prestwood Microgranite in the northern part of the cauldron is pink porphyritic biotite microadamellite (68590025, 70571105-6). Phenocrysts include subhedral embayed β-quartz, euhedral orthoclase perthite, and minor oligoclase. Orthoclase forms slightly poikilitic laths up to 15 mm long, many with corroded margins. Micrographic intergrowths are common. The feldspars are usually rather altered and the biotite (up to 3%) is commonly chloritized. The groundmass is aphanitic. Sample 70571097 is similar, but the groundmass is finer-grained and it has therefore been classified as a rhyodacite. Sample 70571107 is a dark grey rhyodacite containing pale pink phenocrysts of alkali feldspar and plagioclase.

The three samples of porphyritic hornblende-biotite microgranodiorite (68590415, 70571103-4) contain phenocrysts of rounded embayed quartz, euhedral zoned oligoclase-andesine, and minor orthoclase perthite set in an aphanitic groundmass. Biotite and hornblende are the main ferromagnesian constituents, the latter being largely replaced by biotite, epidote, and calcite.

The grey porphyritic dacite (70571091-4) shows some similarities to the microgranodiorite, but the groundmass is usually cryptocrystalline and shows fluidal textures. The phenocrysts consist of rounded embayed β-quartz, euhedral zoned oligoclase-andesine, and minor sanidine cryptoperthite. Most of the alkali feldspar occurs in the groundmass, which is unevenly devitrified. Plagioclase is usually saussuritized and alkali feldspar is kaolinized. Biotite (1-5%) is commonly chloritized and hornblende is almost entirely replaced by epidote, calcite, and chlorite. Accessory minerals include zircon, apatite, sphene, allanite, and opaque minerals.

Two samples from dykes (70571108-9) are both porphyritic dacites; 70571108 is similar to the dacites just described, with abundant phenocrysts of quartz and plagioclase, but 70571109 is only slightly porphyritic. The groundmass is aphanitic to cryptocrystalline.

Only one sample (70571095), a slightly porphyritic rhyodacite, can be unequivocally assigned to the Cumberland Range Volcanics.

Economic mineralization. Some of the auriferous lodes of the Etheridge goldfield lie in or near the Prestwood Microgranite and may be genetically related to it (White, 1965). The silver-lead deposits of the Green Hills area also appear to be associated with Upper Palaeozoic acid igneous rocks. The lodes occur in association with acid dykes that are probably related to the rocks of the Cumberland Range cauldron.

Bagstowe Ring Dyke Complex

The Bagstowe and Lochaber Ring Complexes are situated in the southern part of the Georgetown Inlier, at the northern end of a large downfaulted block of Dumbano Granite and Precambrian metamorphics which covers an area about 65 km by 35 km and trends north-northeast. The northern end of the block coincides with the ring fault of the Lochaber Complex and the southern end is defined by a semicircular fault. The general form of the structure suggests that it may represent a deeply eroded cauldron subsidence area (Branch, 1966).

The Bagstowe Complex covers an area of about 340 km^2 and comprises three major overlapping ring structures. The oldest, at the southwestern end of the complex, is the Mount Rous Ring Dyke, which is truncated by the composite central complex. The youngest is the northeast stock and its associated central ring dyke, about 10 km in diameter.

Branch (1966, p. 69) has recognized six centres of intrusion:

Centre 1. Mount Rous Ring Dyke (hornblende - biotite microgranodiorite: samples 68590026, 70571135, 1137);
Centre 2. Grey ring dykes (rhyolites and rhyodacite: 70571130, 1141, 1144-6, 1149-50);
Centre 3. Augite-hornblende trachyandesite ring dyke (70571143);
Centre 4. Four Mile Creek Stock (hornblende-biotite microadamellite);
Centre 5. Pink ring dykes (lithic tuffs and rhyodacite: 70571142) and east-west ring dyke (hornblende-biotite microadamellite: 70571158);
Centre 6. Northeast stock and central ring dyke (leucocratic biotite microadamellite: 70571151-4).

The intrusions related to centres 2 to 5 form the central complex.

The remaining samples were mostly collected from various dykes and cone sheets, mainly in the southern part of the complex. These minor intrusions range from rhyolite to andesite and hornblende-quartz diorite. Samples 70571159-61 are from the rhyodacitic and dacitic volcanics that crop out about 4 km north of Bagstowe homestead.

In general, the sequence of intrusion is from more basic to more acid rocks, with the exception of the trachyandesite ring dyke. More detailed descriptions of the various rock types and structures are given by Branch (1966).

Petrography. The Mount Rous Ring Dyke is composed of porphyritic hornblende-biotite microgranodiorite. The phenocrysts are predominantly zoned oligoclase-labradorite, with subordinate embayed quartz, kaolinized alkali feldspar, hornblende, and biotite. The groundmass is commonly micrographic. Basic xenoliths are relatively common.

The trachyandesite ring dyke consists of porphyritic augite-quartz trachyandesite grading into andesite (70571143). The phenocrysts are mainly zoned andesine-labradorite, together with augite and hornblende. Other intermediate rocks include hornblende-quartz microdiorite (70571155-6), in which sphene is a prominent accessory mineral.

The majority of the ring dykes are rhyolite (70571141, 1149) or rhyodacite (70571130, 1142, 1144-6, 1150), although a little dacite is also present. Most of the rhyodacites are porphyritic, but aphyric varieties also occur. Phenocrysts include embayed β-quartz, turbid orthoclase perthite, and zoned sericitized oligoclase-andesine. The most common ferromagnesian mineral is biotite, which is usually partly chloritized. Hornblende occurs in a few specimens, but is usually more or less pseudomorphed by biotite or chlorite. The groundmass is commonly cryptocrystalline and occasionally spherulitic. Xenoliths, mostly of Dumbano Granite, are fairly abundant. The volcanic samples from the area about 4 km north of Bagstowe homestead (70571159-61) include rhyodacite and dacite welded tuffs.

Minor intrusions include rhyolite (70571133, 1136, 1148, 1163), rhyodacite (70571134), dacite (70571147), and andesite (70571140). The more acid rocks are mostly spherulitic and sparsely porphyritic.

The granitic rocks of the northeast stock (70571151-4) and the east-west ring dyke (70571158) are biotite adamellite or microadamellite. The major constituents are quartz, orthoclase perthite, and zoned corroded oligoclase or oligoclase-andesine. Dark reddish brown biotite (up to 5%) is usually rather chloritized. Hornblende is either absent or present in only trace amounts. Minor constituents comprise epidote, apatite, allanite, sphene, and opaque minerals. The more leucocratic rocks are similar to the Elizabeth Creek Granite.

Lochaber Ring Complex

The Lochaber Ring Complex lies immediately to the north of the Bagstowe Complex and covers an area of about 450 km^2. On the western side of the complex, a large block of volcanic rocks—the Butlers Volcanics—has been downfaulted in a cauldron-like structure. The volcanics are predominantly rhyodacite welded tuffs, with subordinate rhyolites. They are intruded by a small plug of hornblende-augite-quartz micromonzonite and a stock of microadamellite.

The eastern half of the complex consists of a large stock of biotite adamellite and granite —the Lochaber Granite. The marginal zones of this intrusion are fine-grained and porphyritic. The Lochaber Granite was probably emplaced by major block foundering, controlled by ring fracturing (Branch, 1966).

Petrography. One sample of Butlers Volcanics, a porphyritic rhyodacite (68590106), was analysed. Phenocrysts comprise quartz, alkali feldspar, and plagioclase, and the groundmass is micrographic.

The two analysed samples of Lochaber Granite (68590128-9) are both leucocratic granites, although 68590129 contains a little chloritized biotite. Alkali feldspar (possibly microcline) is extensively altered and subhedral plagioclase is zoned from oligoclase to albite. Micrographic intergrowths are well developed and both samples contain fluorite and muscovite. The Lochaber Granite is similar in many respects to the Elizabeth Creek Granite.

Economic geology. A few tons of wolfram and molybdenite have been produced from a small quartz reef in the Lochaber Granite. The surrounding granite is greisenized and contains topaz.

Elizabeth Creek Granite

The Elizabeth Creek Granite forms numerous batholiths and stocks with a total area of about 5000 km^2, mainly in the northeastern part of the Georgetown Inlier, but also extending into the Hodgkinson Basin. Intrusions thought to be related to the Elizabeth Creek Granite include the Prestwood Microgranite and the Lochaber Granite (Branch, 1966). The intrusive contacts of the granite are usually sharp and generally appear to be controlled by pre-existing basement faults. Many of the stocks are more or less elliptical and were probably emplaced during major block subsidence controlled by ring-fracturing (Branch, 1966). The depth of cover during emplacement has been estimated by Branch (1966, p. 99) as about 300 m in the eastern Newcastle Range and about 600 m in the Featherbed Cauldron.

The Elizabeth Creek Granite is believed to intrude the Kalunga Granodiorite and is intruded by the Atlanta and Watsonville Granites, the Bakerville Granodiorite, and numerous acid dykes in the Herberton/Mount Garnet area (Blake, 1972). The sediments of the Hodgkinson Formation are extensively hornfelsed, but the effects on the intruded acid volcanics are generally confined to a narrow zone within a few metres of the granite contact. In some areas the granite has a chilled margin of porphyritic microgranite.

In some localities the Elizabeth Creek Granite appears to grade into other types of Upper Palaeozoic granite. Near Stannary Hills it seems to have gradational contacts with the Atlanta Granite (Blake, 1972). Gradational contacts are also common in the Chillagoe area (de Keyser & Wolff, 1964) and in the area south of the Tate River.

Rb-Sr dating suggests that the Elizabeth Creek Granite is mostly older than the Herbert River Granite, with an age of about 320 to 325 m.y., although there is evidence that the Elizabeth Creek Granite in the southern part of the Atherton Sheet area is only about 300 m.y. old. The small stocks between Wolfram Camp and Bamford Hill are also of this younger age. Indicated initial $^{87}Sr/^{86}Sr$ ratios range from 0.710 to 0.716 (Black, 1974). Muscovite from a mineralized vein in the Elizabeth Creek Granite at Wolfram Camp yielded a K-Ar age of 280 m.y. (Richards et al., 1966). Rb-Sr dating of mica concentrates from mineral veins in the Herberton/Mount Garnet area fall in the range 312 to 322 m.y., suggesting that the formation of these veins 'was initiated during the main phase of Elizabeth Creek Granite emplacement and continued for at least the next 10 m.y.' (Black, 1974).

The Elizabeth Creek Granite is typically a rather homogeneous pink leucocratic biotite adamellite, which grades locally into granite. Many varieties, particularly those that are fine-grained, are porphyritic. Aplites are common in some localities, particularly in the Herberton/Mount Garnet area, but pegmatites are rare. Xenoliths are uncommon, even near the margins of the intrusions. Greisens are characteristic of the Elizabeth Creek Granite, particularly where the granite is mineralized. Branch (1966, p. 100) recognized three types of greisen: (i) greisenization along joints, grading into unaltered granite; (ii) greisenized granite dykes; and (iii) diffuse greisenization of large, irregular areas, without well defined boundaries. Tin, tungsten, molybdenum, and copper mineralization are associated with them. The greisens were probably formed by pneumatolytic alteration of granite in the roof zones of the intrusions during the final stages of crystallization of the magma.

The fine-grained grey to pink hornblende-bearing adamellite south of Petford was thought to represent a contaminated variety of the Elizabeth Creek Granite by Branch (1966), whereas de Keyser & Wolff (1964) regarded it as a separate body. The intrusion is unmineralized and contains relatively abundant xenoliths. The body of Elizabeth Creek Granite south of Chillagoe was also thought to have been contaminated, in its eastern part, by Palaeozoic sediments (Branch, 1966).

Petrography. The typical Elizabeth Creek Granite is a medium-grained pink or orange leucocratic adamellite containing up to 5 percent of biotite. Gradations into granite are common, however, and fine-grained porphyritic varieties of both adamellite and granite occur locally. The texture is usually allotriomorphic granular and occasionally hypidiomorphic granular.

Quartz (25-40%) occurs as composite anhedral grains, many of which form bleb-like aggregates; some are embayed. Alkali feldspar (30-60%) includes both orthoclase perthite and microcline perthite, the latter being generally more abundant. Orthoclase tends to occur in the finer-grained rocks, either because they cooled more rapidly than the coarser-grained varieties, or because the magmas that formed the coarse-grained rocks were richer in volatiles which would tend to favour the crystallization of microcline on cooling (Parsons & Boyd, 1971). The microcline is usually more perthitic than the orthoclase and contains up to 50 percent albite. The alkali feldspar is generally anhedral and commonly poikilitic, and micrographic intergrowths with quartz are common. Plagioclase (10-35%) occurs as euhedral to subhedral laths of oligoclase or less commonly oligoclase-andesine (An_{18-30}). Zoning is usually weak or absent, although albite commonly occurs as rims around the potash feldspar. Myremekite occurs in some samples, but is not common. Both alkali feldspar and plagioclase occur as phenocrysts in porphyritic varieties. Kaolinization of alkali feldspar and sericitization of plagioclase are common, particularly in areas where greisens are abundant.

Greenish brown or reddish brown pleochroic biotite (up to 5%) is the usual ferromagnesian mineral. It occurs in aggregates of shredded crystals and is usually partly altered to chlorite and iron oxide. Hornblende is a minor constituent in a few samples (68490001G, 68590060, 0071; 70571012, 1261). It is extensively replaced by biotite or altered to epidote, chlorite, and calcite. Branch (1966) considered the presence of amphibole to be an indication of contamination by basic igneous rocks; but many of the hornblende-bearing samples are leucocratic varieties which cannot have been significantly contaminated by basic material, so that, in these cases at least, the hornblende is more likely to represent a relict amphibole which was present in an unfractionated less siliceous parent magma. Muscovite is generally uncommon, except as an alteration product of feldspar.

Accessory minerals include zircon, apatite, allanite, sphene, opaque minerals, and, characteristically, fluorite. Epidote, sericite, and calcite may also be present; cassiterite, topaz, and tourmaline occur in a few samples.

The fine to medium-grained hornblende-biotite adamellite cropping out south of Petford is not typical of the Elizabeth Creek Granite. It is slightly porphyritic, with phenocrysts of quartz, microcline or orthoclase, and oligoclase-andesine, and grades into microgranite (de Keyser & Wolff, 1964). Allanite is a characteristic accessory mineral.

The Elizabeth Creek Granite can be distinguished from the Herbert River Granite by the widespread deuteritic alteration of the feldspars, and chloritization of biotite, etc., the lack of zoning of plagioclase, the abundance of fluorite, the low content of accessory minerals, the common occurrence of greisens, and its generally more leucocratic character.

Greisenized varieties of the Elizabeth Creek Granite are characterized by the development of muscovite at the expense of feldspar. Variable amounts of protolithionite or lepidolite, or both, may be present. Accessory minerals include fluorite, topaz, cassiterite, wolfram, arsenopyrite, iron oxides, molybdenite, monazite, siderite, galena, bismuthinite, stibnite, copper minerals, and chalcedony (Blake, 1972).

Economic mineralization. The most important economic minerals associated with the Elizabeth Creek Granite are those of tin, molybdenum, and tungsten, although copper, silver, lead, bismuth, antimony, and gold have also been mined.

The Herberton Tinfield is the most important area and has yielded over 110 000 tonnes of tin concentrate or 15 percent of the total tin produced in Australia between 1879 and 1968 (Blake, 1970). The primary deposits include greisen lodes in the granite, chlorite-cassiterite and quartz-cassiterite lodes in both granite and country rocks, cassiterite-bearing quartz-tourmaline lodes within the Hodgkinson Formation sediments, and complex sulphide lodes containing cassiterite associated with pyrite, chalcopyrite, and other sulphides. Irregular greisens containing disseminated cassiterite are probably the source of much of the alluvial cassiterite from which most present production comes.

Tungsten occurs in lodes mostly within the Elizabeth Creek Granite, but also in the Hodgkinson Formation close to the contacts. The tungsten lodes tend to be associated with pale grey porphyritic varieties of granite, whereas the tin lodes are typically associated with a pale pink non-porphyritic variety (Blake, 1970). The most common types of tungsten deposit are greisen lodes containing wolfram and in many cases molybdenite and bismuth minerals. The deposits at Wolfram Camp and Bamford Hill include both disseminated orebodies in greisen and quartz pipes containing wolfram, molybdenite, and bismuth (de Keyser & Wolff, 1964).

Copper minerals are widely distributed in the Herberton Tinfield; the largest mine is at Mount Garnet. Small quantities of lead, silver, antimony, and zinc have also been produced.

Fluorite is a common gangue mineral in many of the tin and tungsten lodes and has been an important product in the Chillagoe Mineral Field, where it forms numerous lodes (de Keyser & Wolff, 1964).

Blake & Smith (1970) have related the mineral deposits of the Herberton area to four zones: tungsten zone, mainly confined to the Elizabeth Creek Granite, passing progressively outwards into tin, copper, and lead zones. Branch (1966) has noted the occurrence of various types of vertical mineral zoning, which in most cases is normal, the higher-temperature minerals being deposited nearest to the intrusion.

The copper mineralization of the Eveleigh homestead/Einasleigh area may be related to the Elizabeth Creek Granite, a small stock of which intrudes the Newcastle Range Volcanics in the area (Branch, 1966).

More detailed descriptions of the economic geology, as well as descriptions of individual mines, are given by Zimmerman et al. (1963), de Keyser & Wolff (1964), White (1965), de Keyser & Lucas (1968), and Blake (1970, 1972).

Hales Siding Granite

The Hales Siding Granite crops out a few kilometres south of Stannary Hills and covers a total area of about 10 km^2 (Blake, 1972). The main rock type is a leucocratic pale pink medium-grained biotite adamellite or granite. Numerous veins of aplitic granite, which may be related to the Hales Siding Granite, occur in the adjacent Bakerville Granodiorite.

The Hales Siding Granite was originally mapped as part of the Elizabeth Creek Granite (Best, 1962), but though it intrudes mineralized sediments of the Hodgkinson Formation, it is itself unmineralized, and for this reason was considered by Blake (1972) to be younger than the Elizabeth Creek Granite.

Petrography. The Hales Siding Granite is petrographically similar to the Elizabeth Creek Granite. Grainsize ranges from coarse to fine and the texture is allotriomorphic granular. Myrmekitic intergrowths are common. Perthitic orthoclase or oligoclase-andesine and quartz are the other major constituents. Biotite (up to 5%) occurs as aggregates of shredded unevenly chloritized crystals. The commonest accessory minerals are zircon, apatite, allanite, and magnetite; epidote, sericite, chlorite, and calcite occur as alteration products.

Hammonds Creek Granodiorite

The main outcrop of the Hammonds Creek Granodiorite is about 3 km west of Mount Garnet, where it covers an area of about 30 km^2 (Blake, 1972). It was originally mapped as Herbert River Granite (Zimmerman et al., 1963). The predominant rock type is a fine to medium-grained grey hornblende-biotite granodiorite, although adamellite and quartz diorite also occur. Thin aplite veins are common and contain variable amounts of pyrite. Ironstained gossanous rocks composed of quartz, sericite, pyrite, and kaolinite were interpreted as altered aplites by Blake (1972).

The Hammonds Creek Granodiorite intrudes the Hodgkinson Formation. Because it is unmineralized, it was thought by Blake (1972) to be younger than the Elizabeth Creek Granite. This has since been confirmed by isotopic dating (Black, 1974). Biotite-rich xenoliths are common, particularly near the contact with the Hodgkinson Formation, although Blake (1972, p. 50) considered that there is little evidence to suggest that the Hammonds Creek Granodiorite is a hybrid rock and thought that it had probably crystallized directly from a granodioritic magma.

Petrography. The granodiorite is generally fine to medium-grained, with a hypidiomorphic granular texture. The cores of many of the subhedral zoned crystals of oligoclase-andesine are sericitized or saussuritized. Quartz and turbid anhedral crystals of orthoclase or microcline perthite are usually interstitial. Brown biotite (up to 15%) is commonly somewhat altered to chlorite, epidote, or calcite. Actinolite occurs as a minor alteration product of pale brownish green hornblende (up to 10%). Blake (1972) has recorded the occurrence of augite and hypersthene in some specimens, although none was noted in the analysed samples. The main accessory minerals are allanite, apatite, epidote, magnetite, pyrite, sphene, and zircon.

Nymbool Granite

The Nymbool Granite crops out over a total area of about 10 km^2 near Nymbool, about 9 km west-northwest of Mount Garnet. It was previously considered to be part of the Herbert River Granite (Zimmerman et al., 1963). It is typically a grey medium to coarse-grained biotite adamellite, with abundant biotite-rich xenoliths. Thin veins of aplite are common (Blake, 1972).

The Nymbool Granite intrudes sediments of the Hodgkinson Formation. Its relationship to the nearby Elizabeth Creek Granite is uncertain, but Rb-Sr dating indicates that the two granites are roughly the same age (Black, 1974).

No mineralization is known to be associated with the Nymbool Granite.

Petrography. The typical Nymbool Granite is a medium to coarse-grained sparsely porphyritic biotite adamellite, although some granite is also present. The main constituents are quartz (20-40%), alkali feldspar (30-50%), plagioclase (15-35%), and brown biotite (5-10%). Alkali feldspar occurs mainly as turbid anhedral crystals of orthoclase microperthite, although microcline perthite is present in one sample (67490095R). Zoned oligoclase-andesine occurs as scattered phenocrysts and in the groundmass. Many of the feldspars are partly altered to sericite and epidote. Accessory minerals include allanite, apatite, zircon, and magnetite.

Bakerville Granodiorite

The small body of granodiorite, which covers an area of about 8 km^2 at Bakerville, was named the Bakerville Granodiorite by Blake (1972). It had previously been included in the Herbert River Granite (Best, 1962). Exposures are poor and the rock is deeply weathered.

The predominant rock type is a dark grey medium - grained hornblende - biotite granodiorite, with abundant biotite-rich xenoliths. Thin veins of aplite occur locally.

The Bakerville Granodiorite is unmineralized and was therefore considered to be younger than the Elizabeth Creek Granite by Blake (1972). A Rb-Sr age of 308 m.y. has recently been obtained (Black, 1974).

Petrography. The Bakerville Granodiorite is typically medium-grained and has a hypidiomorphic granular texture. Quartz (20-35%) is generally anhedral and interstitial. Plagioclase (40-60%) occurs as subhedral laths, zoned from calcic andesine (An_{45-48}) to oligoclase. The cores of many of the crystals are sericitized or saussuritized. Orthoclase (5-10%) is interstitial, turbid, and slightly perthitic.

Hornblende (up to 10%) forms green pleochroic, subhedral crystals, many of which are slightly chloritized and crowded with opaque inclusions. Reddish brown strongly pleochroic biotite (up to 10%) shows some alteration to chlorite and contains abundant inclusions of zircon and magnetite. The most common accessory minerals are zircon, allanite, epidote, apatite, and opaque minerals.

The granitic aplites (67490010R) consist largely of quartz and microcline with subordinate oligoclase and minor biotite.

Kalunga Granodiorite

The Kalunga Granodiorite crops out over an area of about 50 km^2 to the south of Herberton. It was originally included with the Herbert River Granite (Best, 1962), but was renamed by Blake (1972).

The rocks show a considerable range of composition and may represent more than one intrusion. The most common rock type is a grey medium-grained hornblende-biotite granodiorite grading into adamellite. Biotite adamellite (without hornblende) and aplite also occur. Some varieties are porphyritic and small mafic xenoliths are common. Some of the granitic rocks are markedly heterogeneous and may be of hybrid origin (Blake, 1972).

The Kalunga Granodiorite intrudes and marginally hornfelses sediments of the Hodgkinson Formation and probably also intrudes the Glen Gordon Volcanics. According to Blake (1972), it is intruded by the Elizabeth Creek Granite but shows little secondary alteration and appears to be unmineralized. A Rb-Sr biotite age of 282 m.y. probably represents the age of much of the Kalunga Granodiorite (Black, 1974).

Petrography. The Kalunga Granodiorite is generally medium-grained with a hypidiomorphic granular texture, although the more acid varieties are allotriomorphic granular. Quartz is anhedral and interstitial. Orthoclase is turbid and usually perthitic and occurs both as anhedral interstitial grains and larger poikilitic crystals. Many of the subhedral zoned crystals of oligoclase-andesine are sericitized. Brown strongly pleochroic biotite and green to brown pleochroic hornblende are the other major constituents. The main accessory minerals are allanite, apatite, sphene, zircon, and opaque minerals, together with secondary chlorite, epidote, and sericite. Blake (1972) recorded the presence of relict crystals of augite and occasional grains of hypersthene in some specimens, but neither is present in the analysed samples.

Watsonville Granite

The Watsonville Granite, previously mapped as Herbert River Granite (Best, 1962), was renamed by Blake (1972). It crops out over an area of about 130 km^2 in the northeastern part of the Herberton 1-mile Sheet area.

The Watsonville Granite generally consists of homogeneous pale pink or greyish medium to coarse-grained biotite adamellite, which generally contains feldspar phenocrysts. Although dark grey xenoliths are widespread, they are not abundant. Veins of aplite, microgranite, and quartz-feldspar pegmatite occur in a few locations. The Watsonville Granite is distinguished from the Elizabeth Creek Granite by its well developed spheroidal weathering, and by the general absence of quartz blebs, cross-cutting dykes, greisens, and mineralization (Blake, 1972).

The granite intrudes the Hodgkinson Formation, Elizabeth Creek Granite, Walsh Bluff Volcanics, and Slaughter Yard Creek Volcanics and was thought to be intruded by the Bakerville Granodiorite (Blake, 1972). Rb-Sr dating has given an Early Permian age concordant with that of the Mareeba Granite (Black, 1974).

Petrography. The typical Watsonville Granite ranges from medium to coarse-grained, with an allotriomorphic granular texture. The major constituents are quartz (25-40%), orthoclase microperthite (25-45%), plagioclase (20-35%), and biotite (up to 8%). Quartz is normally anhedral and is sometimes strained and fractured. It does not normally form bleb-like aggregates, although exceptions do occur (e.g. sample 67490003R). Microperthitic orthoclase occurs as anhedral, locally poikilitic, crystals many of which are turbid and kaolinized. Many of the anhedral to subhedral laths of zoned andesine-oligoclase have sericitized or saussuritized cores. Intergrowths of quartz and albite occur between adjacent crystals of plagioclase and alkali feldspar. Brown or reddish brown biotite occurs in aggregates of shredded flakes and is locally chloritized. The main accessory minerals are zircon, apatite, allanite, epidote, and occasionally tourmaline, which shows a marked yellow to bluish green pleochroism, and fluorite.

Effects of post-crystalline deformation include the presence of strained quartz grains showing undulose extinction and fracturing, and deformed feldspars and biotite. Although the Watsonville Granite appears to be unmineralized, it has undergone slight pneumatolytic alteration. with local development of fluorite and tourmaline.

Atlanta Granite

The Atlanta Granite crops out north of Stannary Hills and west of Collins Weir. It was originally mapped as Herbert River Granite (Best, 1962).

The main rock type is a pale grey or pink leucocratic biotite adamellite, which is similar to the Elizabeth Creek Granite. Abundant phenocrysts of plagioclase and blebs of quartz are present in the rocks of the western outcrop, which appears to grade into porphyritic Elizabeth Creek Granite. In the eastern outcrop phenocrysts are absent, except in contaminated varieties which contain plagioclase phenocrysts up to 6 cm long. The contaminated varieties also contain aplite veins, pegmatites, and melanocratic patches, as well as small dark grey xenoliths (Blake, 1972).

The general similarity of the Atlanta and Elizabeth Creek Granites led Blake (1972) to suggest that both may have been derived from the same magma, although no economic mineralization is known to be associated with the former.

Petrography. Quartz (30-50%) is generally anhedral and interstitial, but locally occurs as well developed blebs. Alkali feldspar (20-45%) occurs as orthoclase or microcline microperthite and is generally turbid. Plagioclase (15-45%) forms subhedral, commonly sericitized crystals of albite or albite-oligoclase, although andesine occurs in the cores of some phenocrysts. Brown strongly pleochroic biotite (up to 5%) is commonly partly chloritized. Magnetite is a common accessory mineral.

Only one sample (67490047R), a biotite granite, was analysed.

Unnamed granitic rocks of the Herberton area

Four samples from the porphyritic 'microgranite' intrusion in the Silver Valley area (Blake, 1972) were analysed. The most common variety is a porphyritic microgranodiorite (68490181A,C, 0182). The phenocrysts consist mainly of plagioclase, with some quartz, alkali feldspar, and chloritic pseudomorphs after biotite and hornblende. Small 'microdiorite' xenoliths are abundant and the matrix is quartzofeldspathic. The feldspars are extensively altered to sericite, calcite, epidote, etc. A sample of porphyritic microadamellite (68490181B) contains a higher proportion of alkali feldspar.

A single sample of hornblende-biotite-quartz diorite (67490053) from the body north of Stannary Hills was also analysed. This mass consists largely of hornblende-biotite granodiorite, with some quartz diorite and intermediate hybrid rocks. It is probably younger than the Elizabeth Creek Granite and is unmineralized (Blake, 1972).

Herbert River Granite

The Herbert River Granite crops out mainly in the northeastern part of the Georgetown Inlier and in the adjacent shelf zone of the Hodgkinson Basin. It covers a total area of about 2700 km^2 and forms several widely separated intrusions (Pl. 1), the major ones being: (i) an irregular body extending northwards from St Ronans homestead to Almaden, with an offshoot trending in a northwesterly direction; (ii) the area south of Bulleringer homestead; and (iii) the type area around the Herbert River falls.

The intrusions in the Herberton and Mount Garnet 1-mile Sheet areas, which were originally correlated with the Herbert River Granite (Best, 1962; Branch, 1966), have since been remapped in more detail and shown to consist of a variety of rock types of different ages (Blake, 1972). They include the Kalunga, Hammonds Creek, and Bakerville Granodiorites and the Atlanta, Watsonville, and Nymbool Granites, which have already been described. In the Chillagoe-Almaden area the presence of six main groups of granitic rocks, one of which was correlated with the Herbert River Granite, has been established, although boundaries between the various types are usually gradational (de Keyser & Wolff, 1964). More detailed mapping of other outcrops of Herbert River Granite may also reveal a more complex history of intrusion than has so far been established.

The Herbert River Granite typically ranges from biotite adamellite to hornblende-biotite granodiorite, although minor granites are also present. In hand specimen it is usually grey and commonly contains phenocrysts of pink alkali feldspar. Aplites, pegmatites, flow banding, and lineations are uncommon (Branch, 1966).

Rb-Sr dating (Black, 1974) has indicated that the Herbert River Granite is generally younger than the Elizabeth Creek Granite, having yielded a mean age of 288 ± 18 m.y., with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7115 ± 0.0017. Biotite ages suggest that the

Herbert River Granite in the Almaden-Dargalong area is about 305 m.y. old.

Petrography. The Herbert River Granite ranges in composition from biotite granite to hornblende-biotite granodiorite, although adamellite predominates.

The biotite adamellite is generally medium to coarse-grained, although microadamellite occurs locally. The texture is allotriomorphic granular. Quartz is anhedral and may be partly recrystallized, particularly at grain boundaries. The alkali feldspar includes both orthoclase and microcline, and forms both anhedral poikilitic phenocrysts and interstitial grains. Microcline is usually perthitic, but orthoclase is less commonly so. The microcline shows uneven extinction and twinning that could possibly be due to the incomplete inversion of orthoclase to microcline (Mackenzie, 1954). It may be significant in this connexion that sample 70571267 contains both orthoclase and microcline. Micrographic intergrowths of alkali feldspar and quartz are common. The alkali feldspars frequently show some degree of sericitization or kaolinization. Plagioclase commonly forms large phenocrysts of oligoclase-andesine (An_{24-32}). It is almost invariably zoned, but the zoning may be obscured by sericitization or saussuritization. The plagioclase has low-temperature optical properties (Branch, 1966). Myrmekite occurs in some samples.

Brown or greenish brown biotite (up to 7%) occurs both as scattered flakes and as aggregates, and is commonly partly chloritized. Green hornblende is present in a few samples, but is usually partly replaced by epidote and biotite or chlorite, or both.

The few granites are generally finer-grained than the adamellites and grade into microgranite. The alkali feldspar may be orthoclase or microcline, some of which is perthitic; the plagioclase is zoned albite-oligoclase.

The most common accessory minerals are zircon, epidote, allanite, apatite, and opaque minerals. A few specimens, particularly of the more leucocratic varieties, contain fluorite and some of these (e.g. 68590074) may be related to the Elizabeth Creek Granite.

Granodiorites are most common in the Herbert River area. The alkali feldspar is usually perthitic microcline, and the plagioclase is zoned oligoclase-andesine (An_{28-35}). Hornblende is a common constituent, in addition to biotite, but commonly shows evidence of alteration and some degree of replacement by epidote, biotite, or chlorite. Accessory minerals are generally more abundant than in the more acid rocks, and include zircon, allanite, apatite, sphene, and opaque minerals. Xenoliths are most common in the more basic varieties of Herbert River Granite.

Economic mineralization. Copper, lead, and tungsten mineralization appear to be associated with contaminated varieties of the Herbert River Granite (Branch, 1966). Small copper and lead-bearing greisen lodes in metasomatized hornblende-quartz micromonzonite have been worked in the Princess Hills area. A little wolfram and scheelite have been extracted from quartz lodes in an isolated stock of Herbert River Granite about 20 km northwest of Camel Creek homestead (White, 1965; Branch, 1966).

Ixe Microgranodiorite

The Ixe Microgranodiorite forms two small stocks, each about 25 km^2 in area, north of Burlington homestead in the Atherton Sheet area. The rock is dark grey, fine to medium-grained, and contains white feldspar phenocrysts up to 7 mm in length. It grades into a coarser-grained rock identical with the Herbert River Granite and is considered to be genetically related to it (Branch, 1966). Rb-Sr dating, however, has given an age similar to that of most of the Elizabeth Creek Granite (Black, 1974).

Petrography. Although it was classified as a granodiorite by Branch (1966), the three analysed samples of Ixe Microgranodiorite are all adamellites, in which plagioclase is generally more abundant than alkali feldspar. The rocks are fine to medium-grained and porphyritic; the texture is monzonitic, with large poikilitic crystals of alkali feldspar enclosing euhedral crystals of plagioclase.

Quartz (15-25%) is anhedral. Alkali feldspar (30-35%) is usually orthoclase perthite and forms anhedral poikilitic crystals. Plagioclase (35-45%) is zoned and commonly sericitized oligoclase-andesine. Quartz, alkali feldspar, and plagioclase occur both as phenocrysts and in the groundmass. Biotite (7-10%) is pleochroic from pale yellow to dark brown and shows slight chloritization. Hornblende occurs in one sample, but is largely pseudomorphed by chlorite and epidote. Accessory minerals include zircon, apatite, and opaque minerals.

Almaden Granite

The Almaden Granite crops out over an area of about 550 km^2, and extends north-northwest from Almaden to beyond the Walsh

River. There is a smaller intrusion immediately to the north of Petford and some of the more basic intrusions in the Ingham Sheet area have been correlated with the Almaden Granite (de Keyser et al., 1965; de Keyser & Lucas, 1968).

The main rock type is a grey and commonly porphyritic hornblende-biotite granodiorite, which is generally coarse-grained around Almaden, but grades into porphyritic microgranodiorite near the Walsh River (Branch, 1966). Subordinate adamellite and intermediate to basic rocks, including quartz diorite and quartz gabbro, are also present, the latter being particularly common in the Petford area.

Branch (1966) considered that the Almaden Granite was derived by contamination of Herbert River Granite magma with a more basic magma. The volcanics of the First Episode (i.e., the Nychum Volcanics) include basaltic and andesitic flows and were thought to have been the source of the basic magma. Evidence used in support of this argument included the abundance of basic to intermediate xenoliths in the Almaden Granite, the gradational contacts between Almaden and Herbert River Granites (e.g. south of Almaden), and the presence of calcic cores in plagioclase crystals in the Almaden Granite. Assimilation of limestone of the Silurian Chillagoe Formation was also thought to have caused some local contamination of the granite magmas (Branch, 1966). De Keyser & Wolff (1964), however, were of the opinion that the various granitic rocks of the Chillagoe area, including the Almaden, Elizabeth Creek, and Herbert River Granites, merely represent individual members of a magmatic differentiation series. They were not able to make distinctions between the various granites with certainty, owing to the presence of gradational varieties.

The Almaden Granite was considered by Branch (1966) to be the same age as the Herbert River Granite. Rb-Sr isotopic studies (Black & Richards, 1972a) are consistent with a derivation of the Almaden Granite by mixing of basic magma with a magma of similar composition to the Herbert River Granite, as suggested by Branch (1966), and have indicated an age similar to that of the Herbert River Granite (i.e., about 309 m.y.) (Black, 1974). Intrusive contacts are sharp and thermal metamorphism slight except in the limestone areas, where limestone has been completely recrystallized and skarn rocks formed. Some of the most important copper and silver-lead deposits of the Chillagoe area are associated with these contact rocks (de Keyser & Wolff, 1964).

Petrography. The typical Almaden Granite is a medium-grained hornblende-biotite granodiorite with a hypidiomorphic granular texture. Quartz (15-30%) is normally anhedral and interstitial, although subhedral phenocrysts occur in some samples. Orthoclase (up to 20%) occurs as poikilitic or interstitial crystals and is rarely perthitic. Plagioclase (40-55%) forms euhedral zoned phenocrysts, generally of oligoclase-andesine composition (An_{28-48}), but some have more calcic cores (An_{60-92}) (Branch, 1966). Greenish or reddish brown biotite (up to 10%) is most common in the finer-grained rocks and is commonly partly chloritized. Green pleochroic hornblende (up to 10%) is commonly pseudomorphed by biotite, chlorite, or epidote. The presence of augite has been noted by de Keyser & Wolff (1964). The adamellites are texturally similar, but contain a higher proportion of alkali feldspar and less hornblende and biotite. Accessory minerals include zircon, apatite, allanite, sphene, epidote, opaque minerals and, less commonly, tourmaline.

Most of the quartz diorites (70571018, 1288, 1290) are from the intrusion just north of Petford, although similar rocks occur near Koorboora and in the Chillagoe-Almaden area (70571285). Quartz gabbros are also present in these areas (de Keyser & Wolff, 1964). The quartz diorites are generally medium-grained, with a hypidiomorphic granular texture. Quartz (5-15%) and orthoclase (5-10%) are interstitial. Plagioclase (40-65%) is strongly zoned andesine-labradorite. Biotite and hornblende are the main mafic minerals, the latter usually showing some degree of alteration. Pyroxene, where present, is invariably uralitized. Hypersthene occurs in two of the analysed samples (70571288, 1290), whilst the presence of augite has been noted by de Keyser & Wolff (1964). Accessory minerals include apatite, sphene, epidote, zircon, and opaque minerals.

Economic mineralization. The copper and silver-lead mineralization of the Chillagoe area, which is spatially associated with the Almaden Granite, has been described by de Keyser & Wolff (1964). The deposits occur in contact replacement lodes in limestone or along contact faults. The lodes contain varying proportions of silver-lead and copper minerals, with sphalerite accompanying the lead minerals in many places. Bismuth is usually present as an impurity in the copper lodes.

The gold in quartz-fluorite-kaolin lodes in Almaden Granite near Fluorspar siding was thought by Branch (1966) to have been derived from the Elizabeth Creek Granite.

Isotopic studies by Black & Richards (1972b) have shown that the Almaden Granite is not directly related to the lead deposits of the Chillagoe area. These authors considered that the ore lead was probably derived by extensive mixing of a fairly uniform lead component from the acid magmas with readily leachable country-rock lead.

Unnamed granitic rocks of the Ingham and Innisfail 1:250 000 Sheet areas

The extensive intrusions in the Ingham and Innisfail Sheet areas (Cgb on the Ingham Sheet, but C-Pgu on Pl. 1) include a range of granitic rocks which have not been mapped in detail because of the dense cover of rain forest, the deep weathering, and the rugged terrain (de Keyser & Lucas, 1968). Some of the rock types resemble the Elizabeth Creek, Herbert River, or Almaden Granites, although gradations appear to be common (de Keyser et al., 1965).

The most common rock types include pink leucocratic even-grained alaskite; grey to pink biotite granite and adamellite; grey hornblende-biotite adamellite; cream arfvedsonite granite or alaskite; microgranite, microadamellite, aplite, and pegmatite. Many of the rock types are porphyritic. The alaskites resemble the Elizabeth Creek Granite and are widespread south of the Herbert River Gorge. Many of the biotite adamellites and hornblende-biotite adamellites are related to the Herbert River Granite and occur mainly north of the Herbert River Gorge (de Keyser & Lucas, 1968). The granite in the northwest corner of the Ingham Sheet area is, in fact, continuous with the Herbert River Granite in the Einasleigh Sheet area. In many places, microgranite appears to represent a chilled border zone. The arfvedsonite granite of Hinchinbrook Island (68590121) has been described by de Keyser (1966).

The granodiorites and more basic rocks have been correlated with the Almaden Granite (de Keyser et al., 1965). This group includes rocks ranging from olivine gabbro to hornblende-biotite adamellite, granodiorite being the most common. Hornblende-biotite and hypersthene-hornblende-biotite diorite and quartz diorite also occur. The presence of abundant basic xenoliths and of gradations between the various rock types led de Keyser et al. (1965) to suggest that much of the diorite and granodiorite was produced by the assimilation of basic rock by a more acid magma, although it was considered that some of the granodiorite could have been derived by differentiation of primary basic magma.

The granites have indurated the Middle Palaeozoic sediments which they intrude, with the local development of biotite or garnet hornfels, whilst the intruded Glen Gordon Volcanics are commonly recrystallized. The field relationships indicate a complex history of multi-phase emplacement, the more acid rocks being generally younger than the less acid varieties (de Keyser et al., 1965). K-Ar age determinations have indicated a Permo-Carboniferous age for the granites, although the data suggest that there were several phases of intrusion (Richards et al., 1966).

Petrography. Two samples (68590110, 0119) are very similar to the Herbert River Granite of the Atherton and Einasleigh Sheet areas. They are medium to coarse-grained biotite adamellites with an allotriomorphic granular texture. Zoned oligoclase-andesine, poikilitic slightly perthitic microcline, and quartz are the main constituents. Biotite occurs as platy aggregates and allanite is a widespread accessory mineral.

The Elizabeth Creek Granite type (68590112-5, 0118) is generally medium-grained with an allotriomorphic granular texture. It grades into a more leucocratic variety (alaskite), characterized by micrographic textures, sodic plagioclase, chloritization of biotite, sericitic alteration, and the presence of fluorite. Most of the mineralization in the area appears to be associated with this granite, in which the effects of deuteric alteration are widespread.

Two samples of hornblende-biotite adamellite (68590116-7) are probably related to the Almaden Granite. This variety is comparatively rich in accessory minerals, including allanite, apatite, sphene, epidote, and opaque minerals.

Economic mineralization. Only tin and tungsten have been produced in any quantity. Mineralization appears to be mostly related to the pink leucocratic biotite granite (Elizabeth Creek type). Tin occurs either in alluvial deposits, or in lodes in the granite and adjoining sediments. Wolfram occurs mainly in chloritic lodes and quartz reefs in the granite. Bismuth, molybdenum, lead, zinc, gold, and silver occur in small quantities (de Keyser et al., 1965; de Keyser & Lucas, 1968).

Tully Granite Complex

The Tully Granite Complex covers an area about 70 km long by 25 km wide, which extends from Tully in the south to near Malanda in the north. It is a heterogeneous composite body, ranging in composition from quartz gabbro, through tonalite, granodiorite, and adamellite, to acid micrographic granite, although granodiorite and adamellite predominate (de Keyser, 1964; de Keyser & Lucas, 1968). The complex can be distinguished from the Mareeba Granite by the occurrence of hornblende, by the absence of muscovite, and by the wide range of composition.

The complex intrudes the Middle Palaeozoic Barron River Metamorphics, with only slight contact metamorphic effects. De Keyser (1964) suggested that the granitic rocks may be comagmatic with the Glen Gordon Volcanics. K-Ar age determination has indicated a Permo-Carboniferous age for the complex, although the results suggest a complex history of intrusion. Some results suggest correlation with the Herbert River Granite, whilst others indicate that some components may have formed during the later Mareeba event (Richards et al., 1966).

Petrography. The analysed samples range from hornblende-biotite adamellite (68590088, 0091-2), through hornblende-biotite granodiorite (68590094) to quartz diorite (68590095). They are generally medium to coarse-grained, with an allotriomorphic granular texture in the acid rocks and a hypidiomorphic granular texture in the more basic varieties. The alkali feldspar forms large perthitic crystals moulded onto subhedral zoned oligoclase-andesine, whereas quartz occurs in granular aggregates that commonly fill fractures in the feldspars. Biotite is usually partly chloritized and is associated with green hornblende in aggregates or 'microxenoliths'. The amphibole is commonly pseudomorphed by biotite. Pyroxene occurs in the more basic rocks. Accessory minerals are fairly abundant and include zircon, apatite, allanite, sphene, epidote, and opaque minerals.

Economic mineralization. Some gold has been obtained from the Russell River and Jordan Creek goldfields. The gold is mostly alluvial, but in the Jordan Creek field it occurs in quartz veins and leaders in decomposed granite. Some cassiterite was obtained from the auriferous gravels of the Russell River field (de Keyser, 1964; de Keyser & Lucas, 1968), although its origin is uncertain.

Mareeba Granite

The Mareeba Granite comprises several large intrusions and a number of smaller stocks, altogether about 3000 km^2 in area, which intrude the Middle Palaeozoic sediments and metamorphics of the Hodgkinson Basin between Innisfail in the south and the Bloomfield River in the north. The intrusions are mostly elongated in a north-northwesterly direction roughly parallel to the regional strike. Intrusion took place after the main phase of folding and cleavage formation. Contact metamorphic effects include the development of 'spotted' schist, biotite-quartz hornfels, and andalusite schist (Amos & de Keyser, 1964).

The most common rock types are biotite and biotite-muscovite adamellites, which are generally grey, porphyritic, and medium to coarse-grained. Granodiorite, leucogranite, and muscovite microgranite also occur. Patches of greisen, tourmaline-bearing granite, pegmatite, aplite, and granitic dykes are common and are probably the main sources of the tin worked in the area (Amos & de Keyser, 1964; de Keyser, 1964; Fardon & de Keyser, 1964; Morgan, 1964b; de Keyser & Lucas, 1968). The two outcrops of diorite about 15 km west of Curraghmore were included by de Keyser & Lucas (1968) with the Mareeba Granite. A single K-Ar date on a sample from one of these intrusions is consistent with this interpretation (Richards et al., 1966).

The mean K-Ar age obtained for the Mareeba Granite is 264 ± 2 m.y. (E. Permian) (Richards et al., 1966), although Rb-Sr dating suggests an age of 288 ± 9 m.y. (Black, 1974). Thus the Mareeba Granite is significantly younger than the Herbert River and Elizabeth Creek Granites, but older than the Finlayson and Trevethan Granites farther north. A sample (68590042 from China Camp) from the intrusion north and east of the Daintree River, which differs in mineral composition and grainsize from the normal Mareeba Granite (Amos & de Keyser, 1964), yielded an age which is comparable with these younger granites (Richards et al., 1966; Black, 1974). Two samples from the Bellenden Ker Range and two from the Cairns Sheet area appear to be younger than the other Mareeba Granite samples and may also belong to the group that includes the Finlayson Granite. Three of the samples were collected close to zones of strong shearing, however, so that the ages are somewhat unreliable (Richards et al., 1966).

Petrography. The predominant rock type is a medium to coarse-grained biotite adamellite, with or without muscovite, and with an allotriomorphic granular texture. The plagioclase is usually zoned oligoclase, with sericitized cores, although albite and andesine also occur. Alkali feldspar forms large poikilitic crystals of perthitic microcline, which de Keyser & Lucas (1968) considered to be late-stage porphyroblasts, rather than true phenocrysts, since they contain inclusions of biotite and corroded grains of plagioclase and quartz. The reddish brown strongly pleochroic biotite is commonly partly altered to chlorite and contains numerous inclusions of zircon with pleochroic haloes. Much of the muscovite is secondary and derived from the alteration of feldspar, although in some samples it is as abundant as biotite. Iron-rich pleochroic bluish green tourmaline is a common accessory and appears to have crystallized rather late. The development of tourmaline is commonly accompanied by the bleaching and alteration of the biotite. The margins of the tourmaline crystals are generally darker and more iron-rich, the iron probably being derived from the biotite. The appearance of tourmaline at the expense of biotite has also been noted in the granites of southwest England (Exley & Stone, 1964). Other accessory minerals include apatite, allanite, epidote, fluorite, and opaque minerals; euhedral garnet occurs locally.

The granites (s.s.) are petrographically similar to the adamellites, except for the higher proportion of alkali feldspar, the rather more sodic plagioclase which exhibits only slight zoning, and the reduction in the proportion of biotite. None of the analysed granites contains tourmaline. The grains of plagioclase commonly show corroded margins adjacent to microcline.

The granodiorites are generally medium-grained and have an equigranular hypidiomorphic texture. Quartz occurs as composite grains with sutured margins; the alkali feldspar is generally perthitic microcline; and the plagioclase is usually partly sericitized zoned oligoclase-andesine. Biotite is crowded with small zircons and pleochroic haloes and is associated with apatite and iron oxide. It normally shows only slight alteration to chlorite, although it is generally bleached when associated with tourmaline.

A number of Mareeba Granite samples show deformational effects, such as undulose extinction and granulation of quartz, some fracturing and recrystallization of the feldspars, and a preferred orientation of biotite crystals. Deuteric alteration is widespread in most of the rocks.

Economic mineralization. The Mareeba Granite has associated tin, tungsten, and copper mineralization.

Alluvial tin has been worked in many of the creeks around the granite tablelands north of Mount Molloy. The cassiterite was derived from small stanniferous quartz veins and pegmatites, and possibly patches of greisen (de Keyser & Lucas, 1968). Lode tin has been worked at China Camp. The deposits occur as disseminated cassiterite in weathered greisenized granite, traversed by tin-bearing quartz-tourmaline veins (Amos & de Keyser, 1964). A little tin, both alluvial and lode, has been recovered from around Hartleys Creek in the Cairns Sheet area (Fardon & de Keyser, 1964).

Wolfram occurs at several localities, notably Mount Carbine and Mount Perseverance, in association with a little tin, copper, and molybdenum. Mount Carbine has been an important producer, ranking with Wolfram Camp and Bamford Hill as one of the three chief sources of wolfram and scheelite in Queensland (Amos & de Keyser, 1964; de Keyser & Lucas, 1968). Copper occurs near Mount Molloy in association with sphalerite (Amos & de Keyser, 1964).

Little economic mineralization is associated with the intrusions in the Innisfail Sheet area, although tin, tungsten, molybdenum, and a little copper and bismuth occur in the Tinaroo group of lodes, about 16 km north-northeast of Atherton (de Keyser, 1964). The gold deposits of the Mulgrave River and Bartle Frere goldfields appear to be associated with the Mareeba Granite (de Keyser, 1964).

Cannibal Creek Granite

The Cannibal Creek Granite includes one intrusion of about 110 km^2, together with a small stock to the east of the main body. The most common variety is a medium to coarse-grained biotite-muscovite adamellite, which is generally somewhat foliated and sparsely porphyritic. The intrusion has a chilled margin of flow-banded adamellite (Amos & de Keyser, 1964; de Keyser & Lucas, 1968). Only one sample, a muscovite-biotite granite (68590040), was analysed.

The Cannibal Creek granite was considered by Amos & de Keyser (1964) to be the same age as the Mareeba Granite. The tin-bearing lodes of Cannibal Creek may possibly be related to this granite (Amos & de Keyser, 1964; de Keyser & Lucas, 1968).

Trevethan Granite

The main body of the Trevethan Granite crops out about 20 km south of Cooktown, where it forms the bare bouldery Black Mountain. The main rock type is a pale grey medium to coarse-grained and commonly porphyritic actinolite-biotite granodiorite, rather similar to the Almaden Granite. More basic quartz diorites appear to have been emplaced before the main intrusion (Morgan, 1965; Lucas & de Keyser, 1965a; de Keyser & Lucas, 1968).

The granite intrudes Devonian sediments of the Hodgkinson Formation. K-Ar age determinations have indicated a Middle Permian age (247 ± 6 m.y., Richards et al., 1966). There appears to be no economic mineralization associated with the Trevethan Granite.

Petrography. The typical actinolite-biotite granodiorite consists of zoned oligoclase-andesine, pale green actinolitic amphibole (probably secondary), brown partly chloritized biotite, quartz, and a little interstitial microcline. The texture is hypidiomorphic granular. Biotite and actinolite occur in association and there is some pseudomorphing of the amphibole by biotite. Relict clinopyroxene is present in some samples. The main accessory minerals are apatite, sphene, zircon, and opaque iron oxide.

Sample 68590005 was taken from an acid porphyry dyke which intrudes the granite.

Puckley Granite

The Puckley Granite crops out over a total area of about 130 km^2 in the Cooktown and Cape Melville Sheet areas, although the total extent is unknown because of the cover of Mesozoic sandstone. The main rock type is a medium to coarse-grained porphyritic biotite adamellite, with a little muscovite occurring locally (Lucas & de Keyser, 1965a,b; Morgan, 1965; de Keyser & Lucas, 1968). A tourmaline-bearing variety occurs in the Jeannie River headwater region (Morgan, 1964a).

The granite has altered the surrounding Devonian sediments of the Hodgkinson Formation and is overlain by Jurassic and Cretaceous sediments. It is correlated with the Mareeba Granite (264 ± 2 m.y.) on the basis of K-Ar dating (Richards et al., 1966). No known economic mineralization is associated with the Puckley Granite, although some of the gold, tin, copper, and tungsten mineralization in the area could be related to it.

Petrography. The main constituents are quartz (25-40%), orthoclase (20-40%), plagioclase (25-40%), and biotite (up to 12%). Compared with the Finlayson Granite, the plagioclase in the Puckley Granite is generally more calcic and the alkali feldspar is orthoclase rather than microcline (de Keyser & Lucas, 1968).

Only one sample, a biotite adamellite (68590009), was analysed.

Finlayson Granite

The Finlayson Granite forms a number of intrusions, totalling about 160 km^2 in area, in the Annan River Tinfield, south of Cooktown. There is also a small intrusion at Cooktown. The main rock types are medium to coarse-grained porphyritic biotite adamellite and granite, which are commonly tourmaline-bearing. A chilled margin is usually present (Lucas & de Keyser, 1965a; Morgan, 1965; de Keyser & Lucas, 1968).

The Finlayson Granite intrudes the Devonian sediments of the Hodgkinson Formation and K-Ar dating has indicated an age similar to that of the Trevethan Granite (247 ± 6 m.y.) (Richards et al., 1966). If an upward adjustment of 6 percent is used to permit a more meaningful comparison with the Rb-Sr ages of other Upper Palaeozoic granite rocks (see Black & Richards, 1972a), this age becomes 262 m.y.

Petrography. The major constituents are anhedral microcline microperthite (both as phenocrysts and in the groundmass), zoned and commonly saussuritized oligoclase, and quartz. Biotite contains inclusions of zircon and apatite and is generally partly chloritized. Bluish green to brown tourmaline occurs as clusters of anhedral poikilitic crystals, although its abundance varies considerably from one sample to another. Secondary muscovite is common, but accessory minerals are generally rare. One sample (68590007) contains fluorite. Deuteric alteration is common in the Finlayson Granite and is associated with mechanical deformation that resulted in strained quartz grains and broken feldspars.

The sample from China Camp (68590042), although classed as Mareeba Granite, is petrographically rather similar to the Finlayson Granite and has yielded a similar age (Amos & de Keyser, 1964; Richards et al., 1966; Black, 1974).

Economic mineralization. The tin mineralization of the Annan River Tinfield, which includes both greisen and stanniferous quartz-tourmaline lode deposits, is associated with the Finlayson Granite. The tin occurs in association with small amounts of wolfram, molybdenite, galena, and native copper (de Keyser & Lucas, 1968).

Altanmoui Granite

The name Altanmoui Granite has been applied to all granite outcrops along the coast north of latitude 14°41′S. At Cape Melville, the rock consists mainly of grey medium-grained porphyritic biotite adamellite. The southeastern part of the intrusion is more varied and includes porphyritic biotite microgranite, aplitic granite, tourmaline-muscovite pegmatite, and some hornblende-bearing rocks. Porphyritic biotite adamellite occurs at Barrow Point, whilst in the Altanmoui Range the suite includes porphyritic biotite microgranite, foliated muscovite-biotite granite, and pegmatitic aplite (Morgan, 1964a; Lucas & de Keyser, 1965b; de Keyser & Lucas, 1968).

The intruded Devonian sediments of the Hodgkinson Formation are generally altered and hornfelsed, although the contact zones are usually narrow (Lucas & de Keyser, 1965b). The Altanmoui Granite is demonstrably post-Devonian and pre-Jurassic and may be the same age as the Finlayson and Trevethan Granites (Middle Permian).

Petrography. The three analysed samples (68590001-3) range from biotite adamellite to biotite granite. The plagioclase is commonly zoned oligoclase-andesine in the more basic rocks and albite-oligoclase in the more acid. Perthitic microcline, quartz, and reddish brown biotite are the other major constituents. Hornblende occurs in one sample, but most of it is pseudomorphed by biotite, whereas biotite is commonly partly chloritized. Epidote, allanite, apatite, zircon, and opaque minerals are the main accessories.

Economic mineralization. Cassiterite occurs in alluvial deposits at Barrow Point and wolfram has been reported from a granite-slate contact in the Altanmoui Range. Gold and tungsten have been mined on a small smale in the area and uneconomic deposits of antimony and copper also occur. The Altamoui Granite is thought to be the source of part of this mineralization (Lucas, 1964).

Gurrumba Ring Complex

The Gurrumba Ring Complex, referred to as the Gurrumba Volcanic Neck by Branch (1966), has an elliptical outcrop about 5 km long and 3 km wide, and is completely surrounded by Elizabeth Creek Granite. It is situated about 20 km northwest of Mount Garnet. The complex consists of an outer ring dyke of acid to basic igneous rocks surrounding sediments of the Hodgkinson Formation, which in turn surround the acid Gurrumba Volcanics and a small mass of quartz diorite (Blake, 1972).

The ring dyke consists mainly of olivine gabbro, pink granophyre, and a variety of intermediate hybrid rocks, mostly of quartz diorite composition. Over much of the outcrop these rock types are intimately associated in a net-veined complex in which basic and intermediate hybrid rocks occur as inclusions within the granophyre. Blake (1972) considered that the net-veined complex was formed by the commingling of acid (granophyre) and basic (olivine gabbro) magmas, the intermediate hybrid rocks crystallizing from hybrid magmas. The same author has suggested that the acid magmas that formed the Gurrumba Volcanics and the granophyres could have been derived by melting and remobilization of Elizabeth Creek Granite by olivine gabbro magma at depth. If this was the case, a certain amount of contamination of the acid melt with more basic material would be necessary to produce at least some of the granophyres (e.g. 67490080R).

The Gurrumba Volcanics consist of pale grey flow-banded and autobrecciated 'rhyolite' containing small phenocrysts of turbid feldspar and much secondary pyrite and sericite.

Petrography. The olivine gabbro (67490073, 0076, 0078) is medium-grained and contains bytownite (70-75%), pyroxene (10-20%), olivine (5-10%), and opaque minerals (2-3%). Olivine is extensively serpentinized and most of the augite and hypersthene are replaced by pale green tremolite-actinolite. Talc (after olivine) and epidote, chlorite, and biotite (after pyroxene) are the other minor alteration products.

The granophyres generally contain small phenocrysts of sodic plagioclase and chloritized biotite in a fine-grained micrographic groundmass of quartz and turbid alkali feldspar (Blake, 1972). The analysed sample (67490080R) is a porphyritic rhyodacite and contains phenocrysts of alkali feldspar and plagioclase set in a micrographic groundmass. The acid hybrid rocks are petrographically very similar.

The basic hybrids, including quartz diorite grading into quartz andesite, are generally aphyric. They contain zoned oligoclase-andesine or oligoclase-labradorite, augite, hornblende, and interstitial quartz and alkali feldspar. The ferromagnesian minerals are generally extensively altered. Sample 67490075 is a porphyritic andesite containing phenocrysts of andesine and chloritic pseudomorphs.

One sample of a slightly porphyritic micro-adamellite (67490079R) was analysed.

Newcastle Range Volcanics

The Newcastle Range and Eastern Newcastle Range Cauldron Subsidence Areas cover a total area of about 2500 km^2 in the central part of the Georgetown Inlier. They consist of two downfaulted blocks of Upper Palaeozoic volcanics, flanked by Precambrian granites and metamorphics. The main Newcastle Range Cauldron extends for about 110 km in a north-south direction and averages about 20 km in width. The Eastern Newcastle Range Cauldron measures about 25 km by 15 km. The structures are bounded by linear faults and ring fractures which may have been controlled by pre-existing basement fractures. A number of acid dykes intrude the Forsayth Granite to the south and east of the eastern cauldron and may represent part of an older polygonal ring structure (Branch, 1966). The volcanics of the eastern cauldron are intruded by a small stock of Elizabeth Creek Granite. Small quantities of tin and copper have been extracted from greisen dykes in this granite.

The stratigraphic succession in the Eastern Newcastle Range, where the volcanics unconformably overlie Forsayth Granite, is given by Branch (1966, p. 21).

	Thickness (m)	
Upper Welded Tuff Member	300	Pink to grey porphyritic rhyodacite welded tuff
Middle Composite Member	100	Rhyodacite welded tuff interbedded with airfall tuff, volcanic agglomerate, and occasional thin beds of tuffaceous sandstone and shale. A flow of olivine basalt, 10 m thick, is also present
Basal Sedimentary Member	100	Predominantly shale and conglomerate

Successions in the main Newcastle Range are generally similar and include porphyritic pigeonite-hornblende-quartz andesite, quartz trachyandesite, and spherulitic rhyolite in addition to the predominant rhyodacite welded tuff units. A coarse volcanic agglomerate, up to 60 m thick, is present in the central part of the range.

Rb-Sr dating of two samples of the Newcastle Range Volcanics suggested a Late Devonian to Early Carboniferous age (Richards et al., 1966), although more recent work has indicated that they are Carboniferous (about 318 m.y.: Black, 1973, 1974).

Petrography. The most abundant rock type in the Newcastle Range is a porphyritic rhyodacite welded tuff, which ranges in colour from pink, through purple, to grey. Phenocrysts consist mainly of embayed β-quartz and euhedral oligoclase-andesine with subordinate alkali feldspar. The rhyodacite grades into rhyolite with a higher proportion of alkali feldspar phenocrysts (70571171, 1229-31). Alkali feldspar is frequently kaolinized and iron-stained, but anorthoclase has been identified in some samples. Plagioclase is also stained and altered, particularly in the cores. Calcite, sericite, and epidote occur as alteration products. The plagioclase has optical properties transitional from high to low temperature (Branch, 1966). The most common mafic mineral is biotite, which is always strongly chloritized. Hornblende was noted in only one sample (70571229) and is largely pseudomorphed by chlorite, epidote, and iron oxide. The groundmass is invariably devitrified and is commonly spherulitic. Relict shards are present in many samples and flattened fragments of devitrified pumice are common, particularly in samples 70571205-6 and 1229-30. The degree of welding is usually moderate. In some cases the groundmass is recrystallized to such an extent that the original eutaxitic texture has been almost obliterated. A few samples are amygdaloidal. Accessory minerals include zircon, sphene, apatite, and opaque minerals.

Samples 70571193 and 1214 are sparsely porphyritic rhyolites with a well developed banding. Phenocrysts include quartz, plagioclase, and alkali feldspar, and the groundmass is rich in alkali feldspar and quartz. The groundmass is cryptocrystalline and partly spherulitic, but the appearance in hand specimen suggests that these rocks have a pyroclastic origin. Sample 70571200 was collected from a prominent rhyolite dyke on the western side of the Newcastle Range. It consists of phenocrysts which include β-quartz, alkali feldspar, and oligoclase set in a partly spherulitic groundmass.

More basic rocks include dacites and a single andesite. The andesite (68590013) is from the northern end of the Newcastle Range and contains phenocrysts of andesine-labradorite and augite in a partly glassy groundmass. Augite is partly replaced by chlorite.

Some of the dacitic rocks (70571201-2, 1212) are welded tuffs. They contain phenocrysts of andesine and subordinate quartz and chloritic pseudomorphs in an ironstained cryptocrystalline groundmass. Relict eutaxitic textures are recognizable and some samples contain devitrified pumice fragments and xenoliths. These rocks are near to quartz trachyandesite in composition and contain up to about 25 percent of alkali feldspar in the groundmass.

The porphyritic dacites (70571209-11, 1213) from the eastern side of the main Newcastle Range are generally similar, but the limonite-stained, cryptocrystalline groundmass does not show evidence of a pyroclastic origin. Mafic minerals are pseudomorphed by epidote, chlorite, calcite, iron oxide, etc.

Many of the Newcastle Range Volcanics show extensive deuteric or hydrothermal alteration. The feldspars are kaolinized or saussuritized and most of the ferromagnesian minerals are completely replaced by alteration products. The groundmass is usually ironstained and contains a variety of secondary minerals including calcite, epidote, chlorite, and occasionally zeolites.

Featherbed Volcanics

The Featherbed Volcanics crop out over an area of about 3000 km^2 within the Featherbed Cauldron Subsidence Area. They are downfaulted in two large blocks that cover an area about 100 km long and 30 km broad and are flanked by Middle Palaeozoic sediments of the Hodgkinson Formation and by Upper Palaeozoic granitic rocks. The volcanics unconformably overlie the Almaden Granite. East of Almaden, the boundary of the cauldron is defined by the Tennyson Ring Dyke, a large volcanic vent structure.

The volcanics between the northwestern and southeastern parts of the cauldron have been extensively shattered and altered and are intruded by a number of stocks of Elizabeth Creek Granite, extending from Bamford Hill to Wolfram Camp. The granite is associated with tin, tungsten, molybdenum, and bismuth mineralization. The structure of the Featherbed cauldron has been described in more detail by Branch (1966).

The stratigraphic succession in the northwestern part of the cauldron (16 km northeast of Chillagoe) according to Branch (1966) is as follows:

	Thickness (m)	
Third Member	200	Predominantly grey augite-biotite rhyodacite welded tuffs
Second Member	120	Pink rhyodacite welded tuffs and flows, with amygdales
First Member	0–200	Flow-banded pink lenticular rhyolite
	15	Grey arfvedsonite-epidote rhyodacite (probably a dyke)

In the southeastern cauldron subsidence area, west of Stannary Hills, the volcanics consist mainly of the thick grey welded tuff sheet of the third member. The Tennyson Ring Dyke is composed mostly of light pink and grey, fluidized, porphyritic rhyodacite, cut by pipes filled with tuff and volcanic breccia-agglomerate (Branch, 1966).

Rb-Sr dating has shown that the Featherbed Volcanics are generally younger than the Elizabeth Creek Granite, although there is a considerable variation (possibly as much as 50 m.y.) in age, the volcanics from the eastern cauldron being older than those from the western (Black, 1974).

Petrography. The Featherbed Volcanics are predominantly of rhyodacitic composition, although rhyolite and minor dacite also occur. The rocks usually contain 20 percent or more of phenocrysts of quartz, alkali feldspar, plagioclase, and ferromagnesian minerals. The phenocrysts range from 1 mm to 2 cm or more across, but are generally fragmented in the pyroclastic rocks. The phenocrysts of β-quartz are anhedral to subhedral and usually corroded and embayed. The subhedral laths of plagioclase consist of zoned oligoclase or oligoclase-andesine with albite rims and are commonly saussuritized. The plagioclase has transitional to high-temperature optical properties (Branch, 1966). Alkali feldspar is either sanidine, anorthoclase, or fine perthite, the latter being most common in the strongly welded zones which have cooled more slowly.

Dark brown pleochroic biotite (up to 5%) occurs in most specimens, but is usually more or less chloritized. Up to 3 percent of amphibole, usually hornblende, but occasionally arfvedsonite, is present in the dacites and some of the rhyodacites. Augite and rarely hypersthene are present in a few samples, but show extensive alteration to amphibole, chlorite, epidote, etc. The pyroclastic rocks also contain small, angular xenoliths, usually of fine-grained acid rock (Blake, 1972).

The quartzofeldspathic groundmass is almost invariably devitrified, aphanitic to cryptocrystalline, and occasionally spherulitic. Eutaxitic textures are preserved in some samples, but in others the degree of recrystallization is such that their assumed pyroclastic origin is not apparent in thin section. Shards, which show moderate to complete welding, and occasional pumice fragments can be recognized in the less recrystallized welded tuffs.

The rhyolites (70571005, 1007, 1010, 1026-28, 1039-40) are most common in the flow-banded units at the base of the succession and are characterized by their lower proportions of albite-oligoclase phenocrysts and ferromagnesian minerals (usually chloritized biotite). The dacites (70571011, 1014) contain phenocrysts of plagioclase, with or without quartz.

Amygdales containing one or more of chalcedony, chlorite, and calcite are present in some of the welded tuffs and flows. Within the second member, the number and size of vesicles appear to increase and the degree of flow banding to decrease towards the top of the sheet. This is probably due to an increase in the fluidity and volatile content of the magma, as suggested by Branch (1966). The degree of compaction and welding decreases towards the top of the sheets, the upper member showing very little welding except near the base. The upper member is entirely recrystallized and highly porphyritic, indicating a considerable degree of crystallization before extrusion.

The volcanics near the intrusions of Elizabeth Creek Granite, northeast of Petford, are extensively altered and recrystallized, with kaolinization of alkali feldspar, chlorination of biotite, and the development of fluorite, epidote, and muscovite.

Compared with the other Upper Palaeozoic volcanic rocks, the Featherbed Volcanics tend to be richer in phenocrysts. They are also rather less altered, as evidenced by the occurrence of pyroxene in a number of specimens.

Slaughter Yard Creek Volcanics

The Slaughter Yard Creek Volcanics cover an area of about 15 km^2 between Watsonville and Herberton (Blake, 1972). They were previously mapped as Glen Gordon Volcanics (Best, 1962; Branch, 1966). They consist predominantly of pale grey rhyolitic lavas in the northern part of the outcrop and pink or grey intrusive porphyritic rhyodacites in the central and southern parts.

The Slaughter Yard Creek Volcanics overlie the Elizabeth Creek Granite and are intruded by the Watsonville Granite. They were therefore considered by Blake (1972) to be Early Permian in age. This has been confirmed by Rb-Sr dating, which has given an age of 281 ± 3 m.y. (Black, 1974).

Petrography. The rhyolitic lavas (67490055R-6R, 0060R, 0066R) are sparsely porphyritic or non-porphyritic, and are generally flow-banded. The groundmass is usually microcrystalline to cryptocrystalline and is commonly spherulitic or micrographic. Sample 67490065R is a porphyritic rhyodacite in which the presence of relict shards indicates a pyroclastic origin.

The dyke rocks (67490057-9R) are porphyritic rhyodacites. The phenocrysts consist mainly of quartz, alkali feldspar, sericitized oligoclase, and chloritic pseudomorphs after biotite. The alkali feldspar is commonly sanidine, although it is usually very altered. The groundmass is very fine-grained, and commonly spherulitic, and contains small flakes of altered biotite and opaque minerals.

Blake (1972) considered the dykes and lavas to be contemporaneous, but their differences in composition suggest that the analysed dykes, at least, were not the feeders for the extrusive rocks.

Nanyeta Volcanics

The Nanyeta Volcanics occupy an area of about 60 km^2 within the Nanyeta Cauldron Subsidence Area. The cauldron has been deeply eroded and the Hodgkinson Formation sediments, on which the volcanics were deposited, are partly exposed. The small area of volcanics south of Newellton, which was mapped as Nanyeta Volcanics by Branch (1966), was included in the Glen Gordon Volcanics by Blake (1972).

The Nanyeta Volcanics unconformably overlie Precambrian metamorphics and Middle Palaeozoic sediments and are intruded by the Elizabeth Creek Granite. They were correlated by Branch (1966) with the Sunday Creek Volcanics and considered to be unconformably overlain by the Glen Gordon Volcanics. Blake (1972), however, correlated them with both the Glen Gordon and Featherbed Volcanics. A Rb-Sr age of 295 ± 10 m.y. has been obtained on the Nanyeta Volcanics by Black (1974).

In the type section at Smiths Creek, 8 km northwest of Mount Garnet, the Nanyeta Volcanics are about 160 m thick (Branch, 1966). They range from andesite to rhyolite and include welded tuff, lavas, agglomerate, and airfall tuff. The colour ranges from dark grey, through purple and pink, to cream.

Petrography. The welded tuff units are mostly of rhyodacite composition (67490106, 0108-9, 0116R). They are sparsely to highly porphyritic, with phenocrysts of oligoclase-andesine, alkali feldspar, and embayed quartz set in an aphanitic to cryptocrystalline and, in places, partly glassy groundmass. Alkali feldspar is usually kaolinized and ironstained and plagioclase is sericitized. Shards are poorly preserved, but devitrified pumice fragments occur in some samples. Amygdales filled with quartz, chlorite, and calcite are present in one sample (67490109). Biotite is usually pseudomorphed by chlorite, calcite, and iron oxides. Relict hornblende is rare. Calcite, epidote, chlorite, sericite, and opaque minerals are common minor constituents.

The rhyolites (67490110R, 68590063) are aphyric to sparsely porphyritic with a partly spherulitic groundmass. Only the latter sample has a recognizably pyroclastic origin.

The hornblende - augite andesite (67490117R) contains rare phenocrysts of andesine(An_{42-44}) set in a fine-grained trachytic groundmass. Augite and hornblende are largely pseudomorphed by epidote, chlorite, and iron oxide.

The Nanyeta Volcanics are petrographically very similar to the Glen Gordon Volcanics, which partly explains the difficulties in distinguishing them in the field. Both are characterized by extensive deuteric alteration.

Walsh Bluff Volcanics

The Walsh Bluff Volcanics crop out in the northern part of the Glen Gordon Cauldron Subsidence Area to the west of Atherton, where they cover an area of about 230 km^2. They consist mainly of rhyodacite welded tuff with subordinate rhyodacite lavas and agglomerates. Many of the acid dykes in the Collins Weir area can probably be correlated with the Walsh Bluff Volcanics (Branch, 1966; Blake, 1972).

The relationship of the Walsh Bluff Volcanics to some of the other igneous rocks in the area is somewhat controversial. According to Branch (1966), they are intruded by the Elizabeth Creek Granite and are possibly related to the Glen Gordon and Featherbed Volcanics. In the opinion of Blake (1972), however, they unconformably overlie the Elizabeth Creek Granite. Rb-Sr dating has indicated that they are younger than the Elizabeth Creek Granite, with an age of about 285 m.y. (Black, 1974).

Petrography. The analysed rocks are all rhyodacites and include both aphyric and porphyritic varieties. The phenocrysts consist mainly of quartz, alkali feldspar, and plagioclase, as well as chloritic pseudomorphs after biotite. The groundmass ranges from partly glassy to aphanitic and may be spherulitic. Only one sample (67490049R) is recognizably a welded tuff and contains flattened fragments of devitrified pumice. Epidote, sericite, calcite, and opaque minerals are common minor constituents.

Glen Gordon Volcanics

The Glen Gordon Cauldron Subsidence Area is a remnant cauldron on the eastern edge of the Georgetown Inlier. It extends from near Glen Ruth homestead north-northwest for about 100 km to Walsh Bluff (Branch, 1966). The Glen Gordon Volcanics crop out over an area of about 800 km^2 within the cauldron. A number of explosion vents along the western boundary fault of the cauldron were considered by Branch (1966) to be the source of the airfall deposits.

Rhyodacite to rhyolite welded tuff is the predominant rock type, with subordinate dacite and minor trachyandesite and augite-quartz andesite. Interbedded tuffaceous sandstone and siltstone are also present. Breccia and agglomerate are rare, except east of Silver Valley, where there is a deposit of breccia and agglomerate 60 m thick.

The extensive volcanics to the south, along the Herbert River, were tentatively included with the Glen Gordon Volcanics by de Keyser et al. (1965). They include porphyritic rhyolite, rhyodacite welded tuff, and porphyritic biotite-quartz trachyandesite (Branch, 1966).

The Glen Gordon Volcanics are intruded by the Elizabeth Creek Granite and are hornfelsed and locally greisenized near the contact. They were considered by Branch (1966) to overlie the Sunday Creek Volcanics unconformably and were correlated with the Featherbed Volcanics. Blake (1972), on the other hand, correlated them with the Sunday Creek Volcanics.

Petrography. The rock types present range from andesite to rhyolite, although rhyodacite and rhyolite predominate. Many of the samples are welded tuffs; flow-banded rhyolite is particularly abundant near Glen Gordon homestead and south of Ravenshoe. They are generally sparsely porphyritic, with less than 10 percent of phenocrysts, although quartz, kaolinized alkali feldspar, and altered albite-oligoclase all occur. The groundmass is usually cryptocrystalline and is generally partly spherulitic, although in a few cases it is partly glassy. Devitrified flattened pumice fragments are conspicuous in many samples and relict shards are occasionally present. Ferromagnesian minerals (mostly biotite) are replaced by various secondary minerals, including chlorite, calcite, epidote, and iron oxides. Some of the tuffs show little or no welding and a number contain abundant lithic fragments (67490016R-7R, 68490007G). Sample 68490008G is a volcanic breccia containing large fragments of tuff, up to 10 cm across, in addition to vitric fragments and feldspar phenocrysts, set in a cryptocrystalline groundmass.

The dacites (67490015R, 0018R) contain phenocrysts of oligoclase-andesine in a cryptocrystalline groundmass. Alkali feldspar and quartz are restricted to the groundmass. Mafic minerals are pseudomorphed by chlorite, epidote, calcite, and iron oxide.

The andesite (68490009G) contains rare andesine phenocrysts in an aphanitic to cryptocrystalline groundmass. Augite shows extensive marginal replacement by chlorite and epidote, and small flakes of chlorite are present in the groundmass.

Hydrothermal alteration is a conspicuous feature of the Glen Gordon Volcanics, like many of the other Upper Palaeozoic volcanics. The alkali feldspars are usually kaolinized and plagioclase is sericitized or saussuritized, or both. Fresh primary ferromagnesian minerals are rare and there is considerable development of chlorite, epidote, calcite, iron oxides, and other secondary minerals.

Agate Creek Volcanics

The Agate Creek Volcanics crop out over an area of about 65 km^2, 25 km north of Gilberton homestead. They consist largely of rhyodacite welded tuff sheets, trachyandesite and augite andesite flows, and extensive agglomerate and lithic tuff (Branch, 1966). The trachyandesite, andesite, and basalt? are notable for the presence of abundant agate amygdales.

Only one sample of the Agate Creek Volcanics, an intensely altered andesite (68590027), was analysed.

Boxwood Volcanics

The Boxwood Volcanics crop out over an area of about 30 km^2 within the Boxwood Ring Complex. The main unit is a massive grey rhyodacite welded tuff, and subordinate flows of dacite and pink rhyolite are also present (Branch, 1966). A single sample of porphyritic rhyodacite (68590051) was analysed. It contains both hornblende and allanite and in this respect is similar to some of the rhyodacites in the Featherbed Volcanics.

Minor intrusions

Dykes are widespread in the region, particularly in areas where Upper Palaeozoic rocks crop out. They range from rhyolite to dolerite, although rhyodacites are the most common. The rhyolites and rhyodacites are usually porphyritic, with phenocrysts of quartz, alkali feldspar, plagioclase, and in places biotite. The groundmass is generally either micrographic or spherulitic.

The andesites (70571016, 1041) are generally very fine-grained and contain sparse plagioclase phenocrysts.

GEOCHEMISTRY

A total of 562 samples were analysed by X-ray fluorescence spectrometry for Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P, Ga, Rb, Sr, Y, Zr, Ba, La, Ce, Pb, Th, and U and by atomic absorption spectroscopy for Li, Be, Cr, Co, Ni, Cu, Zn, and Sn. Ferrous iron, H_2O, CO_2, and F were determined by the Australian Mineral Development Laboratories. Only those samples in which carbonate was observed in thin section were analysed for CO_2 and only a selection (mostly Elizabeth Creek Granite) was analysed for F. Samples crushed in a tungsten carbide vessel were not analysed for Co and those crushed in a chrome-steel vessel were not analysed for Cr, because of contamination. Brief details of the methods used, together with estimates of accuracy and detection limits, are given in the Appendix. A complete list of the analytical results, together with CIPW norms and certain element ratios, is given in Sheraton (1974). All major oxide concentrations are given in weight percent and trace elements in parts per million.

Esmeralda Granite and Croydon Volcanics

The very similar chemistry of the Esmeralda Granite and Croydon Volcanics (Figs. 1-21, 32, 35, 42; Table 3) strongly supports the suggestion of Branch (1966) that they are comagmatic. They are, however, chemically distinct from the Upper Palaeozoic acid igneous rocks of the Georgetown Inlier, with which they were correlated by Branch (1966).

The range of composition is relatively restricted, and most of the samples contain between 69 and 75 percent SiO_2. Individual samples plot on fairly well defined trends on silica variation diagrams (Figs. 20, 21). The alkali-lime index of Peacock (1931) (i.e., the SiO_2 content at which the Na_2O+K_2O and CaO variation curves cross) is about 60, within the range of calc-alkaline rocks. The Croydon Volcanics with a few exceptions tend to be slightly more siliceous. There is a suggestion of two separate trends in the plot of total FeO against SiO_2 (Fig. 20), although these could not be related to any obvious petrological features of the rocks. The more mafic rocks are richer in FeO than most other calc-alkaline suites, including the Upper Palaeozoic acid igneous rocks, whereas MgO contents are consistently low, leading to high FeO(total)/MgO ratios and low Niggli mg values (Fig. 35; Table 3). Relative FeO to MgO enrichment is shown in Figure 37. FeO(total)/FeO+MgO remains roughly constant with increasing SiO_2 and does not show the late iron-enrichment characteristic of most calc-alkaline suites. The Esmeralda Granite/Croydon Volcanic trend is, in fact, more similar to the most highly differentiated members of the Skaergaard intrusion, which shows early iron-enrichment (Wager, 1960), although it is not suggested that the former were derived by differentiation of basic magma. A more probable explanation is that the acid magmas were produced by partial melting of material with an unusually high Fe/Mg ratio. The presence of almandine-rich garnet in these rocks may, in part, be a consequence of the high Fe/Mg ratio, although such garnet may crystallize from acid calc-alkaline magmas with considerably lower Fe/Mg ratios (Green & Ringwood, 1968b).

The K_2O contents are relatively high and Na_2O contents low, so that K_2O/Na_2O ratios (mostly between 1.5 and 3) and Niggli k values are generally higher than the Upper Palaeozoic rocks and many other calc-alkaline suites (Fig. 32). At least two samples (70571043-4) appear to have suffered depletion of Na and probably, to some extent K. Noble (1967) has shown that leaching of Na and K from natural glasses may accompany hydration. Lipman et al. (1969) have suggested that there appears to be a loss of alkalis only in secondarily hydrated rocks, whereas the compositions of rhyolite lavas that crystallized at the time of emplacement and initial cooling closely approximate the compositions of the magmas. The high water contents and oxidation ratios (Fe'''/Fe'') of samples 70571043 and 1044 are consistent with such alkali loss during alteration and hydration, although it is difficult to decide whether these were late magmatic or strictly post-magmatic processes. As well as loss of Na and K, the two samples also appear to have been depleted in CaO, Pb, Li, Zn and Rb, and possibly Cu and Sr. The high SiO_2 content (80.4%) of 70571044 suggests some degree of silicification.

The variation diagrams show normal calc-alkaline trends for the other major elements (Fig. 20) and for most of the trace elements (Fig. 21). Trace element abundances are mostly close to average for moderately fractionated granitic rocks; Rb, and to some extent Li, Th, and U are relatively high, and Cr, Ni, Cu, and Sr are low (Table 3, Figs. 1-18. The K/Rb ratios (averages for Esmeralda Granite and Croydon Volcanics are 143 and 156, respectively) and the Mg/Li ratios (averages are 47 and 65) are low, and the Rb/Sr ratios (averages are 3.7 and 4.3) are high (Fig. 19, Table 3). The contents of Sn, Pb, and Zn are all rather higher than abundances given by Turekian & Wedepohl (1961) for average low-calcium granite and by Taylor (1968) for average granite (Table 9). Y, Zr, and possibly Ce are rather higher than average, possibly reflecting the contents of accessory minerals (zircon, garnet, etc.). Ga is also slightly higher than the average granites of Taylor (1968) and Turekian & Wedepohl (1961) and the Al/Ga ratios are consequently slightly lower than normal.

There are some differences between the trace element contents of the Esmeralda Granite and Croydon Volcanics, notably the higher Li and lower Zn, Ba, La, Y, and Ce contents of the former, although only the difference in Ba content appears to be really significant (Table

TABLE 3. AVERAGE COMPOSITIONS OF THE ESMERALDA, FORSAYTH, AND ROBIN HOOD GRANITES, CROYDON VOLCANICS, AND STOCKYARD CREEK SILTSTONE

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
SiO_2	72.1	72.8	65.8	74.9	72.2	69.3	70.6	72.5	72.9	62.0	68.3
TiO_2	0.31	0.36	0.69	0.12	0.26	0.49	0.24	0.15	0.23	0.81	0.45
Al_2O_3	13.33	12.52	13.17	13.49	14.20	14.68	15.49	15.53	15.14	15.54	14.80
Fe_2O_3	0.95	1.24	4.83*	0.17	0.40	0.67	0.58	0.16	0.18	2.17	1.44
FeO	1.99	2.18	—	0.79	1.62	2.90	1.35	1.00	1.40	4.53	2.37
MnO	0.05	0.07	0.01	0.02	0.04	0.05	0.05	0.02	0.04	0.11	0.07
MgO	0.29	0.27	0.57	0.25	0.71	1.30	0.76	0.29	0.62	2.85	1.51
CaO	1.39	1.01	0.03	1.23	1.72	2.39	2.68	1.71	1.76	4.78	3.23
Na_2O	2.62	2.05	0.28	3.20	2.90	2.55	4.12	6.1	3.6	2.7	3.3
K_2O	5.03	5.19	3.58	5.06	5.07	4.41	2.83	2.09	3.28	2.38	3.26
P_2O_5	0.14	0.15	0.08	0.07	0.13	0.25	0.08	0.03	0.07	0.27	0.11
H_2O	1.42	1.52	2.65	0.57	0.70	0.73	0.82	0.48	1.20	0.96	0.92
TOTAL	99.62	99.36	98.69	99.87	99.95	99.72	99.60	100.06	100.42	99.10	99.76
Li	37	25	15	19	19	23	11	18	42	12	18
Be	4.4	4.2	2.0	3.5	3.5	4.0	2.5	2.0	5.5	3.0	2.5
Cr	∼4	∼4	59	8	17	44	19	∼4	16	∼70	36
Co	—	—	—	—	—	—	—	∼4	—	∼20	—
Ni	∼3	∼3	<3	<3	∼4	10	∼8	∼3	<3	29	15
Cu	7	9	7	2	3	9	2	3	7	10	16
Zn	79	102	4	19	39	55	40	18	42	114	58
Ga	21	21	20	15	16	19	19	21	18	22	20
Rb	291	277	175	251	268	285	79	127	105	90	94
Sr	78	65	72	133	224	188	728	678	325	1 000	688
Y	59	85	36	32	18	31	14	5	16	24	21
Zr	236	294	256	107	143	247	82	82	72	231	126
Sn	∼5	∼5	<4	<4	<4	<4	<4	<4	<4	<4	<4
Ba	585	951	510	450	653	738	960	910	1 065	820	1 020
La	47	61	28	29	44	82	13	3	20	50	26
Ce	103	131	44	52	82	148	22	∼7	49	76	40
Pb	51	53	14	42	36	30	30	20	36	15	23
Th	27	29	22	24	28	40	4	2	10	12	7
U	9	9	5	8	4	7	<2	<2	2	<2	<2
Mg/Li	47	65	230	79	225	340	415	97	89	1 430	505
Rb/Sr	3.7	4.3	2.4	1.89	1.20	1.52	0.109	0.187	0.32	0.090	0.137

K/Rb	143	156	170	167	157	128	297	137	259	219	288
Ba/Sr	7.5	14.6	7.1	3.4	2.9	3.9	1.32	1.34	3.3	0.82	1.48
Ba/Rb	2.0	3.4	2.9	1.79	2.4	2.6	12.2	7.2	10.1	9.1	10.9
K/Ba	71	45	58	93	64	50	25	19	26	24	27
Ca/Sr	127	111	∼3	66	55	91	26	18	39	34	34
Ca/Y	168	85	∼6	280	680	550	1 370	2 400	790	1 420	1 100
K/Pb	820	810	2 100	1 000	1 170	1 220	780	870	760	1 300	1 180
Th/U	3.0	3.2	4.4	3.0	7.0	5.7	—	—	5.0	—	—
K/U	4 600	4 800	5 900	5 200	10 500	5 200	—	—	14 000	—	—
Al/Ga	3 400	3 200	3 500	4 800	4 700	4 100	4 300	3 900	4 500	3 700	3 900
mg	0.14	0.12	0.18	0.31	0.38	0.39	0.41	0.29	0.41	0.43	0.42
k	0.56	0.62	0.89	0.51	0.53	0.53	0.31	0.18	0.38	0.36	0.39
No. of samples	30	21	4	8	9	7	10	2	2	2	3

* Total iron as Fe_2O_3.

1. Esmeralda Granite.
2. Croydon Volcanics.
3. Stockyard Creek Siltstone (total includes 7.0% C).

Forsayth Granite

4. Leucocratic granites and adamellites.
5. Slightly porphyritic granites and adamellites.
6. Melanocratic porphyritic adamellites, etc.
7. Granodiorites.
8. Granodiorites near Forest Home Homestead.
9. Adamellites near Dargalong.
10. Tonalites.

Robin Hood Granite

11. Granodiorites.

3; Fig. 13). The variations in La, Y, and Ce may be explained by variable minor mineral contents and the lower Ba of the Esmeralda Granite may be due to depletion during the final stages of fractionation (only the most siliceous samples have Ba contents which are significantly lower than the volcanics). Fractional crystallization could well have been more effective in depleting the residual magma in Ba (as well as causing slight enrichment in Rb) during the longer cooling history of the Esmeralda Granite compared with the Croydon Volcanics. Taylor et al. (1968) found that leucogranites from the Snowy Mountains are depleted in Ba and Sr and enriched in Rb relative to the rhyolites of the North Island, New Zealand, which have similar major element compositions. These authors suggested that the leucogranites were derived by fractional crystallization and the rhyolites by partial melting. There seems no reason to doubt that both the Esmeralda Granite and Croydon Volcanics were derived from the same parent magma and a greater degree of fractional crystallization in the case of the granitic rocks is probably adequate to explain the observed chemical differences.

Forsayth and Robin Hood Granites

The Forsayth and Robin Hood Granites, which are at least in part of Precambrian age, form a geochemically heterogeneous group. If they are considered as a single group no well defined chemical trends are apparent. Silica variation diagrams show a considerable scatter, especially for Na_2O, K_2O, P_2O_5, and many trace elements, although element abundances are fairly typical of calc-alkaline rocks in general (Figs. 22, 23). The Peacock (1931) alkali-lime index is about 61, which is the dividing line between the calc-alkaline and calcic divisions.

An attempt was made to subdivide the various rock types that constitute the Forsayth Granite on the basis of petrography and field relations, to see if there are any significant chemical differences between groups. In the Forsayth area, a distinction was made between a porphyritic melanocratic type and a relatively leucocratic non-porphyritic to slightly porphyritic variety. A third, intermediate category was also used (see p. 5). The compositional fields of these groups overlap considerably and chemical trends are not very well defined. The marked reduction in scatter compared with the Forsayth Granite as a whole, however, suggests that the granites and adamellites of the Forsayth area are, at least, related. The less siliceous rocks are higher in CaO, FeO, MgO, Cr, Ni, Cu, Zn, Zr, La, and Ce and lower in Pb. Be, Li, Rb, Y, Sr, Ba, Th, and U show little systematic variation with SiO_2, although Th appears to be slightly higher in the melanocratic group (Figs. 22, 23). The K_2O/Na_2O ratios of the three groups are similar (Fig. 32) and there is little correlation between the K_2O/Na_2O ratio (or Niggli k) and SiO_2 content. This may, to some extent, be due to alkali metasomatism during metamorphism, so that rocks with different SiO_2 contents tend to assume similar alkali ratios. It is also probable that metamorphism has caused the migration of other elements, particularly Rb, Th, and U, which would explain the absence of the normal trends on silica variation diagrams. Th and U are particularly susceptible to secondary redistribution after crystallization of a magma (Ragland et al., 1967; Cook & Rogers, 1968), and the action of a fluid phase during metamorphism could produce the observed variations (Smithson & Heier, 1971). K/Rb ratios actually increase slightly and Ba/Rb decreases with increasing SiO_2 (Table 3), the reverse of the normal fractionation trends (Taylor, 1965; Taylor et al., 1968). Cu is low and Th and possibly U are high compared with the average granites of Turekian & Wedepohl (1961) and Taylor (1968) (Table 9).

The granodiorites have lower K_2O/Na_2O ratios and plot on a different trend to the above groups on a K_2O-Na_2O-CaO diagram (Fig. 32). They are lower in P_2O_5, Li, Be, Cu, Rb, Y, Zr, La, Ce, Th, and U, and higher in Sr (Figs. 22, 23; Table 3) and are clearly unrelated to the granitic rocks of the Forsayth area. The granodiorites from the intrusions southeast of Forest Home homestead are chemically dissimilar to the other granodiorites, having considerably lower K_2O/Na_2O ratios. Na_2O contents are particularly high (average of two samples is 6.15%). The Forest Home granodiorites are certainly not related to the Esmeralda Granite, as suggested by White (1965), but may well be related to the granodiorites farther south, including the intrusion 10 km west-southwest of Green Hills Outstation, although no analyses of these are yet available.

The muscovite-biotite adamellites from the intrusion near Dargalong also have relatively low K_2O/Na_2O ratios (Fig. 32). U, Th, and Rb are lower, whereas Be, Li, Ba, and Sr are higher than the adamellites from the main batholith in the Forsayth area (Fig. 23; Table 3). The tonalites from north of Kidston show no obvious correlations with any of the other groups.

The Robin Hood Granite samples plot as two distinct groups on the variation diagram: the granodiorites on the one hand and the adamellites and granites on the other (Figs. 22, 23, 32, 35). According to J. H. C. Bain (pers. comm.) only the granodiorites should be assigned to the Robin Hood Granite (or Robin Hood Granodiorite), whereas the more leucocratic rocks now named the Digger Creek Granite appear to be older and are possibly related to the Robertson River Metamorphics. The Robin Hood granodiorites are generally similar to the Forsayth granodiorites, except for their slightly higher K_2O/Na_2O ratios and considerably higher Cu contents (average of 16 ppm compared with 2 ppm for the Forsayth granodiorites) (Table 3). In spite of this, the Cu contents of the Robin Hood granodiorites are by no means high for such rocks (Turekian & Wedepohl (1961) quote 30 ppm for average high-calcium granite). One sample (biotite granite, 68590018A) contains 48 ppm Cu, and a leucocratic muscovite granite (70571128) contains 61 ppm U. The latter sample was collected from the eastern side of the Robin Hood batholith, about 9 km south of Limkins uranium prospect. Many of the leucogranites in the area immediately north of Percyville are characterized by anomalously high radioactivity (J. H. C. Bain, pers. comm.). Sn is below the detection limit of 4 ppm in all but two samples of the Forsayth Granite and in all Robin Hood Granite samples.

Dumbano Granite and Dido Granodiorite

The group of Siluro-Devonian intrusive rocks do not lie on smooth variation curves, and at least two parent magmas were probably involved in their formation.

The Dumbano Granite has a relatively restricted range of composition, the majority of samples containing between 70 and 76 percent SiO_2 (Fig. 24). The main exception is a single sample of quartz diorite (70571162) that is low in P_2O_5, MgO, TiO_2 and possibly FeO, MnO, Ce, La, and Zr and high in Na_2O, Al_2O_3, Pb, Ni, and possibly Zn and Ga, relative to the main trend (Figs. 24, 25). There is a large variation in K_2O, which ranges from over 5 percent in the most siliceous rocks down to about 1 percent in the trondhjemites. As a consequence, the K_2O/Na_2O ratio varies over a wide range (Fig. 32). Many trace elements also show wide variations, particularly Pb, Ce, La, Ba, Zr, Rb, and Li (Figs. 1-18, 25). Th is relatively high in a few of the more siliceous samples, but both Th and U are generally low. Zr, La, and Ce, and particularly Li and Cu, are low compared with the average granites of Turekian & Wedepohl (1961) and Taylor (1968), but the other trace elements, including Pb and Zn, are close to average (Tables 4, 9). The granites, adamellites, and granodiorites appear to lie on a single variation trend, but the trondhjemites do not seem to belong to the same differentiation series, being relatively high in CaO and Sr, and low in MnO, K_2O, and Y (Figs. 24, 25). The main Dumbano trend is similar to that of the Forsayth granodiorites.

The Dido Granodiorite consists of tonalite, quartz diorite, and olivine gabbro. The tonalites appear to lie on the main Dumbano trend, with notably low Ni and Cu, although they are slightly higher in Sr and Zr. The quartz diorites form a chemically distinct group with high K_2O/Na_2O ratios similar to the tonalites of the Forsayth Granite (Figs. 24, 25, 32; Table 4). The quartz diorites are relatively high in Rb and Y, and possibly in Ba, La, and Ce, and are particularly high in Cu (average 97 ppm) compared with the other Dido Granodiorite samples. They are, however, generally similar to the low-silica diorites of Gulson et al. (1972), apart from their relatively low Sr, Ni, and Cr and high Ba, Pb, La, Ce, and Zr contents. The relationship of the olivine gabbro to these other rock types is uncertain. It is low in TiO_2, FeO, MnO, and P_2O_5 and high in Al_2O_3, MgO, and Ni. The aplite from the Dido Granodiorite (70571186A) has a very high MnO content (0.32%), consistent with the presence of spessartine-rich garnet. This sample is also notably high in Be, and low in Li, Sr, Zr, Ba, La, Ce, Pb, and Th. Sn is below the detection limit (4 ppm) in all samples of Dumbano Granite and all but one of the Dido Granodiorite.

To summarize, the majority of the Dumbano Granite samples (with the exception of the trondhjemites and quartz diorites), together with the tonalites of the Dido Granodiorite, appear to form a single magmatic differentiation series. It is possible that some of the Forsayth Granite, particularly the granodiorites, may form part of this suite; field and geochronological evidence are not incompatible with such a hypothesis. The Dumbano trondhjemites and Dido quartz diorites appear

TABLE 4. AVERAGE COMPOSITIONS OF THE DUMBANO GRANITE AND DIDO GRANODIORITE

	1	*2*	*3*	*4*	*5*	*6*	*7*
SiO_2	74.5	71.7	70.8	61.0	45.2	66.7	53.9
TiO_2	0.12	0.21	0.22	0.25	0.33	0.40	1.06
Al_2O_3	14.09	15.12	16.13	20.19	23.58	16.90	17.23
Fe_2O_3	0.35	0.83	0.36	1.38	1.65	1.38	3.35
FeO	0.64	1.14	1.22	2.15	5.50	2.07	5.73
MnO	0.03	0.03	0.02	0.07	0.11	0.08	0.16
MgO	0.20	0.48	0.58	0.99	8.69	1.29	3.81
CaO	1.33	2.48	4.44	5.82	13.20	5.13	8.36
Na_2O	4.04	4.4	4.35	5.4	1.05	4.02	2.35
K_2O	4.37	2.52	0.85	1.34	0.10	1.39	1.81
P_2O_5	0.22	0.05	0.06	0.06	0.03	0.15	0.41
H_2O	0.47	0.59	0.85	1.11	0.78	0.66	1.10
TOTAL	100.36	99.55	99.88	99.76	100.22	100.17	99.27
Li	6	8	6	5	1	8	5
Be	2.8	2.5	2.0	2.5	1.0	2.0	2.5
Cr	5	$\sim$9	4	21	231	8	18
Co	—	$\sim$5	—	—	—	—	—
Ni	<3	$\sim$3	<3	16	149	$\sim$3	7
Cu	1	2	2	24	50	2	97
Zn	31	43	59	111	48	60	84
Ga	16	18	16	22	13	18	19
Rb	170	76	41	36	1	41	54
Sr	201	413	811	1 024	588	788	882
Y	17	17	3	10	6	10	20
Zr	92	114	115	110	22	165	151
Sn	<4	<4	<4	<4	<4	<4	<4
Ba	774	890	435	735	31	525	723
La	24	27	13	11	9	26	36
Ce	40	47	25	23	<7	42	55
Pb	33	24	15	17	<2	8	8
Th	18	12	4	3	2	6	2
U	$\sim$3	<2	<2	<2	<2	<2	<2
Mg/Li	200	360	580	1 200	50 000	970	4 600
Rb/Sr	0.85	0.184	0.051	0.035	0.002	0.052	0.061
K/Rb	213	275	172	308	$\sim$800	281	278
Ba/Sr	3.9	2.2	0.54	0.72	0.053	0.67	0.82
Ba/Rb	4.6	11.7	10.6	20	$\sim$31	12.8	13.4
K/Ba	47	24	16.2	15.1	26	22	21
Ca/Sr	47	43	39	41	160	47	68
Ca/Y	560	1 040	11 000	4 200	16 000	3 700	3 000
K/Pb	1 100	870	470	650	—	1 400	1 900
Th/U	6	—	—	—	—	—	—
K/U	12 000	—	—	—	—	—	—
Al/Ga	4 700	4 500	5 300	4 900	9 500	5 000	4 800
mg	0.27	0.31	0.40	0.34	0.68	0.40	0.43
k	0.42	0.28	0.11	0.14	0.06	0.19	0.33
No of samples	12	3	3	1	1	9	3

Dumbano Granite

1. Adamellites and granites.
2. Granodiorites.
3. Trondhjemites.
4. Quartz diorite.

Dido Granodiorite

5. Olivine gabbro.
6. Tonalites.
7. Quartz diorites.

Means for Co are based on fewer analyses than those for other elements.

to be unrelated to this group, or to one another, and presumably represent separate magma types. It remains to be seen whether more detailed field and geochemical studies support this conclusion. The order of intrusion of the various rock types is at present unknown, nor is it known with certainty that all members of the suite are of similar age. There is a compositional gap between the Dumbano granodiorites and Dido tonalites on the K_2O-Na_2O-CaO diagram (Fig. 32) which may have some petrogenetic significance, although it could equally well be due to inadequate sampling.

Upper Palaeozoic igneous rocks

The Upper Palaeozoic igneous rocks plot on well defined calc-alkaline variation trends for most elements (Figs 26-31, 33, 34, 36, 43, 44). Comparison of the granitic rocks, together with a few intermediate and basic intrusive rocks, with the volcanics and associated dyke rocks shows that the compositional fields are virtually identical and that the rocks form a geochemically homogeneous group (Figs 1-18; Table 8). This strongly supports Branch's (1966) hypothesis that the intrusive and extrusive rocks are comagmatic. For this reason, with few exceptions, the Upper Palaeozoic igneous rocks may be treated as a single group.

The restricted compositional range of the Upper Palaeozoic igneous rocks is noteworthy —only about 6 percent of the intrusive rocks and 9 percent of the volcanics contain less than 65 percent SiO_2, and about 80 percent of the granitic rocks and 78 percent of the volcanics contain more than 70 percent SiO_2. Very few samples contain less than 60 percent SiO_2, although the intrusive rocks include a few diorites and gabbros, and andesites occur in the Newcastle Range, Nanyeta, and Glen Gordon Volcanics and in the Bagstowe Ring Dyke Complex. The Peacock (1931) alkali-lime index is about 62, or just within the calcic field (Fig. 38). Plotting the alkalinity ratio of Wright (1969) against SiO_2 shows that the majority of the samples plot within the calc-alkaline field, although many of the most siliceous rocks fall in the alkaline field (Fig. 39). This appears to be characteristic of many generally calc-alkaline associations, however, and does not preclude a comagmatic origin for the members of the suite. The rather arbitrary distinction between rocks with K_2O/Na_2O ratios greater than 1 and less than 1 was not used (see Wright, 1969, p. 374). Relative enrichment in FeO relative to MgO is shown in Figure 37. The variation is one of relatively late iron-enrichment, typical of the Bowen trend and characteristic of most calc-alkaline suites.

Silica variation diagrams (Figs 26-31) show normal calc-alkaline trends for most elements —TiO_2, Al_2O_3, FeO, MnO, MgO, CaO, P_2O_5, Cr, Co, Ni, Cu, Zn, and Sr decrease, and K_2O, Li, Be, Rb, Y, Ce, Pb, Th, and U, and possibly La, increase with differentiation; the Rb/Sr and K/Ba ratios increase, Mg/Li, K/Rb, and Ca/Y ratios decrease, and the Ba/Rb ratios decrease in the most felsic rocks. Ga shows a slight tendency to increase in late differentiates. Saha et al. (1968) have shown that Ga increases slightly with differentiation index in the rocks of the Singhbhum Granitic Complex in India, although Borisenok & Tauson (1959) found that Ga varies little with differentiation, except for a slight increase in aplite dykes, in the granitoids of the Susamyr Batholith in central Tien Shan. The Al/Ga ratio tends to decrease with differentiation, an observation similar to that of Bowden (1964) for the Younger Granites of Northern Nigeria, although de Albuquerque (1971) found no systematic variation in the granitic rocks of Northern Portugal. Ba increases initially during fractionation, but shows strong depletion in late differentiates. Na_2O, Zr, and Zn show little systematic variation, although the latter tends to decrease slightly with increasing SiO_2.

Abundances of most trace elements are close to values given by Turekian & Wedepohl (1961) for average low-calcium granite and by Taylor (1968) for average granite, although Sn, Th, and U are slightly higher than average, and Cu and Ba tend to be low. The less siliceous rocks (granodiorites, etc.) are low in Ni, Cu, and Sr and high in Rb and Th compared with the average granodiorite of Taylor (1968) (Tables 5-9). The differences are not great, however, and the overall chemistry is similar to comparable calc-alkaline intrusive suites from many parts of the world (Nockolds & Allen, 1953; Kolbe, 1966; Kolbe & Taylor, 1966). The relatively low Sr, Cr, Ni, Co, and Ba contents are similar to values given by Bloomfield (1970) for the post-orogenic plutons of Malawi, which show much lower abundances of these elements than orogenic intrusions of the same area.

In spite of the general similarity, there are a few minor differences between the volcanic and granitic rocks. Probably the most significant of these is the greater variation in alkali contents of the volcanics (Figs. 28, 33). A number

TABLE 5. AVERAGE COMPOSITIONS OF THE UPPER PALAEOZOIC INTRUSIVE ROCKS

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
SiO_2	76.9	76.4	74.1	72.9	72.4	74.7	73.5	75.3	73.2	75.0
TiO_2	0.05	0.10	0.23	0.24	0.22	0.25	0.31	0.15	0.26	0.21
Al_2O_3	12.49	12.42	13.23	14.26	14.94	13.28	13.16	13.01	13.06	12.84
Fe_2O_3	0.53	0.33	0.61	0.29	0.20	0.37	0.24	0.47	0.51	0.38
FeO	0.23	0.95	1.15	1.68	1.27	1.36	2.21	0.90	2.94	1.57
MnO	0.03	0.03	0.04	0.05	0.05	0.05	0.05	0.03	0.04	0.04
MgO	0.03	0.11	0.47	0.40	0.43	0.40	0.33	0.18	0.43	0.31
CaO	0.43	0.71	1.62	1.38	1.34	0.76	1.27	1.19	1.82	1.21
Na_2O	4.05	3.63	3.4	3.37	3.2	2.95	3.35	3.55	2.6	3.45
K_2O	4.52	4.74	4.72	4.27	4.55	4.79	4.54	4.51	4.02	4.41
P_2O_5	0.00	0.02	0.05	0.13	0.16	0.17	0.08	0.02	0.07	0.05
H_2O	0.63	0.66	0.57	0.74	0.77	0.69	0.61	0.65	1.07	0.70
TOTAL	99.89	100.10	100.19	99.71	99.53	99.77	99.65	99.96	100.02	100.17
Li	33	30	16	69	103	94	72	24	33	41
Be	5.0	5.6	2.5	3.4	8.0	3.5	5.5	4.0	2.5	4.0
F	3 000	~2 100	—	—	—	—	—	—	—	—
Cr	—	~3	~3	—	—	—	—	—	—	—
Co	4	~3	—	~5	3	4	4	—	—	—
Ni	<3	<3	<3	~3	<3	3	~3	<3	4	~3
Cu	2	6	3	6	7	8	7	7	8	4
Zn	47	33	23	50	55	32	52	39	46	48
Ga	22	18	13	18	17	16	18	14	15	17
Rb	398	427	235	356	305	389	273	355	218	248
Sr	8	26	110	88	83	43	67	64	107	71
Y	155	95	31	32	21	41	55	54	40	49
Zr	97	125	115	109	94	115	240	102	129	162
Sn	<4	~5	<4	9	8	16	10	<4	<4	<4
Ba	6	149	453	223	250	138	450	218	562	409
La	80	44	58	41	7	10	33	33	26	38
Ce	169	84	61	36	22	29	68	66	59	72
Pb	36	32	15	26	30	25	29	29	29	31
Th	49	46	30	14	8	17	23	42	20	27
U	7	11	4	5	4	9	4	10	4	5
Mg/Li	5	22	177	35	25	26	28	45	78	46
Rb/Sr	50	16.4	2.1	4.1	3.7	9.1	4.1	5.6	2.0	3.5
K/Rb	94	92	167	100	124	102	138	105	153	148
Ba/Sr	0.75	5.7	4.1	2.5	3.0	3.2	6.7	3.4	5.3	5.8
Ba/Rb	0.015	0.35	1.93	0.63	0.82	0.35	1.65	0.61	2.6	1.65
K/Ba	6 300	264	86	159	151	288	84	172	59	89
Ca/Sr	380	195	105	112	116	126	136	133	122	122
Ca/Y	20	53	370	310	460	133	165	158	330	177
K/Pb	1 040	1 230	2 600	1 360	1 260	1 590	1 300	1 290	1 150	1 180
Th/U	7.0	4.2	7.5	2.8	2.0	1.9	5.8	4.2	5.0	5.4
K/U	5 400	3 600	9 800	7 100	9 500	4 400	9 400	3 700	8 300	7 300
Al/Ga	3 000	3 700	5 400	4 200	4 700	4 400	3 900	4 900	4 600	4 000
mg	0.06	0.11	0.32	0.26	0.34	0.30	0.18	0.19	0.18	0.21
k	0.42	0.46	0.48	0.46	0.48	0.52	0.47	0.46	0.50	0.46
No. of samples	2	73	5	23	1	6	3	6	7	7

1. Lochaber Granite.
2. Elizabeth Creek Granite.
3. Elizabeth Creek Granite from south of Petford.
4. Mareeba Granite.
5. Cannibal Creek Granite.
6. Finlayson Granite.
7. Altanmoui Granite.
8. Hales Siding Granite.
9. Nymbool Granite.
10. Watsonville Granite.

Means for F, Cr, and Co are based on fewer analyses than those for other elements.
Three exceptionally high values were omitted when calculating means: Elizabeth Creek Granite, 248 ppm Li (67490001); Mareeba Granite, 281 ppm Li (68590044), and 100 ppm Be (68590087).

TABLE 5.—*continued*

11	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*
73.6	72.2	71.7	66.8	69.6	58.9	65.0	67.7	57.9	55.8	44.4
0.24	0.28	0.33	0.51	0.38	0.85	0.75	0.46	0.80	0.74	0.24
13.39	14.03	13.99	15.58	14.90	16.59	15.03	14.87	16.90	16.66	25.18
0.45	0.50	0.67	1.50	1.26	2.00	0.56	1.29	2.04	1.85	2.34
1.52	1.52	1.86	2.78	1.75	4.10	4.28	2.57	5.11	5.63	3.67
0.04	0.04	0.05	0.09	0.04	0.10	0.09	0.06	0.13	0.23	0.10
0.42	0.58	0.73	1.44	1.07	3.96	2.92	1.79	4.00	4.69	6.35
1.59	1.97	2.21	4.13	3.14	6.67	4.56	4.02	7.49	7.10	14.39
3.67	3.8	3.55	3.3	3.7	2.9	2.6	2.97	2.35	2.9	1.0
4.18	3.83	4.24	2.63	2.77	1.80	2.86	3.26	1.96	2.47	0.16
0.06	0.07	0.08	0.11	0.09	0.16	0.17	0.08	0.12	0.10	0.02
0.51	0.87	0.82	1.01	1.09	1.54	0.71	0.92	1.21	1.37	1.70
99.67	99.69	100.23	99.88	99.79	99.57	99.53	99.99	100.01	99.54	99.55
29	37	23	20	9	8	23	21	15	27	2
3.8	4.5	4.0	2.0	2.0	2.0	2.5	2.0	2.0	3.0	1.0
—	—	—	—	—	—	—	—	—	—	—
4	10	—	—	—	—	—	22	50	66	—
∼7	—	—	—	—	—	15	∼11	—	—	—
<3	∼3	∼3	∼3	4	33	20	∼4	22	13	24
3	2	10	4	14	27	13	8	31	28	8
28	32	37	53	41	78	50	38	65	86	41
16	17	17	16	16	19	17	14	16	16	15
233	221	294	134	90	65	127	156	118	182	6
101	146	103	195	300	357	251	179	240	163	399
43	49	50	30	19	23	28	26	28	41	4
141	171	166	159	159	131	167	110	94	82	19
<4	<4	∼5	<4	<4	<4	<4	<4	<4	<4	<4
465	598	362	441	597	450	368	378	225	310	46
41	42	32	26	27	26	27	27	23	35	<2
78	73	65	46	49	36	47	47	36	55	<7
25	27	31	15	14	12	11	19	17	20	4
29	27	31	16	12	10	11	21	14	10	<2
5	4	7	4	<2	2	∼3	3	3	3	<2
87	94	191	435	715	3 000	765	513	1 600	1 050	19 000
2.3	1.51	2.9	0.69	0.30	0.18	0.51	0.87	0.49	1.12	0.015
149	144	120	163	255	229	187	173	138	113	221
4.6	4.1	3.5	2.3	1.99	1.26	1.47	2.1	0.94	1.90	0.115
2.0	2.7	1.23	3.3	6.6	6.9	2.9	2.4	1.91	1.70	8
75	53	97	49	39	33	65	72	72	66	29
113	96	153	151	75	133	93	161	220	310	260
260	290	320	980	1 180	2 100	1 160	1 100	1 910	1 240	26 000
1 390	1 180	1 140	1 460	1 640	1 240	2 200	1 420	960	1 030	330
5.8	6.8	4.4	4.0	—	5	4	7.0	4.7	3.3	—
6 900	7 900	5 000	5 500	—	7 500	8 000	9 000	5 400	6 800	—
4 400	4 400	4 400	5 200	4 900	4 600	4 700	5 600	5 600	5 500	8 900
0.28	0.34	0.34	0.38	0.39	0.54	0.52	0.46	0.50	0.53	0.66
0.43	0.40	0.44	0.35	0.33	0.29	0.42	0.42	0.35	0.36	0.09
40	3	8	4	5	1	2	11	4	2	3

11. Herbert River Granite.
12. Ixe Microgranodiorite.
13. Kalunga Granodiorite.
14. Bakerville Granodiorite.
15. Hammonds Creek Granodiorite: granodiorites.
16. Hammonds Creek Granodiorite: quartz diorite.
17. Trevethan Granite.

Almaden Granite

18. Granodiorites and adamellite.
19. Quartz diorites.
20. Xenoliths.
21. Gurrumba Ring Complex: olivine gabbros.

of volcanic rocks are enriched in K and depleted in Na (67490024R, 0110R, 0118R, 68590027, 0062, 70571200) or enriched in Na and depleted in K (68590061, 70571207, 1212, 1214). One sample of the Featherbed Volcanics (70571040) is depleted in Na, but does not appear to be enriched in K. Felsic rocks (rhyolites and rhyodacites) appear to be most susceptible to alkali metasomatism, although more basic rocks may also be affected (e.g. 68590027, an andesite from the Agate Creek Volcanics). Pyroclastics are more susceptible to alteration than lavas, a high proportion of the metasomatized samples being banded rhyolites or rhyodacite tuffs (cf. Scott, 1966). At least two of the altered samples (67490024R, 70571040) appear to have been silicified and most have relatively high water contents and high oxidation ratios ($Fe^{III}/Fe^{II} + Fe^{III}$). The groups that show the highest degree of alteration and the greatest variation of alkali ratios are the Glen Gordon, Nanyeta, and Newcastle Range Volcanics. Alkali metasomatism is considered to be a post-magmatic process accompanying hydration of the rocks, possibly during devitrification (Noble, 1967; Lipman et al., 1969; Scott, 1971). It is not clear under what conditions enrichment in either K or Na occurs, although a number of factors including pressure, temperature, rock composition, and composition of the coexisting fluid phase were probably important. According to Orville (1963), rocks at a lower temperature will tend to be enriched in Na relative to K, compared to rocks of the same bulk composition at a higher temperature. In addition, rocks poor in Ca will tend to be enriched in K, whereas rocks rich in Ca will be relatively depleted in K. Pressure has also been shown to influence the equilibrium between rock and fluid phase (Perchuk & Andrianova, 1970). Thus it is probable that variations in rock composition and temperature will be of particular importance in determining the type of alkali metasomatism (Na or K) which occurs. In most cases there appears to have been a redistribution of alkalis with a roughly 1:1 substitution of K for Na, or vice versa, similar to that described in keratophyres from New Zealand by Battey (1955). Ultrapotassic acid volcanics containing up to 12 percent K_2O have been described from the East Carpathians (Radulescu, 1966). The high K_2O contents were attributed to potash metamorphism by ascending solutions.

Apart from Na and K, certain other elements appear to have been depleted in the altered volcanics—Li and, in some cases, Cu (68590061, 70571207, 1212) and Pb (70571200, 1212, 1214). This is the opposite relationship to that described by Tremlett (1972) for the acid volcanics of Lleyn in North Wales, which were shown to be enriched in Li during metasomatic alteration. Rb follows K and is depleted in rocks which are low in K_2O. There is some evidence for depletion of U in the Newcastle Range Volcanics, which have similar Th contents to the other Upper Palaeozoic volcanics, but are much lower in U (Table 6). Th/U and K/U ratios are consequently high. Rosholt & Noble (1969) have shown that acid volcanics may be strongly depleted in U as a result of groundwater leaching. One altered sample of the Nanyeta Volcanics (tuff 68590062), with 9.07 percent K_2O, contains 1390 ppm Zn, 1390 ppm Pb, and 73 ppm Cu. Thus, it is possible that metasomatic alteration by alkali-rich hydrothermal solutions, accompanied by removal of elements such as U, Cu, Pb, and Zn, may under certain circumstances, be followed by redeposition and significant concentration of these elements and perhaps the formation of economic deposits.

The extrusive rocks, particularly the Glen Gordon, Walsh Bluff, Slaughter Yard Creek, Nanyeta, and the less siliceous of the Newcastle Range Volcanics, tend to have lower MgO contents than the granitic rocks, and the Glen Gordon Volcanics are also generally lower in CaO and P_2O_5 than the majority of the Upper Palaeozoic igneous rocks. Some of the volcanic rocks, notably the Newcastle Range dacites, are relatively high in Zr (Tables 5, 6).

The most highly fractionated granitic rocks, including the Lochaber, Elizabeth Creek, Mareeba (in part), and Finlayson Granites, show particularly strong depletion in Sr and Ba and enrichment in Li, Be, Rb, Y, Sn, Th, and U, and to some extent, Pb and Ga. The low Ni contents of these granites are similar to those of the Snowy Mountains leucogranites and suggest that they did not originate from basic magma (Kolbe & Taylor, 1966). The Finlayson, Mareeba, and Altanmoui Granites have particularly high Li contents (averages of 94, 69, and 72 ppm, respectively) and the abundance of tourmaline in the Finlayson and Mareeba Granites suggests that they are also rich in B. The Elizabeth Creek Granite is rich in F, Rb, and Th (Table 5)—the average F content of 22 samples is 2100 ppm. Most of these elements show variable, rather than consistently high concentrations, however, attesting to their mobility during late-magmatic pro-

TABLE 6. AVERAGE COMPOSITIONS OF THE ROCKS OF THE CUMBERLAND RANGE CAULDRON SUBSIDENCE AREA AND UPPER PALAEOZOIC VOLCANICS

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
SiO_2	69.3	68.8	74.0	72.1	71.0	72.8	73.7	71.3	75.1	72.7
TiO_2	0.40	0.29	0.22	0.29	0.44	0.27	0.20	0.36	0.11	0.30
Al_2O_3	15.65	15.33	13.06	13.30	13.15	13.55	13.11	13.92	13.06	13.13
Fe_2O_3	0.45	0.63	0.52	0.79	1.69	0.77	0.47	1.40	0.53	1.26
FeO	1.60	1.14	1.29	1.37	1.47	1.49	1.32	1.28	0.89	1.36
MnO	0.03	0.02	0.04	0.05	0.06	0.05	0.03	0.10	0.03	0.06
MgO	1.08	1.17	0.25	0.93	0.65	0.48	0.27	0.52	0.10	0.44
CaO	3.27	2.33	1.03	0.91	1.65	1.78	1.04	1.61	0.73	1.23
Na_2O	4.55	4.87	3.65	3.55	3.64	3.16	3.55	3.41	3.75	3.54
K_2O	2.41	2.37	4.94	4.70	4.10	4.40	4.51	4.48	4.63	4.23
P_2O_5	0.09	0.08	0.05	0.05	0.11	0.05	0.04	0.06	0.03	0.05
H_2O	0.84	1.67	0.83	1.50	1.15	1.03	1.09	1.26	0.96	1.37
TOTAL	99.67	99.80	99.88	99.54	99.11	99.83	99.33	99.70	99.92	99.67
Li	18	23	20	57	8	22	14	13	22	17
Be	2.5	2.5	4.5	7.5	2.7	2.9	4.0	2.5	4.0	2.7
Cr	17	21	~3	8	8	5	—	—	—	—
Ni	~5	12	~3	~4	~4	<3	<3	<3	<3	<3
Cu	5	6	2	3	8	6	5	5	11	9
Zn	56	67	37	34	59	44	40	42	40	59
Ga	20	22	18	21	17	16	17	15	18	17
Rb	94	94	224	377	140	243	240	238	249	202
Sr	392	398	87	81	123	105	63	145	52	93
Y	5	5	39	78	48	48	49	47	53	54
Zr	113	96	151	148	252	172	167	191	142	221
Sn	<4	<4	<4	<4	<4	<4	~4	<4	~7	<4
Ba	472	562	347	470	916	450	412	645	376	556
La	15	11	63	49	62	43	35	35	30	41
Ce	20	18	110	99	105	87	78	70	61	74
Pb	23	22	30	30	26	23	24	17	26	27
Th	5	4	34	25	22	32	22	21	20	22
U	<2	<2	6	10	~2	6	6	4	4	4
Mg/Li	360	306	75	98	490	131	116	241	27	156
Rb/Sr	0.24	0.24	2.6	4.7	1.14	2.3	3.8	1.64	4.8	2.2
K/Rb	213	209	183	103	243	150	156	156	154	174
Ba/Sr	1.20	1.41	4.0	5.8	7.4	4.3	6.5	4.4	7.2	6.0
Ba/Rb	5.0	6.0	1.55	1.25	6.5	1.85	1.72	2.7	1.51	2.8
K/Ba	42	35	118	83	37	81	91	58	102	63
Ca/Sr	60	42	85	80	96	121	118	79	100	95
Ca/Y	4 700	3 300	189	83	250	260	152	250	98	163
K/Pb	870	890	1 370	1 300	1 310	1 590	1 560	2 200	1 480	1 300
Th/U	—	—	5.7	2.5	11	5.3	3.7	5.3	5.0	5.5
K/U	—	—	6 800	3 900	17 000	6 100	6 200	9 300	9 600	8 800
Al/Ga	4 100	3 700	3 800	3 400	4 100	4 500	4 100	4 900	3 800	4 100
mg	0.49	0.54	0.20	0.44	0.28	0.27	0.21	0.26	0.09	0.24
k	0.26	0.24	0.47	0.47	0.42	0.48	0.46	0.46	0.45	0.44
No. of samples	3	6	3	3	28	44	8	12	5	21

Cumberland Range Cauldron Subsidence Area

1. Microgranodiorites.
2. Dacites (total includes 1.10% CO_2).
3. Microadamellites.
4. Rhyodacites.
5. Newcastle Range Volcanics.
6. Featherbed Volcanics.
7. Slaughter Yard Creek Volcanics.
8. Nanyeta Volcanics.
9. Walsh Bluff Volcanics.
10. Glen Gordon Volcanics.

Means for Cr are based on fewer analyses than those for other elements. A few exceptionally high values were omitted when calculating means: Newcastle Range Volcanics, 900 ppm Zn (70571210); Featherbed Volcanics, 1000 ppm Sn, 488 ppm Pb, and 137 ppm Cu (68490018B); Nanyeta Volcanics, 1390 ppm Zn, 1390 Pb, and 73 ppm Cu (68590062).

TABLE 7. AVERAGE COMPOSITIONS OF THE BAGSTOWE DYKE COMPLEX

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
SiO_2	69.8	76.9	72.9	71.0	66.2	65.1	60.3	56.3
TiO_2	0.50	0.12	0.29	0.36	0.66	0.62	1.07	1.76
Al_2O_3	14.67	12.67	14.12	14.89	15.72	16.42	16.24	15.83
Fe_2O_3	1.21	0.49	0.70	0.92	1.71	1.34	2.03	3.96
FeO	1.73	0.47	1.14	1.41	2.08	2.27	3.75	5.10
MnO	0.06	0.02	0.06	0.05	0.07	0.07	0.10	0.15
MgO	1.04	0.11	0.48	0.71	1.73	1.58	2.58	3.25
CaO	2.51	0.39	1.63	2.20	3.54	3.96	4.79	6.59
Na_2O	3.89	3.75	4.2	4.0	3.6	4.0	3.35	3.6
K_2O	3.73	4.71	4.14	3.91	3.06	3.05	2.73	1.92
P_2O_5	0.10	0.02	0.06	0.08	0.15	0.15	0.32	0.24
H_2O	0.91	0.53	0.53	0.64	1.59	1.00	2.49	1.45
TOTAL	100.15	100.18	100.25	100.17	100.11	99.56	99.75	100.15
Li	15	9	15	20	20	19	18	7
Be	3.0	3.0	3.0	3.0	2.5	3.0	3.5	2.5
Cr	12	3	5	11	11	15	50	24
Ni	$\sim$6	<3	<3	$\sim$4	12	7	18	12
Cu	8	4	4	5	12	7	15	25
Zn	48	19	45	41	68	56	80	96
Ga	17	14	16	17	18	19	19	20
Rb	155	192	182	166	124	133	94	72
Sr	234	56	172	250	357	368	444	311
Y	20	18	20	18	17	17	29	32
Zr	187	118	172	190	181	205	376	231
Sn	<4	<4	<4	<4	<4	<4	<4	<4
Ba	676	463	807	762	600	645	963	500
La	45	45	43	46	36	44	69	39
Ce	74	81	72	74	59	68	119	48
Pb	25	29	29	26	23	20	17	11
Th	24	32	26	25	20	19	17	12
U	5	7	5	5	4	3	$\sim$2	<2
Mg/Li	417	74	193	215	520	500	860	2 800
Rb/Sr	0.66	3.4	1.06	0.66	0.35	0.36	0.21	0.23
K/Rb	200	204	189	196	205	190	241	221
Ba/Sr	2.9	8.3	4.7	3.0	1.68	1.75	2.2	1.61
Ba/Rb	4.4	2.4	4.4	4.6	4.8	4.8	10.2	6.9
K/Ba	46	84	43	43	42	39	24	32
Ca/Sr	77	50	68	63	71	77	77	152
Ca/Y	900	155	580	870	1 490	1 670	1 180	1 470
K/Pb	1 240	1 350	1 180	1 250	1 100	1 270	1 330	1 450
Th/U	4.8	4.6	5.2	5.0	5.0	6.3	8.5	—
K/U	6 200	5 600	6 900	6 500	6 300	8 400	$\sim$11 000	—
Al/Ga	4 600	4 800	4 700	4 600	4 600	4 600	4 500	4 200
mg	0.39	0.15	0.31	0.36	0.46	0.44	0.45	0.40
k	0.38	0.45	0.40	0.39	0.36	0.33	0.35	0.26
No. of samples	29	6	6	7	3	3	2	2

1. All samples.
2. Rhyolites.
3. Adamellites.
4. Rhyodacites
5. Dacites.
6. Mount Rous Ring Dyke.
7. Andesites.
8. Diorites.

cesses. Rb in particular, shows a distinct bimodal distribution in the Elizabeth Creek Granite (Fig. 8). Cu, although generally decreasing with differentiation, also shows rather variable abundances, including some relatively high values, in the Elizabeth Creek Granite (Fig. 5). The granitic rocks of south-west England, which are characterized by high Li, Rb, F, B, Sn, U, and Pb, and possibly Th, have similar highly variable Cu and Sn con-

TABLE 8. AVERAGE COMPOSITIONS OF THE UPPER PALAEOZOIC VOLCANIC AND GRANITIC ROCKS

	Volcanic Rocks					*Granitic Rocks*				
	mean	*s.d.*	*max.*	*min.*	*r.s.d.*	*mean*	*s.d.*	*max.*	*min.*	*r.s.d.*
SiO_2	72.3	5.0	80.9	53.3	0.07	73.4	4.3	78.6	52.9	0.06
TiO_2	0.31	0.28	1.55	0.02	0.90	0.24	0.20	1.20	0.01	0.83
Al_2O_3	13.37	1.32	19.17	9.83	0.10	13.42	1.22	17.94	11.43	0.09
Fe_2O_3	1.11	0.96	7.56	0.00	0.86	0.54	0.48	3.40	0.00	0.89
FeO	1.40	0.98	4.95	<0.05	0.70	1.59	1.11	8.30	0.20	0.70
MnO	0.06	0.05	0.37	0.00	0.83	0.05	0.03	0.16	0.00	0.60
MgO	0.49	0.68	4.47	0.00	1.39	0.56	0.86	6.65	0.00	1.54
CaO	1.54	1.46	9.08	0.01	0.95	1.66	1.49	9.22	0.18	0.90
Na_2O	3.42	0.86	6.8	0.13	0.25	3.47	0.57	5.0	0.46	0.16
K_2O	4.32	1.13	9.10	0.69	0.26	4.22	0.86	6.73	1.14	0.20
P_2O_5	0.06	0.07	0.53	0.00	1.17	0.06	0.06	0.36	0.00	1.00
H_2O	1.14	0.57	4.20	0.37	0.50	0.72	0.31	2.41	0.20	0.43
TOTAL	99.52					99.93				
Li	16	11	61	1	0.69	34	28	281	5	0.82
Be	2.9	1.2	10	1.5	0.41	4.1	2.5	100	1.0	0.61
F	—	—	1 100	500	—	—	—	4 500	400	—
Cr	6	—	40	<3	—	8	—	81	<3	—
Co	—	—	28	3	—	5	—	18	<3	—
Ni	~3	—	56	<3	—	~3	—	40	<3	—
Cu	7	6	137	1	0.86	6	10	91	<1	1.7
Zn	50	28	1 390	12	0.56	37	22	161	9	0.59
Ga	16	3	25	8	0.19	17	3	40	11	0.18
Rb	212	87	619	39	0.41	301	161	1 170	65	0.53
Sr	105	78	440	3	0.74	88	79	357	2	0.90
Y	49	15	100	21	0.31	57	39	287	10	0.68
Zr	201	87	639	69	0.43	134	56	405	11	0.42
Sn	<4	—	1 000	<4	—	~5	—	47	<4	—
Ba	605	388	2 235	7	0.64	311	249	1 480	<3	0.80
La	45	21	170	<2	0.47	38	29	240	<2	0.76
Ce	86	32	208	17	0.37	67	31	196	<7	0.46
Pb	24	12	1 390	4	0.50	26	10	65	6	0.38
Th	25	8	42	6	0.32	30	17	81	<2	0.57
U	4	2	10	<2	0.50	7	5	28	<2	0.71
Mg/Li	184		2 200	4		99		3 300	1	
Rb/Sr	2.02		140	0.107		3.42		280	0.16	
K/Rb	169		353	66		116		321	31	
Ba/Sr	5.8		47	0.81		3.5		22	0.22	
Ba/Rb	2.9		13.0	0.017		1.03		14.4	0.006	
K/Ba	59		4 300	19.5		113		10 000	22	
Ca/Sr	105		500	2.6		135		1 600	41	
Ca/Y	220		2 200	~2		210		2 500	11.2	
K/Pb	1 490		10 800	54		1 350		3 900	500	
Th/U	6.3		14	2.3		4.3		16	0.6	
K/U	9 000		22 000	2 900		5 000		22 000	1 200	
Al/Ga	4 400		7 600	2 600		4 200		6 600	1 720	
mg	0.26		0.52	0.00		0.32		0.56	0.00	
k	0.46		0.97	0.06		0.45		0.88	0.22	
No. of samples	120					246				

s.d.—standard deviation.

r.s.d.—relative standard deviation.

tents (Floyd, 1972). K/Rb, Ba/Rb, and Mg/Li ratios are particularly low and Rb/Sr and K/Ba ratios are high in the fractionated rocks. Al/Ga and Ca/Y ratios also tend to be low in some cases. Niggli k values are generally high and mg tends to be low (Table 5, Fig. 19).

Of the intrusive rocks, only the Elizabeth Creek, Mareeba, Cannibal Creek, Finlayson, and Altanmoui Granites, and the Kalunga Granodiorite, have mean Sn contents significantly greater than the detection limit of 4 ppm (Fig. 12). The Finlayson Granite is particularly rich in Sn (average 16 ppm). The Elizabeth Creek Granite has rather a variable Sn content; it was not detected in 26 out of 65 samples. The relatively high Sn content of the Kalunga Granodiorite (about 5 ppm) is largely a consequence of a single high value (17 ppm in sample 67490063R), although several other samples have values of 4 or 5 ppm. The Walsh Bluff Volcanics have a mean Sn content of 7 ppm. These are fairly siliceous rhyodacites, comparable in major element chemistry with the most highly differentiated granitic rocks, but not showing such extreme fractionation. They do, however, have relatively low MgO, CaO, Ba, and Sr and slightly higher Rb and Li than the other extrusive rocks (Table 6). The other groups of volcanics have mean Sn contents of 4 ppm or less. The relationships of geochemistry to tin mineralization is described in detail on pages .

The Elizabeth Creek Granite has a particularly restricted range of composition, virtually all samples containing between 74 and 78 percent SiO_2. TiO_2, FeO, MgO, MnO, CaO, P_2O_5, Cr, Co, and Ni are consistently low and K_2O is relatively high (Figs. 26, 27). The Finlayson Granite is also rather siliceous, with high K_2O and low CaO. It is considerably richer in P_2O_5 than most of the other Upper Palaeozoic rocks (Fig. 26) and has particularly high K_2O/Na_2O ratios. The Mareeba Granite shows a wider range of composition, but is also generally rich in K. The fine-grained hornblende-bearing adamellite, south of Petford, was mapped as Elizabeth Creek Granite, but was considered by de Keyser & Wolff (1964, p. 40) to be a distinct type. Chemically, it is not typical Elizabeth Creek Granite, being less siliceous and relatively unfractionated (Table 5), and has not been included in the averages for this reason.

The most siliceous volcanic rocks do not show such strong fractionation as the intrusive types, and are only slightly enriched in Be, Rb, Y, Pb, Th, and U and depleted in Sr relative to the less siliceous rocks. Ba shows little tendency for depletion. Ni, Co, and Cr are low in the most acid intrusive and extrusive rocks, but since almost all samples contain less than the detection limit of 3 ppm, it is not possible to compare the degree of depletion of these elements in the two groups. The chemical differences are reflected in the averages given in Table 8, the granitic rocks having relatively high contents of Li, Be, Rb, Th, and U, high Rb/Sr and K/Ba ratios, and low Sr, Ba, Zr, Mg/Li, K/Rb, Ba/Rb, and K/U. Taylor et al. (1968) have found that rhyolites and ignimbrites of the North Island of New Zealand are characterized by relatively unfractionated trace element abundances compared with the Snowy Mountains leucogranites. The latter show generally similar abundances of Rb, Ba, Sr, Th, and U to the most fractionated Upper Palaeozoic granitic rocks, although they do not show the strong enrichment in Y of the Elizabeth Creek Granite (Table 9). The extreme fractionation shown by some of the intrusive rocks is probably a consequence of their longer crystallization history compared with the extrusives, leading to a much more effective process of fractional crystallization. Late-magmatic or post-magmatic processes such as greisenization may also have played a part in depleting or enriching the rocks in certain elements. Greisenization is common in the Elizabeth Creek, Mareeba, and Finlayson Granites and may lead to enrichment in F, Li, Rb, and Sn and depletion in Ba and Sr (Hall, 1967, 1969). Marchenko & Shcherbakov (1966) have shown that greisenization can also lead to an increase in Ga content and a decrease in the Al/Ga ratio.

The Herbert River Granite is more heterogeneous than the Elizabeth Creek Granite, although the compositional range is still fairly restricted—most samples contain between 70 and 76 percent SiO_2. Blake's (1972) subdivision of the granitic rocks originally mapped as Herbert River Granite in the Herberton/Mount Garnet area is supported by the chemical data. Most of Blake's units (Hales Siding, Nymbool, Watsonville, and Atlanta Granites; Hammonds Creek, Bakerville, and Kalunga Granodiorites) are geochemically homogeneous and there is little overlap of the compositional fields. The rocks of the Bagstowe Ring Dyke Complex are chemically indistinguishable from the remainder of the Upper Palaeozoic rocks and exhibit a well defined trend with very little scatter (Figs. 31, 34, 44; Table 7). The intrusive rocks of the Tully Granite Complex and the unnamed granitic rocks of the Ingham and Innisfail Sheet areas belong to the same differentiation series. They include a variety of rock types, some of which are geochemically similar to other units, such as the Elizabeth Creek, Herbert River, and Almaden Granites. The riebeckite granite from Hinchinbrook Island (68590121) has a high Na_2O content (4.45%) and Na_2O/K_2O ratio. It is also relatively high in Y, but low in Sr and Ba.

The Almaden Granite samples lie on the same trends as the remainder of the intrusive rocks (Figs. 27, 30), which suggests that they are probably members of the same differentiation series. The Almaden Granite has a rather higher K_2O content and higher K_2O/Na_2O ratio than most of the other granodiorites, such as the Bakerville and Hammonds Creek Granodiorites, but is similar to the Trevethan Granite in this respect. The Hammonds Creek Granodiorite is relatively low in Rb, Th, and U and has a high K/Rb ratio (Table 5). The Almaden Granite shows no appreciable enrichment of CaO relative to FeO, and no enrichment in P_2O_5, TiO_2, Ce, Zr, Ba, or Sr (Lee & van Loenen, 1971) so that contamination of the magma with limestone can only have been very minor (see Branch, 1966, p. 107). Localized assimilation of limestone has been demonstrated, but does not appear to have led to any significant modification in the composition of the magma. The Almaden Granite is relatively low in Ni and high in Th compared with most of the other granodiorites (Table 5; Fig. 27). The quartz diorites are comparable in major element chemistry with the normal diorites of Gulson et al. (1972), although K/Rb ratios are significantly lower.

Branch (1966) has suggested that the Almaden Granite is a hybrid, formed by mixing of acid Herbert River magma with a basaltic magma possibly related to the Nychum Volcanics. Isotopic studies (Black & Richards, 1972a; Black et al., 1972) are consistent with this interpretation. Two mafic xenoliths from the Almaden Granite were analysed. Although they plot on the Almaden Granite trends for most elements, they are relatively high in MnO, Na_2O, Ce, Y, and Rb, and possibly in K_2O, Li, and La, and low in Ni and Sr (Figs. 27, 30). Some of these variations may be attributable to metasomatic introduction of certain elements (particularly alkalis) into the xenoliths. Development of biotite would be accompanied by enrichment of the xenoliths in K, and probably Li. Mafic xenoliths from some British granites were shown to be enriched in Na, K, Rb, Cs, Li, and Zr relative to both the presumed basic source rocks and the host rocks (Farrand, 1960). In some cases, there also appeared to be some enrichment in Cu, Ni, and Cr in the xenoliths. Farrand considered the alteration to be a late-stage magmatic process. There are enough chemical differences (particularly in Ni and MnO contents) between the xenoliths and the Almaden Granite to suggest that the Almaden magma was not derived by simple mixing of a relatively acid magma with basic igneous rocks now represented by the xenoliths. If such a process had occurred, it would be difficult to explain the relatively high MnO contents of the xenoliths when the FeO and MgO contents lie on the same variation curves as the Almaden Granite samples. The relatively sharp margins of most of the xenoliths also suggest that they have not contributed significant quantities of material to contaminate the magma. In any case, the production of a relatively homogeneous granodioritic magma by the assimilation of large amounts of more refractory basic rocks by acid magma does not appear to be a very likely process. It is also difficult to envisage acid-basic hybridism on a batholithic scale producing relatively homogeneous magmas, although such a process may be possible on a smaller scale (Walker & Skelhorn, 1966). Mixing of acid and basic magmas commonly leads to the formation of net-veined complexes and similar structures (Blake et al., 1965) which are not present in the Almaden Granite, but are common in the Gurrumba Ring Complex, where the hybrid origin of the intermediate rock types is not in doubt (Blake, 1972). The abundance of mafic xenoliths in the Almaden Granite (as well as in other relatively mafic rock types) and their rarity in the more siliceous rocks has still to be explained, however. This, together with the fact that the petrography of the xenoliths is often characteristic of that of the host rock, strongly suggests that the xenoliths are cognate. The most likely explanation is that the xenoliths represent the more refractory mafic components of the source rocks (Piwinskii, 1968). The calcic plagioclase cores described by Branch (1966, p. 107) probably have a similar origin, that is they are xenocrysts. The abundance of xenoliths in the Almaden Granite, compared to the more leucocratic granitic rocks, can be explained by the relatively greater degree of partial melting, and hence the greater degree of disintegration of the source rocks, necessary to produce granodioritic magmas. A similar explanation has been suggested by Joyce (1973) for the origin of the granodioritic rocks of the Murrumbidgee batholith, A.C.T., although Joyce preferred a process of contamination of the melt with relict solid material at the source of the magma generation. We consider that the reaction between solid xenoliths and liquid, once melting has ceased, can only have been minor, and not capable of effecting gross changes in the magma composition. In other respects, however, two hypotheses are identical and appear to account adequately for the observed distribution of xenoliths. It is probable that a combination of varying amounts of partial melting with some degree of magmatic differentiation was important in producing the observed chemical variations of the Almaden Granite. The chemistry can best be explained if the majority of the Almaden and other Upper Palaeozoic rocks are regarded as members of the same magmatic differentiation series. De Keyser & Wolff (1964) came to a similar conclusion regarding the granitic rocks of the Chillagoe area. The quartz diorites north of Petford could well have been derived by differentiation of a more basic magma, but the granodiorites are considered to be the products of anatexis. There is a distinct compositional gap (60-64% SiO_2) between these two groups (Fig. 30). Some degree of contamination of the granodiorite by quartz diorite magma, or of quartz diorite or granodiorite magma by more acid material is possible, and would appear to be necessary to account for the isotopic composition of the Almaden Granite (Black & Richards, 1972a; Black et al., 1972), but such a process is considered to have been relatively unimportant in determining the overall composition of the rocks.

The olivine gabbro of the Gurrumba Ring Complex is geochemically rather different from the other intrusive rocks, and plots well off the main variation trends for several elements. It is low in TiO_2, FeO, MnO, P_2O_5, Ni, Cu, and Zn and high in Al_2O_3 (Fig. 30; Table 5). The olivine gabbro magma is, therefore, probably unrelated to the other Upper Palaeozoic magmas.

The rocks of the Cumberland Range Cauldron Subsidence Area fall into two distinct groups, one consisting of microadamellite and rhyodacite, the other of microgranodiorite and dacite. The more felsic group is indistinguishable from the rest of the Upper Palaeozoic rocks, but the more basic group is relatively rich in Na_2O and Sr and poor in TiO_2, FeO, MnO, K_2O, Rb, Y, La, Ce, Th, and U and has low FeO/MgO and K_2O/Na_2O ratios (Fig. 31; Table 6). The microgranodiorites and dacites bear some chemical resemblance to the granodiorites south of Forest Home homestead or to some of the other Forsayth granodiorites, although, in the absence of geochronological data, they are considered to be of Upper Palaeozoic age as suggested by Branch (1966). Two dacite dykes (70571108-9) are chemically similar to the dacites of the Southern Cumberland Range and are probably genetically related to them.

Comparison with the other calc-alkaline magma suites

Variation diagrams, including K_2O-Na_2O-CaO (Figs. 32-34), FMA (Figs. 35, 36), and Q-Or-Pl(An+Ab) (Figs. 42-44) diagrams, for most of the granitic rocks of northeast Queensland show similar trends to those of many other calc-alkaline suites.

The Upper Palaeozoic rocks, in particular, bear a close resemblance to rocks of the Southern California batholith (Larsen, 1948), the Sierra Nevada batholith (Bateman et al., 1963), the Snoqualmie batholith (Erikson, 1969), and the Cascade volcanic lavas (Carmichael, 1964) (Figs. 37, 40, 41, 45). Trace element abundances are close to normal for granitic rocks and are similar to the granites of the Snowy Mountains (Kolbe & Taylor, 1966) and the Cape Granite (Kolbe, 1966), except that the Upper Palaeozoic rocks are higher in Th than the Snowy Mountains granites and higher in Y than both (Table 9). The highly fractionated granitic rocks are comparable in major element chemistry to the Snowy Mountains leucogranites, but show more extreme enrichment in Rb, Ga, Y, Th, and U and depletion in Ba and Sr. In this respect, they are similar to the granitic rocks of southwest England (Exley & Stone, 1964; Floyd, 1972). Compared to the rhyolites of the central part of the North Island of New Zealand (Ewart et al., 1968), the Upper Palaeozoic volcanics have significantly higher contents of Rb, Th, and U. The microgranodiorites and dacites of the Cumberland Range Cauldron Subsidence Area have significantly lower FeO/MgO and K_2O/Na_2O ratios than the other Upper Palaeozoic rocks and are relatively low in Rb, Y, La, Ce, Th, and U (Figs. 34, 36).

The Esmeralda Granite and Croydon Volcanics lie on trends which are characterized by higher FeO/MgO and K_2O/Na_2O ratios than the Upper Palaeozoic rocks (Figs. 32, 35). The trend on an FMA diagram falls outside the limits for calc-alkaline rocks given by Best (1969) (Fig. 41).

The Forsayth and Robin Hood Granites show so much chemical variation that it is almost impossible to draw meaningful trends on variation diagrams, although the average trends are similar to the Upper Palaeozoic rocks (Figs. 32, 35).

The Dumbano Granite and Dido Granodiorite show a very similar trend to the Upper Palaeozoic igneous rocks on an FMA diagram, but all except the most siliceous rocks have lower K_2O/Na_2O ratios (Figs. 32, 35). TiO_2, Li, Be, Cu, Rb, Y, Sn, La, Ce, Th, and U are lower, and Sr and Ba are higher, than in the Upper Palaeozoic rocks. The trend on the K_2O-Na_2O-CaO diagram is closest to that of the Snoqualmie batholith (Erikson, 1969) and is characterized by much later enrichment in K_2O relative to Na_2O compared with the other suites (Fig. 41). This trend may be more apparent than real, however, because it is by no means certain which of the Dumbano and Dido rocks are genetically related to one another and it is possible that two or more superimposed trends are present.

Q-Or-Pl diagrams show two distinct variation trends. The Upper Palaeozoic igneous rocks lie on a trend which extends away from the Pl apex almost directly towards the centre of the diagram (Fig. 43). This trend is similar to those of the granitic rocks of the Cowichan Lake area, Vancouver Island, British Columbia (Fyles, 1955) and the Sierra Nevada batholith (Bateman et al., 1963) (Fig. 45). The rocks of the Bagstowe Ring Dyke Complex show a similar trend with only minimal scatter (Fig. 44). The Cumberland Range Cauldron Subsidence Area samples plot as two distinct groups, of which the microgranodiorite/dacite group is low in Or relative to Pl compared with the main Upper Palaeozoic trend (Fig. 44). The Esmeralda Granite and Croydon Volcanics lie on a similar, but much more restricted, trend (Fig. 42). The Dumbano Granite and Dido Granodiorite lie on a trend which reaches the quartz-feldspar boundary curve at a point near the Q-Pl side of the diagram. This is a consequence of the late potash enrichment. Most of the Dumbano Granite samples contain about 35 percent normative quartz and the trend is nearly parallel to the quartz-feldspar boundary curve at about 3000 bars water pressure (Fig. 42). A somewhat similar, but less extreme, trend is shown by the rocks of the Southern California batholith (Larsen, 1948) (Fig. 45), and the granitic rocks of the Mount Garibaldi area in southwest British Columbia (Mathews, 1958) and the Bald Mountain batholith in northeast Oregon (Taubeneck, 1957) also show similar differentiation trends. The Forsayth and Robin Hood Granites appear to show an intermediate trend (Figs. 42, 45), but little significance can be attached to this because there are at least two unrelated groups present in the Forsayth Granite.

Compositions of biotites

Eighteen biotite samples, mainly from Upper Palaeozoic granitic rocks, but including two from the Esmeralda Granite, one from the Forsayth Granite, and two from mineralized veins in the Elizabeth Creek Granite, were analysed for FeO, MgO, Li, Cr, Cu, Zn, Sn, and Pb by atomic absorption spectroscopy (Table 10).

Fe/Mg ratios of the biotites generally appear to reflect variations of this ratio in the host rocks. Biotites from the Elizabeth Creek Granite have high Fe/Mg ratios; those from the Herbert River and Almaden Granites and the Bakerville and Kalunga Granodiorites have relatively low Fe/Mg ratios. The high FeO content of the biotite from Elizabeth Creek Granite sample 67490155 is due to contamination with secondary chlorite. Electron microprobe analysis by R. N. England has shown that chloritization of this biotite was accompanied by a marked enrichment in Fe.

Li is higher in biotites from the most fractionated granitic rocks and is low in the granodiorites, again reflecting the Li contents of the host rocks. The Li content of biotites has been shown to increase during differentiation (Potap'yev, 1964; Kostetskaya & Petrova, 1966). The two biotites from mineralized veins are relatively high in Li. Comparison of the Li contents of the host rocks with those of the biotites suggests that most of the element is present in the biotite. Kuts & Mishchenko (1963) and Townend (1966) also concluded that Li in granitic rocks occurs mostly in the micas. Li contents are similar to values given by Kostetskaya & Petrova (1966) for biotites from the Dzhidinsk granitic complex in western Transbaikalia.

Cr contents are rather variable. There is possibly a slight correlation with the degree of

TABLE 9. AVERAGE COMPOSITIONS OF GRANITIC AND VOLCANIC ROCKS

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
SiO_2	74.2	71.2	67.2	66.9	68.36	75.75	70.27	74.26	76.07	74.07
TiO_2	0.20	0.40	0.57	0.57	0.42	0.09	0.38	0.18	0.06	0.26
Al_2O_3	13.6	14.7	15.5	15.7	14.69	13.01	14.6	13.2	12.9	13.38
Fe_2O_3										1.03
FeO	1.83*	3.24*	3.80*	3.78*	4.78*	1.18*	3.32*	1.85*	0.95*	0.79
MnO	0.05	0.05	0.07	0.08	0.08	0.04	0.06	0.05	0.02	0.05
MgO	0.27	0.55	1.56	1.57	2.23	0.20	0.93	0.31	0.07	0.29
CaO	0.71	2.00	3.54	3.56	2.89	0.71	1.64	1.25	0.59	1.57
Na_2O	3.48	3.54	3.84	3.84	2.68	3.61	2.92	3.03	3.54	4.03
K_2O	5.05	4.18	3.03	3.07	3.17	4.66	5.00	5.25	5.03	3.35
P_2O_5	0.14	0.16	0.21	0.21						0.05
H_2O										1.01
TOTAL										99.88
Li	40	30	24	25	29	7–65	42	42	28	35
Be	3	5	2	—	—	4.5	4.8	4.5	4.8	—
F	850	850	520	—	—	—	—	—	—	—
Cr	4.1	10	22	30	34	3.8	22	7.8	3.8	1.7
Co	1.0	2	7	10	13.5	<1	6.6	~3.0	<2	—
Ni	4.5	4	15	15	15	<1	8.9	~3.3	<2	—
Cu	10	10	30	25	22	2	9.9	~7	~5	6
Zn	39	40	60	—	—	—	—	—	—	—
Ga	17	20	17	18	20	13.5	21.5	17.5	18	16
Rb	170	145	110	110	121	388	260	267	305	108
Sr	100	285	440	440	190	42	110	77	20	125
Y	40	40	35	30	37	26	26	24	26	25
Zr	175	180	140	140	195	88	216	170	107	160
Sn	3	3	1.5	2	3.0	3.5	3.0	3.2	3.4	1.3
Ba	840	600	420	500	590	270	650	475	~107	870
La	55	55	45	36	41	<10–55	40	34	~15	26
Ce	92	57	81	47	—	—	—	—	—	43.5
Pb	19	30	15	15	29	23	30	33	31	18
Th	17	17	8.5	10	17.0	17.2	21.6	36.9	23.5	11.3
U	3.0	4.8	3.0	2.7	3.8	8.0	6.5	12.0	11.6	2.53
Mg/Li	40	110	390	380	466	—	133	45	15	44
Rb/Sr	1.7	0.51	0.25	0.25	0.64	9.3	2.4	3.5	15.3	0.87
K/Rb	250	240	230	230	218	100	160	163	137	250
Ba/Sr	8.4	2.1	0.95	1.14	3.1	6.4	5.9	6.2	5.4	7.02
Ba/Rb	4.9	4.1	3.8	4.5	4.9	0.70	2.5	1.8	0.35	8.06
K/Ba	50	58	60	51	45	143	64	92	~390	32.3
Ca/Sr	51	50	58	58	109	121	106	116	210	87.9
Ca/Y	130	360	720	850	560	196	450	371	161	426
K/Pb	2 200	1 160	1 680	1 700	910	1 680	1 920	1 320	1 340	1 560
Th/U	5.7	3.5	2.8	3.7	4.5	2.2	3.3	3.1	2.0	4.47
K/U	14 000	7 230	8 400	9 440	6 900	4 800	6 400	3 600	3 600	11 300
Al/Ga	4 200	3 890	4 800	4 620	3 900	5 100	3 600	4 000	3 800	4 500
mg	0.20	0.23	0.42	0.43	0.45	0.23	0.33	0.22	0.09	0.22
k	0.49	0.44	0.34	0.35	0.44	0.46	0.53	0.53	0.48	0.35

* Total iron as FeO.

1. Average low-calcium granite (Turekian & Wedepohl, 1961).
2. Average granite (Taylor, 1968; Zn, Be, and F values from Taylor, 1964).
3. Average high-calcium granite (Turekian & Wedepohl, 1961).
4. Average granodiorite (Taylor, 1968).
5. Average of 20 Snowy Mountains granodiorites and adamellites (Kolbe & Taylor, 1966).
6. Average of 8 Snowy Mountains leucogranites (Kolbe & Taylor, 1966).
7. Average of 17 coarsely-porphyritic granites from the Cape Granite, South Africa (Kolbe, 1966).
8. Average of 9 medium-grained granites from the Cape Granite (Kolbe, 1966).
9. Average of 8 fine-grained granites from the Cape Granite (Kolbe, 1966).
10. Average Taupo rhyolite, Central North Island, New Zealand (Ewart et al., 1968).

differentiation of the host rocks, although even biotites from some of the more fractionated granites have relatively high Cr contents (e.g. 65 ppm in a biotite from the Nymbol Granite).

The Cu content also shows little correlation with either the major element chemistry or the Cu content of the host rocks. There is a tendency for biotites from the fractionated granites to be higher in Cu, the reverse of the relationship found for the host rocks. Three biotites from the Elizabeth Creek Granite and one from the Nymbool Granite contain more than 100 ppm Cu, although the host rocks have relatively low values. Cu contents are generally comparable with the rather variable values reported for biotites from granitic rocks elsewhere (e.g. Bradshaw, 1967; Al-Hashimi & Brownlow, 1970; Lovering et al., 1970).

Zn contents lie in the range 235 to 1045 ppm, similar to values for granitic biotites reported by Tauson & Kravchenko (1956), Putman & Burnham (1963), Bradshaw (1967), Putman & Alfors (1967), and Blaxland (1971). The two biotites from the Almaden Granite have slightly lower Zn contents than most of the other Upper Palaeozoic biotites, and those from the Esmeralda and Forsayth Granites tend to be high in Zn, although the differences are relatively small. There is little correlation between host rock chemistry and the Zn content of the biotites, although the concentrations suggest that a large proportion of the Zn is present in the biotites. Tauson & Kravchenko (1956) found that Zn apparently enters biotite in preference to other minerals in the granitic rocks of the Susamyr batholith in central Tian-Shan, although about 80 percent of the element was extractable with hydrochloric acid.

Sn contents are mostly between 50 and 80 ppm. Only the two biotites from the Esmeralda Granite (30 and 45 ppm) and one from the Forsayth Granite (20 ppm) are lower than this. Values of more than 80 ppm are found in three Elizabeth Creek biotites, and in one from the Watsonville Granite. The highest value (245 ppm) is for a biotite from the Elizabeth Creek Granite, with a corresponding relatively high Sn content of 11 ppm in the host rock. Ivanov & Narnov (1970) found similar Sn contents in biotites from the granitic rocks on the northeastern USSR. The concentrations of Sn in the analysed rocks and biotites suggest that much of the Sn is present in the latter, although whether it occurs in the biotite lattice or as minute inclusions of cassiterite has not been established. Hesp (1971) found that in 67 Australian granites, up to 45 percent of the total Sn is carried by the biotites. A positive correlation of Sn with Li in biotites was also found.

Pb mainly substitutes for K in potash feldspars (Tauson & Kravchenko, 1956; Taylor, 1965). In general, lower concentrations are found for the biotites from the less siliceous rocks (granodiorites, etc.) which are themselves relatively low in Pb. Pb contents in the biotites from northeast Queensland are similar to values reported by Bradshaw (1967) for biotites from British granites which mostly lie in the range 10 to 50 ppm.

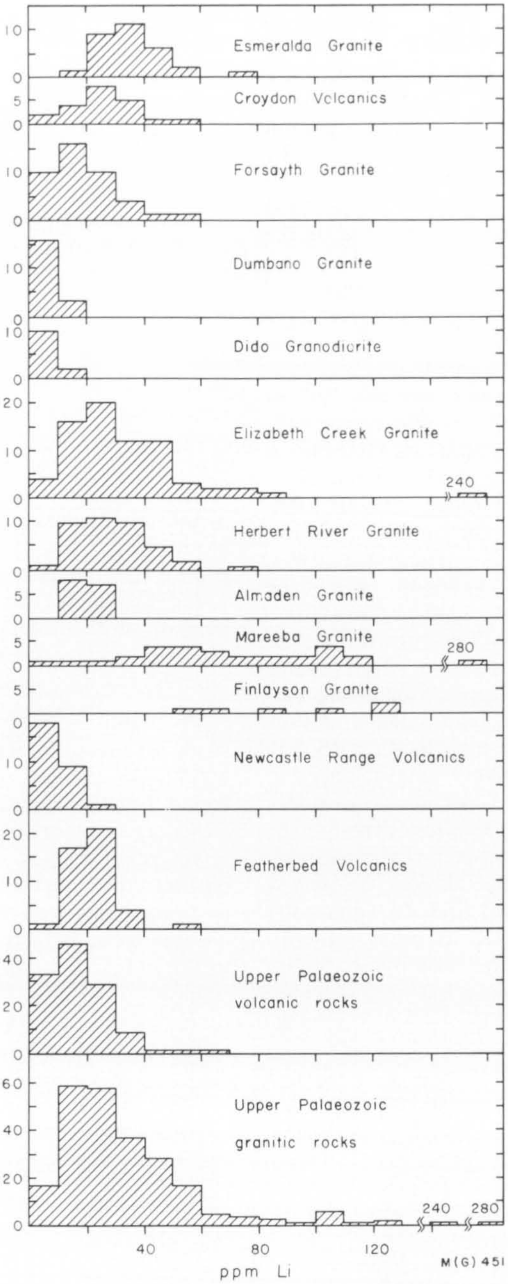


Fig. 1. Frequency distribution of lithium.

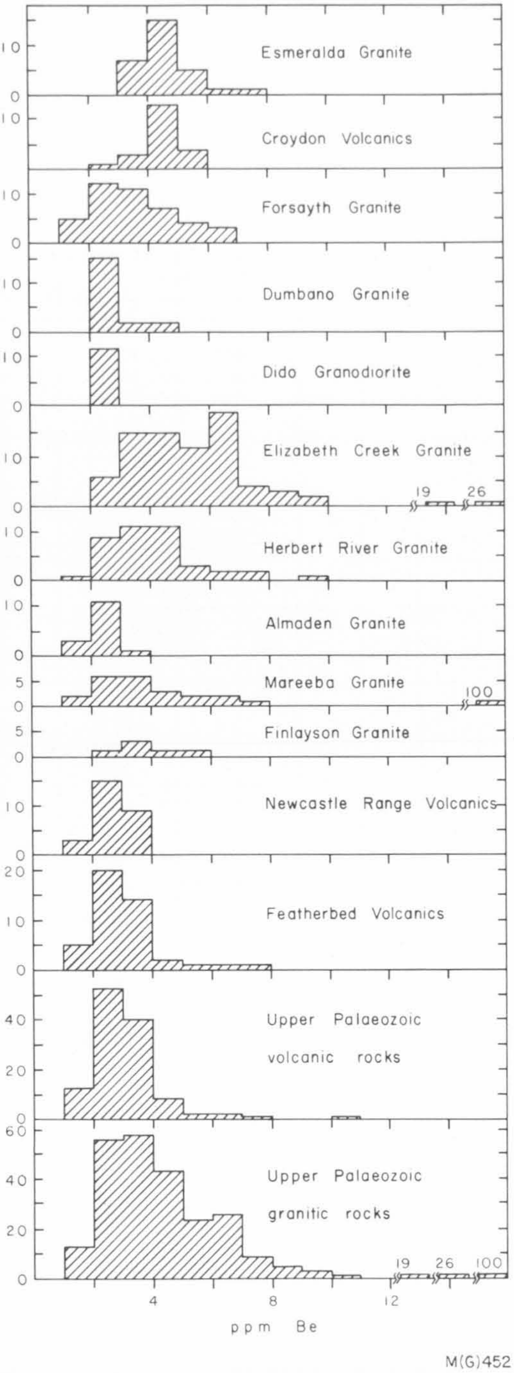


Fig. 2. Frequency distribution of beryllium.

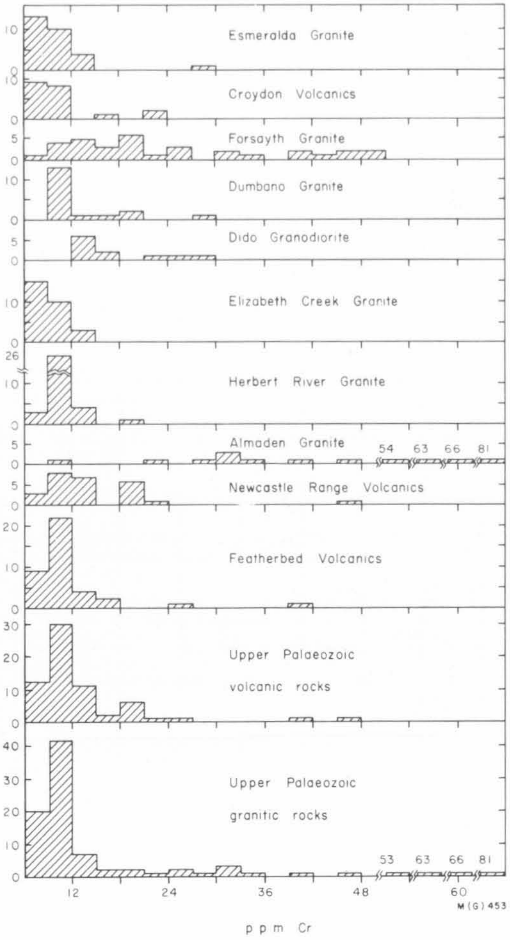


Fig. 3. Frequency distribution of chromium.

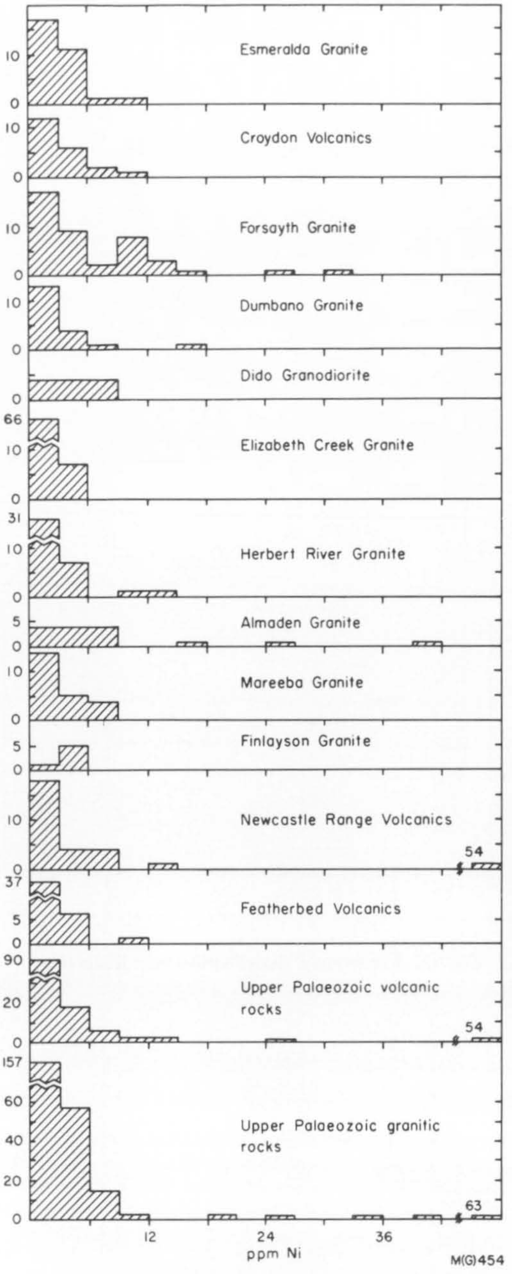


Fig. 4. Frequency distribution of nickel.

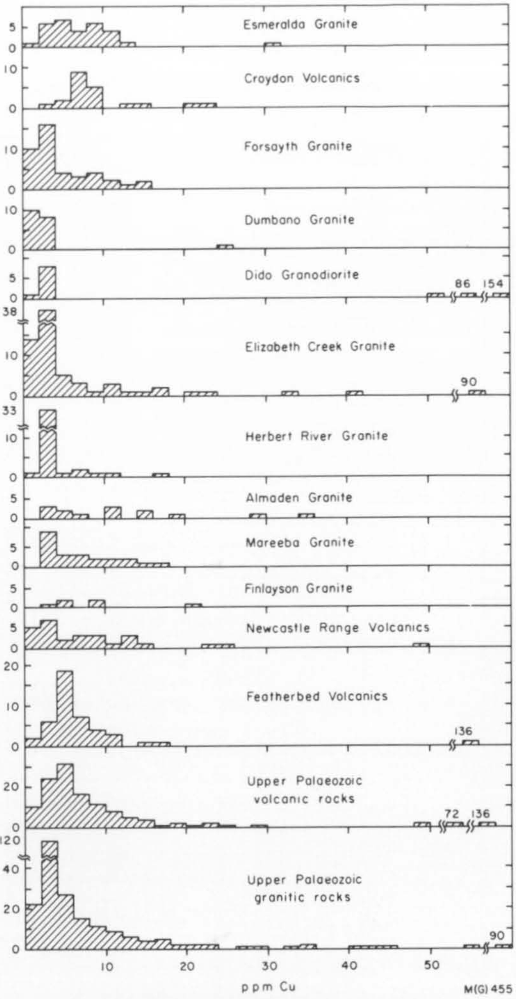


Fig. 5. Frequency distribution of copper.

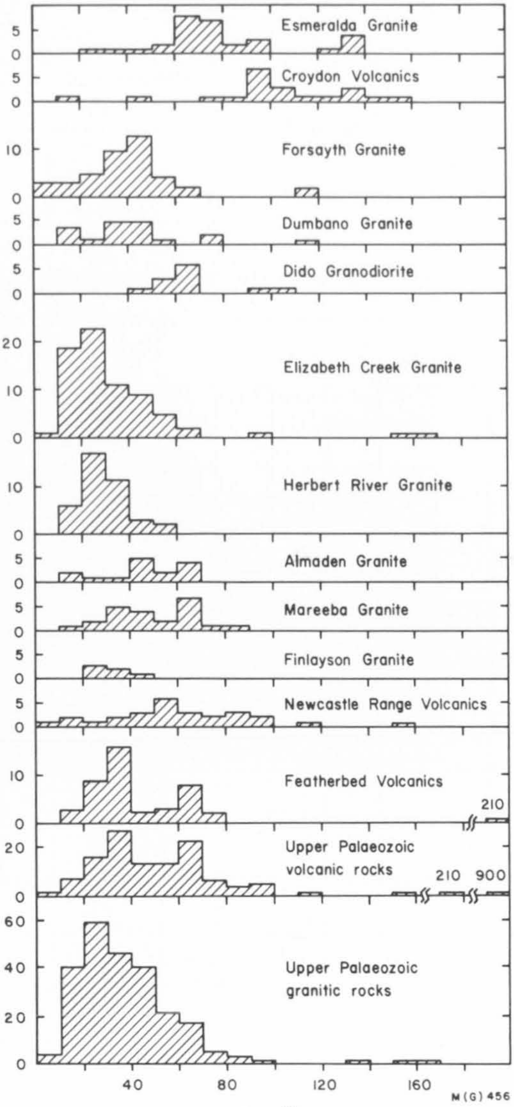


Fig. 6. Frequency distribution of zinc.

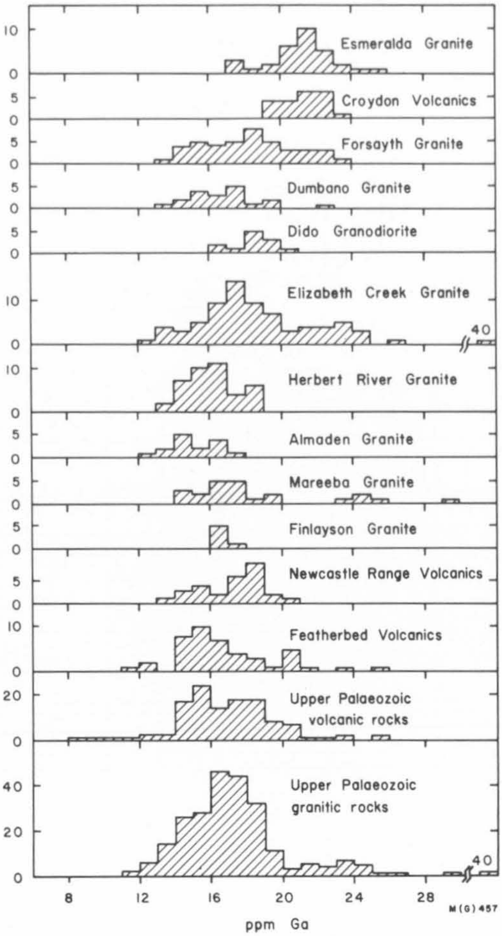


Fig. 7. Frequency distribution of gallium.

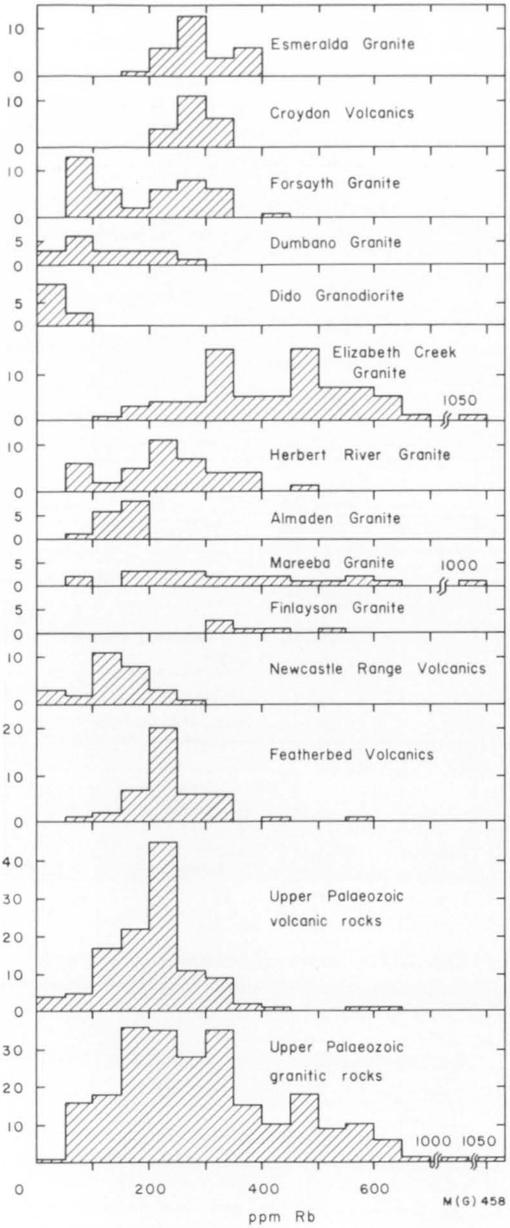


Fig. 8. Frequency distribution of rubidium.

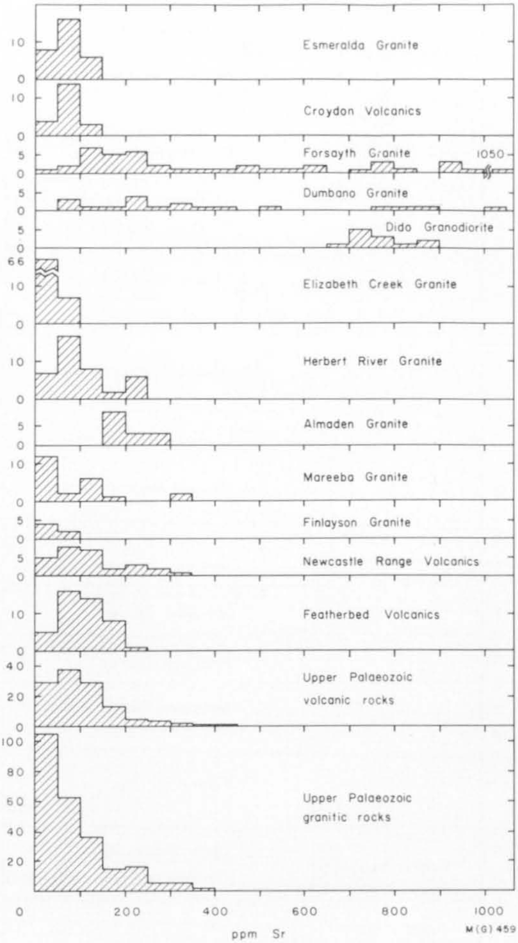


Fig. 9. Frequency distribution of strontium.

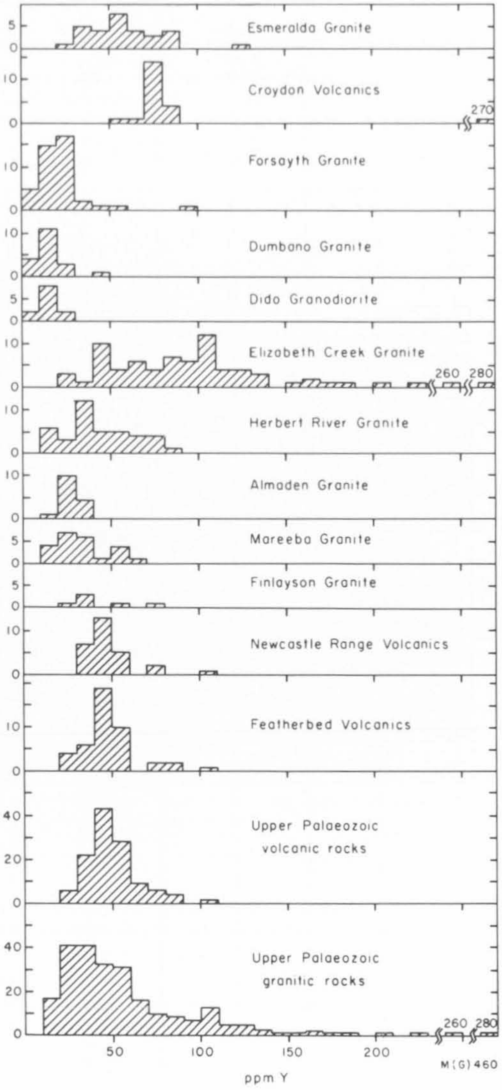


Fig. 10. Frequency distribution of yttrium.

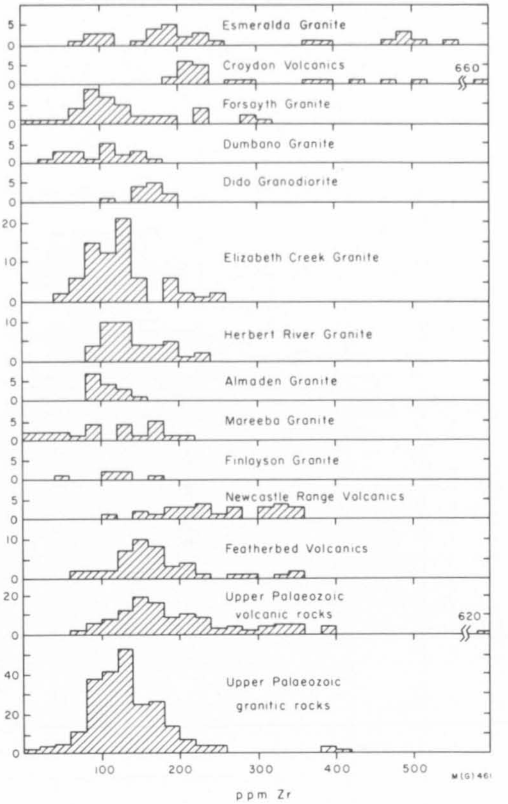


Fig. 11. Frequency distribution of zirconium.

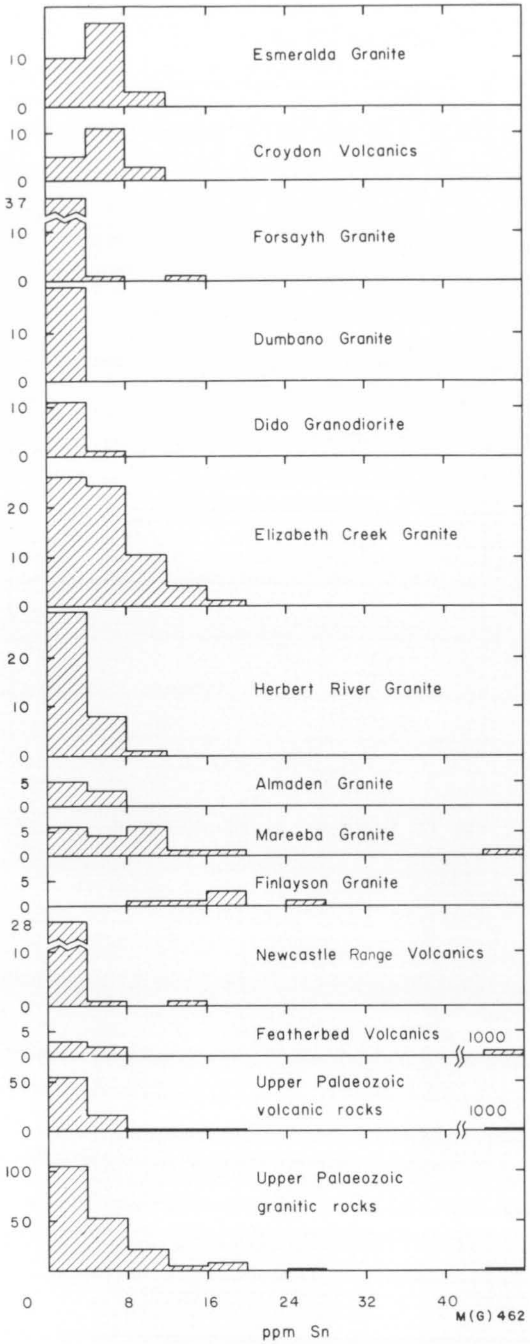


Fig. 12. Frequency distribution of tin.

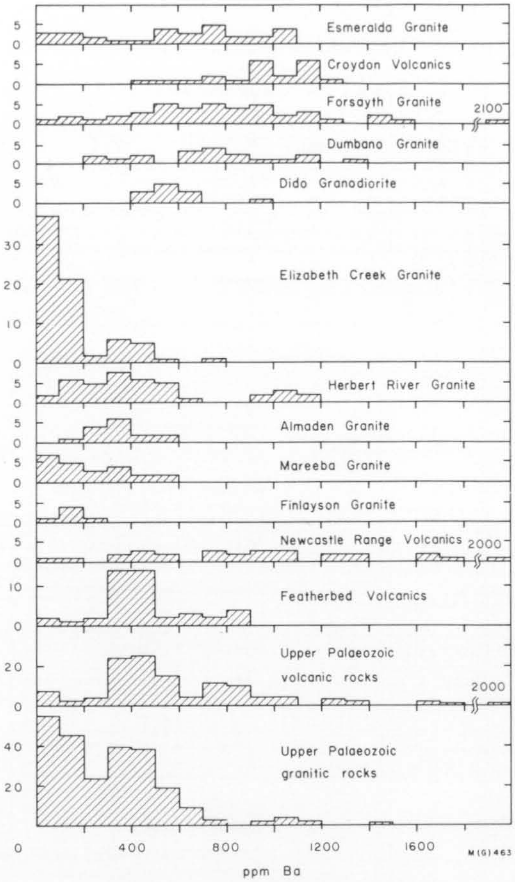


Fig. 13. Frequency distribution of barium.

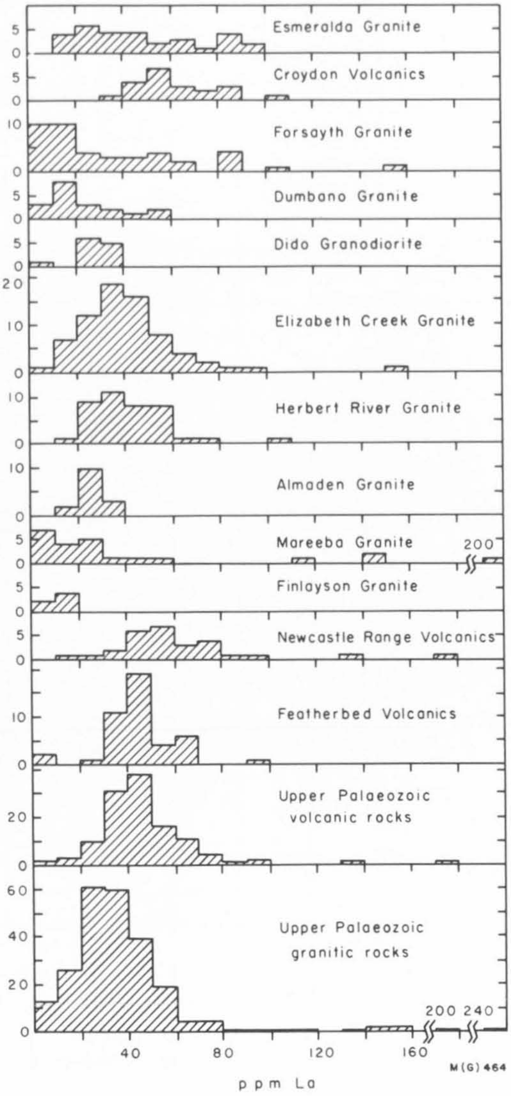


Fig. 14. Frequency dstribution of lanthanum.

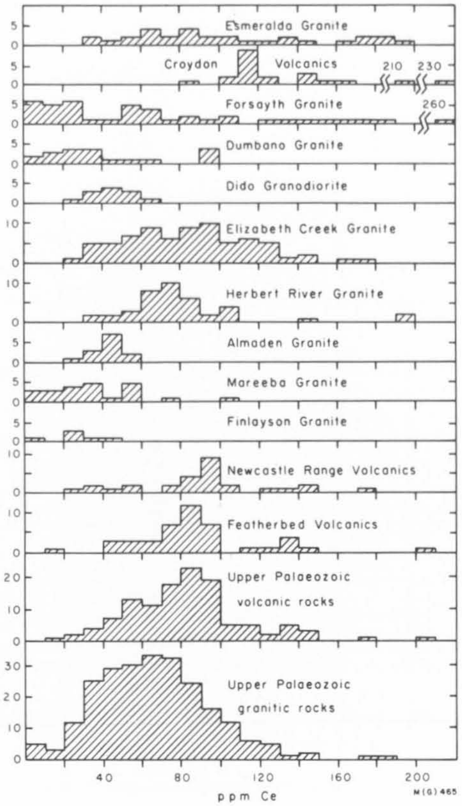


Fig. 15. Frequency distribution of cerium.

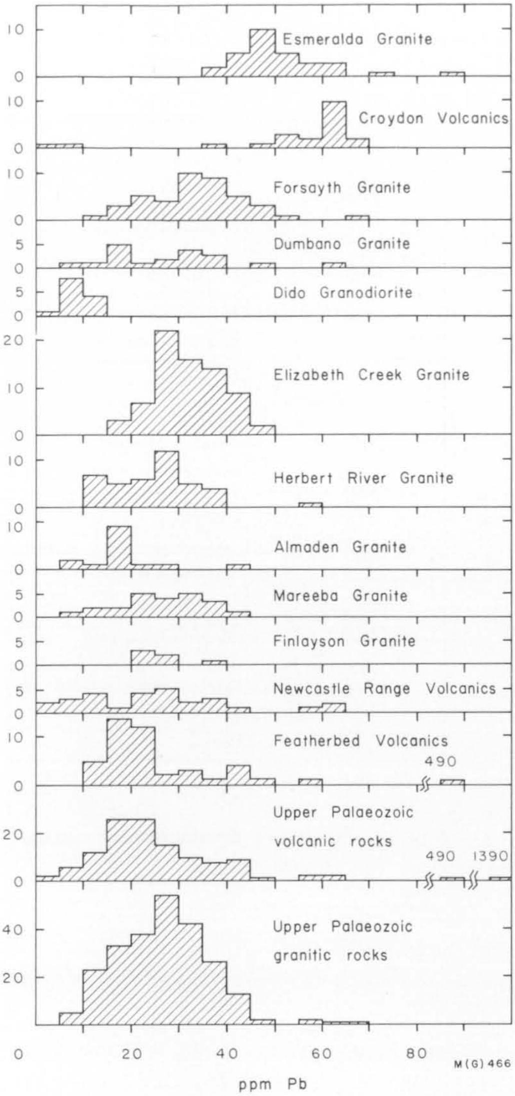


Fig. 16. Frequency distribution of lead.

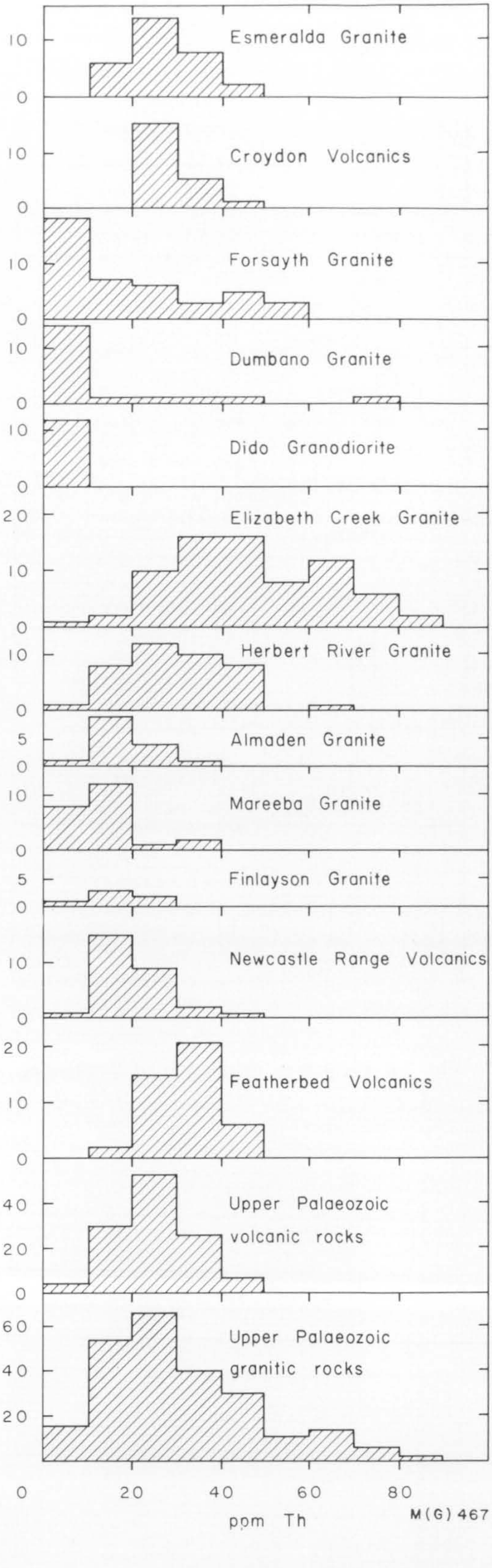


Fig. 17. Frequency distribution of thorium.

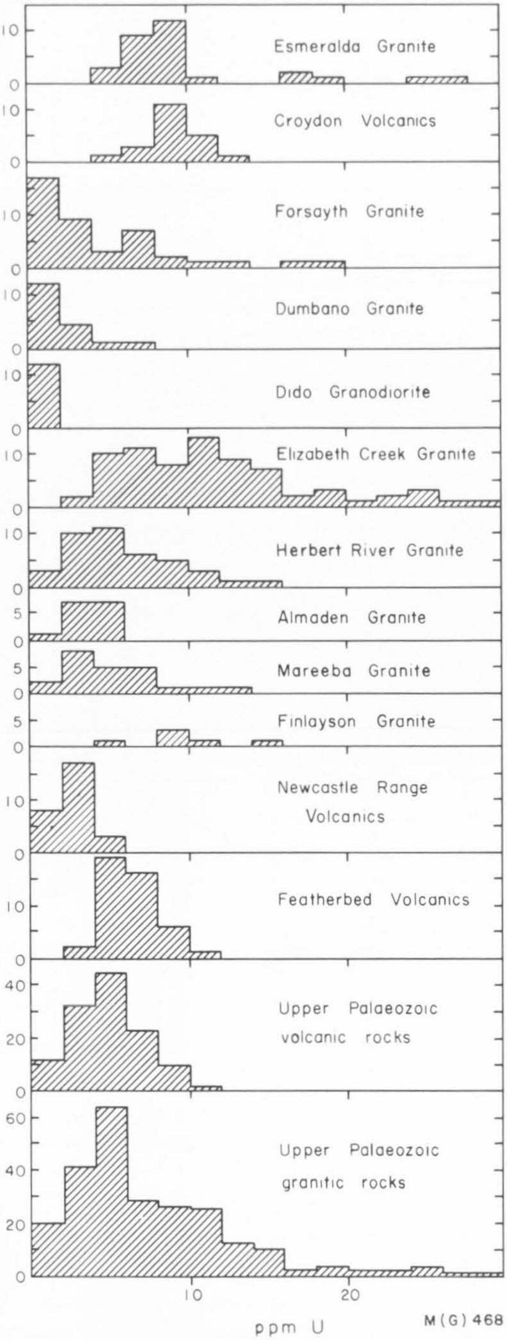


Fig. 18. Frequency distribution of uranium.

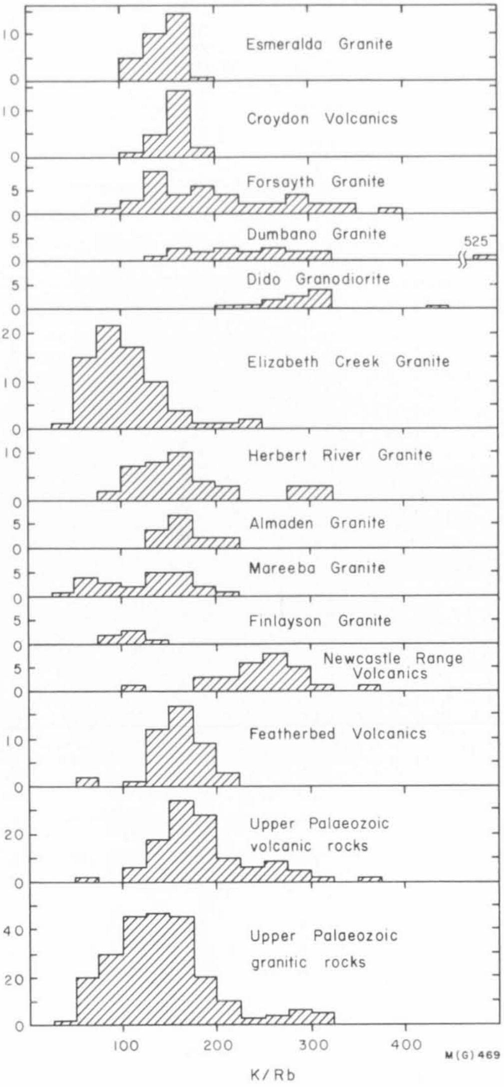
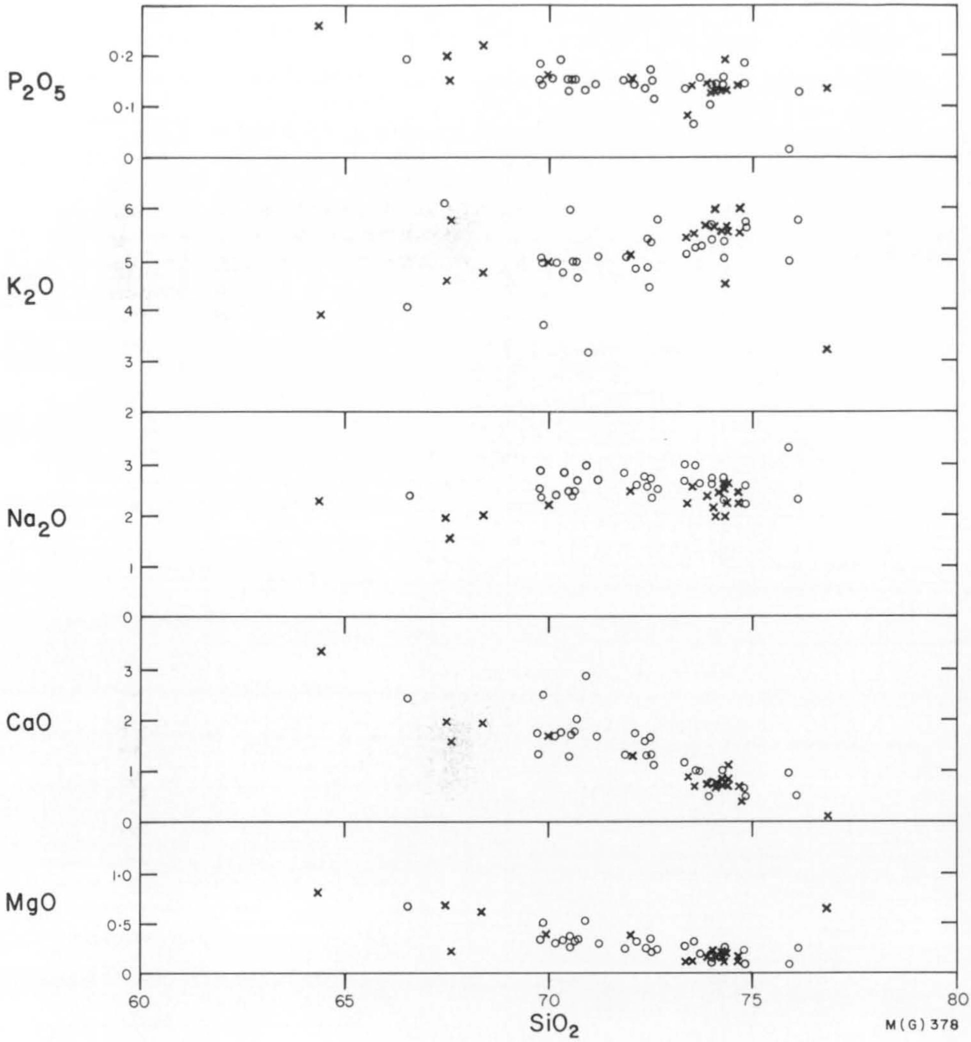


Fig. 19. Frequency distribution of K/Rb.


P$_2$O$_5$
0·2
0·1
0
K$_2$O
6
5
4
3
2
Na$_2$O
3
2
1
0
CaO
3
2
1
0
MgO
1·0
0·5
0
60
65
70
75
80
SiO$_2$
M(G) 378

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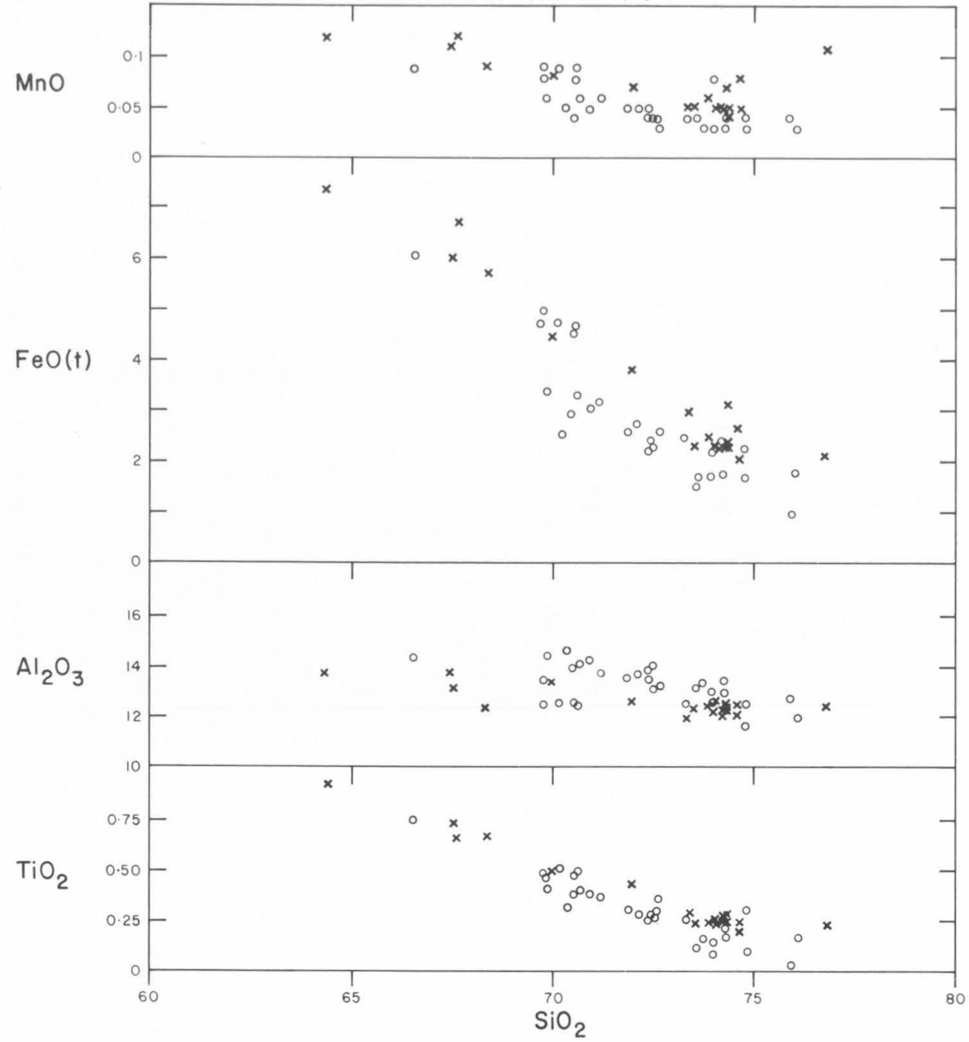
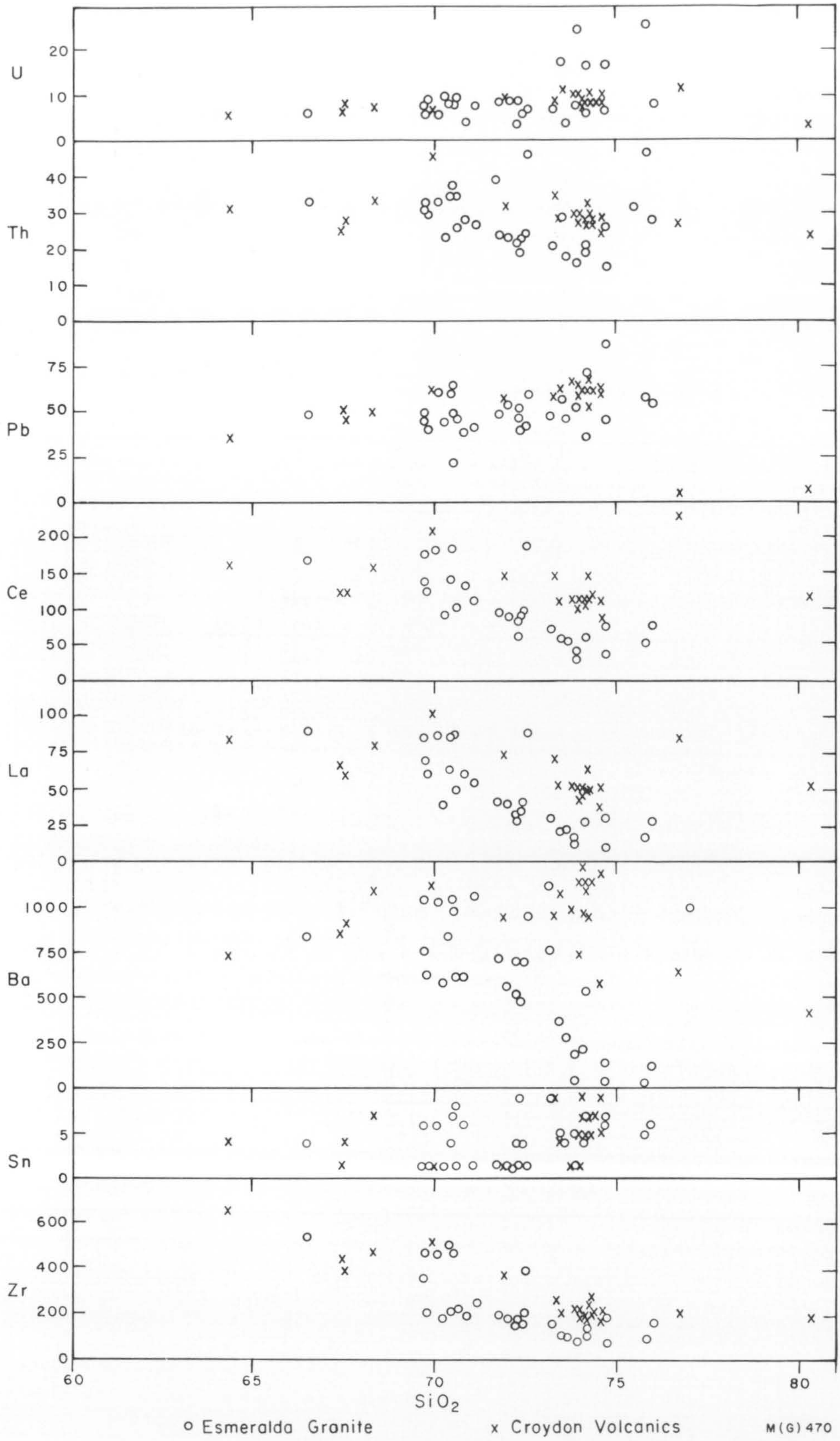


Fig. 20. Variation of major elements against silica for the Esmeralda Granite and Croydon Volcanics.


U
20
10
0
Th
40
30
20
10
0
Pb
75
50
25
0
Ce
200
150
100
50
0
La
100
75
50
25
0
Ba
1000
750
500
250
0
Sn
5
0
Zr
600
400
200
0
60
65
70
75
80
SiO_2
○ Esmeralda Granite
x Croydon Volcanics
M(G) 470

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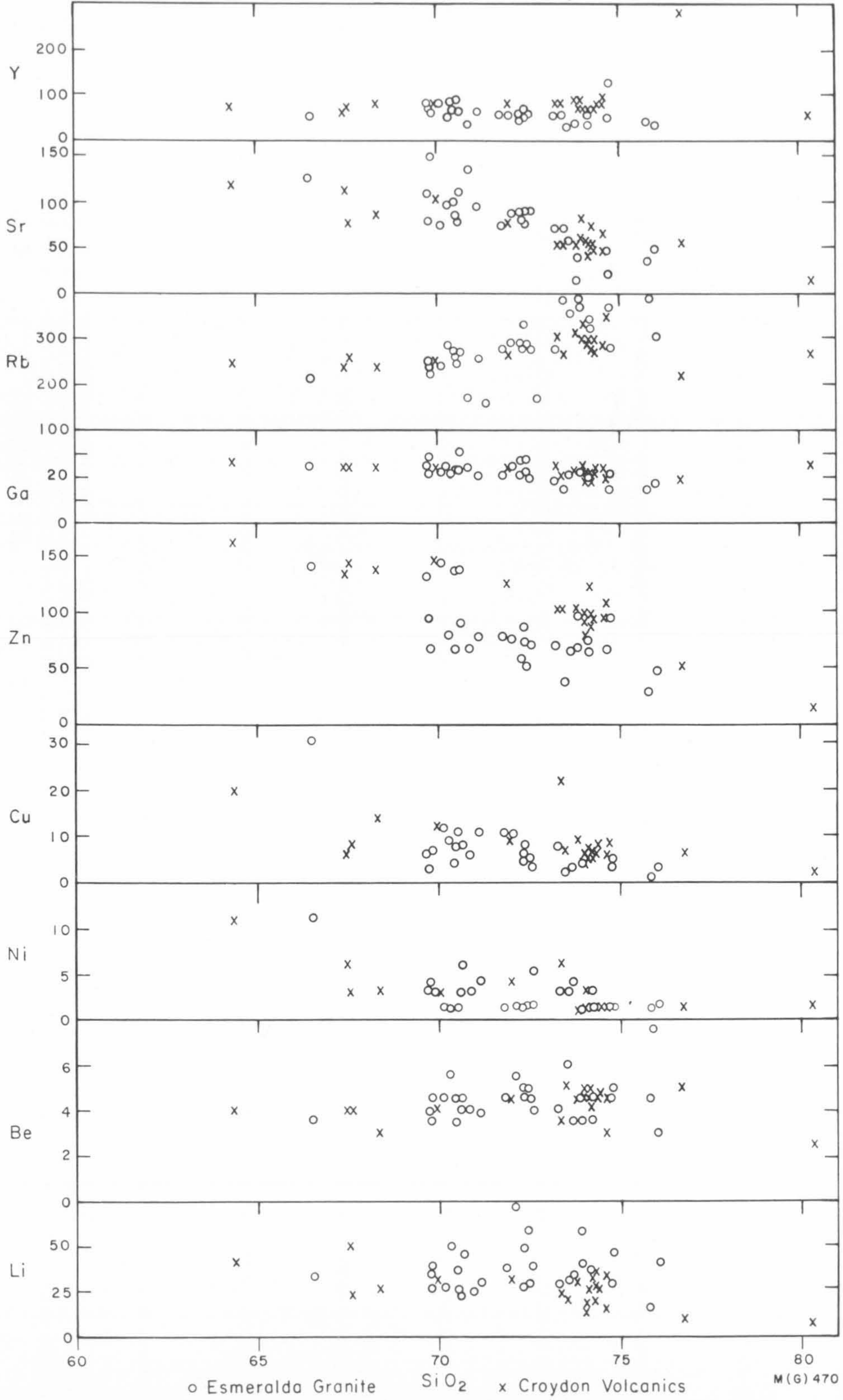
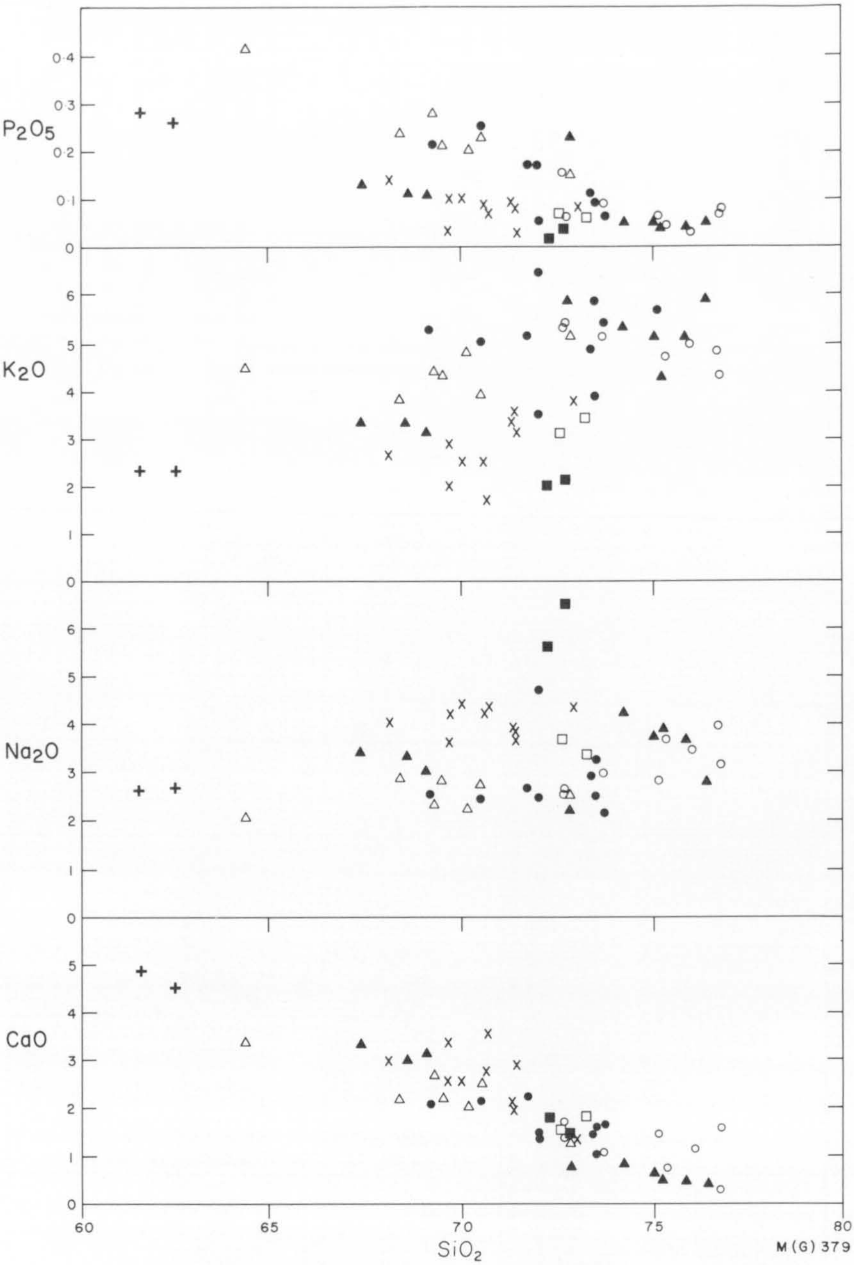


Fig. 21. Variation of trace elements against silica for the Esmeralda Granite and Croydon Volcanics.


P2O5
0.4
0.3
0.2
0.1
0
K2O
6
5
4
3
2
1
0
Na2O
6
5
4
3
2
1
0
CaO
5
4
3
2
1
0
60
65
70
75
80
SiO2
M(G) 379

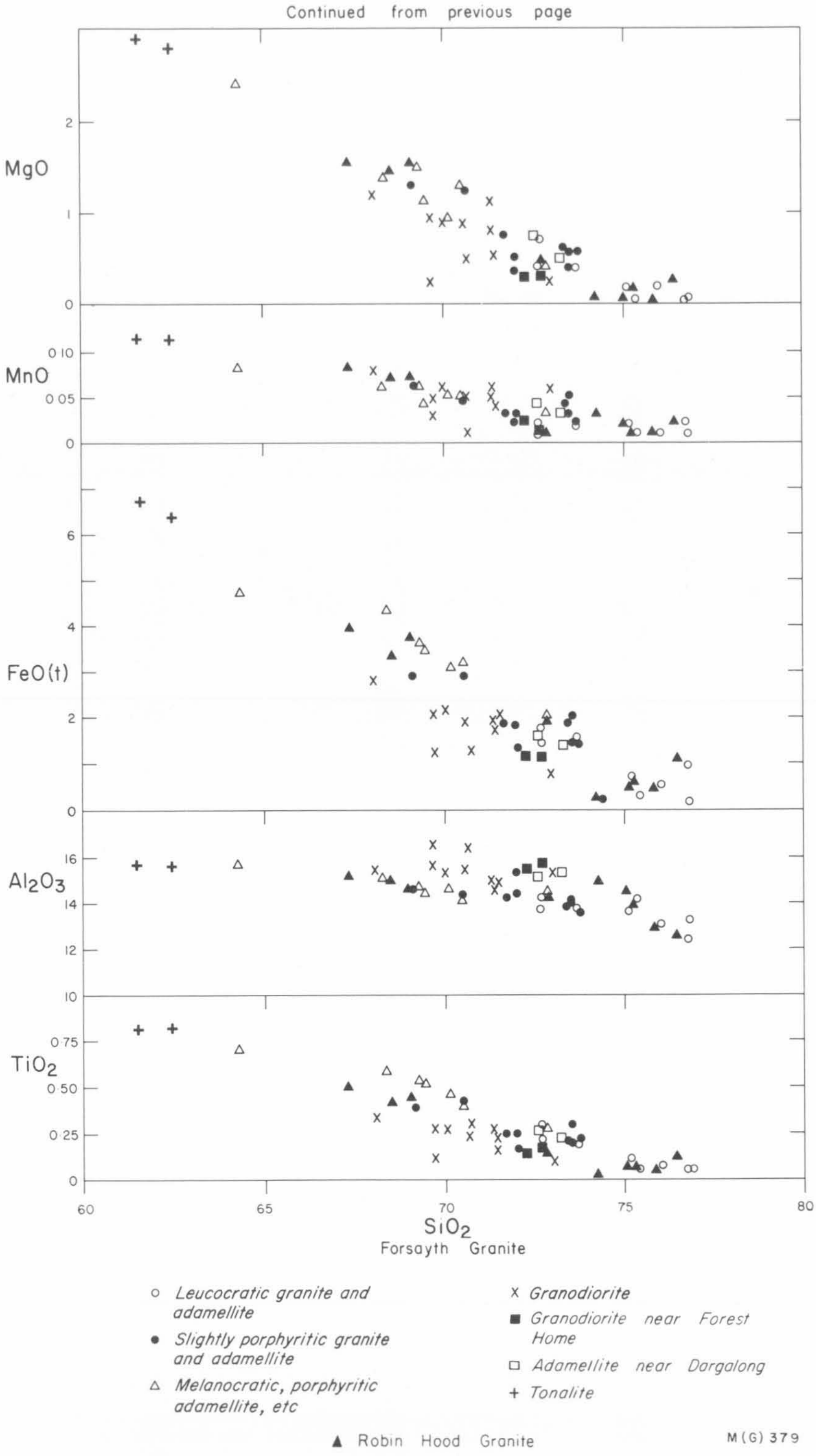
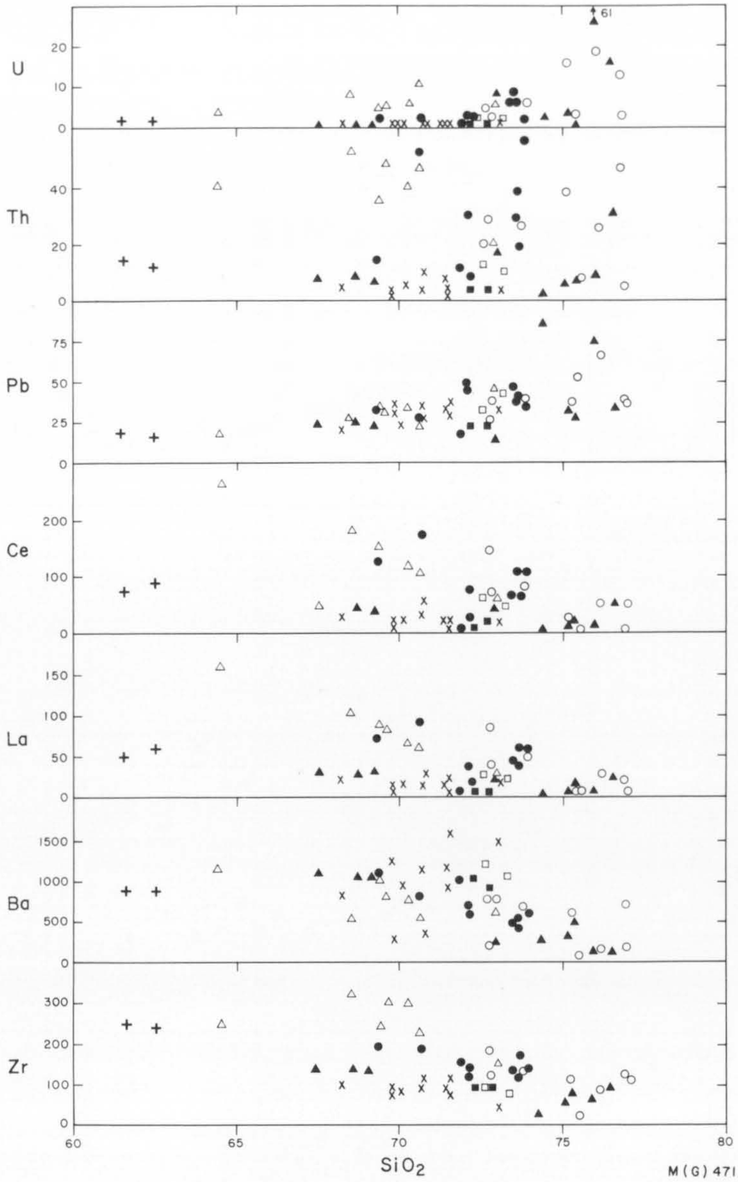


Fig. 22. Variation of major elements against silica for the Forsayth and Robin Hood Granites.


U
20
10
0
61
Th
40
20
0
Pb
75
50
25
0
Ce
200
100
0
La
150
100
50
0
Ba
1500
1000
500
0
Zr
300
200
100
0
60
65
70
75
80
SiO2
M (G) 471

Continued from previous page

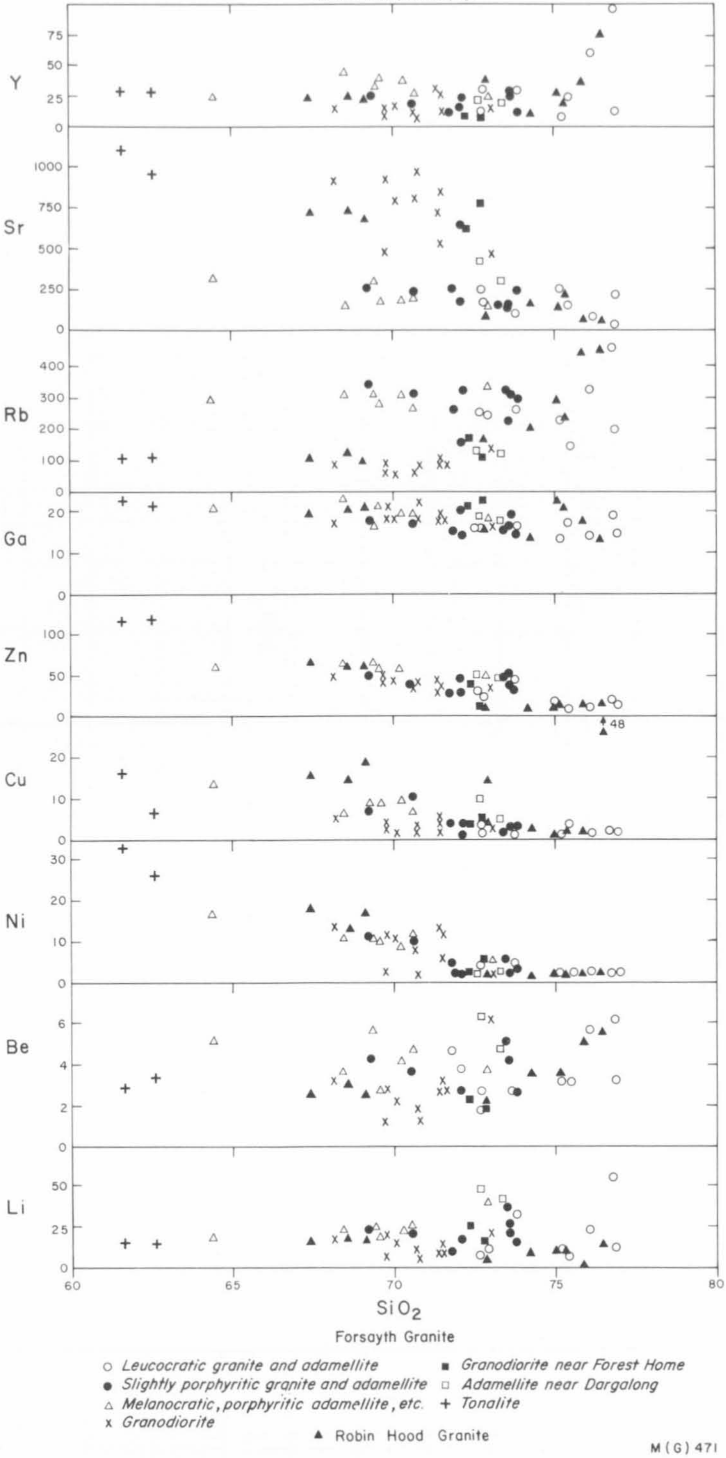
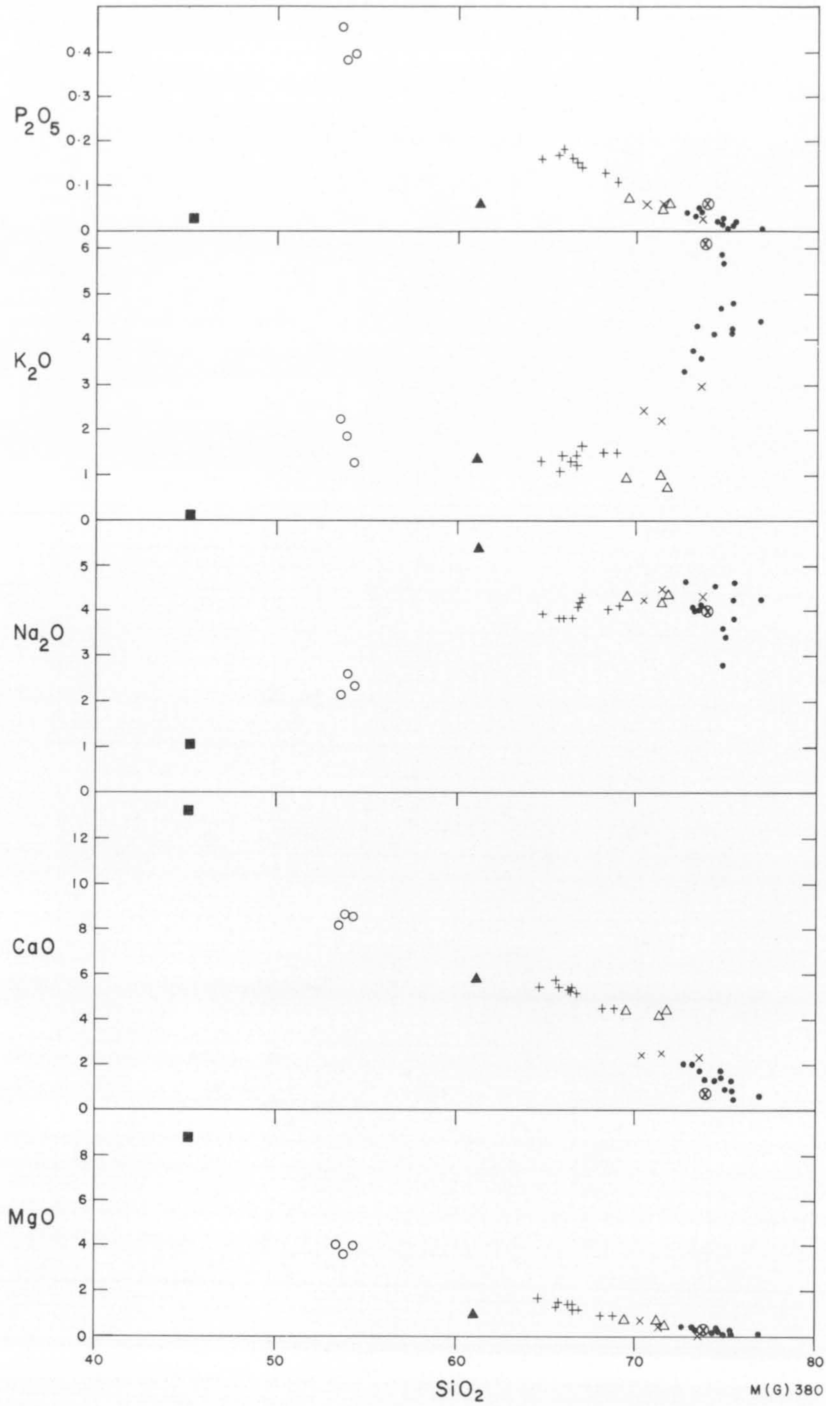


Fig. 23. Variation of trace elements against silica for the Forsayth and Robin Hood Granites.



P_2O_5
0·4
0·3
0·2
0·1
0
K_2O
6
5
4
3
2
1
0
Na_2O
5
4
3
2
1
0
CaO
12
10
8
6
4
2
0
MgO
8
6
4
2
0
40
50
60
70
80
SiO_2
M(G) 380

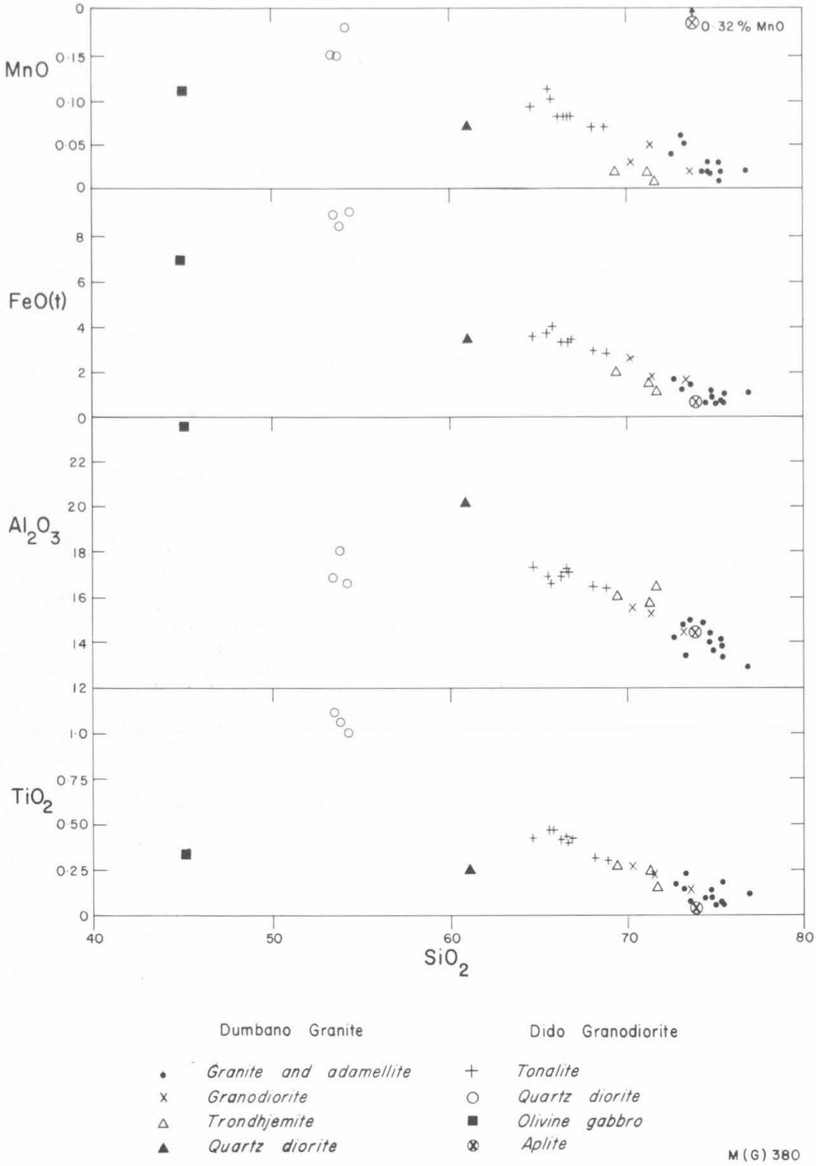
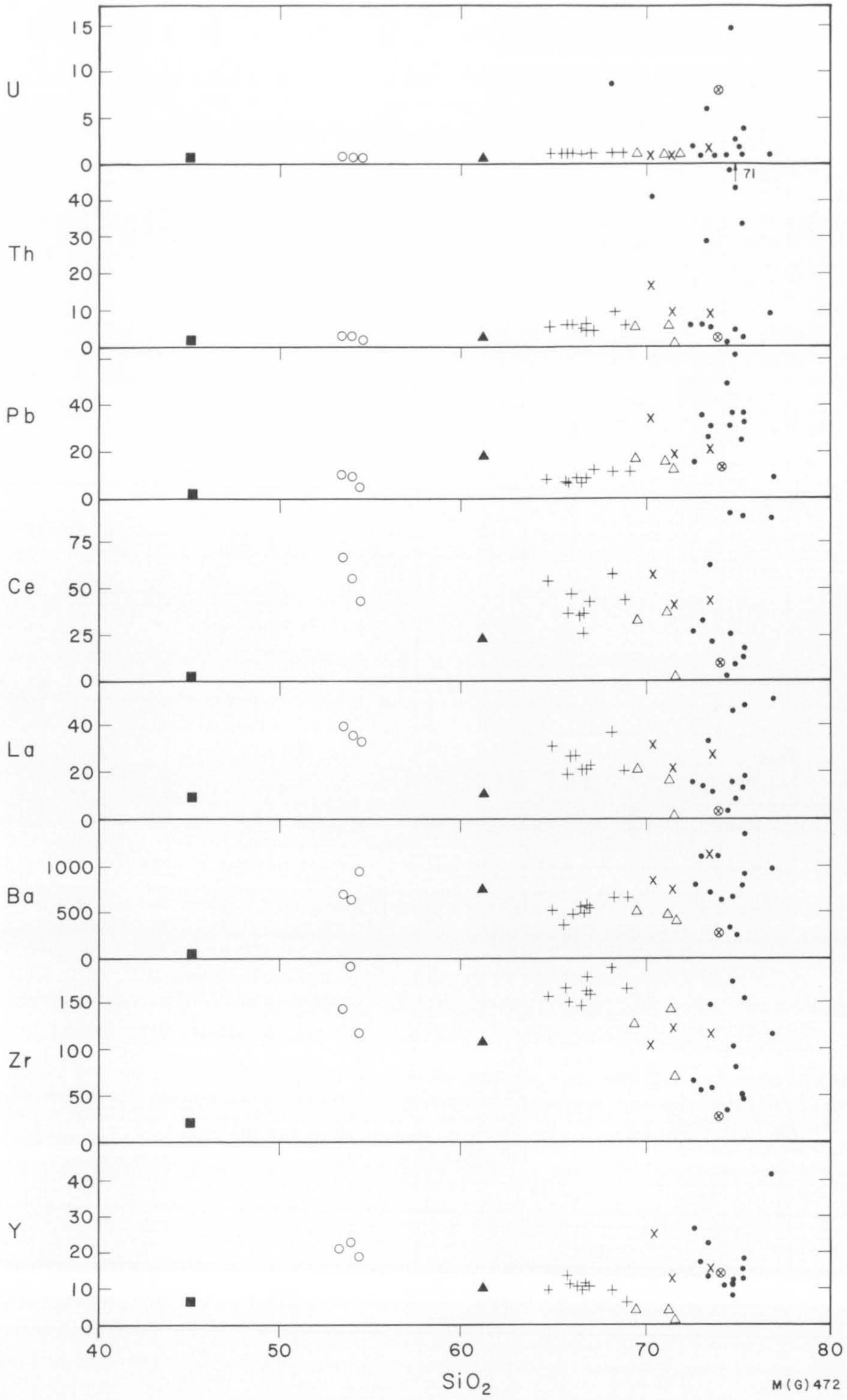


Fig. 24. Variation of major elements against silica for the Dumbano Granite and Dido Granodiorite.


U
15
10
5
0
Th
40
30
20
10
0
Pb
40
20
0
Ce
75
50
25
0
La
40
20
0
Ba
1000
500
0
Zr
150
100
50
0
Y
40
30
20
10
0
71
40
50
60
70
80
SiO_2
M(G)472

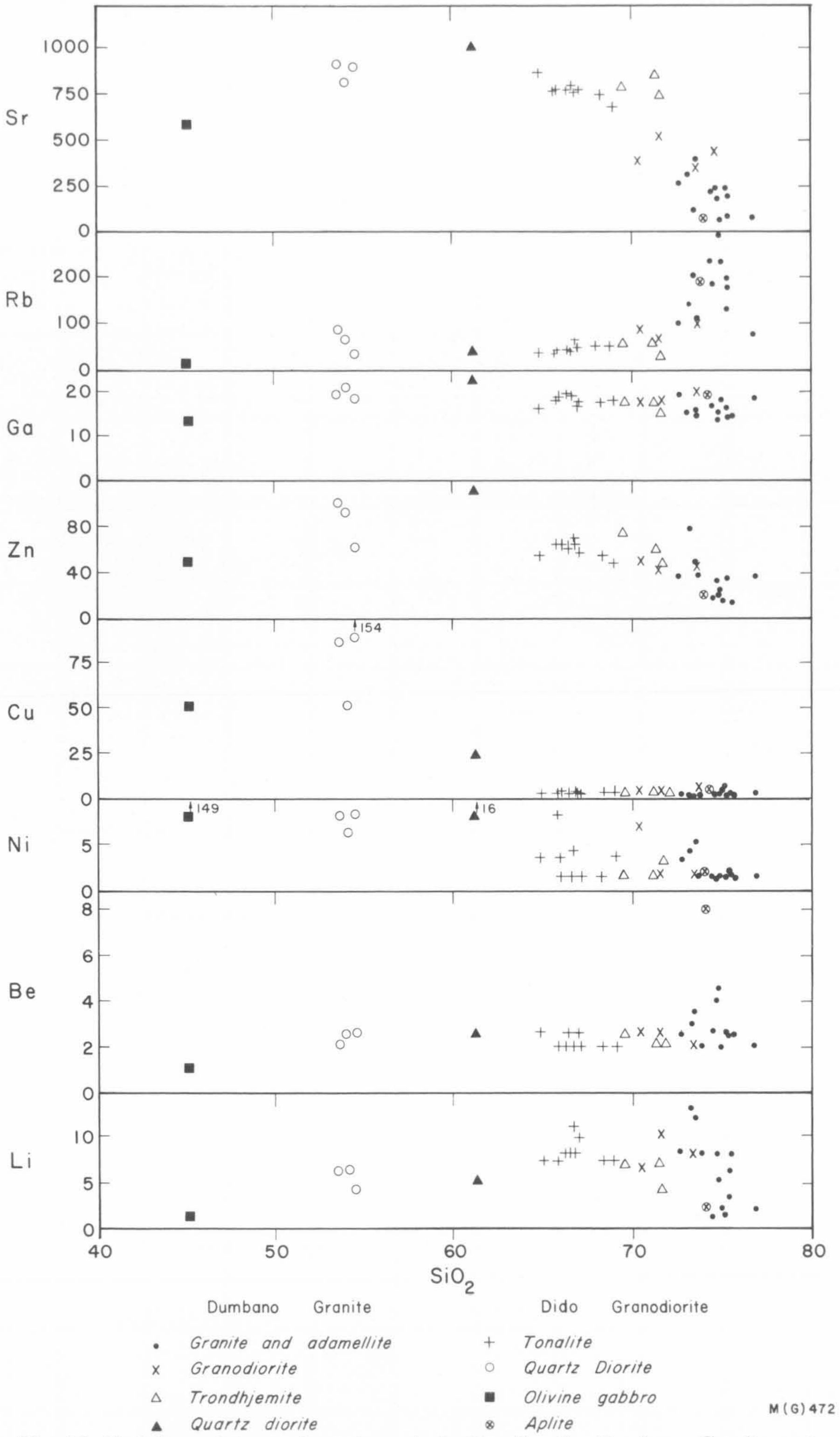
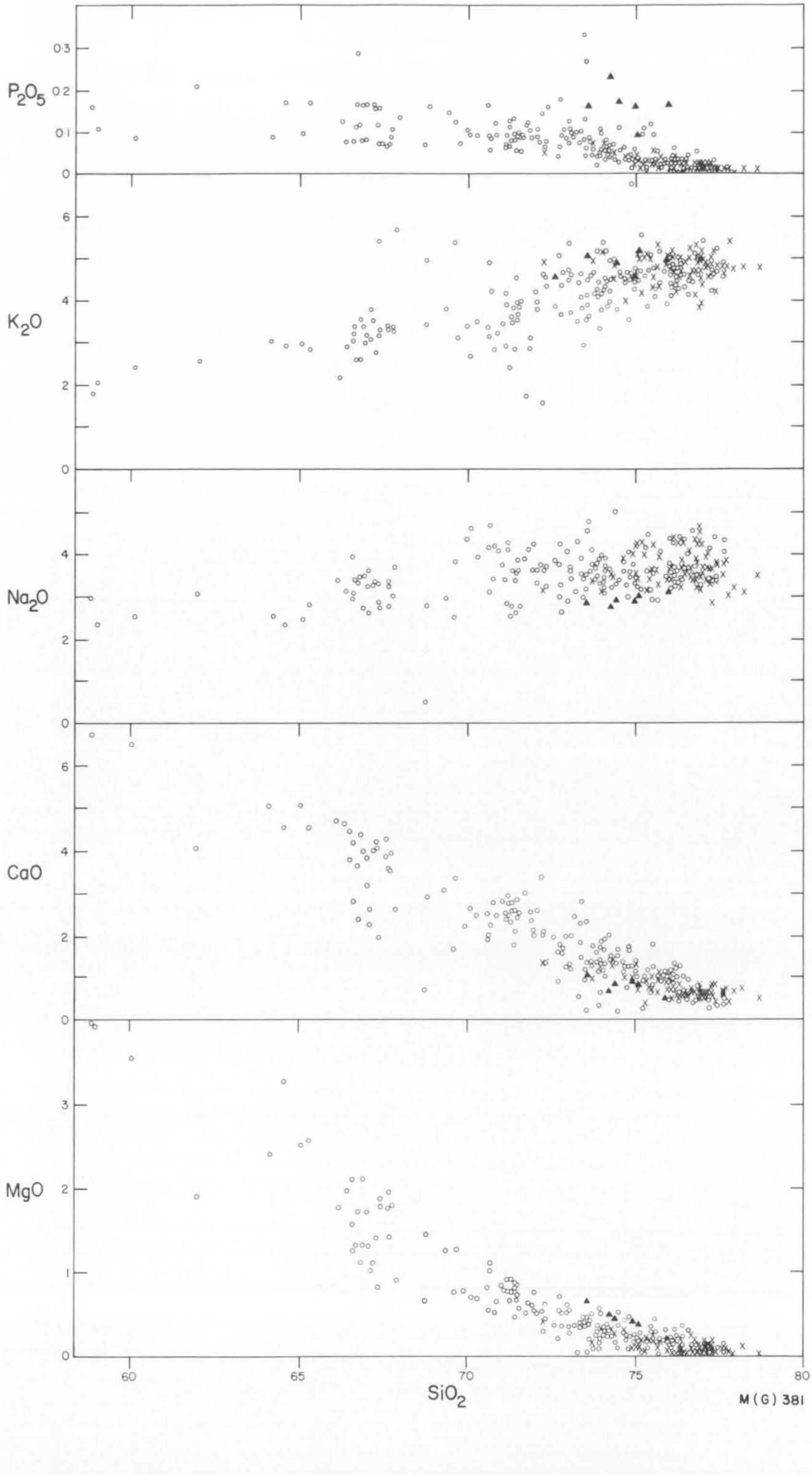


Fig. 25. Variation of trace elements against silica for the Dumbano Granite and Dido Granodiorite.


P_2O_5
0·3
0·2
0·1
0
K_2O
6
4
2
0
Na_2O
4
2
0
CaO
6
4
2
0
MgO
3
2
1
0
60
65
70
75
80
SiO_2
M(G) 381

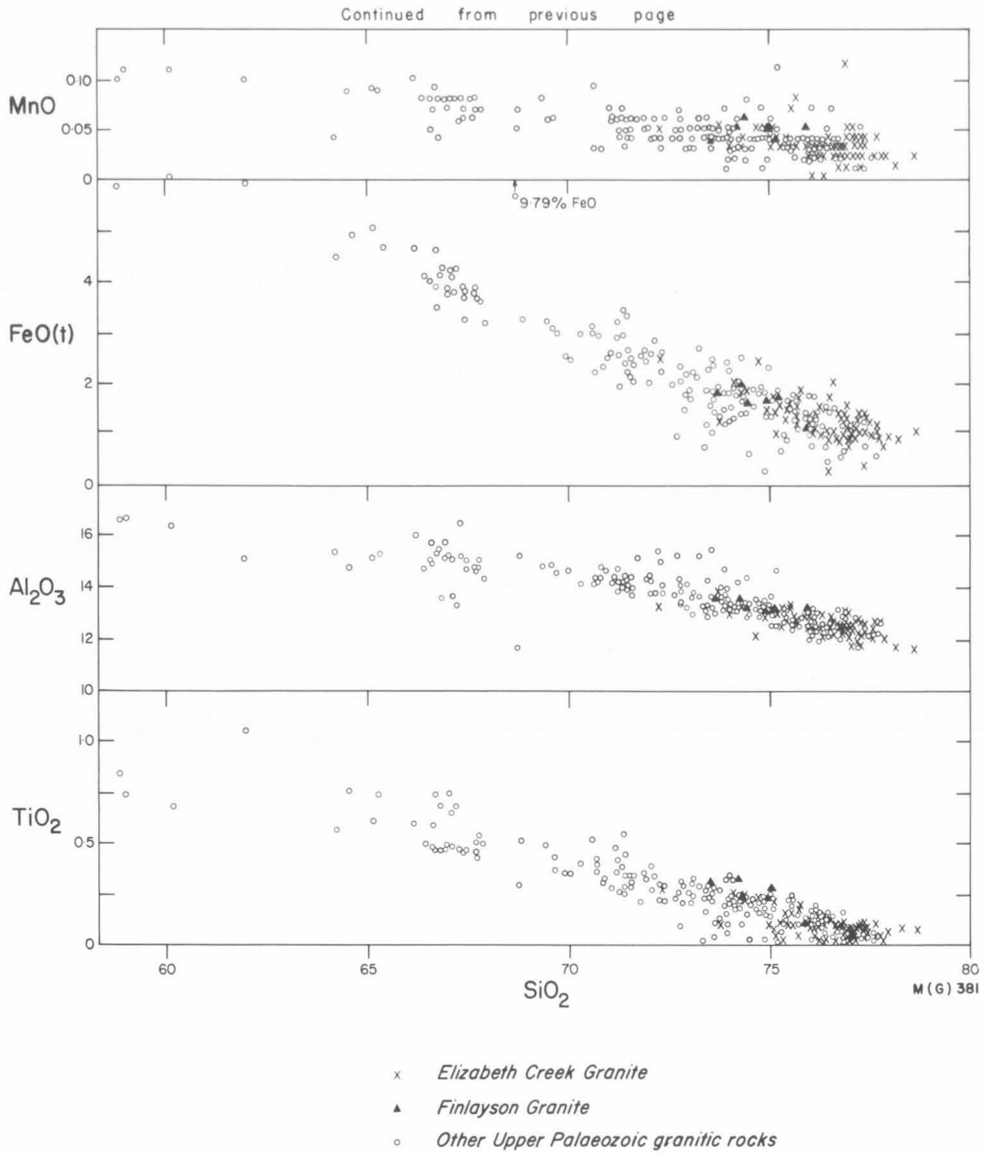
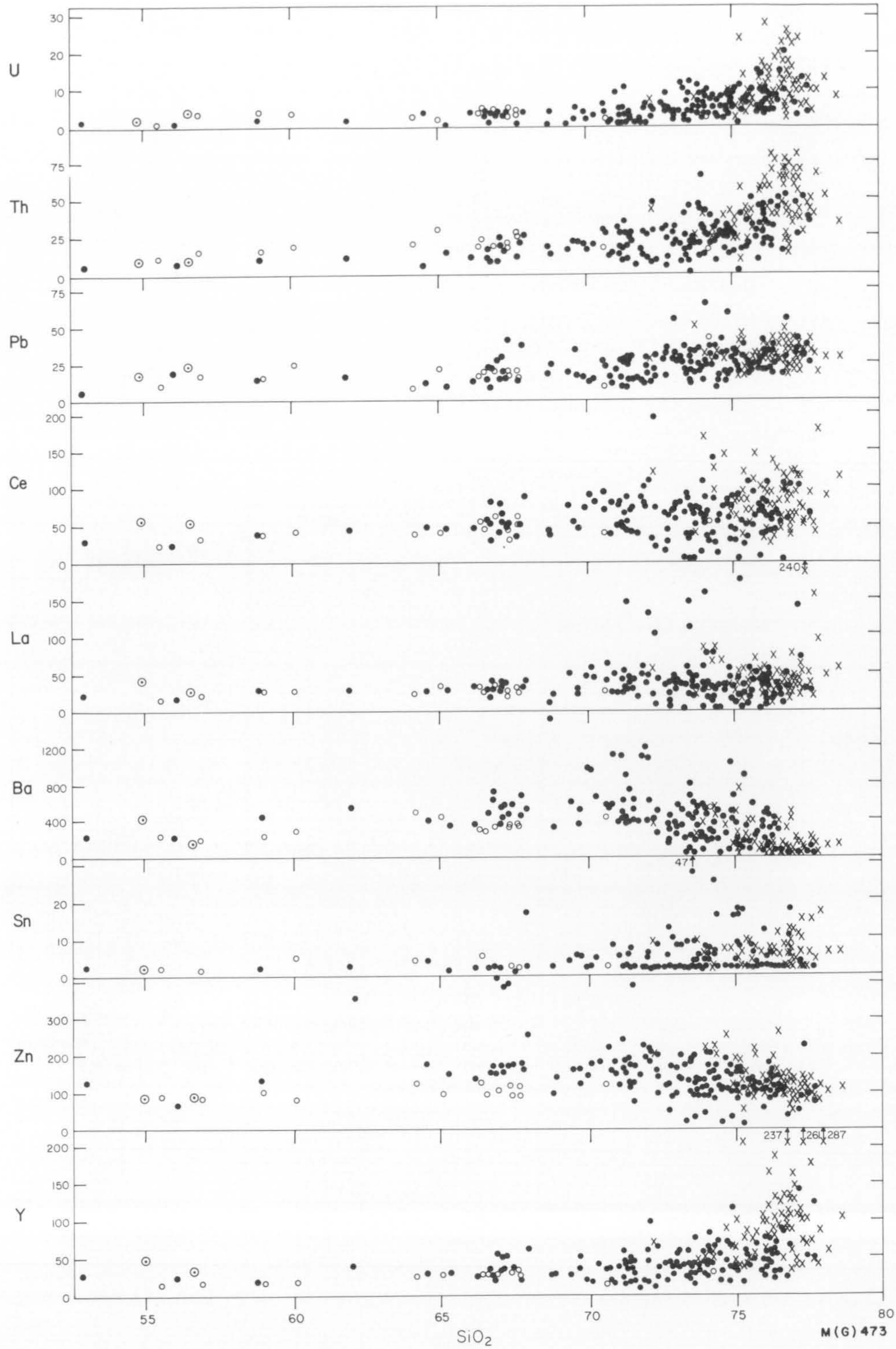


Fig. 26. Variation of major elements against silica for the Upper Palaeozoic granitic rocks.


U
Th
Pb
Ce
La
Ba
Sn
Zn
Y
0
10
20
30
25
50
75
100
150
200
400
800
1200
240
47
300
237
261
287
55
60
65
70
75
80
SiO$_2$
M(G) 473

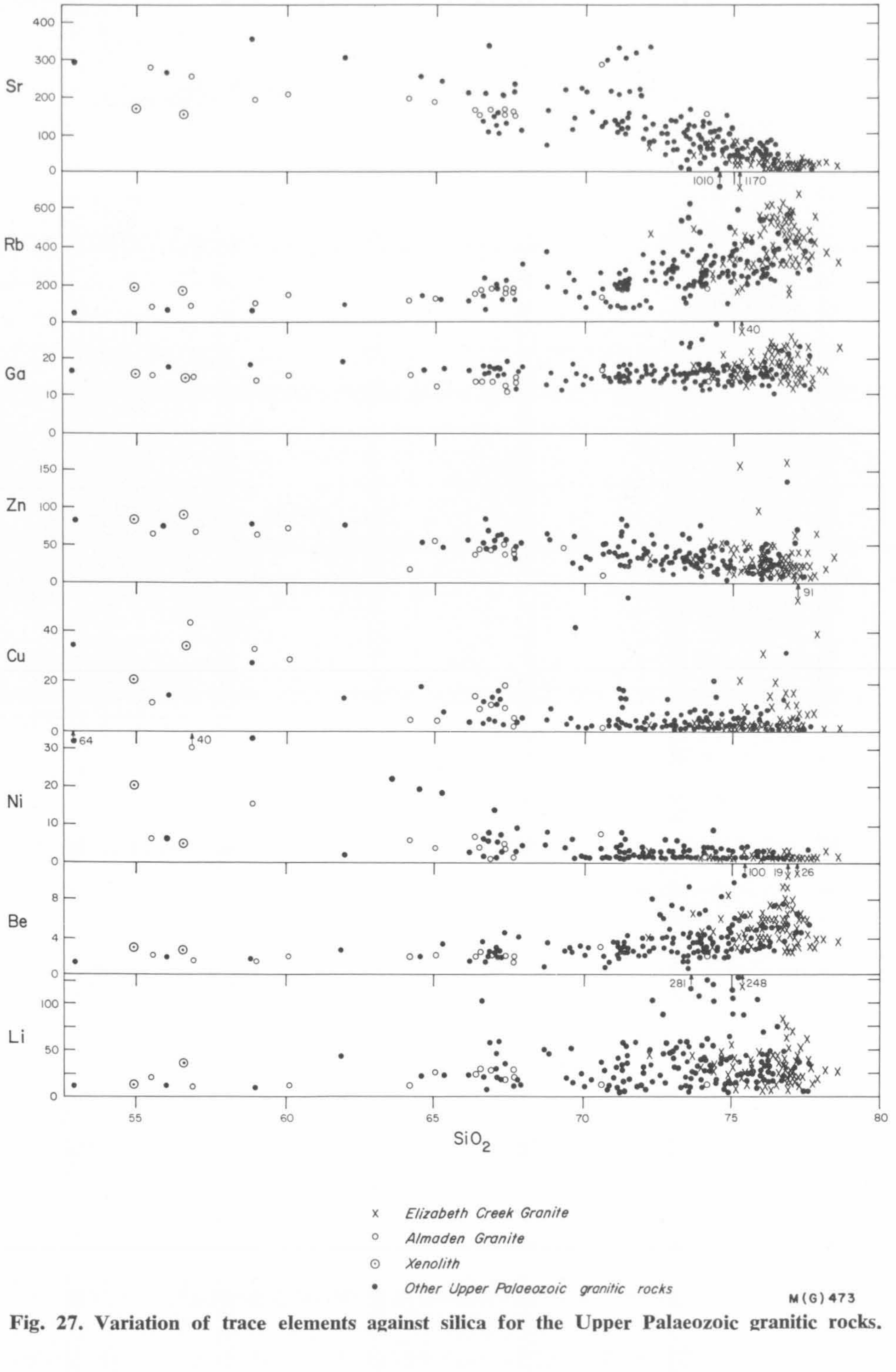
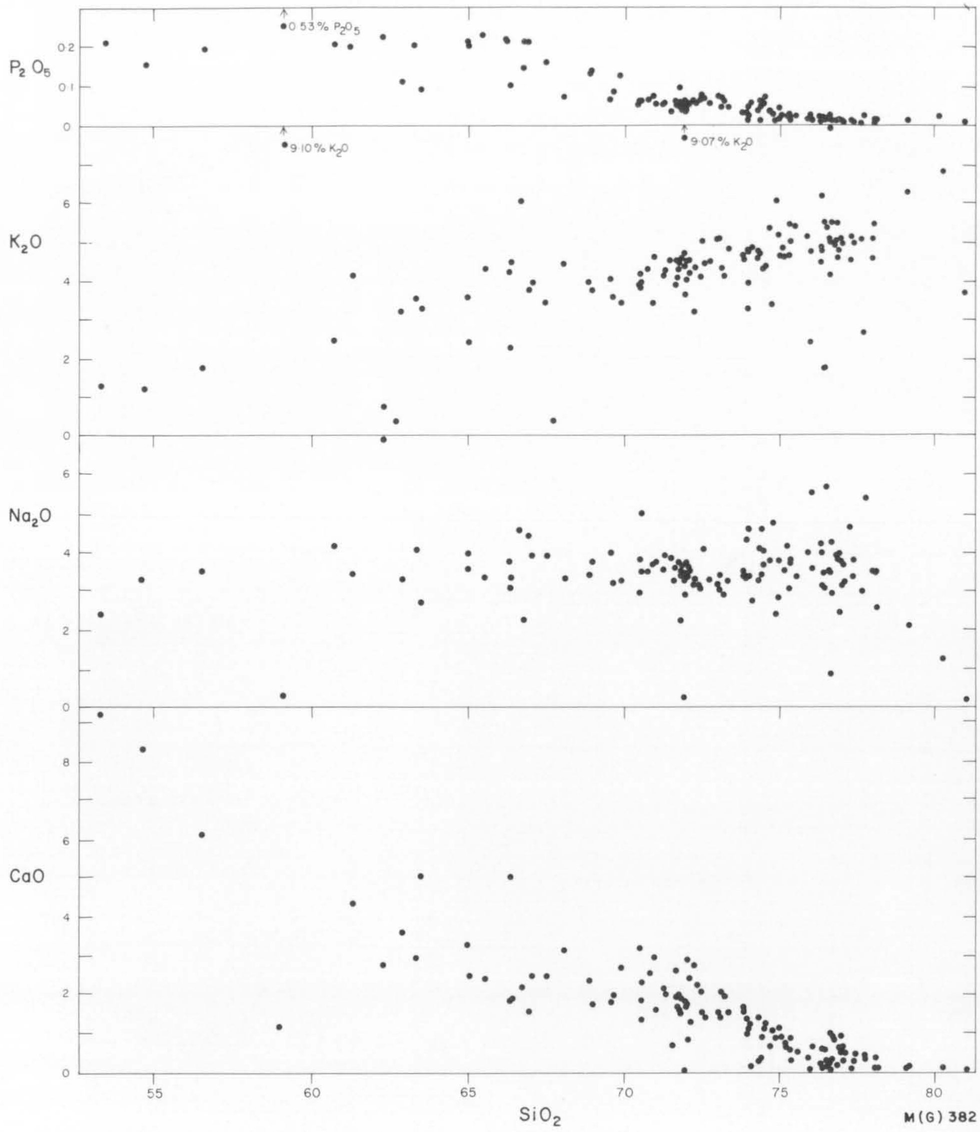


Fig. 27. Variation of trace elements against silica for the Upper Palaeozoic granitic rocks.


P$_2$O$_5$
0.2
0.1
0
0.53% P$_2$O$_5$
K$_2$O
6
4
2
0
9.10% K$_2$O
9.07% K$_2$O
Na$_2$O
6
4
2
0
CaO
8
6
4
2
0
55
60
65
70
75
80
SiO$_2$
M(G) 382

Continued from previous page

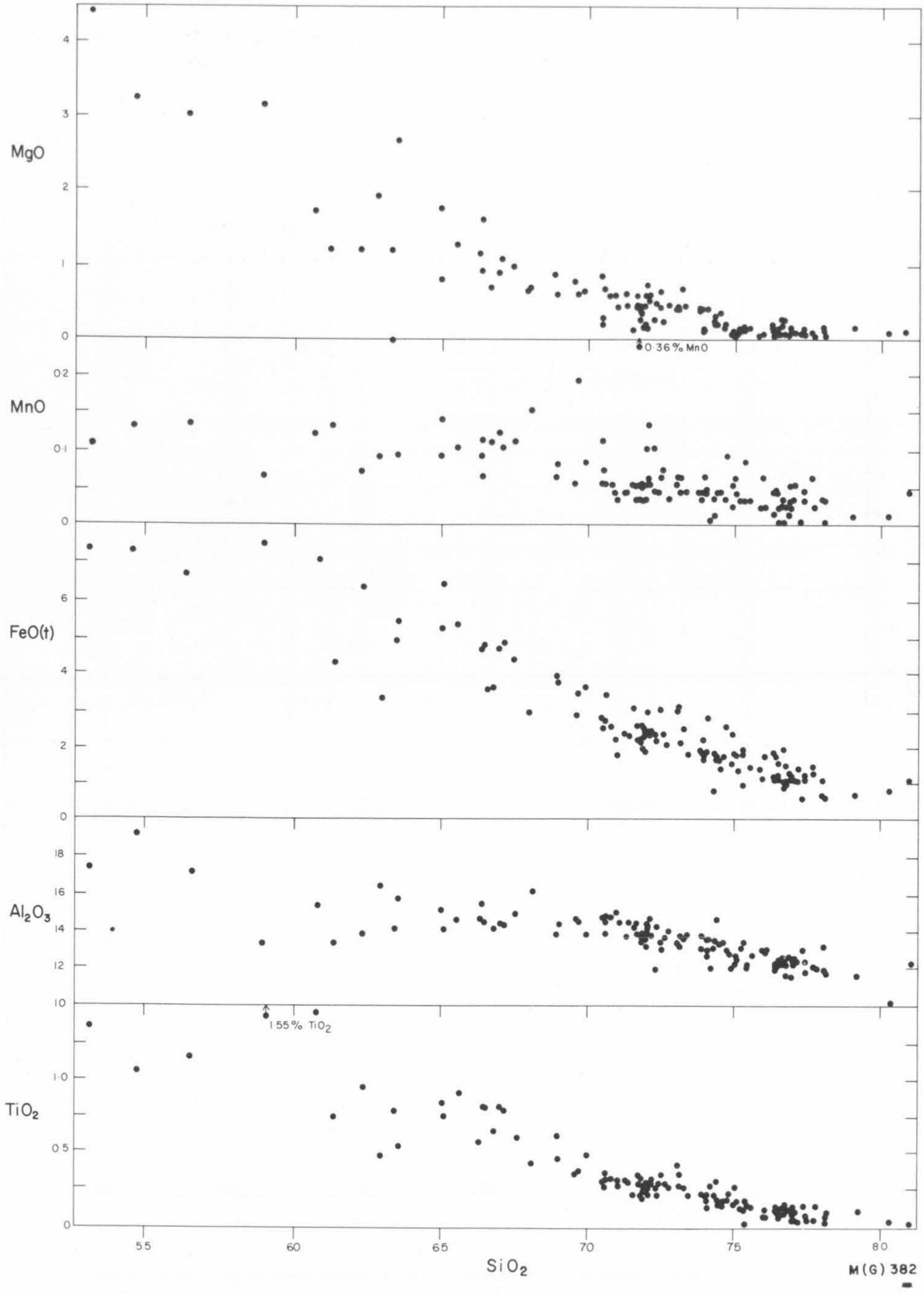
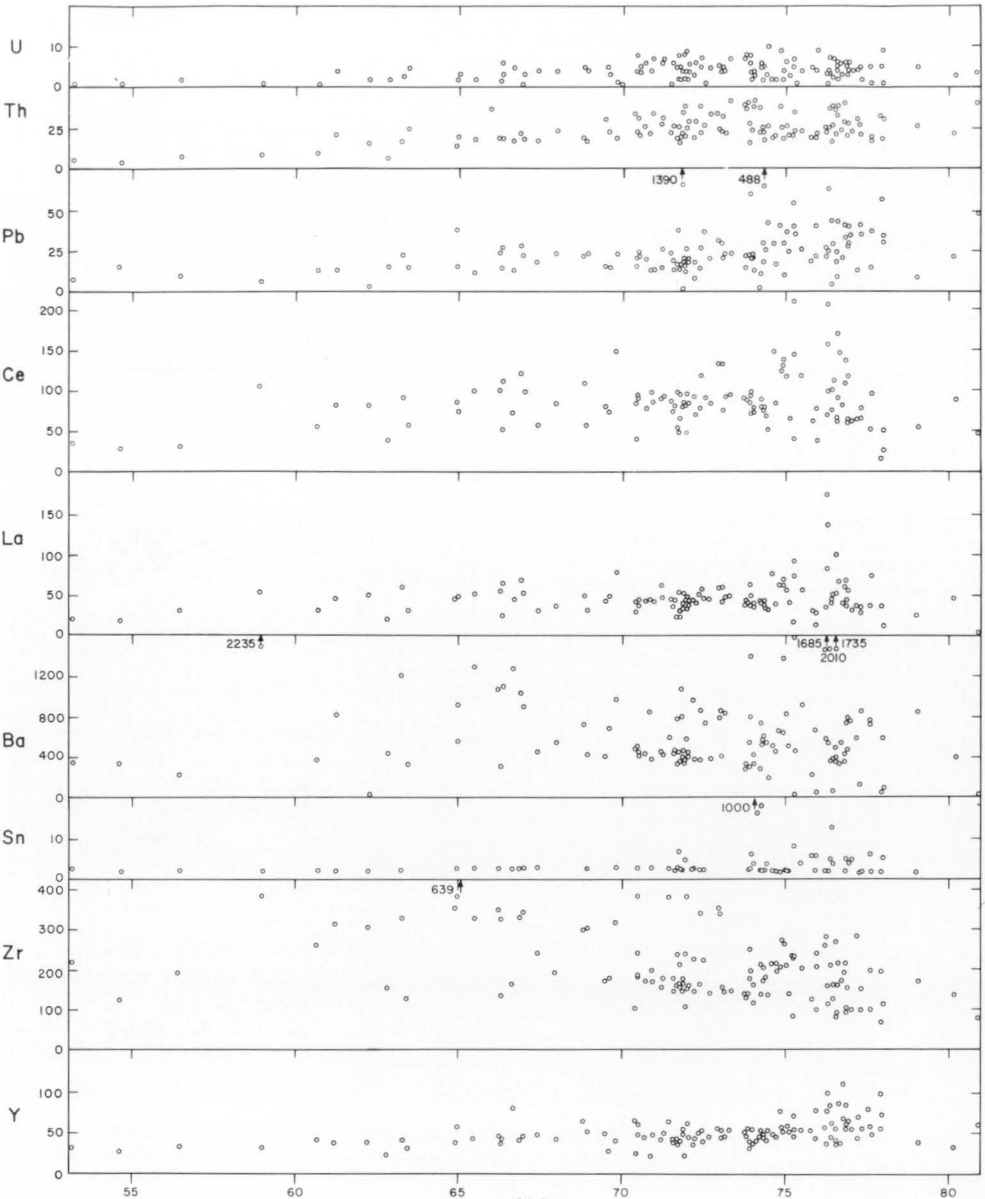


Fig. 28. Variation of major elements against silica for the Upper Palaeozoic volcanic rocks.


U
10
0
Th
25
0
1390
488
Pb
50
25
0
200
Ce
150
100
50
0
La
150
100
50
0
2235
1685
1735
2010
1200
800
Ba
400
0
1000
Sn
10
0
639
400
300
Zr
200
100
0
Y
100
50
0
55
60
65
70
75
80
SiO2
M(G)474

Continued from previous page

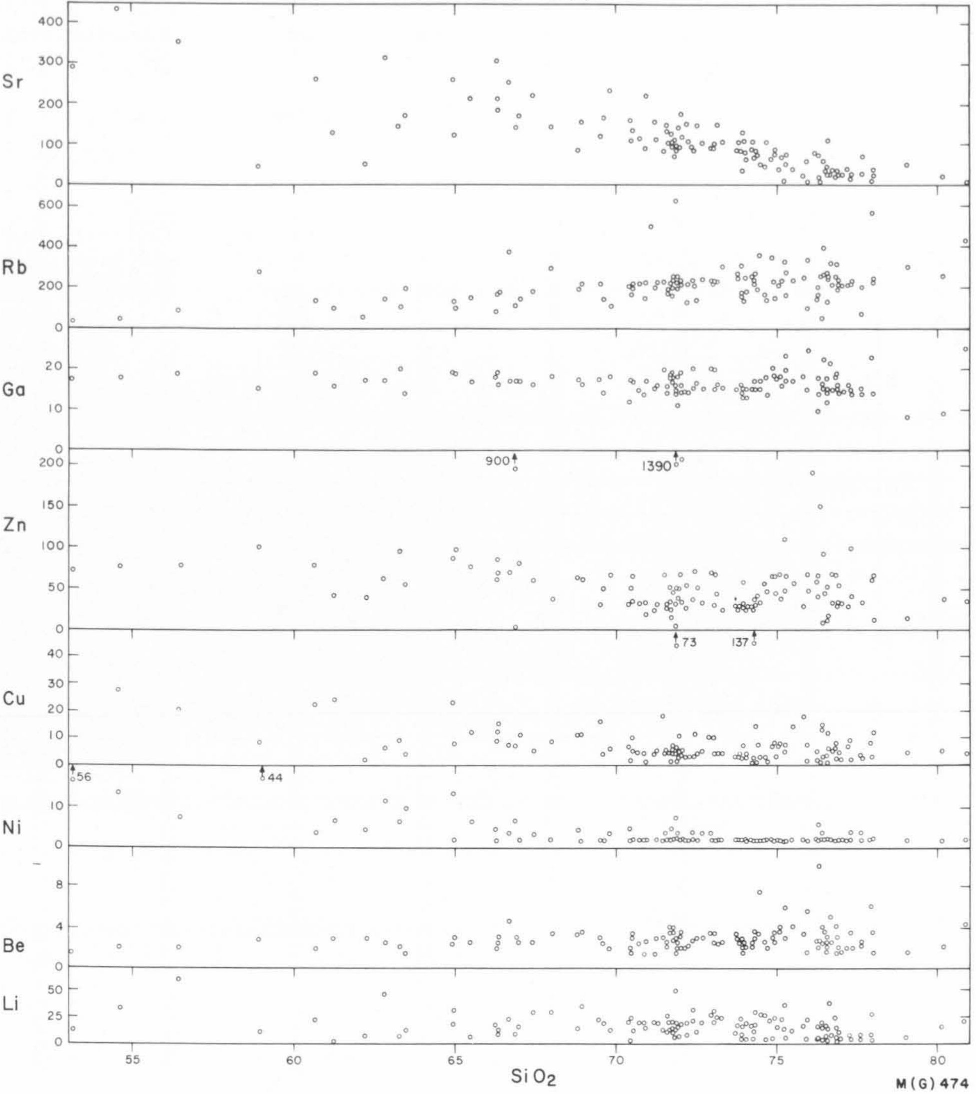
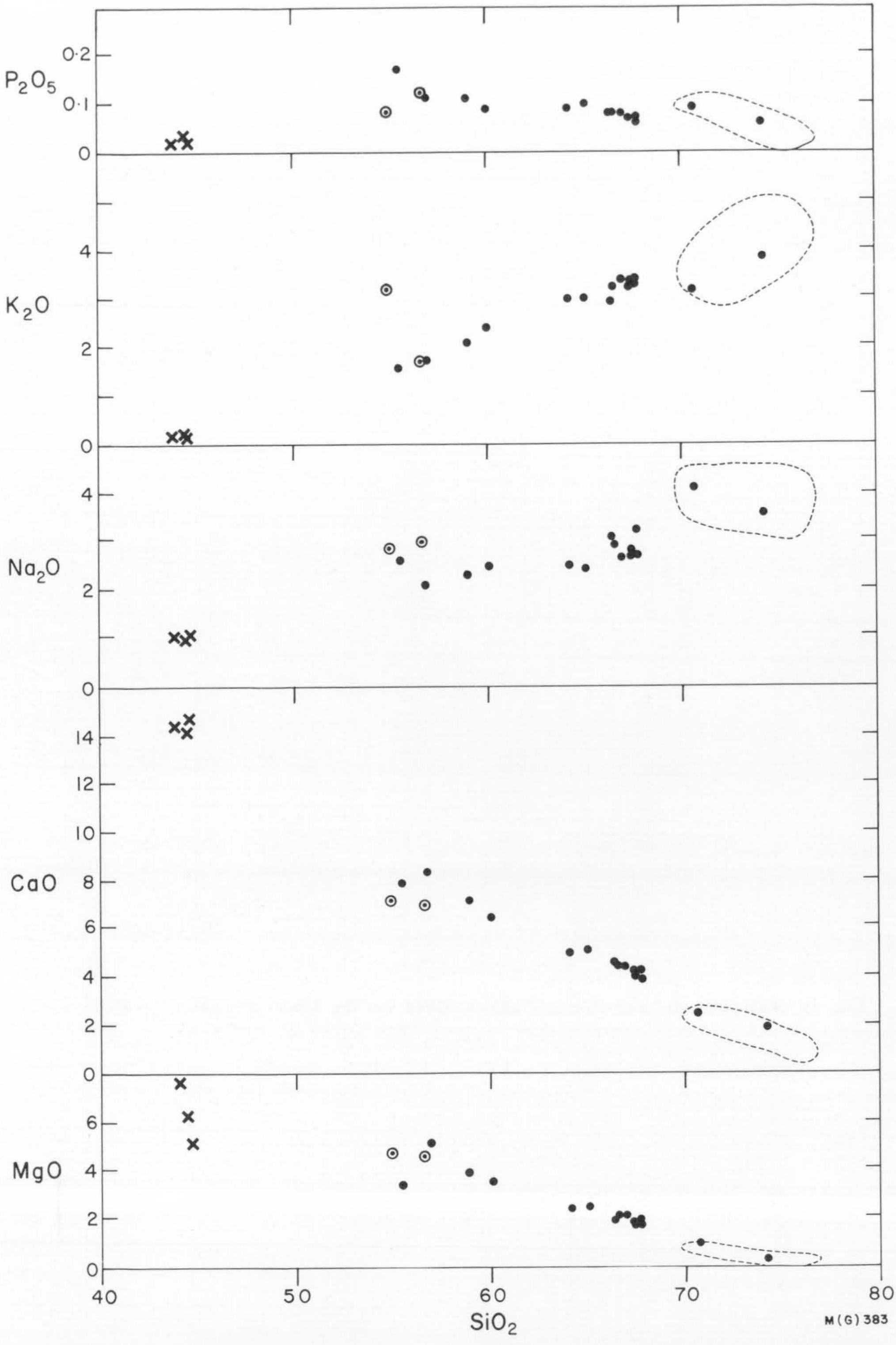


Fig. 29. Variation of trace elements against silica for the Upper Palaeozoic volcanic rocks.


P$_2$O$_5$
0·2
0·1
0
K$_2$O
4
2
0
Na$_2$O
4
2
0
CaO
14
12
10
8
6
4
2
0
MgO
6
4
2
0
40
50
60
70
80
SiO$_2$
M(G) 383

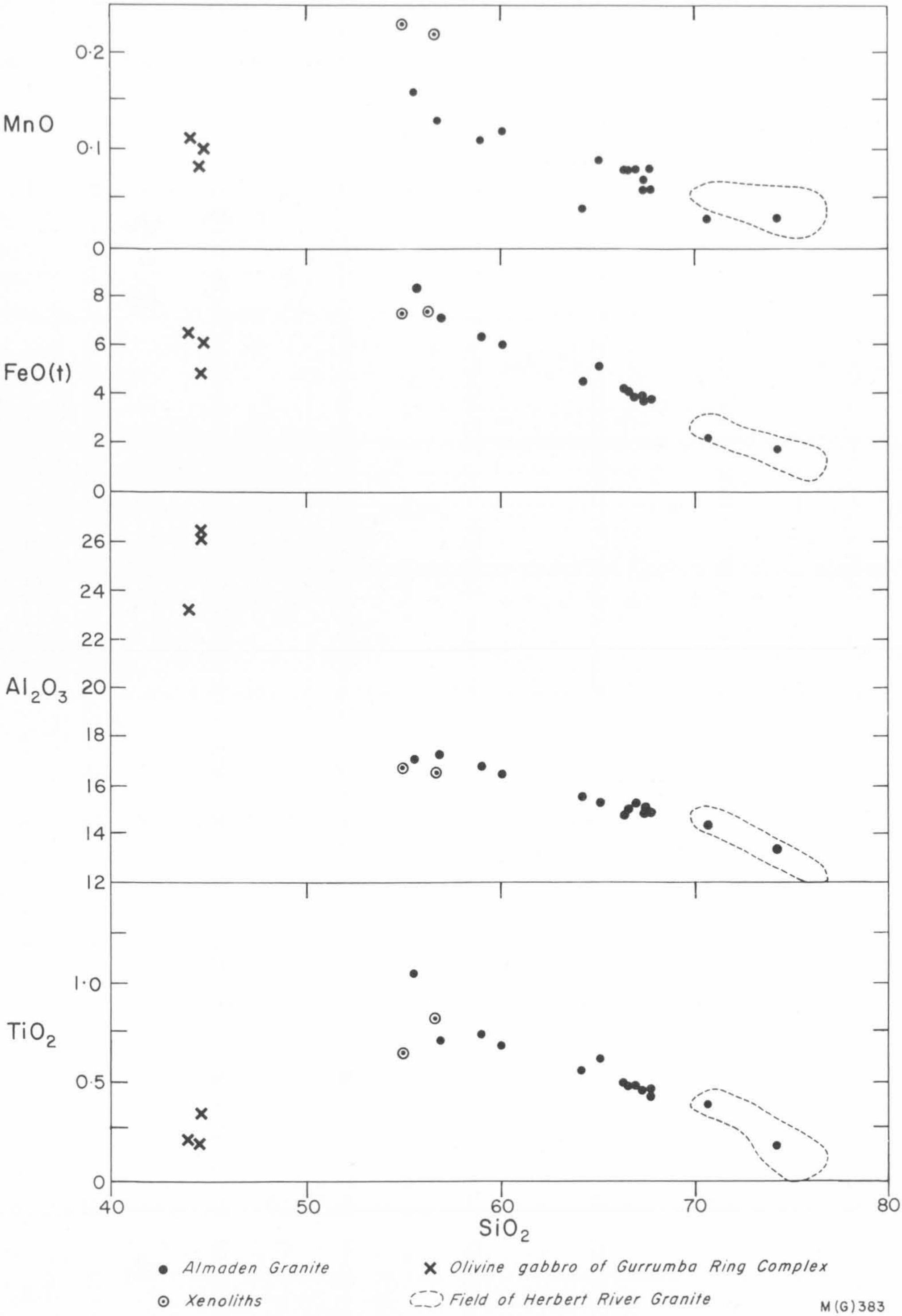
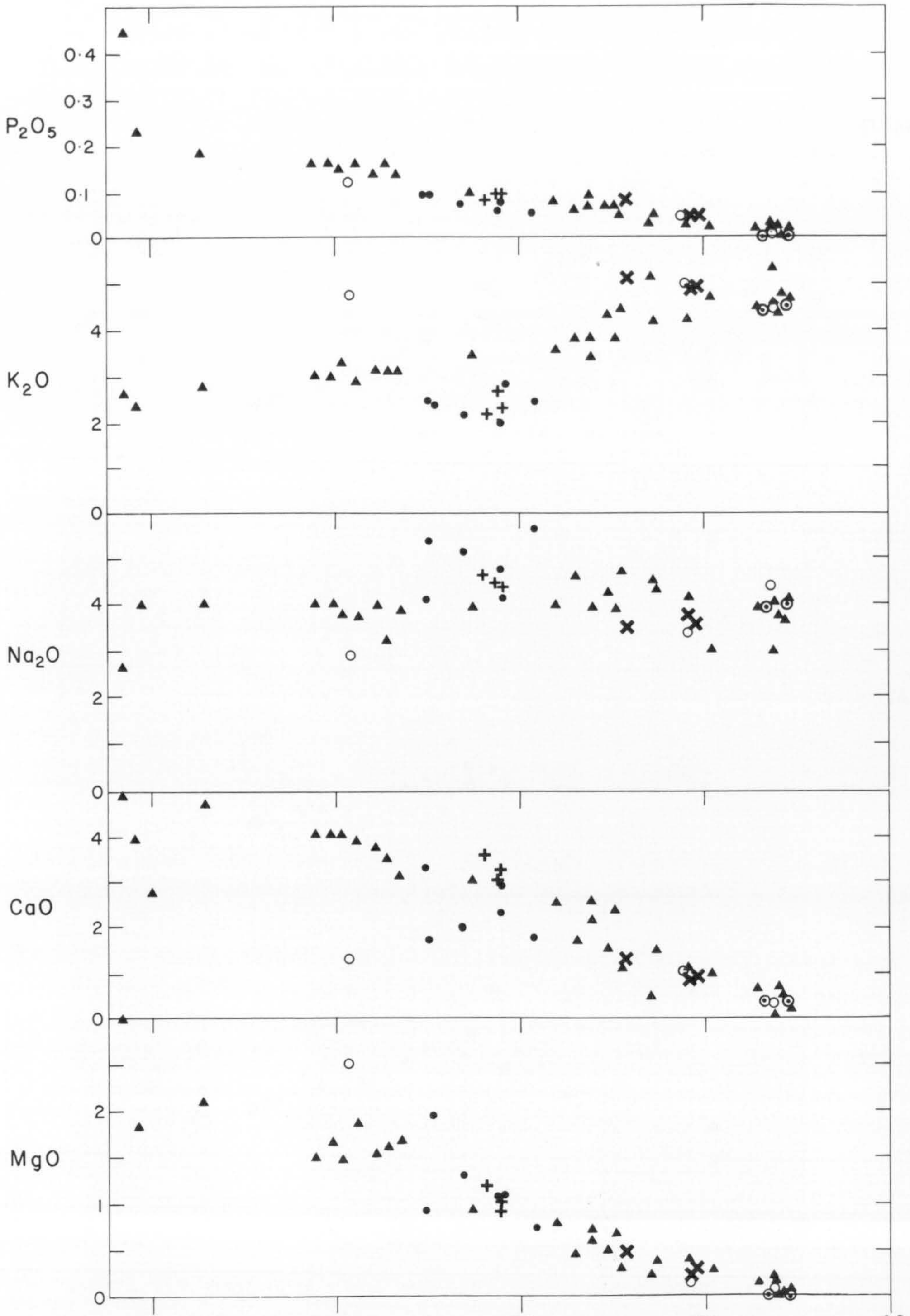


Fig. 30. Variation of major elements against silica for the Almaden Granite and olivine gabbro of the Gurrumba Ring Complex.


P₂O₅
0·4
0·3
0·2
0·1
0
K₂O
4
2
0
Na₂O
4
2
0
CaO
4
2
0
MgO
2
1
0
60
65
70
75
80
SiO₂
M(G) 384

Continued from previous page

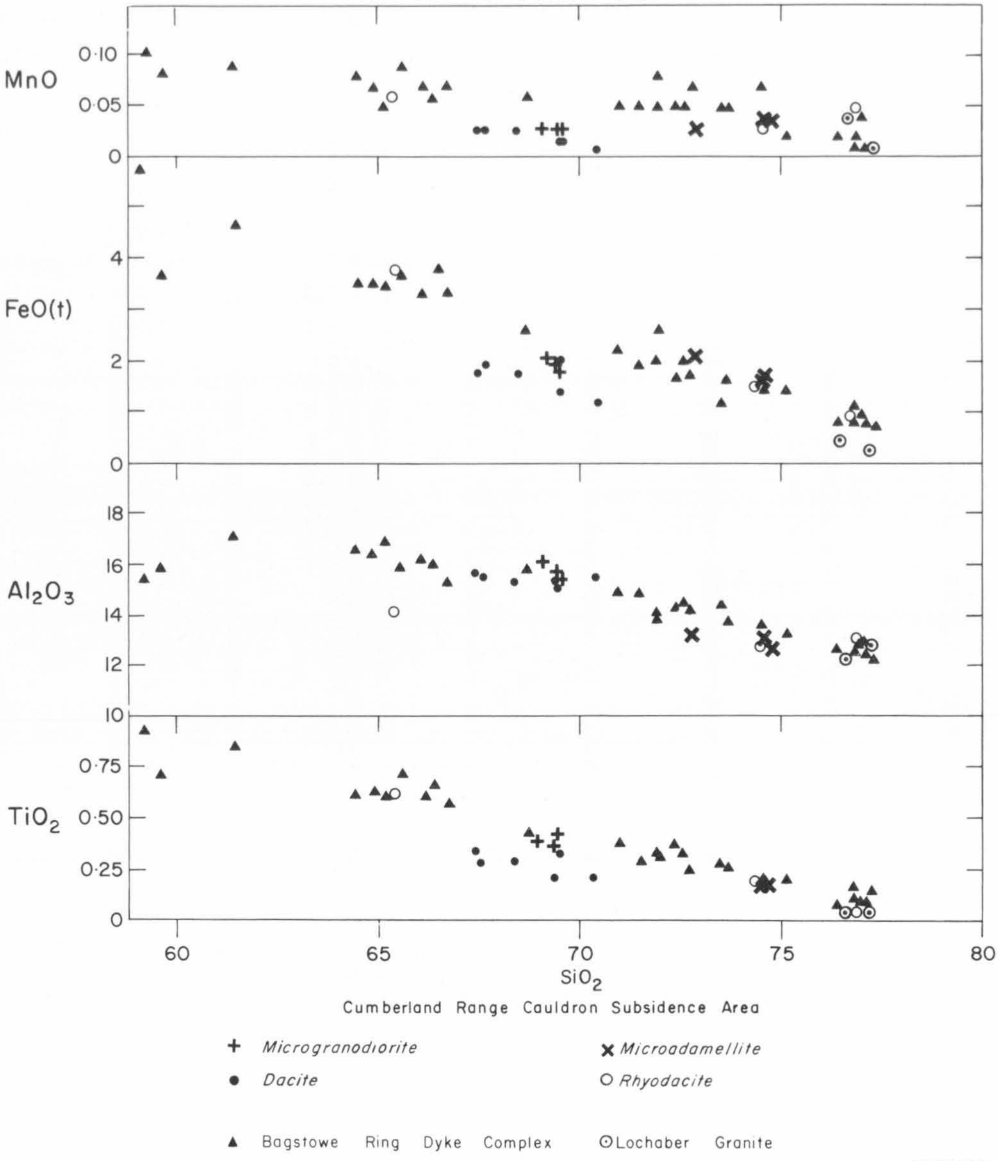


Fig. 31. Variation of major elements against silica for the rocks of the Cumberland Range Cauldron Subsidence Area and Bagstowe Ring Dyke Complex.

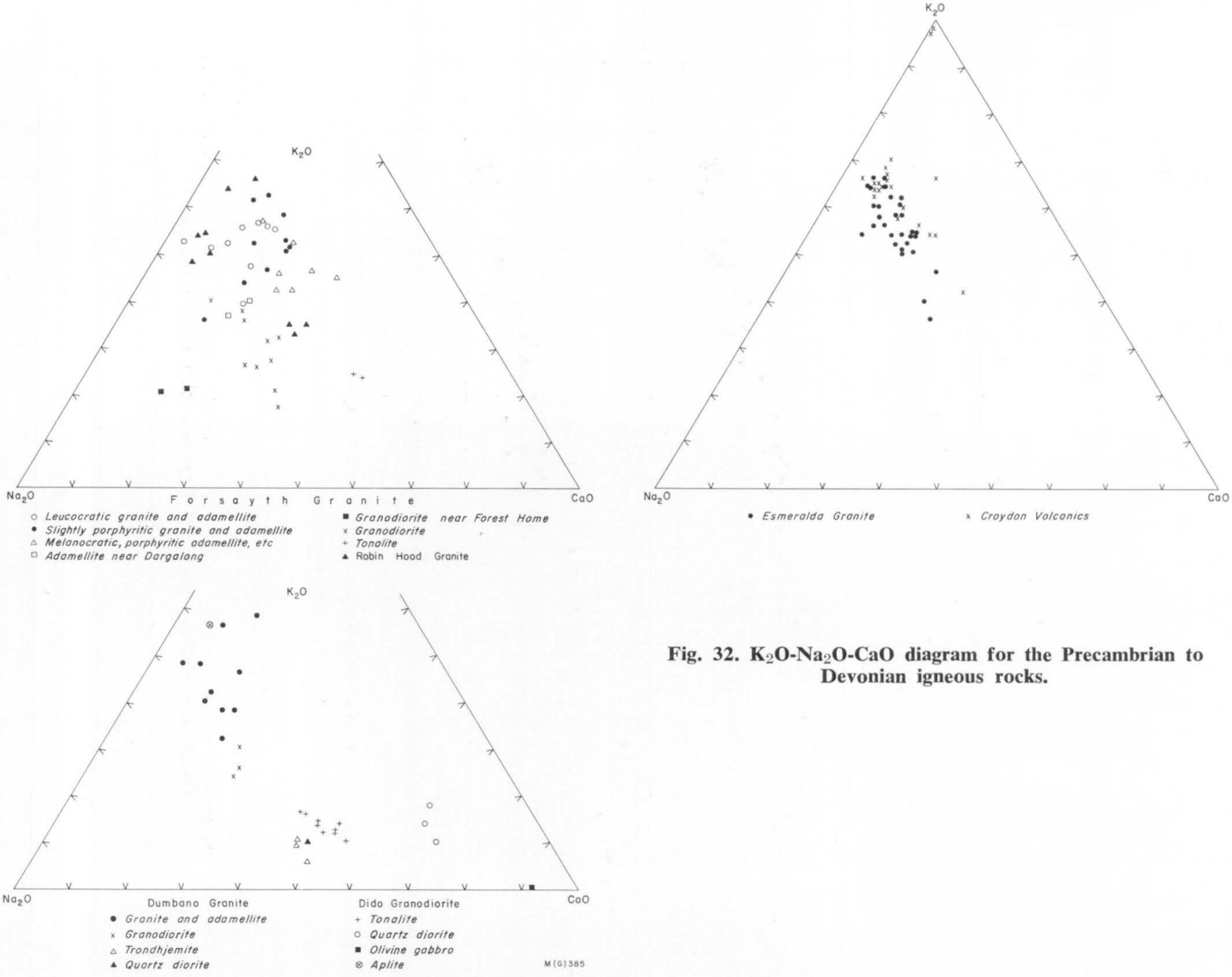


Fig. 32. K_2O-Na_2O-CaO diagram for the Precambrian to Devonian igneous rocks.

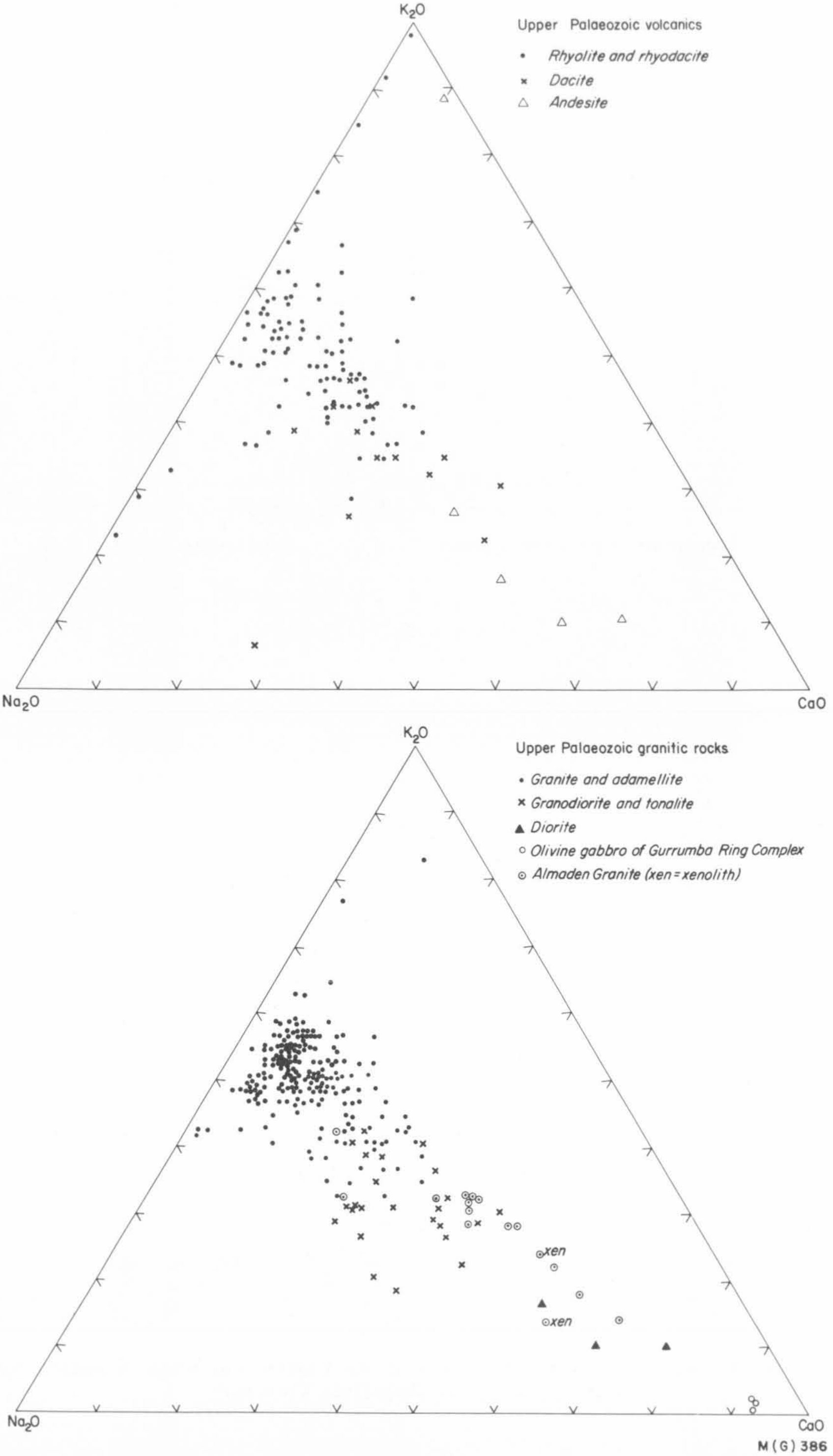
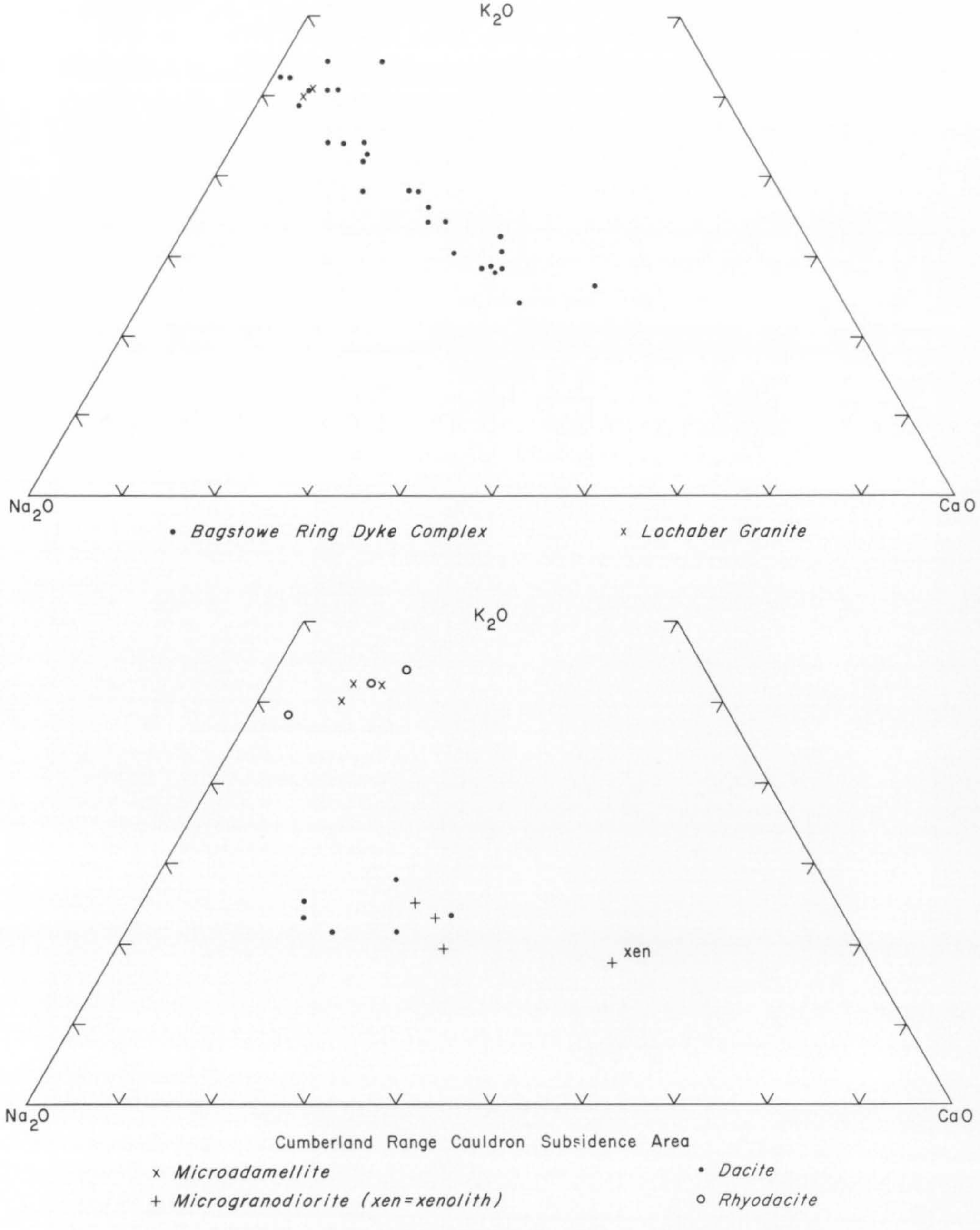
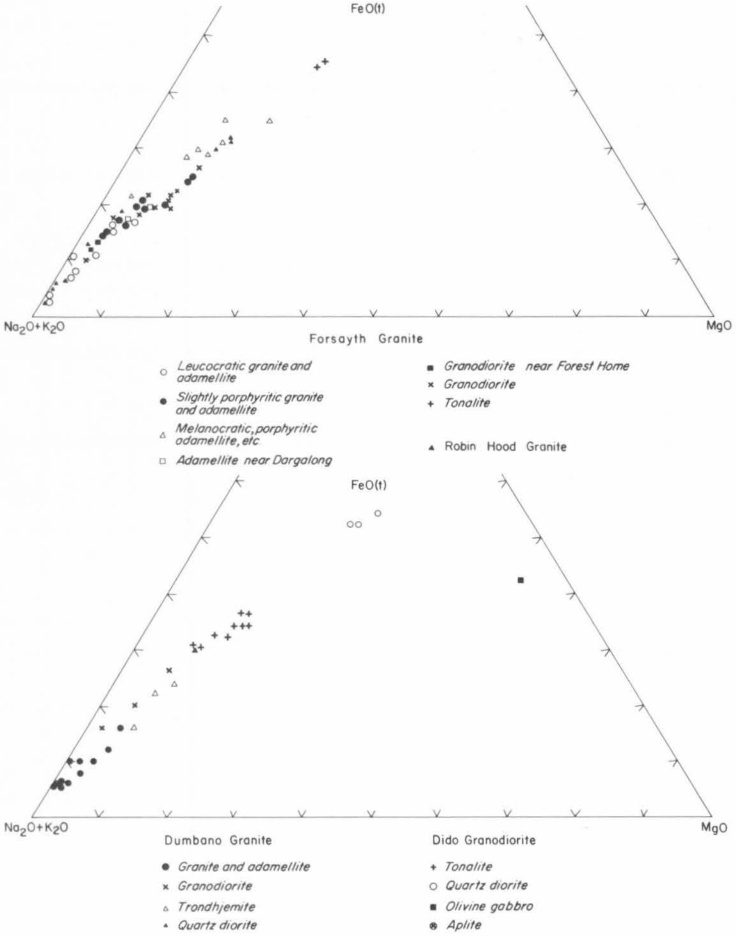


Fig. 33. K_2O-Na_2O-CaO diagrams for the Upper Palaeozoic granitic and volcanic rocks.



M(G)387

Fig. 34. K_2O-Na_2O-CaO diagrams for the rocks of the Cumberland Range Cauldron Subsidence Area and Bagstowe Ring Dyke Complex.



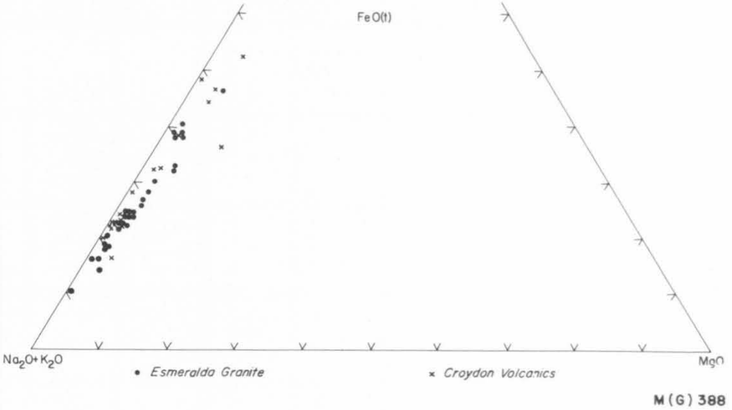


Fig. 35. FMA diagrams for the Precambrian to Devonian igneous rocks.

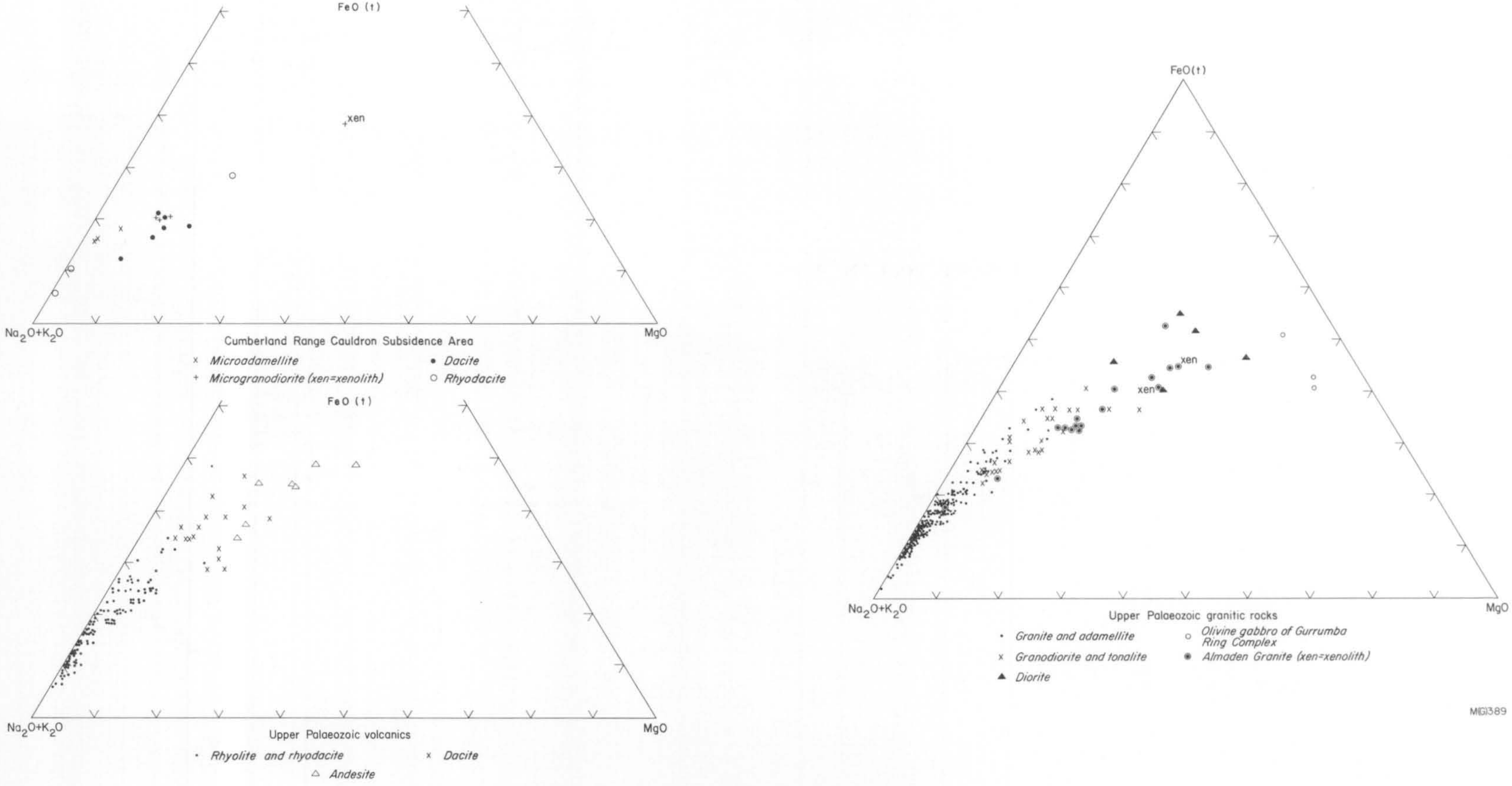


Fig. 36. FMA diagrams for the Upper Palaeozoic igneous rocks.

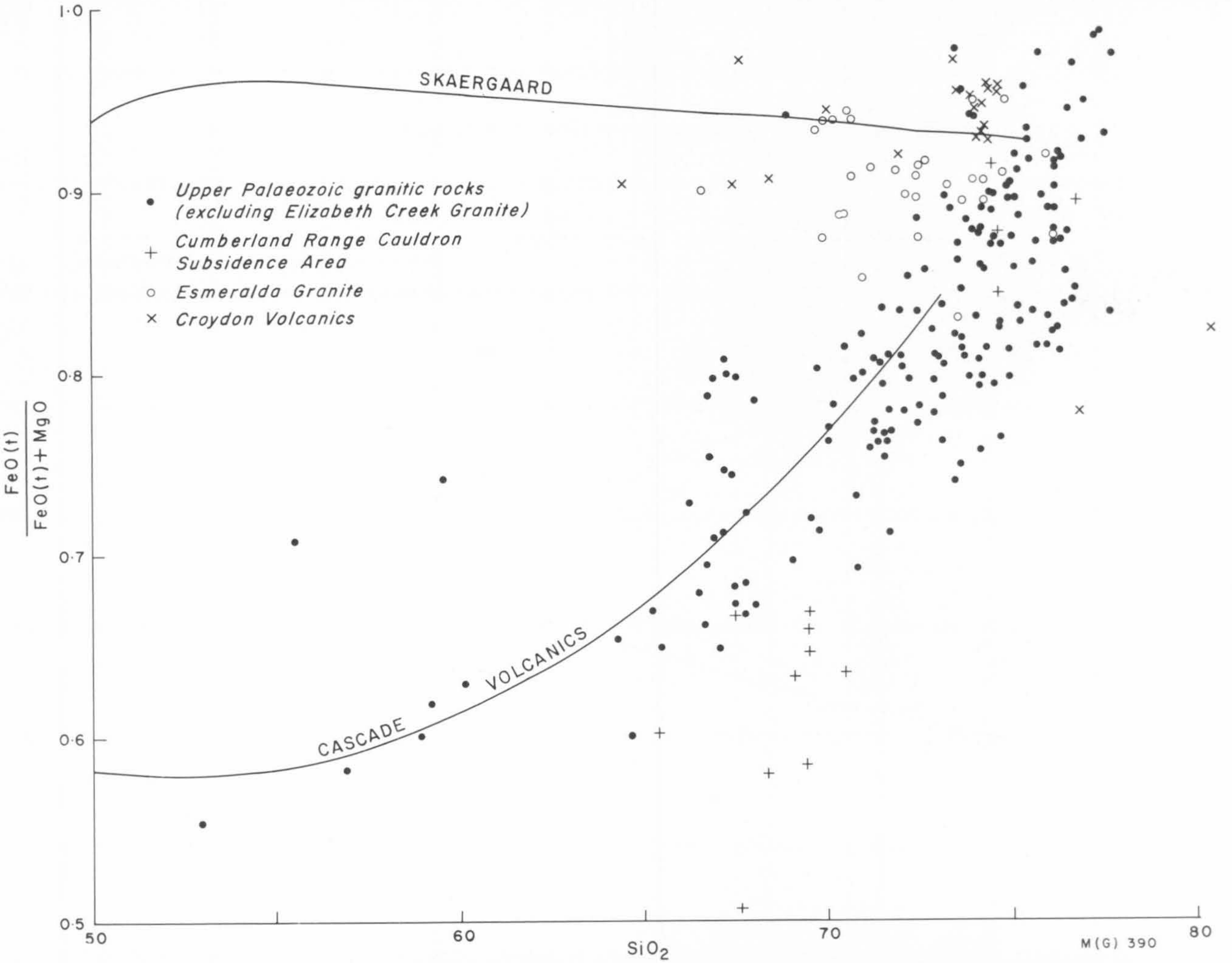


Fig. 37. Relative iron to magnesium fractionation for the Upper Palaeozoic granitic rocks, rocks of the Cumberland Range Cauldron Subsidence area, Esmeralda Granite, and Croydon Volcanics compared with the Cascade volcanics (after Carmichael, 1964) and the Skaergaard intrusion (Wager, 1960).

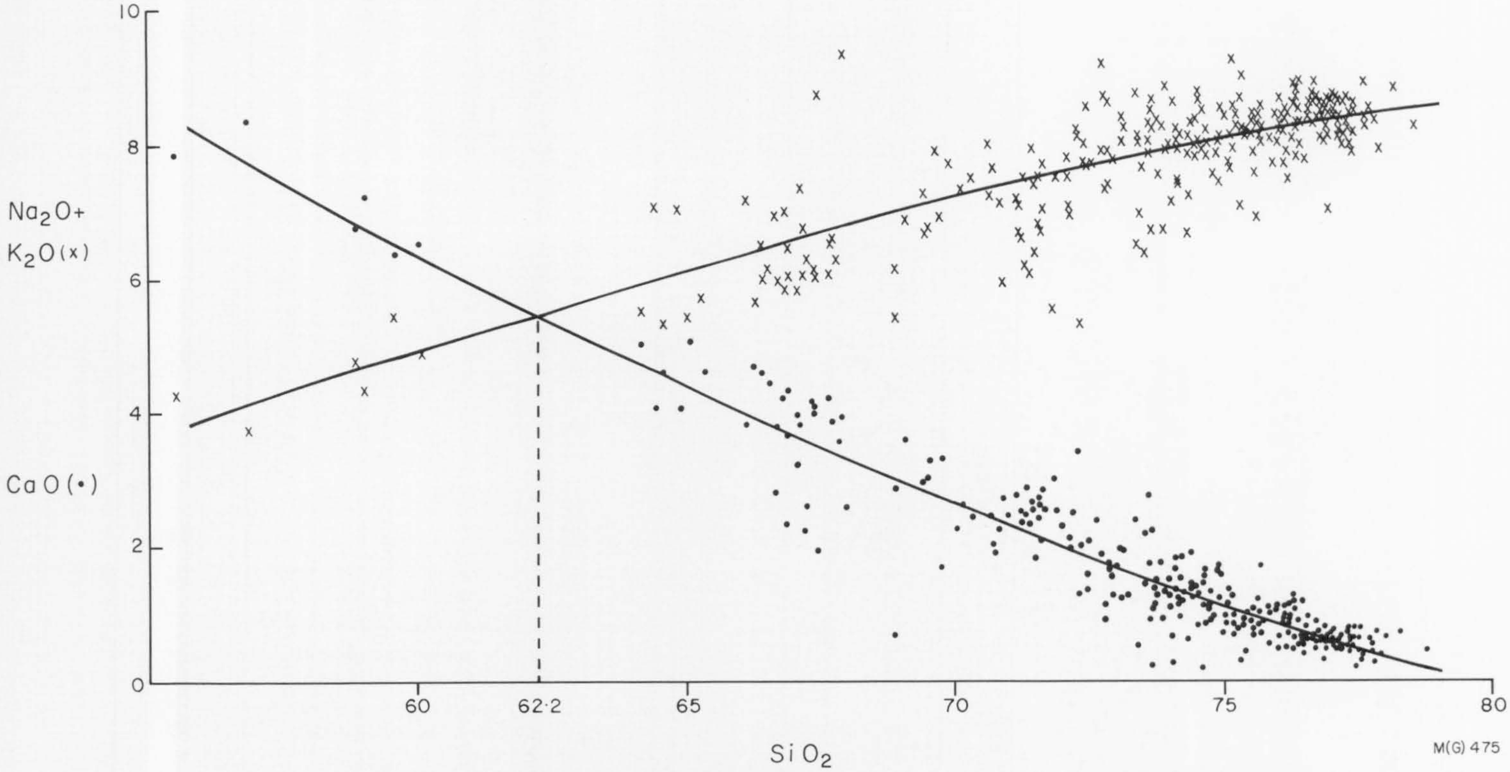


Fig. 38. Alkali-lime index for the Upper Palaeozoic granitic rocks (after Peacock, 1931).

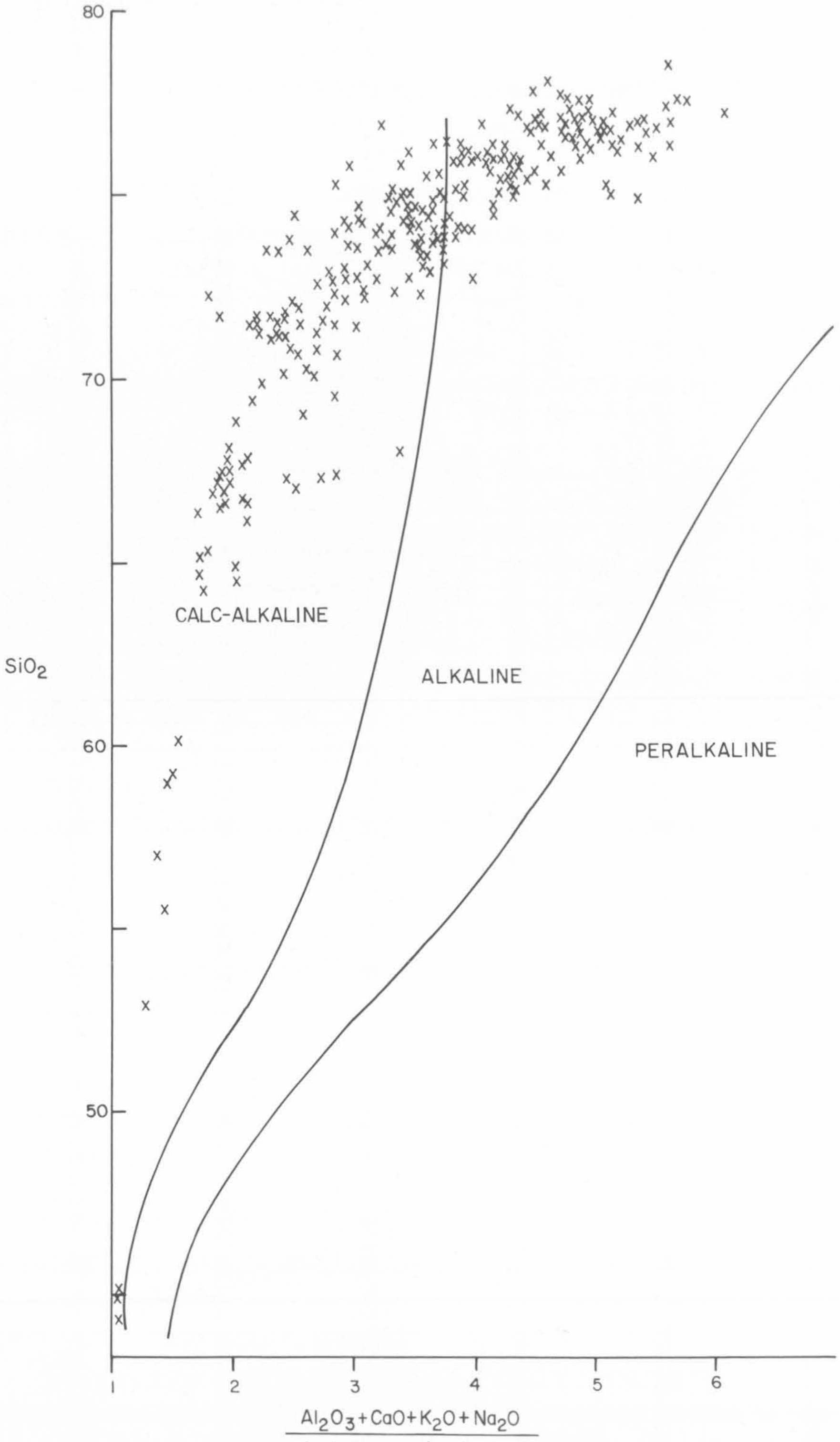
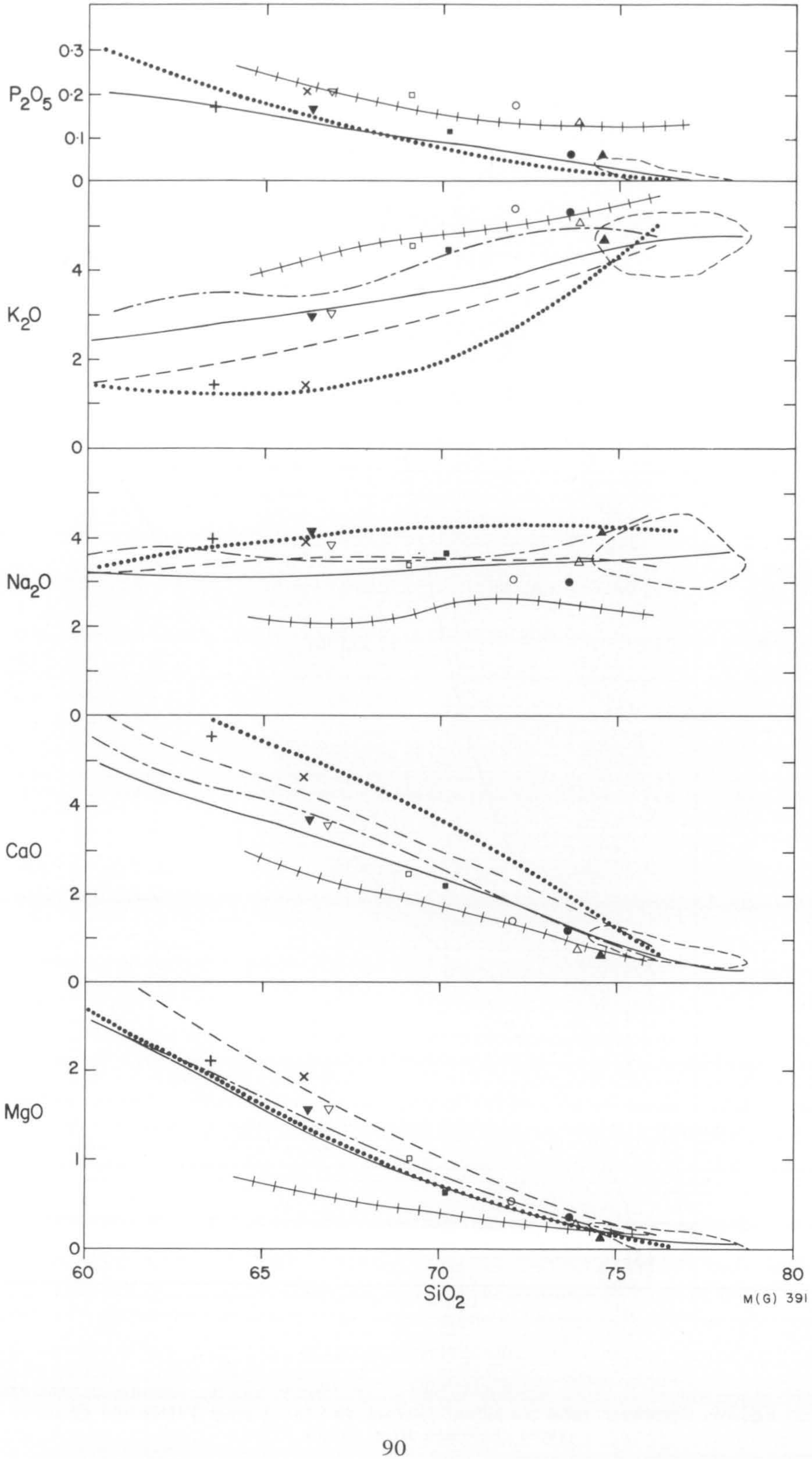


Fig. 39. Alkalinity ratio variation diagram for the Upper Palaeozoic granitic rocks (modified after Wright, 1969).


P₂O₅
0·3
0·2
0·1
0
K₂O
4
2
0
Na₂O
4
2
0
CaO
4
2
0
MgO
2
1
0
60
65
70
75
80
SiO₂
M(G) 391

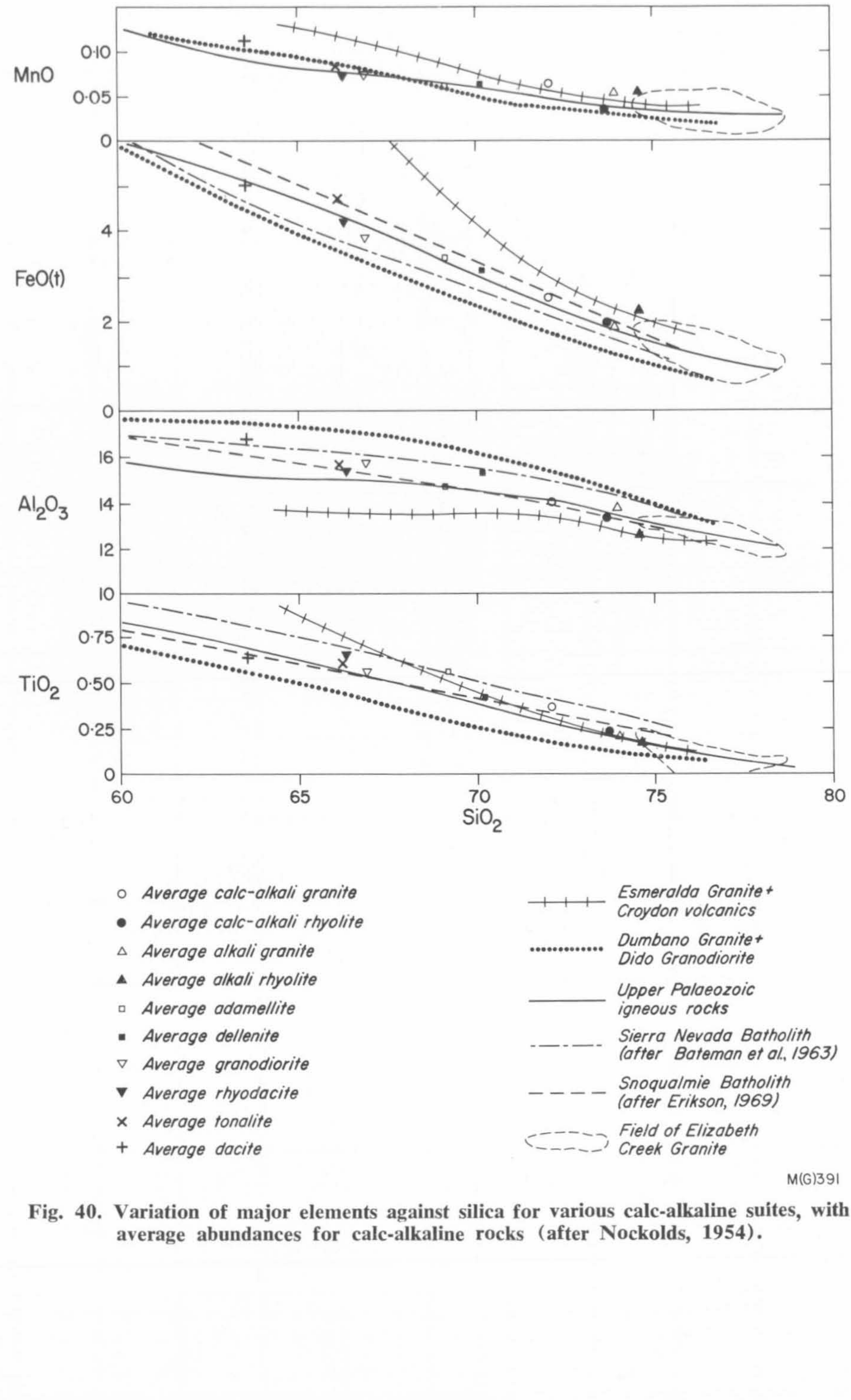


Fig. 40. Variation of major elements against silica for various calc-alkaline suites, with average abundances for calc-alkaline rocks (after Nockolds, 1954).

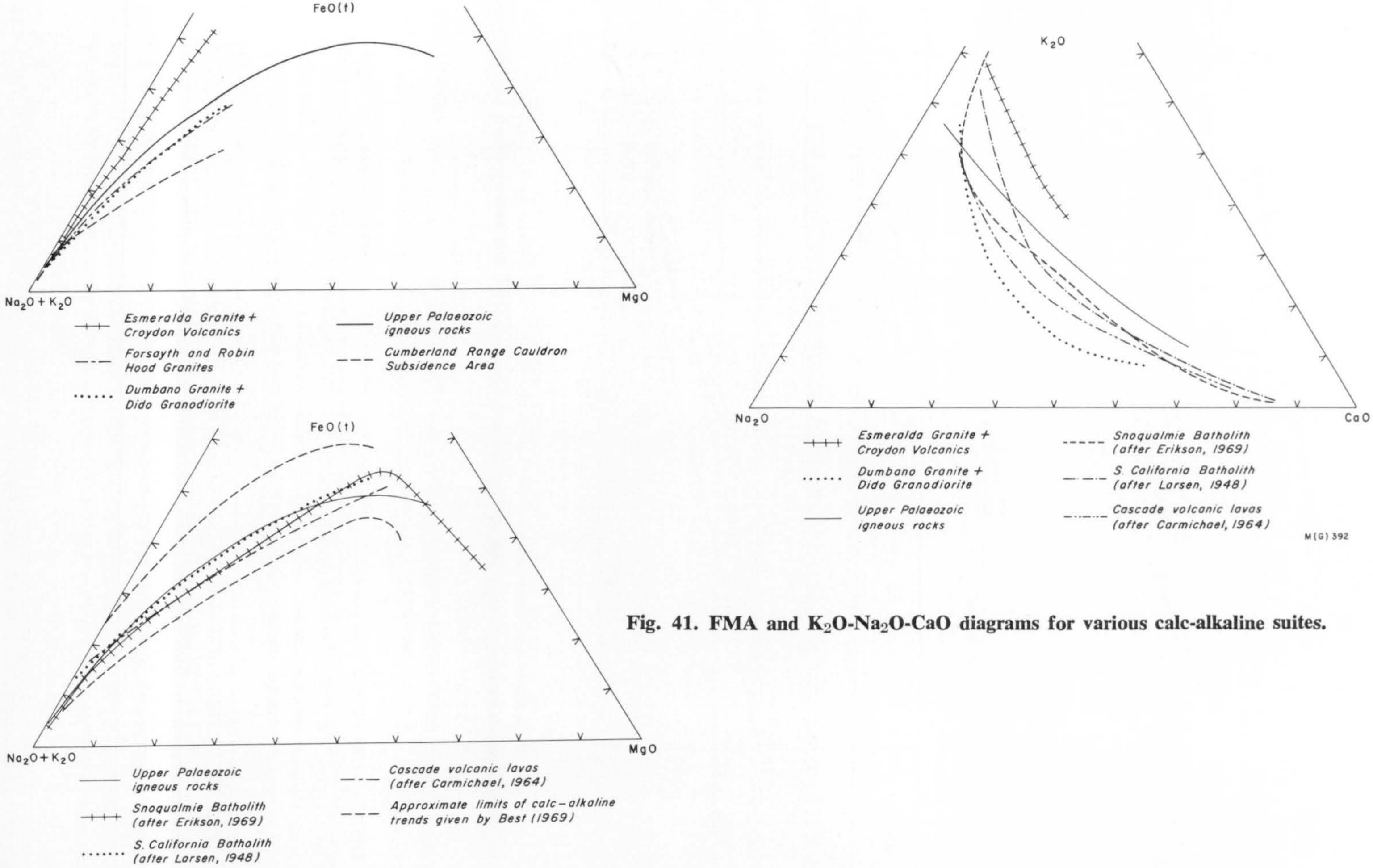
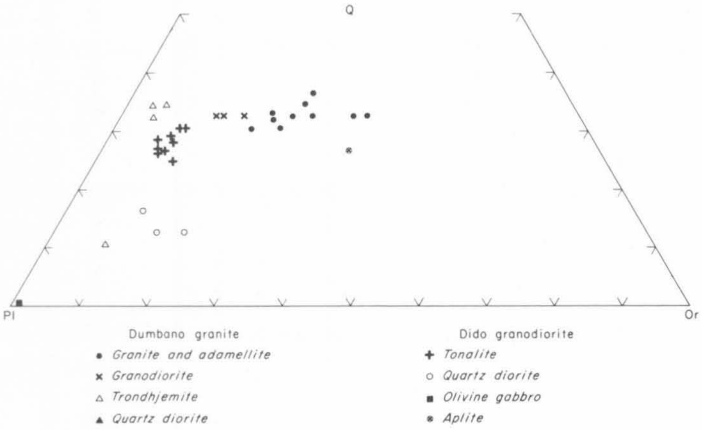
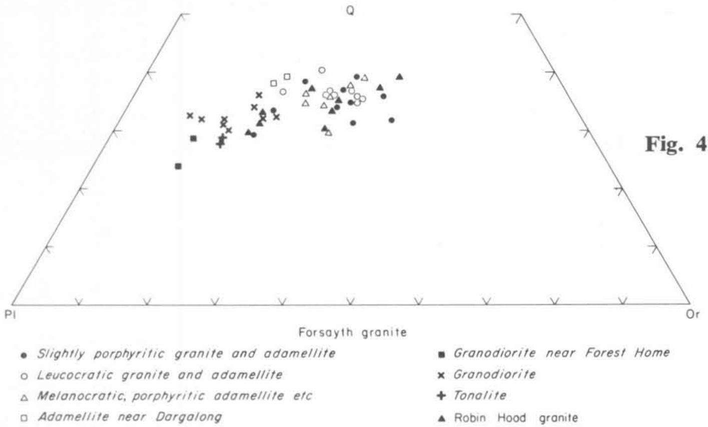


Fig. 41. FMA and K_2O-Na_2O-CaO diagrams for various calc-alkaline suites.





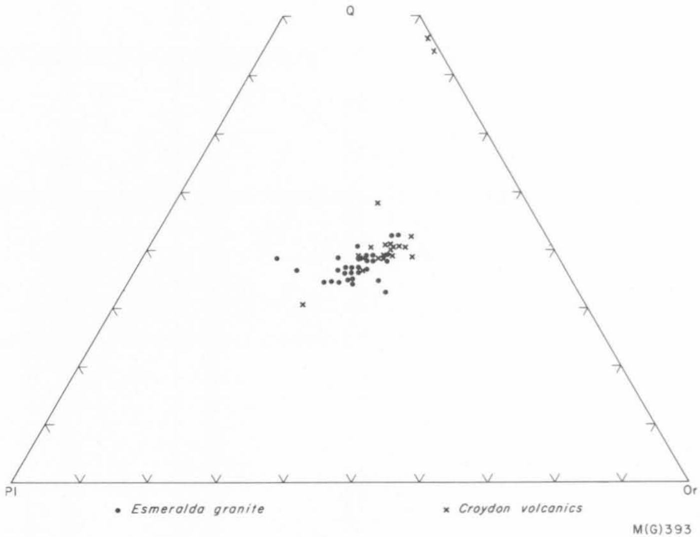
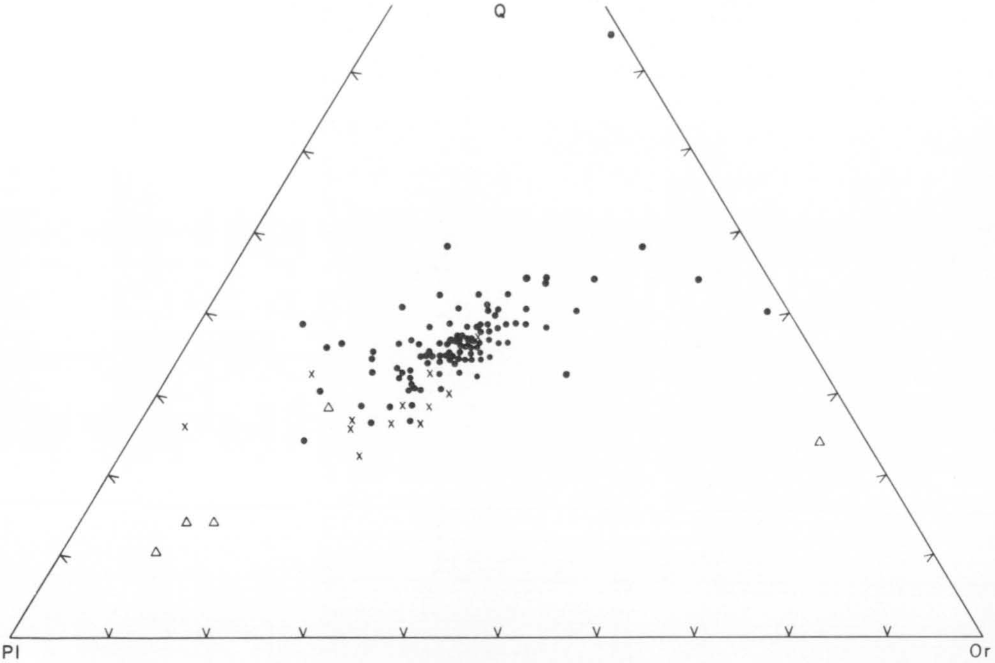
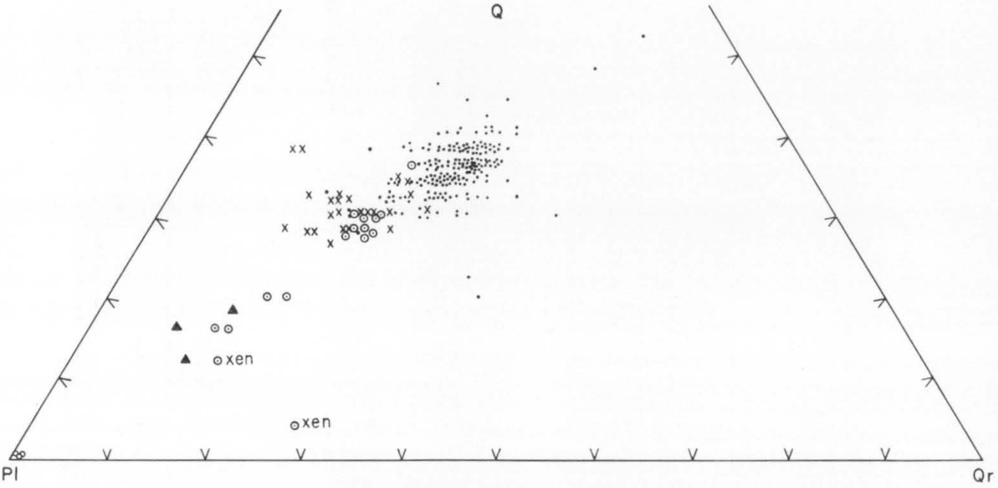


Fig. 42. Normative Q-Pl-Or diagrams for the Precambrian to Devonian igneous rocks.



Upper Palaeozoic volcanics

• *Rhyolite and rhyodacite* △ *Andesite*
× *Dacite*



Upper Palaeozoic granitic rocks

· *Granite and adamellite* ○ *Olivine gabbro of Gurrumba Ring Complex*
× *Granodiorite and tonalite* ⊙ *Almaden Granite (xen = xenolith)*
▲ *Diorite*

M(G) 394

Fig. 43. Normative Q-Pl-Or diagrams for the Upper Palaeozoic granitic and volcanic rocks.

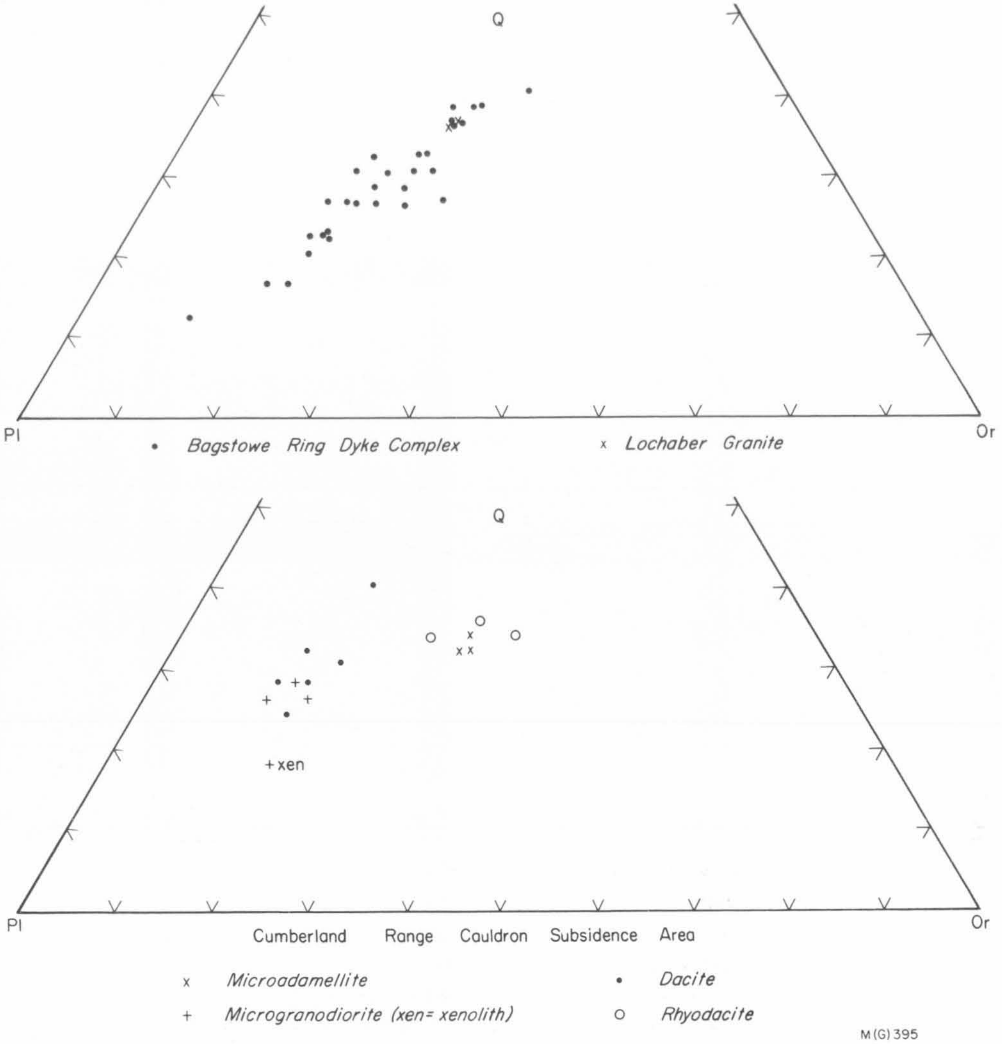


Fig. 44. Normative Q-Pl-Or diagrams for the rocks of the Cumberland Range Cauldron Subsidence Area and Bagstowe Ring Dyke Complex.

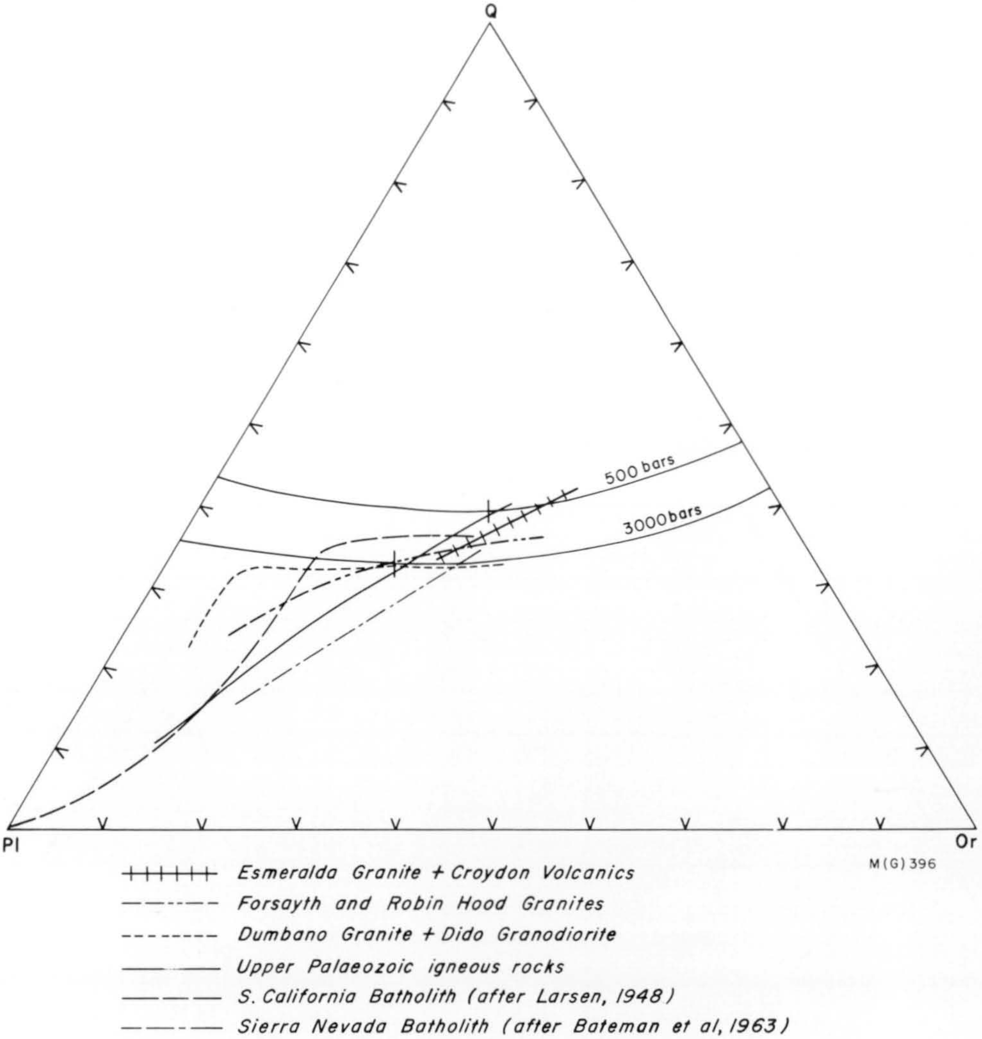


Fig. 45. Normative Q-Pl-Or diagrams for various calc-alkaline suites.

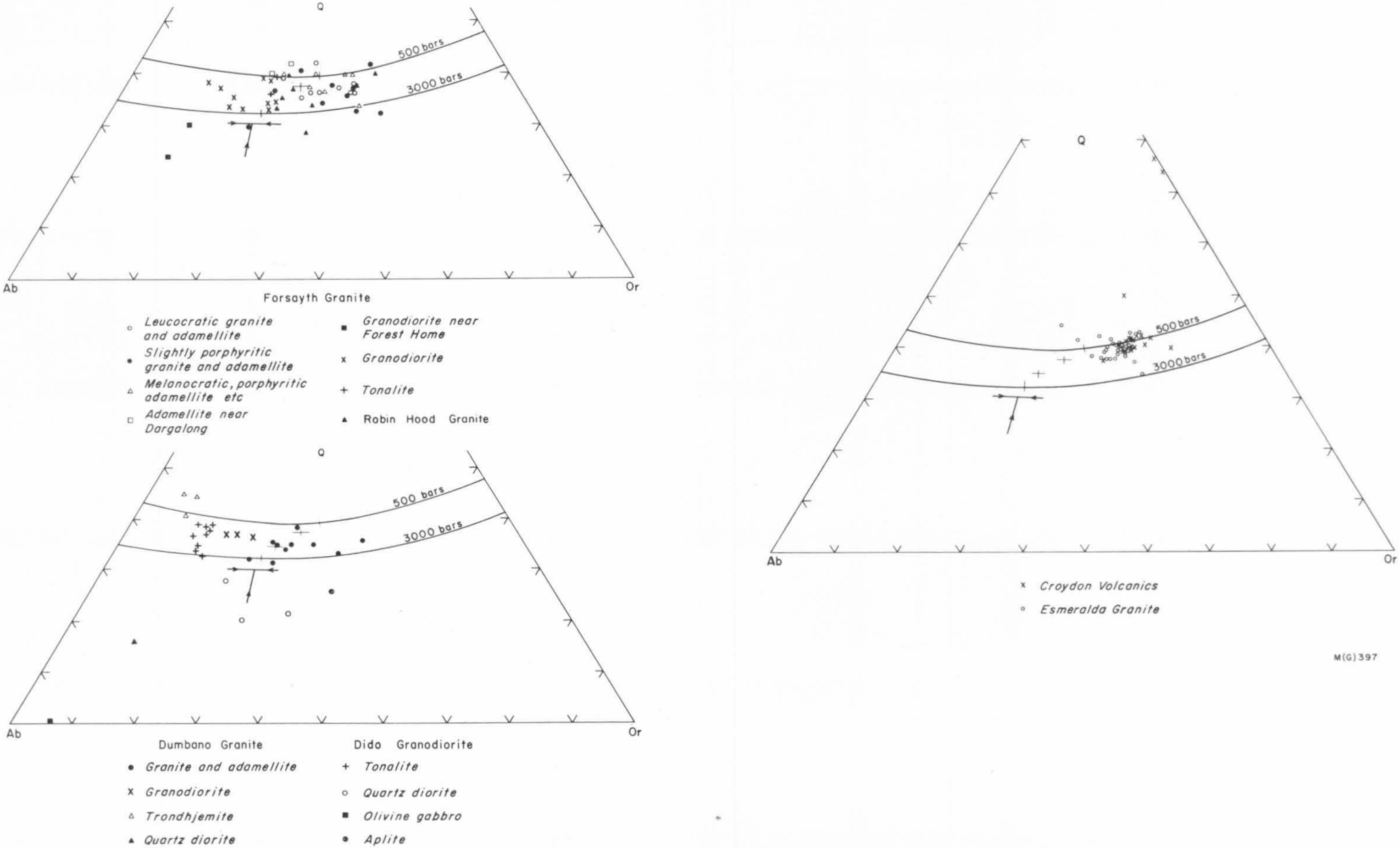
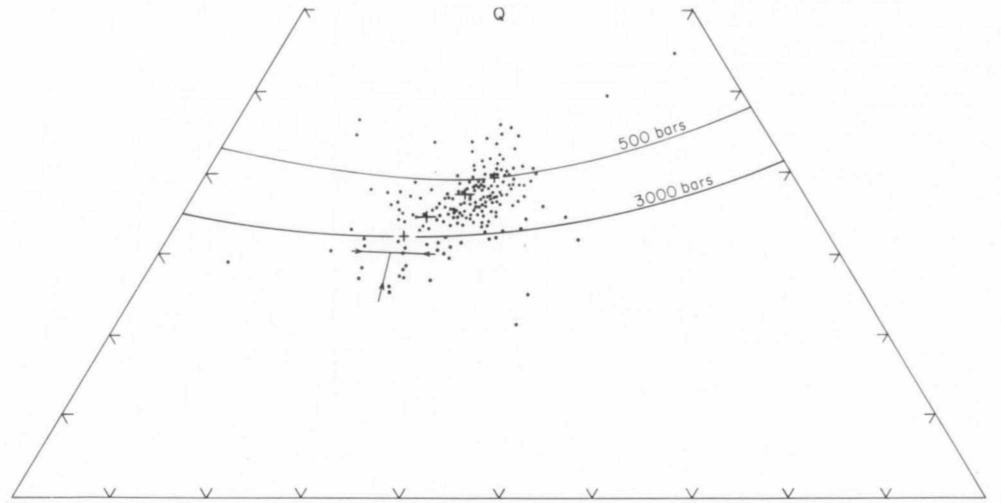
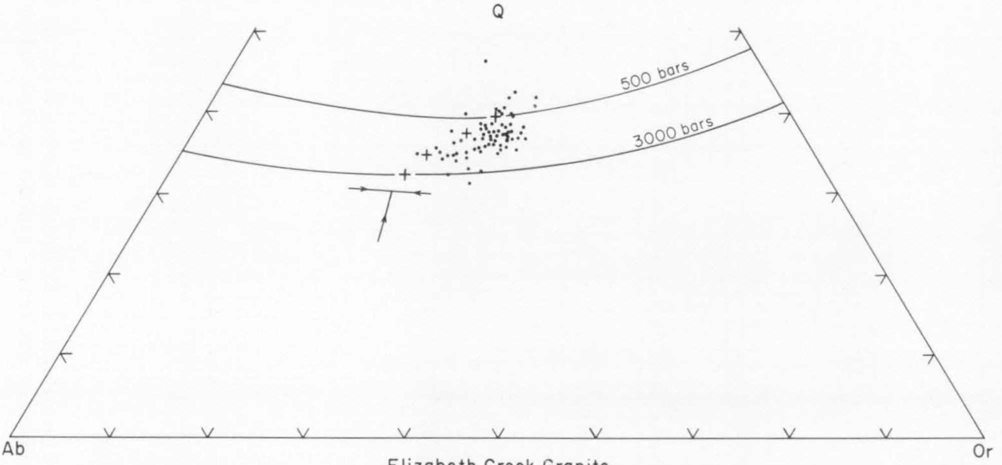


Fig. 46. Normative Q-Ab-Or diagrams for the Precambrian to Devonian igneous rocks showing quartz-feldspar field boundaries at 500 and 3000 bars P_{H_2O}, and positions of quaternary isobaric minima (after Tuttle & Bowen, 1958).



Upper Palaeozoic granitic rocks (excluding Elizabeth Creek Granite)



Elizabeth Creek Granite

Fig. 47. Normative Q-Ab-Or diagrams for the Upper Palaeozoic granitic rocks.

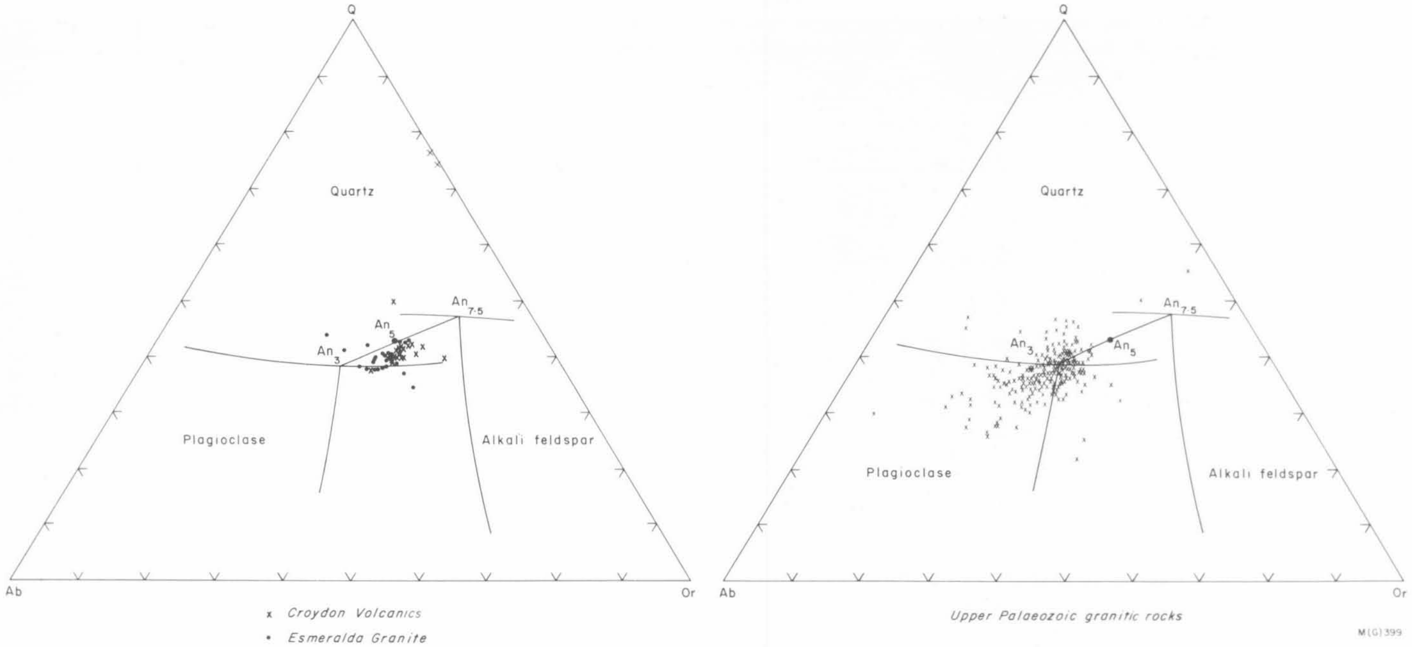


Fig. 48. Normative Q-Ab-Or diagrams for the Esmeralda Granite, Croydon Volcanics, and Upper Palaeozoic granitic rocks showing "piercing points" for the system Q-Ab-Or-An-H_2O at 1000 bars P_{H_2O}, for An contents from 3 to 7.5 percent projected onto the base of the tetrahedron (after James & Hamilton, 1969).

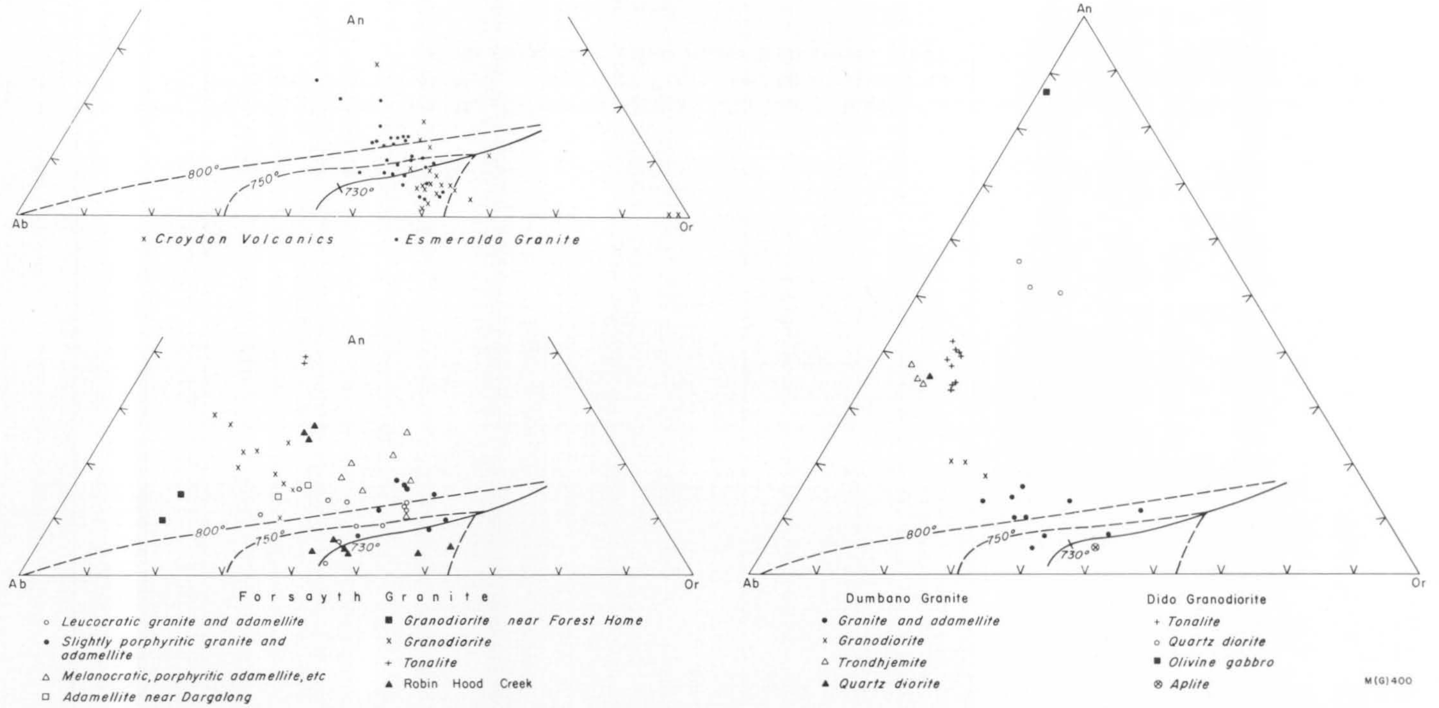
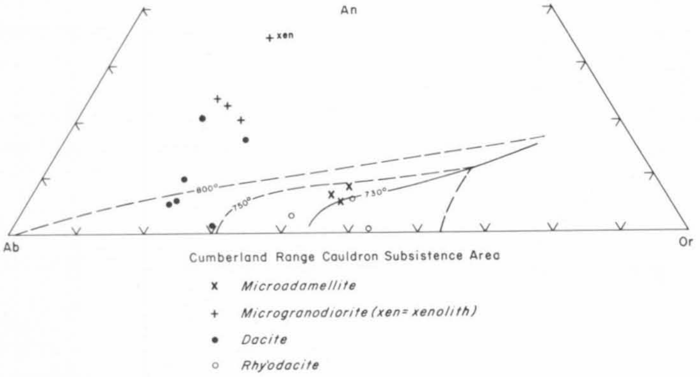
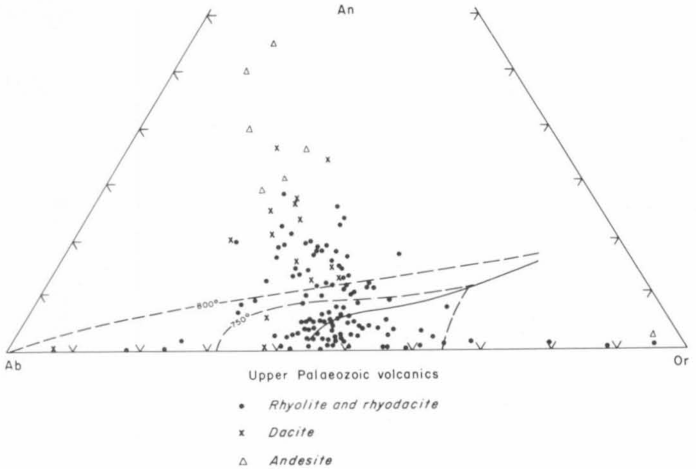


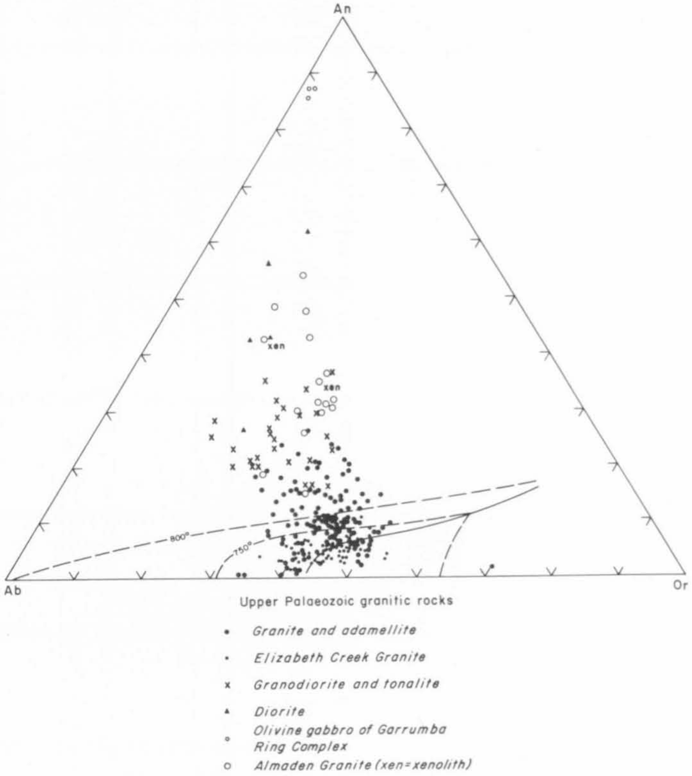
Fig. 49. Normative Ab-Or-An diagrams for the Precambrian to Devonian granitic rocks showing part of the liquidus surface of the quartz-saturated ternary feldspar system at 1000 bars P_{H_2O}, projected onto the Ab-Or-An face of the tetrahedron (after James & Hamilton, 1969).



Cumberland Range Cauldron Subsistence Area



Upper Palaeozoic volcanics



Upper Palaeozoic granitic rocks

M(G) 401

Fig. 50. Normative Ab-Or-An diagrams for the Upper Palaeozoic igneous rocks.

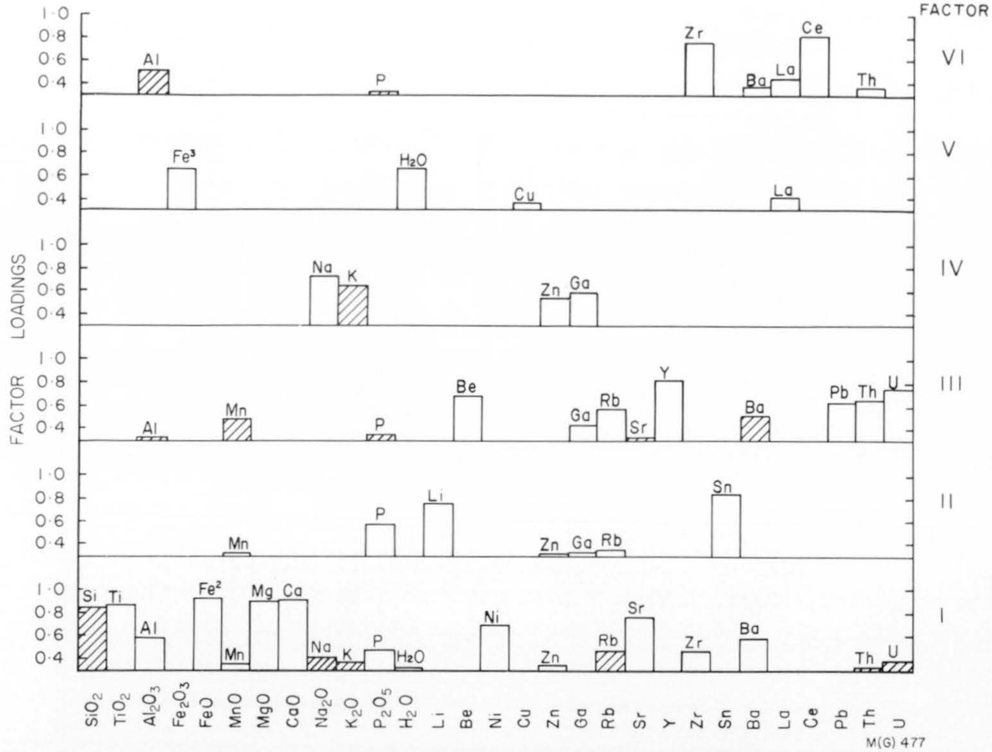


Fig. 51. Factor loadings for the Upper Palaeozoic tin-bearing granites. Shaded loadings are negative and unshaded loadings are positive; loadings with absolute values of less than 0.3 have been omitted.

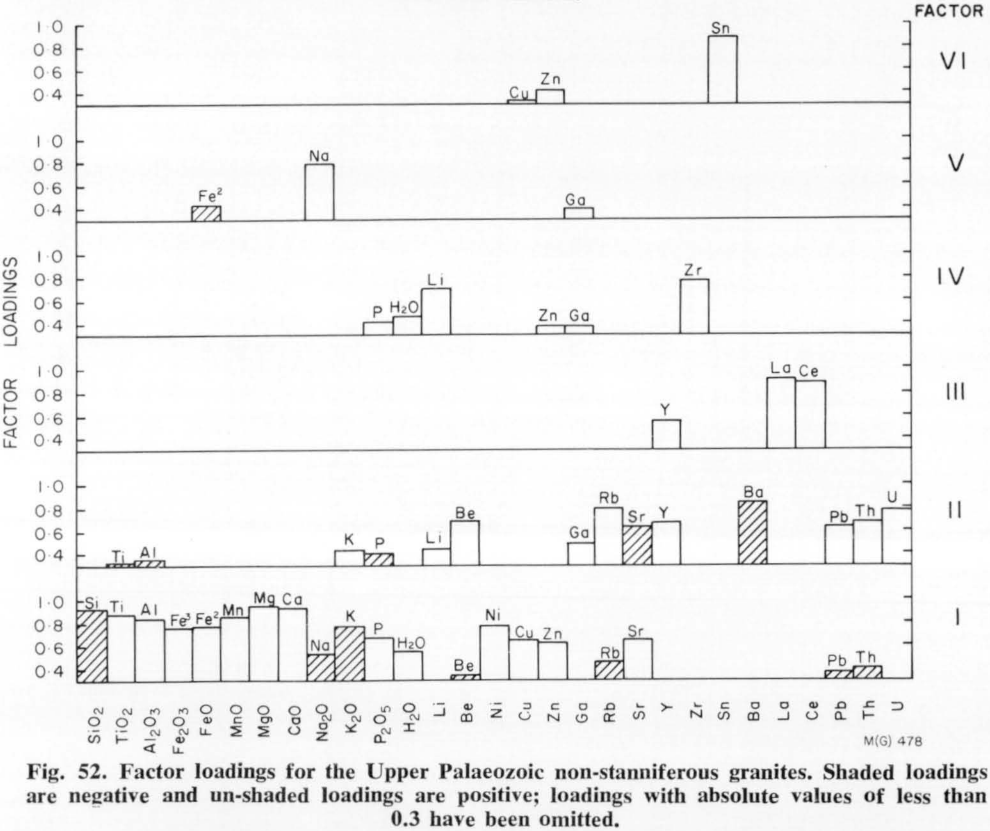


Fig. 52. Factor loadings for the Upper Palaeozoic non-stanniferous granites. Shaded loadings are negative and un-shaded loadings are positive; loadings with absolute values of less than 0.3 have been omitted.

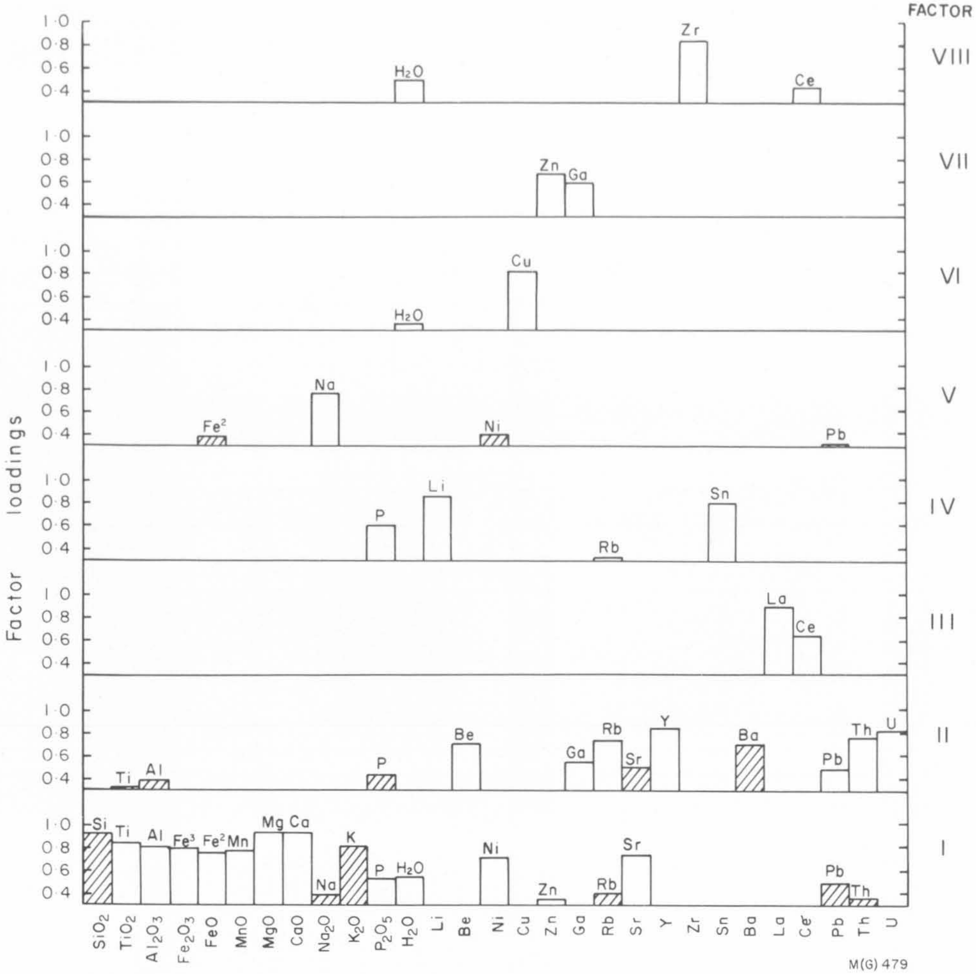


Fig. 53. Factor loadings for all the Upper Palaeozoic granitic rocks. Shaded loadings are negative and unshaded loadings are positive; loadings with absolute values of less than 0.3 have been omitted.

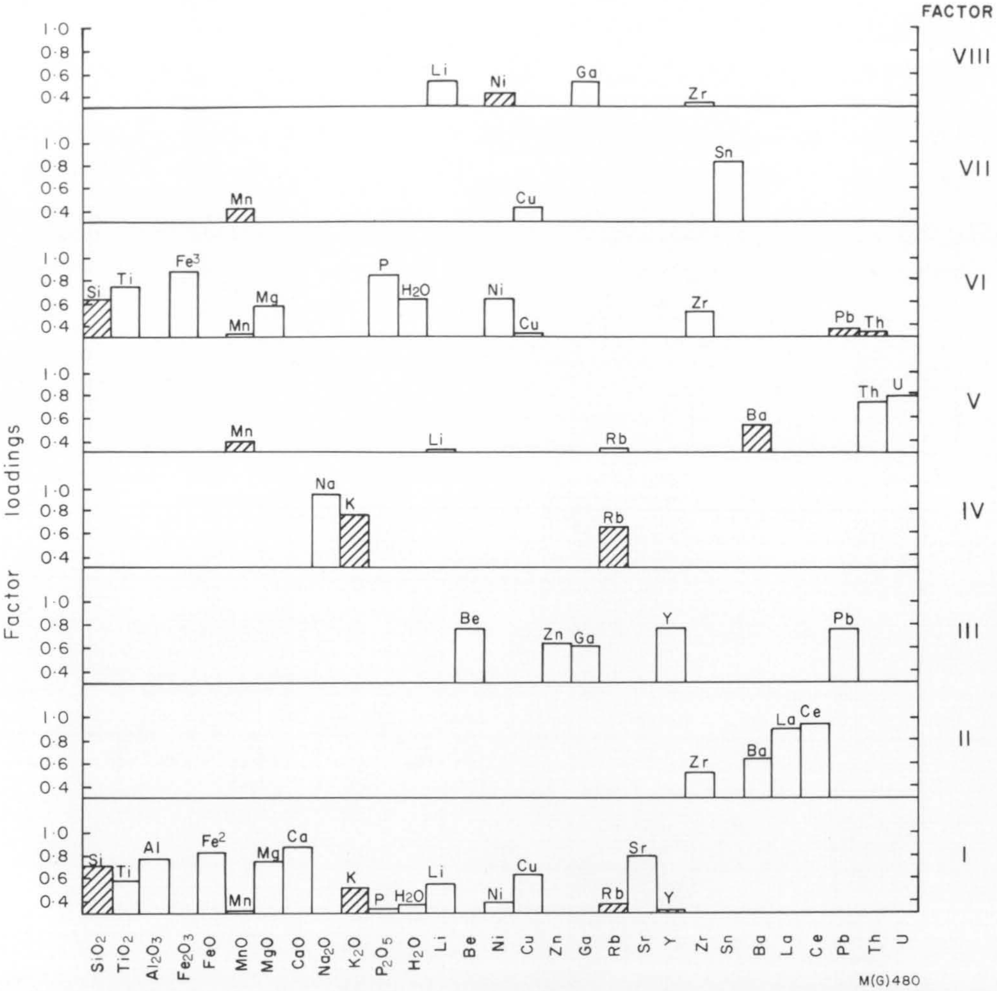


Fig. 54. Factor loadings for the Upper Palaeozoic volcanic rocks. Shaded loading are negative and unshaded loadings are positive; loadings with absolute values of less than 0.3 have been omitted.

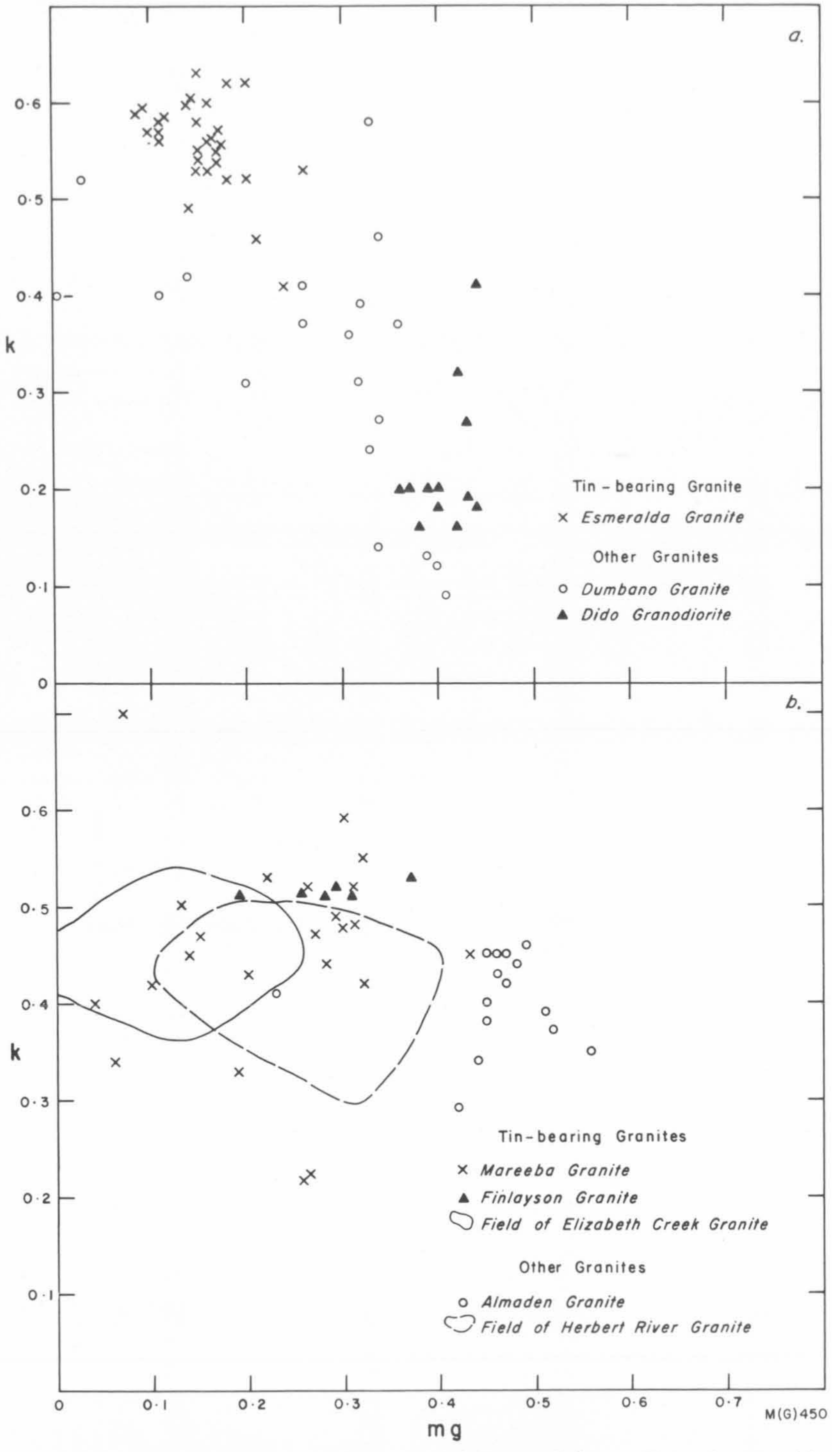


Fig. 55. Plots of Niggli k against mg: (a) Precambrian to Devonian granitic rocks (b) Upper Palaeozoic granitic rocks.

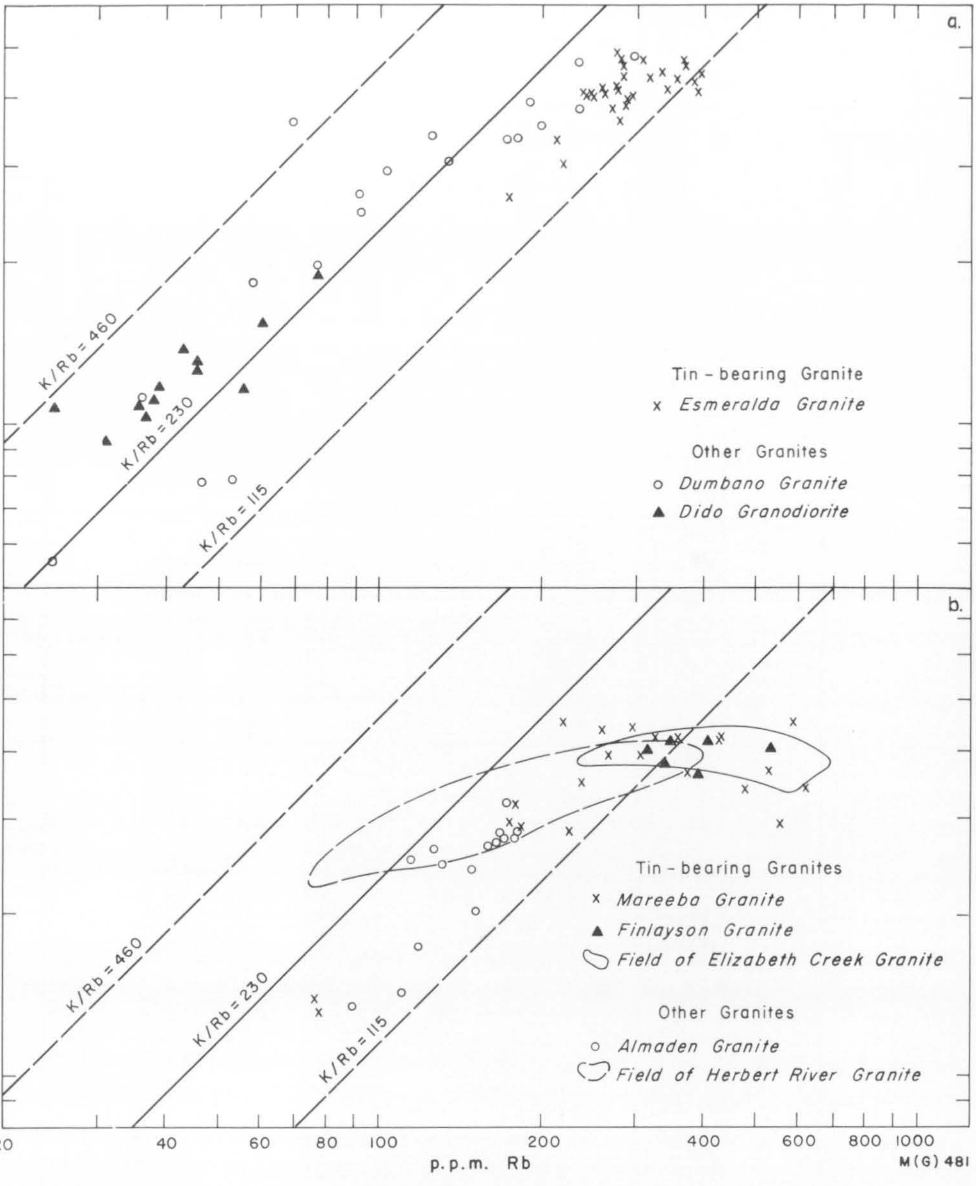


Fig. 56. Plots of K against Rb: (a) Precambrian to Devonian granitic rocks, (b) Upper Palaeozoic granitic rocks.

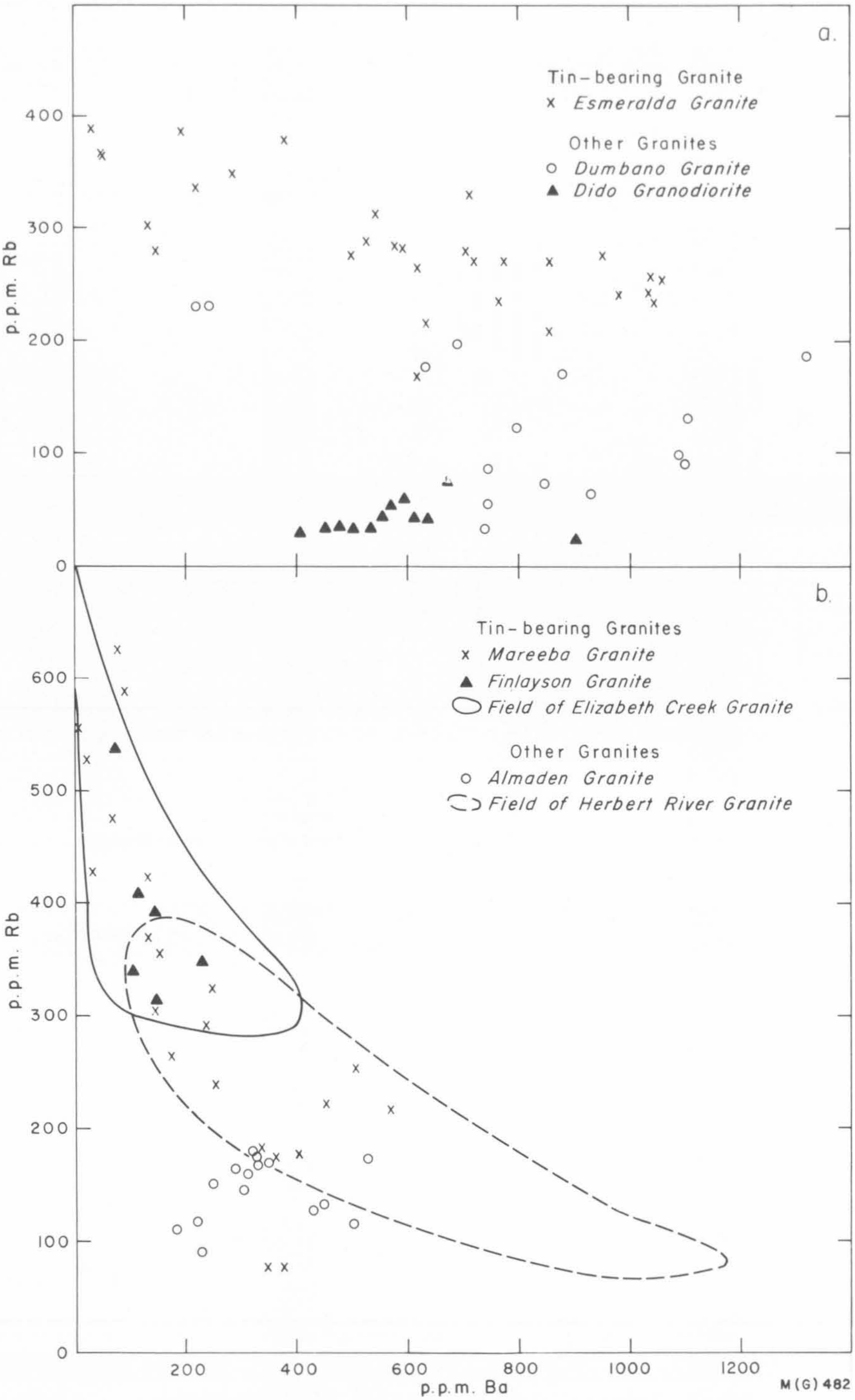


Fig. 57. Plots of Ba against Rb: (a) Precambrian to Devonian granitic rocks. (b) Upper Palaeozoic granitic rocks.

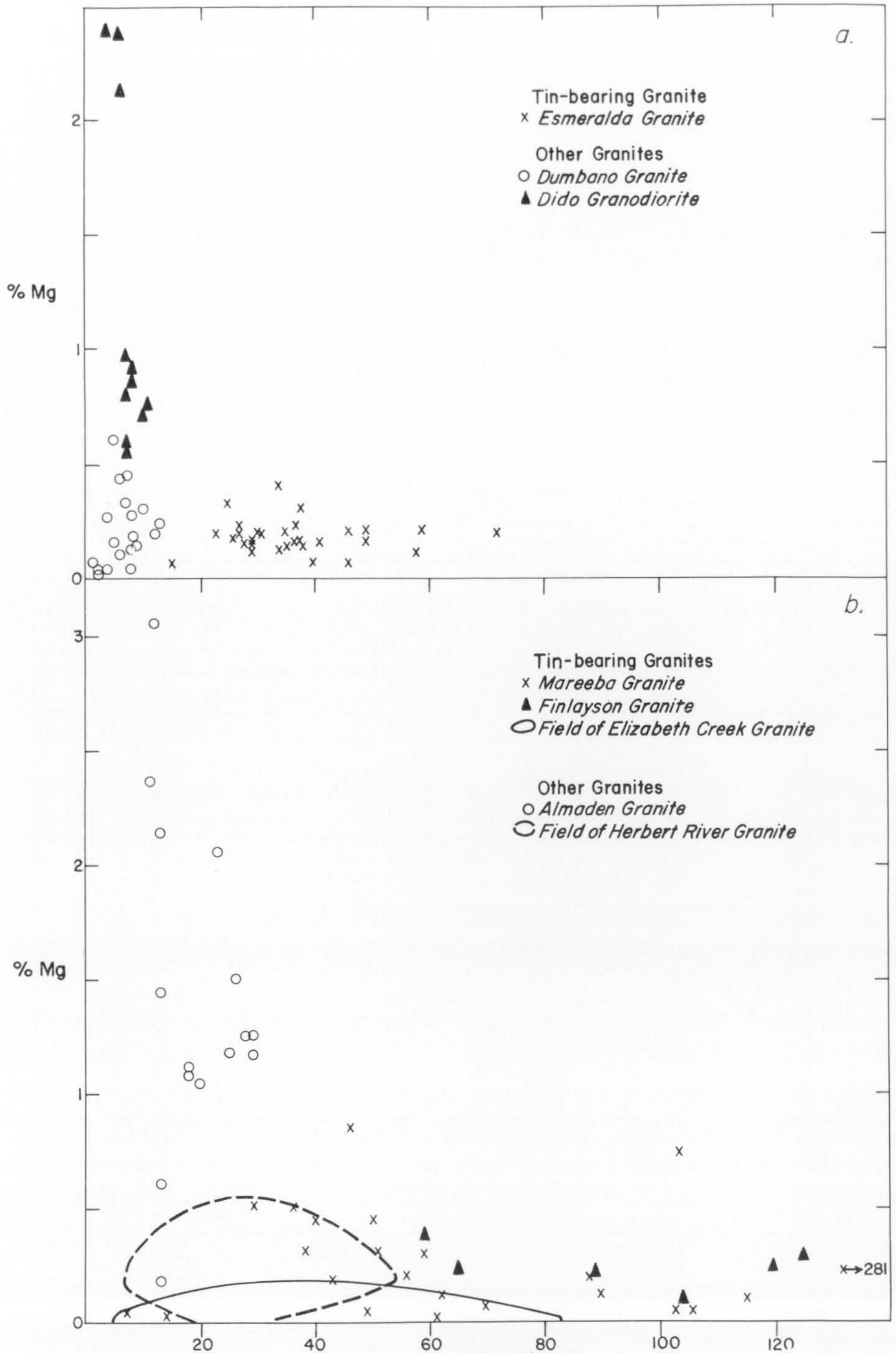


Fig. 58. Plots of Mg against Li: (a) Precambrian to Devonian granitic rocks, (b) Upper Palaeozoic granitic rocks.

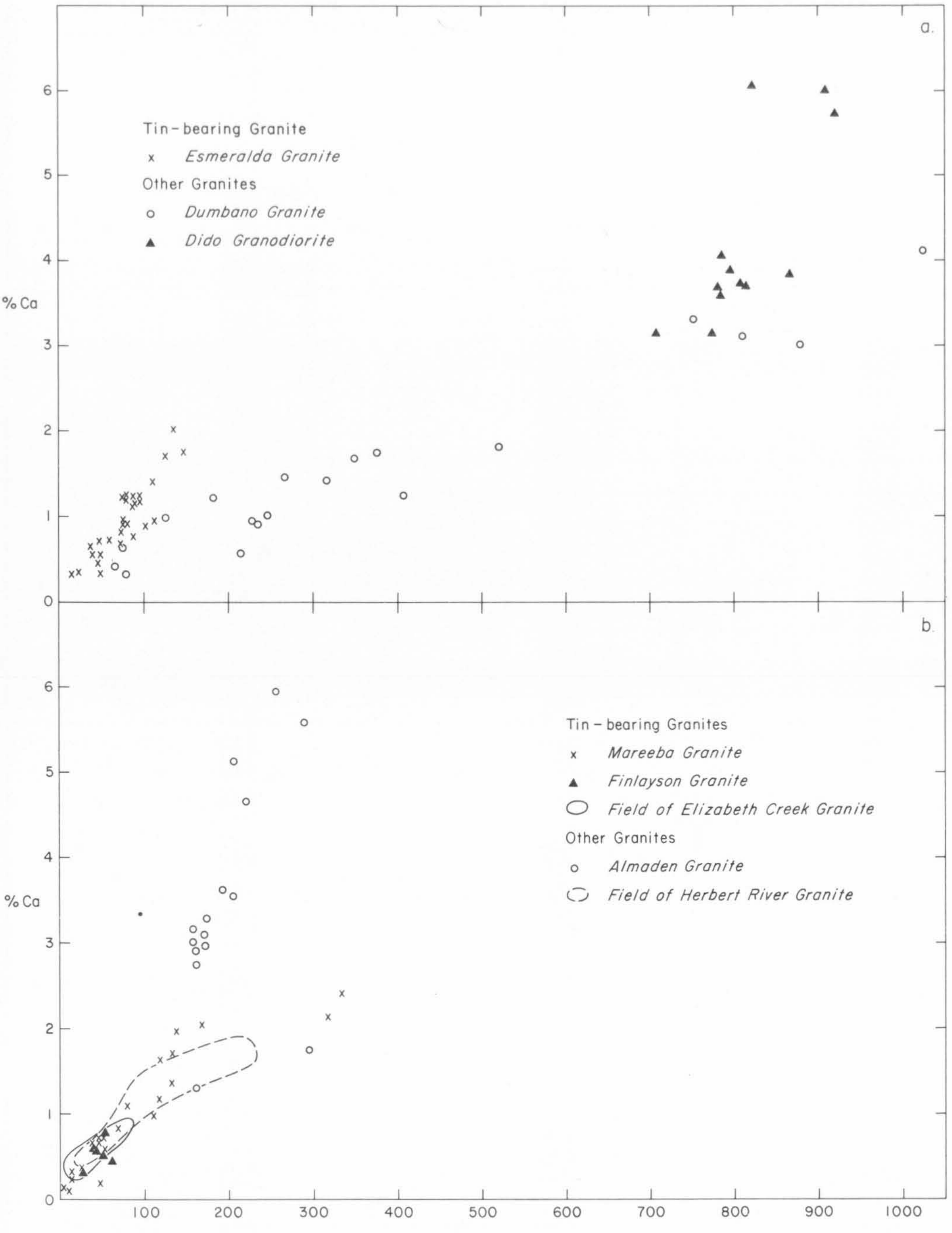


Fig. 59. Plots of Ca against Sr: (a) Precambrian to Devonian granitic rocks, (b) Upper Palaeozoic rocks.

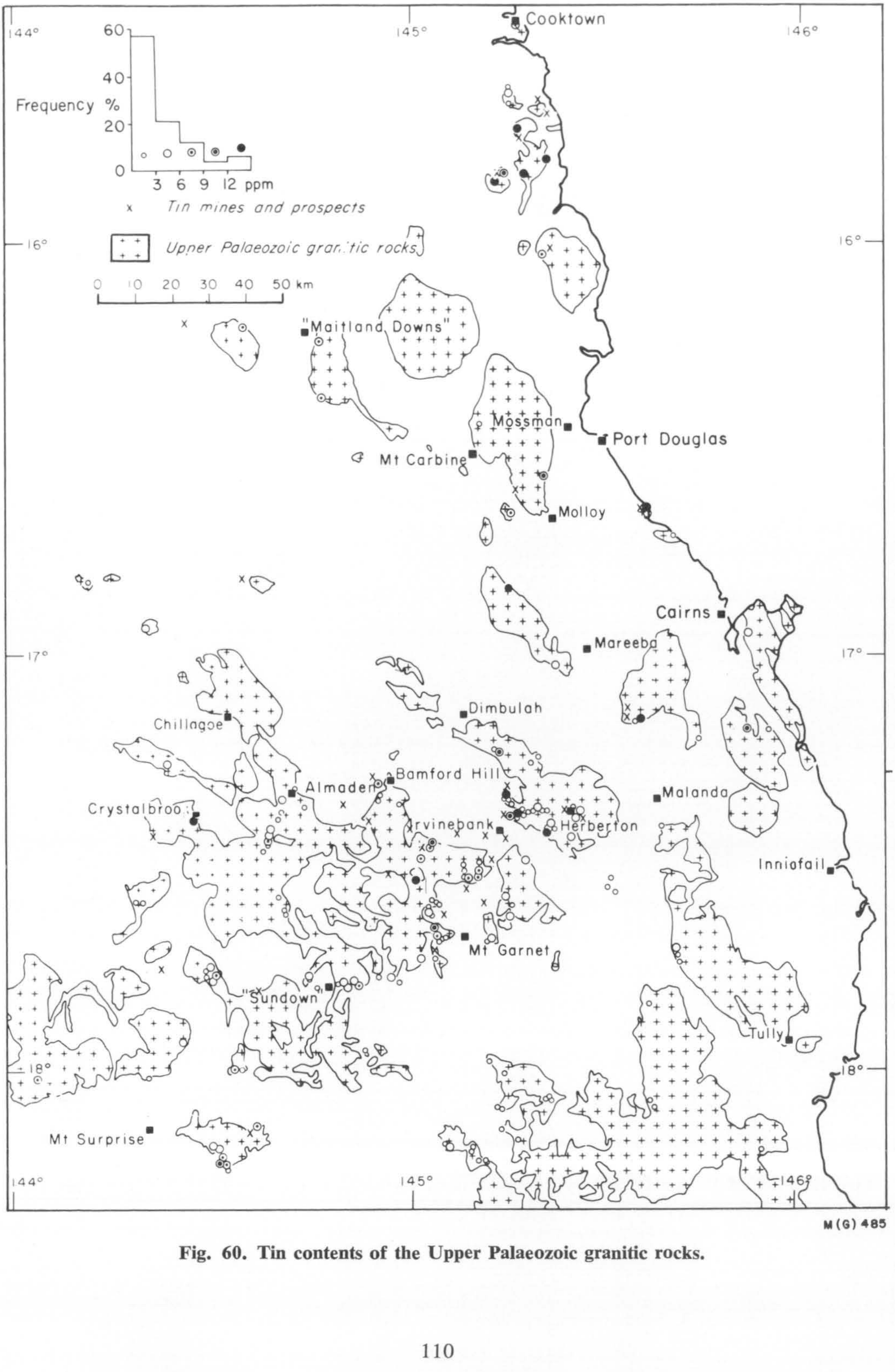


Fig. 60. Tin contents of the Upper Palaeozoic granitic rocks.

Fig. 61. Copper contents of the Upper Palaeozoic granitic rocks.

PETROGENESIS

Esmeralda Granite and Croydon Volcanics

Normative compositions have been plotted on the experimentally derived phase diagrams in the systems Q-Ab-Or-H_2O (after Tuttle & Bowen, 1958) and Q-Ab-Or-An-H_2O (after James & Hamilton, 1969).

The samples plot in a very restricted compositional field in the system Q-Ab-Or-H_2O, and tend to cluster near the quartz-feldspar field boundary at fairly low water pressures (about 500-1000 bars) (Fig. 46). Because of the high K/Na ratios of the samples, the points lie on the Or side of the ternary minimum. Figure 48 shows the relationships in the system Q-Ab-Or-An-H_2O at 1000 bars water pressure. The mean normative An content is about 4 percent, and the greatest concentration of points is near the 'piercing point' (James & Hamilton, 1969, p. 114) at An_4. The high proportion of quartz (up to 80%) in the phenocrysts of the Croydon Volcanics is consistent with the fact that many samples plot just within the quartz field (i.e. the field in which quartz is the liquidus phase). In general, the next phase to crystallize should be alkali feldspar, and finally plagioclase. The proportion of feldspar phenocrysts in the Croydon Volcanics is consistent with this, alkali feldspar being more abundant than plagioclase.

In the quartz-saturated ternary feldspar system at 1000 bars P_{H_2O}, a high proportion of rocks, including the majority of the Croydon Volcanics, fall within the alkali feldspar field (Fig. 49). Almost all the samples plot fairly close to the boundary curve. The data suggest that the Croydon Volcanics, at least, were derived by partial melting of a rather siliceous potash-rich source material. Fractionation of a more mafic parent magma would not give liquids of compositions which plot in the alkali feldspar field (unless extensive contamination with potash-rich material is involved), because once the univariant boundary curve between quartz and two feldspars is reached, three phases crystallize simultaneously and the liquid composition will move along the univariant curve towards the minimum. In other words, the boundary curve cannot be crossed during the normal course of fractional crystallization, although late-magmatic or post-magmatic metasomatic processes can, of course, lead to extreme enrichment. There is no evidence for such alteration in the majority of the Croydon Volcanic samples, and two altered volcanic rocks show, if anything, depletion in K. The chemical similarities between the intrusive and extrusive rocks strongly suggest that they have a common origin and it is probable that the Esmeralda Granite magma was derived by a slightly greater degree of partial melting than the Croydon Volcanic magma. The alternative explanation, that the Croydon Volcanic magma was derived by fractionation of Esmeralda Granite magma, is not considered likely, because the majority of the granite samples plot within the plagioclase field on the Ab-Or-An diagram and fractionation could not produce a liquid as potash-rich as the Croydon Volcanic magma. In any case, the Croydon Volcanics have a rather less fractionated trace element chemistry than the granitic rocks. Once a liquid has reached the unvariant boundary curve, assimilation of significant quantities of potash-rich material is also most unlikely because this would actually raise the melting point of the magma.

The most probable source materials for the Esmeralda-Croydon magma are sialic crustal rocks, fairly rich in K and with high Fe/Mg ratios (see p. 29). The Stockyard Creek Siltstone contains a high proportion of normative quartz and has a high K_2O/Na_2O ratio, but Na_2O and CaO contents are too low for it to be, by itself, a suitable source material. A series of arenaceous sediments, with associated carbonaceous shales similar to the Stockyard Creek Siltstone, or, more probably considering the depth of granitic magma formation, their metamorphosed equivalents, would appear to be the most likely parent material. A proportion of carbonaceous sediments is assumed to have been present because of the relatively abundant graphitic xenoliths in both the Croydon Volcanics and the Esmeralda Granite. These are not, in the main, considered to have been derived from assimilated sediments for reasons given above.

The oversaturation in alumina also suggests an origin from corundum normative sediments or metasediments (Luth et al., 1964; Kleeman, 1965). All the analysed samples are corundum normative, most containing between 1 and 2 percent. Isotopic data are consistent with a predominantly crustal origin for the magmas, initial $^{87}Sr/^{86}Sr$ ratios being about 0.73 (Webb, 1971; Black, 1973). Fractionation of an intermediate or basic parent magma cannot explain the chemical features of the rocks, which belong to the S-type granites (derived by partial melting of sedimentary source materials) of Chappell & White (1974).

The suggested rather low water pressure (less than about 1000 bars) during crystallization is consistent with the shallow depth of emplacement of the Esmeralda Granite, deduced to be between 300 and 600 m by Branch (1966). The negative PT slope of the wet melting curve of granite limits the degree of upward movement of granitic magma formed at particular water pressures and means that only relatively dry magmas can rise into the upper levels of the crust or be erupted as a liquid (Luth, 1969; Cann, 1970).

Forsayth and Robin Hood Granites

The extreme chemical heterogeneity of the Forsayth and Robin Hood Granites makes any generalizations concerning their petrogenesis difficult. In the system Q-Ab-Or-H_2O, most samples plot between the quartz-feldspar boundaries (the 'thermal trough') at 500 and 3000 bars water pressure (Fig. 46). The overall trend is roughly parallel to the boundary curves. Most of the adamellites and granites lie on the Or side of the ternary minima and the granodiorites plot on the Ab side. The three main varieties in the Forsayth area, defined on the basis of petrographic characteristics, do not plot as separate groups on the Q-Ab-Or diagram and there is considerable overlap of the compositional fields. The leucocratic and melanocratic porphyritic types, and the slightly porphyritic variety, have similar K_2O/Na_2O (and Or/Ab) ratios, which suggests that if the leucocratic rocks were derived by fractionation of the more mafic types, extensive alkali metasomatism must have accompanied the metamorphism of the granite. The normative An contents of these rocks are mostly between 5 and 10 percent, so that they would probably all plot within the plagioclase field of the Q-Ab-Or-An-H_2O system. This is consistent with the observation that plagioclase was the first major phase to crystallize in almost all these rocks. In even the most potassic samples, phenocrysts of alkali feldspar are poikilitic and apparently of late crystallization. These 'phenocrysts' are probably in most cases porphyroblasts and their presence indicates at least localized potash metasomatism, either during the late-magmatic or post-magmatic history of the rocks. Marmo (1971, p. 42) has shown that porphyroblastic granitic rocks are characteristic of synkinematic intrusive bodies, so it is reasonable to suggest that metamorphic processes have produced significant changes in the geochemistry of the Forsayth Granite, particularly with regard to the relatively mobile alkali elements.

Little can be deduced about the water pressures under which the magmas crystallized, except that they were probably higher than those suggested for the Esmeralda Granite. This is consistent with a significantly greater depth of intrusion.

Phase relations in the quartz-saturated ternary feldspar system are shown in Figure 49. All the rocks, with the exception of two atypical samples of Robin Hood Granite, which are possibly of metamorphic origin, plot either within the plagioclase field or very close to the boundary curve. There is a large scatter of points and no obvious differentiation trends are apparent. The three granite types of the Forsayth area plot in a relatively restricted field, but even these do not show a well defined trend, although the melanocratic rocks are slightly richer in normative An and the leucocratic rocks plot nearer the boundary curve. The Forsayth granodiorites show a rather poorly defined trend and do not appear to be genetically related to the granitic rocks of the Forsayth area. This is supported by the trace element geochemistry (p. 32). They are richer in Ab than the Robin Hood granodiorites, but are similar in composition to some of the Dumbano granodiorites. The granodiorites of the Forest Home area, which are particularly rich in Ab and low in An and Or seem to be unrelated to any of the other groups.

At least three separate parent magmas appear to have been involved in the formation of the Forsayth Granite. Little can therefore be said regarding the likely differentiation trends and little is known of the order of emplacement of the different rock types. The overall trend of the Forsayth granodiorites is roughly parallel to the quartz-feldspar boundary in the Q-Ab-Or-H_2O system and suggests a parent magma with a relatively high normative Q/Or ratio, that is a relatively low K content (Bateman et al., 1963). Many of the Forsayth Granite samples are quite strongly corundum normative, which suggests that the magmas were derived from sedimentary materials (Luth et al., 1964), and belong to the S-type of Chappell & White (1974).

Dumbano Granite and Dido Granodiorite

The Siluro-Devonian granitic rocks bear some geochemical resemblance to the Forsayth Granite: the majority of samples, including

TABLE 10. BIOTITE ANALYSES

	FeO	*MgO*	*Li*	*Cr*	*Cu*	*Zn*	*Sn*	*Pb*
1	29.0	1.53	385	15	55	1 045	45	43
2	26.1	3.42	280	65	10	620	30	30
3	24.6	5.50	280	85	135	890	20	25
4	31.0	1.38	560	8	147	465	245	35
5	26.0	1.35	625	13	114	370	80	30
6	27.5	1.11	915	10	114	305	80	39
7	34.8	1.23	250	5	39	435	105	81
8	29.8	4.00	450	34	50	580	90	35
9	25.0	4.28	375	65	168	465	80	21
10	22.1	8.43	125	13	43	415	65	13
11	23.9	7.14	185	22	15	470	60	25
12	22.7	9.56	190	19	14	255	80	6
13	27.1	4.32	495	73	56	795	85	38
14	22.9	8.63	180	25	11	455	70	8
15	20.8	10.3	210	73	20	275	55	23
16	17.9	12.3	85	93	33	235	50	6
17	22.1	5.86	680	7	15	245	65	7
18	25.3	3.04	940	5	7	305	65	79

1. Esmeralda Granite, 6 km north of Esmeralda Homestead. E54/12/1*.
2. Esmeralda Granite, 6 km north of Esmeralda Homestead. E54/12/2*.
3. Forsayth Granite (porphyritic biotite-muscovite granite), 5 km SSW of Mount Turner Homestead. 68590021.
4. Elizabeth Creek Granite, 1 km south of Emuford. 67490029R.
5. Elizabeth Creek Granite, 11 km ESE of Emuford. 67490128R.
6. Elizabeth Creek Granite, 15 km ESE of Emuford. 67490132.
7. Elizabeth Creek Granite, 15 km northeast of Mount Garnet. 67490155.
8. Elizabeth Creek Granite, 3 km north of Bullock Creek. GA2957†.
9. Nymbool Granite, 10 km northwest of Mount Garnet. 67490101R.
10. Bakerville Granodiorite, 8 km northwest of Irvinebank. 67490008R.
11. Kalunga Granodiorite, 7 km southwest of Herberton. 67490027R.
12. Kalunga Granodiorite, 7 km south of Herberton. 67490061R.
13. Watsonville Granite, 8 km WNW of Herberton. 67490081.
14. Herbert River Granite, 18 km southwest of Chillagoe. GA2955†.
15. Almaden Granite, 1½ km southeast of Almaden. GA2966†.
16. Almaden Granite (quartz diorite), 2 km ENE of Petford. GA5743†.
17. Mineralized vein in Elizabeth Creek Granite, Black Prince tin mine, 10 km southwest of Irvinebank.
18. Mineralized vein in Elizabeth Creek Granite, John Bull tungsten mine, 17 km northeast of Mount Garnet.

* BMR field sample number.

† BMR geochronology laboratory sample number.

the Dumbano granites, adamellites, and granodiorites and the Dido tonalites, plot between the quartz-feldspar boundaries at 500 and 3000 bars water pressure in the system Q-Ab-Or-H_2O (Fig. 46). The Dumbano trondhjemites plot near the Q-Ab side of the diagram and close to the quartz-feldspar boundary at low water pressures (about 500 bars), which suggests that they are not genetically related to this group. The quartz diorites, as well as the single sample of olivine gabbro, plot well within the plagioclase field. It is not possible to estimate the water pressures under which the magmas crystallized with any degree of certainty. Most of the Dumbano granites and adamellites contain at least 5 percent An, so that comparisons with the system Q-Ab-Or-H_2O are rather tentative. However, water pressures would probably be of the order of 3000 bars or more. If the magma were saturated with water during crystallization, this would correspond to a depth of emplacement of about 11 km. There is little field evidence regarding the depths of emplacement of the Dumbano Granite and Dido Granodiorite, but it is likely that they would be considerably greater than those of the Esmeralda Granite or Upper Palaeozoic intrusives, which mostly crystallized under very thin covers and which are associated with extrusive rocks.

Comparison with experimental data in the system Q-Ab-Or-An-H_2O shows that many of the samples plot on a reasonably well defined differentiation trend that reaches the univariant boundary curve (Fig. 49). The major trend again includes the Dumbano granites, adamellites, and granodiorites, and probably the Dido tonalites, although the latter plot some distance away from the other samples and their genetic relationship to the Dumbano rocks is not absolutely certain. The Dumbano trondhjemites are probably unrelated to this group for reasons given above. The Dido quartz diorites also appear to lie on a different trend, with higher Or/Ab ratios. The Forsayth granodiorites lie close to the main trend, near the Dumbano granodiorites and Dido tonalites, in both the Q-Ab-Or and Ab-Or-An plots, suggesting a possible genetic relationship. The former are, however, relatively high in Cr, Ni, and Pb, and low in La, Ce, and Th (Tables 3, 4).

The data are not adequate to permit an accurate estimate of the composition of the parent magma for the samples on the main trend, although a dioritic or tonalitic composition seems likely. There appear to be no related samples more mafic than the tonalites, although it must be admitted that the sampling is inadequate and the proportions of basic, intermediate, and acid rocks in the intrusions is not known at present. The tonalites are either slightly diopside normative or slightly corundum normative, and most of the Dumbano Granite samples are only slightly corundum normative, so that they probably originated by melting of igneous, rather than sedimentary, materials, and may be classified as I-type granitic rocks (Chappell & White, 1974). The trondhjemites may also have been derived by anatexis of rocks of igneous origin. The quartz diorites, on the other hand, are strongly diopside normative and either represent a primary intermediate magma type or were derived by differentiation of basic magma.

A Q-Or-Pl diagram is used for comparison with data given by Bateman et al. (1963) for a number of North American granitic rock suites (see p. 45) (Fig. 45). A number of these suites plot on trends which extend from near the Pl apex towards Q. When the quartz-feldspar boundary curve is reached (at about 30-40% Q), the trend bends towards the centre of the diagram. The Dumbano and Dido rocks plot on a similar trend, although the more mafic rock types are virtually absent (Fig. 42). The parent magma of such a suite would have a high ratio of normative Q to Or and quartz would begin to crystallize much earlier than alkali feldspar. Enrichment of the melt in K to the extent that potash feldspar is able to crystallize would occur only during the late stages of fractionation.

The aplite (70571186A) plots some distance away from the ternary minimum in the Q-Ab-Or-H_2O system, being relatively low in normative quartz (Fig. 46). This suggests that the aplite does not represent a primary melt composition, but has undergone potash metasomatism. Henley (1972a) has described the formation of elvan (potash-rich quartz porphyry) dykes of southwest England by a process which involved loss of Na and Si. This leads to a trend on the Q-Ab-Or diagram from near the ternary minimum towards the Q-Or side, directly away from the Ab corner. To give a composition similar to that of the aplite, assuming an original composition near the ternary minimum, a net addition of K would be necessary, however.

Upper Palaeozoic igneous rocks

The Upper Palaeozoic intrusive rocks have been plotted on a normative Q-Ab-Or diagram (Fig. 47). Most samples plot close to the ternary minima between about 500 and 3000 bars water pressure, although the trend is toward the minimum at about 500 bars P_{H_2O} or less, suggesting that low water pressures prevailed during crystallization. Since the mean normative An content of the Elizabeth Creek Granite is only about 3 percent, the effect of this component on the system Q-Ab-Or-H_2O will be small and may be disregarded. A water pressure of 1000 bars corresponds to a rather shallow depth of emplacement of about 4 km and 500 bars corresponds to a depth of about 2 km, assuming P_{H_2O} was equal to P_{load} during explacement. Two samples from the small stocks which intrude the Featherbed Volcanics at Eight Mile and Bamford Hills plot near the ternary minimum at about 1000 bars P_{H_2O}. This would correspond to a rather greater depth of emplacement than the value of about 600 m estimated by Branch (1966) in the Featherbed Cauldron, but considering the uncertainties involved in the estimation of water pressures during crystallization, particularly since there is inevitably a certain scatter in the Q-Ab-Or diagram, and considering the uncertain relationships, except in a very general way, between P_{H_2O} and depth of emplacement, the agreement between the geochemical and field evidence is not unreasonable. The data do suggest that the acid magmas crystallized under conditions of rather low water pressure (less than 1000 bars). As Cann (1970) has emphasized, only relatively dry granitic magma can rise very far from its place of formation and be erupted as a liquid, so that low water pressures are consistent with the magmas' having risen to upper crustal levels and with the association of the granitic rocks with voluminous acid volcanics. It is probable that most, if not all, acid extrusive rocks have crystallized under relatively low water pressures (Ross, 1964; Lipman, 1966; Luth, 1969).

Comparison with the system Q-Ab-Or-An-H_2O at 1000 bars water pressure (Fig. 48), shows that the Upper Palaeozoic granitic rocks cluster around the 'piercing point' for a composition containing 3 percent An. The less fractionated granitic rocks (Herbert River Granite, Almaden Granite, etc.) mostly contain at least 5 percent An, so that virtually all samples would plot within the plagioclase field. This is consistent with the petrographic data—in almost all cases where a crystallization sequence could be established, plagioclase was the first phase to crystallize.

In the quartz-saturated ternary feldspar system at 1000 bars P_{H_2O} (Fig. 50), the granitic rocks form a fairly well defined fractionation trend extending from a point inside the plagioclase field near the An corner towards the boundary curve near the ternary minimum of the granite system. Most points lie either within the plagioclase field or within the alkali feldspar field but very close to the boundary curve. The scatter of points within the alkali feldspar field is probably due mainly to analytical errors, and possibly to errors in the experimental data on which the diagram was based, because there is no petrographic evidence for crystallization of alkali feldspar before the beginning of plagioclase crystallization. However, alteration and potash metasomatism can lead to compositions which plot in the alkali feldspar field. The Elizabeth Creek granite samples all plot close to the boundary curve near the ternary minimum.

The volcanic rocks plot on an almost identical trend to the intrusives, although there is a much greater scatter of points near the Ab-Or side, with a number of samples plotting well within the alkali feldspar field. This is attributed to post-magmatic alteration involving alkali metasomatism. Depletion or enrichment in K or Na, or both, with simultaneous loss of Ca, leads to rocks which are very high in either Ab or Or and low in An (Fig. 50). In some cases, notably sample 70571212 from the Newcastle Range Volcanics, development of secondary calcite at the expense of plagioclase means that the amount of An in the norm is considerably reduced (norms include calcite as a component) and samples which would otherwise plot within the plagioclase field plot in the alkali feldspar field. The rocks of the Cumberland Range Cauldron Subsidence Area plot in two separate groups. The microadamellites and rhyodacites plot near the boundary curve (the rhyodacite that plots in the alkali feldspar field contains calcite). The microgranodiorites and dacites plot well within the plagioclase field, and are Or-poor compared with the majority of the Upper Palaeozoic rocks. Several of the dacites contain secondary calcite and are relatively low in normative An. If the normative calcite is recalculated as anorthite, these rocks plot near the microgranodiorites.

The majority of the more siliceous intrusive and extrusive rocks are corundum normative, although the more mafic types, such as the Almaden Granite, are generally diopside normative. A number of Elizabeth Creek samples are slightly diopside normative, but this is probably due to the presence of fluorite in many of the samples, which was not taken into account in the calculation of the norms. If the norms are calculated with fluorite as a component, a number of the diopside normative rocks become corundum normative. This was not possible in all cases, however, because F analyses are not available for all samples.

On the available evidence, it is difficult to postulate a source for the Upper Palaeozoic magmas with any degree of certainty, although all the rocks, except some of the more mafic (basic to intermediate) types, are considered to have a similar origin. The origin of the Almaden Granite has already been discussed (p. 43) and it was concluded that there is no evidence to suggest that it has a fundamentally different origin from the other acid rocks. Preliminary isotopic data, although not at present conclusive, suggest that the isotopic composition of the country rocks (Precambrian metamorphics and Palaeozoic geosynclinal sediments) was generally higher than the rather uniform value for the initial $^{87}Sr/^{86}Sr$ ratio of about 0.710 found for the majority of the intrusive rocks (Black & Richards, 1972a; Black, 1974). If further studies confirm this, then the sialic crustal rocks at present exposed in the Georgetown Inlier and Hodgkinson Basin (which were presumably derived mostly from the inlier) could not have been the main source of the acid magmas. The initial ratio of the Newcastle Range Volcanics (0.7152 ± 0.0011: Black, 1973) is high enough to suggest a greater contribution from normal sialic crustal material, but is still too low for a derivation from Precambrian metamorphics similar to those at present exposed in the Georgetown Inlier. Some of the Featherbed Volcanics also have initial ratios of about 0.715 and those of the Nymbool Granite are as high as 0.722 (Black, 1974). These rather variable initial ratios could be explained by varying degrees of contamination during the ascent of the magma through the crust, possibly by some sort of zone melting process (Hamilton & Myers, 1967). Alternatively, they could be due to variations in the isotopic compositions of the source rocks. It is instructive to compare the initial $^{87}Sr/^{86}Sr$ ratios of the Upper Palaeozoic granitic rocks with that of the Esmeralda Granite (about 0.730), which is considered to have been derived by anatexis of sialic crustal rocks (see p. 112). Initial ratios of the former are probably too low to permit an origin from normal sialic crustal material, but too high for an entirely mantle source to be appropriate. There is no support, either isotopic or geochemical, for the hypothesis of Branch (1966) that the Upper Palaeozoic igneous rocks are the products of two distinct magma types, one derived by fractionation of basic material from the mantle (giving rise to the Elizabeth Creek Granite and the acid volcanics) and one derived by anatexis at the base of the Palaeozoic geosyncline (giving rise to the Herbert River and related granites) (see Black & Richards, 1972a,c).

Many authors have considered the problem of the origin of granitic magmas. A large number of granitic rocks, including the large Phanerozoic batholiths of North America, have initial $^{87}Sr/^{86}Sr$ ratios of about 0.707, that is, between those of basaltic and sialic crustal rocks (see review by Faure & Powell, 1972). Several explanations of this have been proposed. A mixture of mantle-derived materials and crustal rocks, such as a geosynclinal pile containing a high proportion of basic volcanics, would be a possible source material (Hurley et al., 1965; Hamilton & Myers, 1967; Peterman et al., 1967). As outlined above, the available isotopic data for the Hodgkinson Basin sediments are not compatible with this hypothesis, and it is unlikely that wet geosynclinal sediments could give rise to magmas capable of rising to high crustal levels (Cann, 1970). Other authors favour an origin by fractionation of mantle-derived magma, together with varying degrees of contamination by crustal material (Pinson et al., 1962; Hamilton & Myers, 1967; Dickinson, 1970; Kistler et al., 1971; Pushkar et al., 1972). A third alternative is partial melting of lower crustal rocks low in radiogenic Sr (Clifford et al, 1969; Dickinson, 1970; Scott et al., 1971; Pichler & Zeil, 1972).

It is not easy to decide between the last two hypotheses. The low Ni contents of the acid igneous rocks of northeast Queensland suggest that they were not derived by fractionation of basic magma (Kolbe & Taylor, 1966). Moreover, the paucity of basic to intermediate rocks would also be difficult to explain on such a hypothesis. The analysed samples may not be entirely representative of the Upper Palaeozoic igneous rocks, but there is no reason to think that there is any serious bias in the sampling. The Nychum Volcanics, which were not sampled, include some andesites and basalts, but are predominantly acid lavas and welded tuffs (Branch, 1966). It is possible, of course, that more mafic rock types have not been uncovered by erosion and may be present at greater depths in the crust, although there seems to be no reason why mafic magma should not have reached the surface when acid extrusives are so abundant. The other alternative, that the basic and intermediate volcanics have been eroded away, is most unlikely considering that erosion has not proceeded to any great depth. One other possibility deserves attention. Intrusion of mantle-derived (basaltic or andesitic) magma may have caused melting of the lower crustal rocks and consequent generation of acid magma. Such a process could have resulted in the cooling and crystallization of most of the mafic magma before upper crustal levels were reached. Cobbing & Pitcher (1972) came to a similar conclusion regarding the origin of the Coastal Batholith of Central Peru, in which tonalites and adamellites predominate over more mafic rock types, and Brown & Fyfe (1972) have suggested that rising andesitic magmas derived by melting of subducted oceanic crust may lead to fusion of the lower crust.

Most of the Upper Palaeozoic granitic and volcanic rocks belong to the I-type of Chappell & White (1974), and were probably derived from igneous (or meta-igneous) source materials. Exceptions are the more strongly corundum-normative granitic rocks of the Hodgkinson Basin (the Mareeba, Cannibal

Creek, and Finlayson Granites), which are S-type (sedimentary-derived).

The relationship of magma generation to plate tectonics has recently been given considerable attention and a number of authors have related the formation of the granitic batholiths and associated volcanics of orogenic belts with the underthrusting of oceanic crust beneath continental margins (Hamilton, 1969; McKee, 1971; James, 1971; Gilluly, 1971; Floyd, 1972). In some cases, the acid igneous rocks are accompanied by large volumes of basic to intermediate intrusive or extrusive rocks and the acid magmas may well have originated by fractionation of mantle-derived mafic magma (Noble et al., 1973), but in many cases the amounts of mafic rocks are completely inadequate for such an origin to be appropriate (Gilluly, 1971). Stern & Wyllie (1973) concluded from experimental evidence that primary granitic magmas are not derived from subducted material, but form by melting in the crust. Brown (1973) has also presented compelling evidence for a crustal origin for granitic magmas.

Marsden (1972) has postulated the existence of a subduction zone in northeast Australia during the Devonian. Continued underthrusting of the continental margin (i.e. the rigid Georgetown Inlier) by an oceanic plate during the Carboniferous and Permian is consistent with the metamorphism of the Hodgkinson Basin sediments to yield the Barron River and Barnard Metamorphics (de Keyser, 1965; Marsden, 1972, p. 158) and the production of voluminous acid magmas. The temporal progression of Upper Palaeozoic igneous activity from southwest to northeast has been pointed out by Richards et al. (1966). The Siluro-Devonian intrusives occur in the southern part of the Georgetown Inlier and the granitic and volcanic rocks of the central and northeastern parts of the inlier are of Middle Carboniferous to Early Permian age. The intrusive rocks of the Hodgkinson Basin, north of Mareeba, are mostly Early Permian. These relationships can be explained in an analogous manner to the scheme proposed by Mitchell & Garson (1972, p. B21) for the evolution of the Andaman Sea and peninsula Thailand and similar situations where a Benioff zone underlies a continental margin. Descent of a slab of oceanic crust results in the tectonic emplacement of continent-derived sediments on the landward side of the trench or basin (in this case the Hodgkinson Basin). This forces the trench outwards and the Benioff zone migrates away from the continent. As a result, the site of magma generation and hence of igneous activity also moves from the continental margin into the opening marginal basin. The similarity between northeast Queensland and the Thai peninsula is enhanced by the fact that, in both areas, the emplacement of granitic batholiths was accompanied by the formation of tin-tungsten-fluorite deposits. The problems of the source of the ore metals is considered later.

Evidence for the northeasterly migration of igneous activity on a smaller scale has come from detailed mapping of the Bagstowe Ring Dyke Complex by Branch (1966, p. 69). The oldest part of this structure is the Mount Rous Ring dyke, at the southwestern end of the complex, and the youngest is the northeast stock and its associated central ring dyke (see p. 10). According to Rhodes (1971), such overlapping ring complexes result from a drift of continents over 'hot-spots' in the mantle, although the oceanwards migration of a subduction zone, and hence the site of magma generation, would probably result in the formation of similar structures. There is apparently no systematic increase in the K_2O content of the igneous rocks with increasing depth to the subduction zone, as has been found elsewhere (Bateman & Dodge, 1970; Dickinson, 1970). This may be explained by migration of the Benioff zone away from the continental margin, which would tend to obscure such relationships.

Partial fusion of lower crustal rocks, possibly caused by rising basaltic or andesitic magmas derived by melting of subducted oceanic crust, is considered to have been the most important factor in the production of the Upper Palaeozoic acid magmas of northeast Queensland. Such a process may well have been facilitated by the presence of volatiles, such as HF, P_2O_5, and Li_2O, derived from the subduction zone. Volatiles such as these are known to be effective in reducing the melting point of granitic magmas (Wyllie & Tuttle, 1961, 1964). Rocks of the granulite facies are commonly depleted in Rb, leading to low Rb/Sr ratios and hence low $^{87}Sr/^{86}Sr$ ratios compared to lower-grade rocks of similar bulk composition (Spooner & Fairbairn, 1970; Sheraton, 1970; Heier & Thoresen, 1971; Tarney et al., 1972). Such rubidium-poor high-grade rocks may well constitute a high proportion of the lower crust (Heier, 1964; Cann, 1970) and would provide a suitable source material for granitic magmas with 'intermediate' Sr isotope ratios. Brown & Fyfe

(1970) have shown that granitic liquids are not generally water-saturated and can be produced by partial fusion of crustal materials at temperatures and pressures in accord with observations on the metamorphic state of migmatite terrains. Anatexis of relatively anhydrous high-grade metamorphic rocks, such as hornblende granulites, would be expected to yield a fairly dry granitic magma with a suitable isotopic composition. Such parent materials would have relatively low K and Rb contents, but would contain sufficient water in hydrous phases such as biotite and hornblende to permit a significant degree of melting (see Brown & Fyfe, 1972). The amount of melting would need to be rather restricted to produce liquids of granitic to granodioritic composition, significantly enriched in K and Rb relative to the parent material, although melting would not be limited to the extent that only water-saturated melts were produced. Only granitic melts undersaturated in water are capable of reaching high crustal levels (Cann, 1970). However, derivation by different degrees of partial melting is not, by itself, adequate to explain the chemical features of the Upper Palaeozoic igneous rocks. Only a process of fractional crystallization can adequately account for the chemistry of the more siliceous rocks such as the Elizabeth Creek Granite (Taylor et al., 1968). Since, in general, only the upper levels of the batholiths are exposed, and the majority of the intrusive (as well as the extrusive) rocks show some degree of enrichment in elements such as Rb, Th, and U, it is probable that the lower levels of the intrusions are less fractionated and predominantly of granodioritic composition. Brown (1973) has pointed out that fusion of lower crustal rocks under relatively dry conditions is likely to produce mainly dioritic to granodioritic melts that require much less water than granitic liquids for saturation. The Hammonds Creek Granodiorite, which is relatively low in Rb, Th, and U, and has a comparatively high K/Rb ratio, may be more representative of such deep level rocks.

FACTOR ANALYSIS

The geochemical data for the Upper Palaeozoic igneous rocks were used for R-mode factor analysis using the Varimax rotation. In this technique, the original variables are transformed into a smaller set of fundamental variables (factors) that explain the variance of the original data. Each factor, which may reflect definite geological processes, consists of a set of 'loadings' between -1 and $+1$, one for each variable. The higher the absolute value, the greater the effect of the factor on that variable. Geochemically related elements tend to appear in the same factors with the same sign, whereas variables with strong antipathetic relationships usually have the opposite sign. In particular, elements which show strong geochemical coherence (e.g. K and Rb) usually appear in the same factors, and elements which show similar variation trends in fractionated series also tend to be controlled by the same factors. An attempt may thus be made to explain each factor in geologically meaningful terms. The number of factors selected for rotation was rather subjective, although theoretically the number of factors reflecting the underlying structure of the data should be known. A compromise was reached by taking sufficient factors to explain as much of the variance as possible, whilst still retaining some geological meaning for each factor. The method has been outlined in some detail by Davis (1973), and examples of geological applications are given by Vistelius & Ruiz Fuller (1969) and Henley (1970, 1972b).

Four groups of samples were studied, using data for 29 variables (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, H_2O, Li, Be, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Sn, Ba, La, Ce, Pb, Th, and U). The results for 106 samples of tin-bearing granites were compared with those for 136 samples of non-stanniferous granites. These two groups were then combined and compared with 120 samples of volcanic rocks.

Tin-bearing granites

Six factors account for 73 percent of the variance (Fig. 51).

Factor I is an 'acid/basic' factor, that is, it is explained by variations in the proportions of felsic and mafic minerals, particularly ferromagnesian minerals and quartz. TiO_2, Al_2O_3, FeO, MgO, CaO, P_2O_5, Ni, Sr, Zr, and Ba have the highest positive loadings, whereas SiO_2, Rb, and to a lesser extent Na_2O, K_2O, and U, have negative loadings. The loadings on Na_2O and K_2O are relatively low, suggesting that feldspar variation is not an important part of this factor. The inverse correlation of SiO_2 with ferromagnesian elements is to a large extent a function of the closed array problem: the fact that weight percentages, which sum to near 100 percent, are used. This factor accounts for a high proportion of the variance in all groups investigated. K_2O and Rb are not highly correlated (correlation coeff. = 0.27) and Ba shows a negative correlation with SiO_2 (correlation coeff. = —0.57), probably because of the highly fractionated character of the tin-bearing granites, with extreme enrichment in Rb and depletion in Ba.

Factor II controls much of the variations of P_2O_5, Li, and Sn, all of which have positive loadings. Li and Sn are positively correlated (correlation coeff. = 0.64), suggesting a geochemical relationship between these elements in tin-bearing granites—both Sn and Li tend to occur in biotite. The importance of volatiles in the transport and concentration of Sn is discussed below (p. 123).

Factor III is thought to be related to some sort of fractionation or hydrothermal alteration (e.g. greisenization) process, or both. Be, Ga, Rb, Y, Pb, Th, and U oppose Mn and Ba. The former group are all enriched and Ba is depleted in the most strongly fractionated rocks.

Factor IV is partly explained by feldspar variation (plagioclase and alkali feldspar); Na_2O and K_2O have opposite loadings. Zn and Ga are probably unrelated variables—they enter separate factors if more than six are used. The correlation between Na_2O and Ga (correlation coeff. = 0.39) may be due to the high Ga content of plagioclase relative to potash feldspar. Plagioclase from the Cape Granite contains almost twice as much Ga as potash feldspar (Kolbe, 1966).

Factor V determines interrelations of Fe_2O_3 and H_2O. It probably represents an alteration process—formation of secondary hydrous minerals with oxidation of Fe^{II} to Fe^{III}. The low correlation coefficient (0.22) suggests that the two processes oxidation and hydration are more or less independent, and if more factors are calculated, H_2O and Fe_2O_3 do enter separate factors.

In *factor VI,* Zr and Ce, with Ba, La, and Th oppose Al_2O_3. This probably reflects the distribution of accessory minerals such as zircon, allanite, and sphene, all of which are common in the Upper Palaeozoic granitic rocks. Allanite and sphene generally have high concentrations of Ce-earths, whereas Y-earths tend to be concentrated in plagioclase and hornblende (Lyakhovich, 1967).

One element in particular, Cu, is not explained by these six factors. If more factors are taken, Cu appears individually in one of these factors, suggesting that it behaves as an independent variable, possibly entering a sulphide phase.

Non-stanniferous granites

Six factors account for 80 percent of the variance (Fig. 52).

Factor I is again an 'acid/basic' factor. TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, P_2O_5, H_2O, Ni, Cu, Zn, and Sr have high positive loadings and SiO_2, Na_2O, and K_2O, with Be, Rb, Pb, and Th, have negative loadings. This factor appears to reflect interrelations between ferromagnesian minerals, quartz, potash feldspar and, to some extent, plagioclase. Ba and SiO_2 are virtually uncorrelated, but K_2O and Rb are strongly correlated (correlation coeff. = 0.79), showing that late-stage fractionation is less important than in the tin-bearing granites.

Factor II is the factor governing fractionation or late magmatic alteration, or both. Be, Rb, Y, Pb, Th, and U, and to some extent K_2O, Li, and Ga, are opposed by Ba and Sr.

Factor III contains high positive loadings on Y, La, and Ce and is probably connected with the distribution of accessory minerals such as sphene and allanite.

Factor IV controls variations in Li and Zr. These are probably independent variables (the correlation coefficient is only 0.27). Zr variation is presumably a function of the distribution of accessory zircon in the rocks.

Factor V contains Na_2O (with Ga), opposed by FeO, and essentially represents plagioclase variation. Na_2O and Ga are uncorrelated.

Factor VI has a high loading only on Sn, with only a small contribution from Zn. Thus, Sn is behaving as an independent variable, and is not correlated with Li as in the tin-bearing granites. The significance of this factor should not be overemphasized, however, because only about 23 percent of the samples contain detectable amounts of Sn (4 ppm or more).

Once again most of the Cu variation is not explained by six factors. If sufficient factors are taken, it enters a factor of its own. H_2O also appears to act, to some extent, as an independent variable (not all the variation is explained by factor I).

All Upper Palaeozoic granitic rocks

Eight factors explain 82 percent of the variance (Fig 53).

Factor I is the usual 'acid/basic' factor. TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, P_2O_5, H_2O, Ni, and Sr are opposed by SiO_2 and K_2O, with part of Na_2O, Rb, Pb, and Th.

Factor II is the 'fractionation' factor: Be, Ga, Rb, Y, Pb, Th, and U have positive loadings and Sr and Ba, with P_2O_5 and Al_2O_3, have negative loadings.

Factor III includes only La and Ce, and probably reflects accessory mineral contents, particularly of sphene and allanite.

Factor IV contains Li, Sn, and P_2O_5. Sn and Li are quite strongly correlated (correlation coeff. = 0.60).

Factor V represents Na_2O (i.e. plagioclase) variation.

Factor VI suggests that Cu is behaving in a geochemically distinct manner, independent of all other elements. The distribution may reflect some late-magmatic or post-magmatic process, since the Elizabeth Creek Granite, which commonly shows the effects of greisenization, also has relatively variable Cu contents. Alternatively, it may reflect the distribution of a sulphide phase.

Factor VII contains only Zn and Ga, which are only weakly correlated (correlation coeff. = 0.32). There is no obvious reason for the occurrence of these two elements in the same factor.

Factor VIII, with positive loadings of Zr, Ce, and H_2O, reflects at least two independent geological factors—the distribution of accessory minerals (particularly zircon) and alteration (hydration).

Volcanic rocks

Eight factors account for 82 percent of the variance (Fig. 54).

Factor I is the usual 'acid/basic' factor, although the importance of variations in feldspars and minerals which contain ferric iron (i.e. magnetite, ilmenite, and possibly haematite) are insignificant compared with the granitic rocks. Variations in quartz and ferromagnesian minerals appear to be the determining factors. TiO_2, Al_2O_3, FeO, MgO, CaO, Li, Cu, and Sr have high positive loadings; SiO_2 and K_2O, and to a lesser extent Rb and Y, have negative loadings.

Factor II has positive loadings on Zr, Ba, La, and Ce, suggesting variations in the proportions of accessory minerals, including zircon, allanite, and sphene.

Factor III suggests fractionation or late magmatic alteration, or both, with positive loadings on Be, Zn, Ga, Y, and Pb. Be, Y, and Pb increase with fractionation. Zn does not correlate significantly with any of the other elements and may be behaving as a geochemically independent variable. In contrast to the granitic rocks, this factor does not include Rb, which becomes enriched, or Ba, which is depleted in highly fractionated rocks. This is consistent with the relatively unfractionated chemistry of the volcanic rocks.

Factor IV determines feldspar variations: Na_2O has a high positive loading and K_2O and Rb have high negative loadings. K_2O and Rb are quite strongly correlated (correlation coeff. = 0.68). The relatively high negative correlation between Na_2O and K_2O (correlation coeff. = −0.62) may be partly due to alkali metasomatism, with enrichment in either Na or K at the expense of the other.

Factor V includes Th and U (positive loadings), with smaller negative loadings on Ba and MnO. This suggests redistribution of Th and U, which are particularly prone to leaching by hydrothermal fluids. The volcanics show a relatively high degree of alteration which may have been accompanied by Th and U metasomatism. The abnormally high Th/U ratios of the Newcastle Range Volcanics suggest that they may have suffered depletion of U.

Factor VI has positive loadings on TiO_2, Fe_2O_3, MgO, P_2O_5, H_2O, Ni, and Sr, and negative loadings in SiO_2, with small contributions from Pb and Th. It seems likely that several geological processes are involved here. H_2O and part of Fe_2O_3 (correlation coeff. = 0.65) probably represent an alteration factor—hydration accompanied by oxidation of ferrous iron. The contributions of TiO_2, Fe_2O_3 (in part), and Ni suggest variations in magnetite or ilmenite, or both. TiO_2 and Fe_2O_3 are strongly correlated (correlation coeff. = 0.79). P_2O_5 and Zr are probably connected with the abundances of apatite and zircon, respectively. In the case of the granitic rocks (particularly the non-stanniferous granites), TiO_2, Fe_2O_3, and Ni tend to group with the other ferromagnesian elements (FeO, MgO, CaO, etc.), possibly because of a higher correlation between ferromagnesian minerals such as biotite and hornblende, and opaque minerals. In many of the volcanic rocks, the ferromagnesians are almost entirely replaced by secondary minerals. *Factor VII* has the highest loading on Sn, with Cu (positive loading) and Mn (negative loading). Sn is not correlated with either Cu or Li. Not too much significance should be attached to this factor, because only 18 samples contain 4 ppm or more Sn.

Factor VIII includes Li and Ga (positive loadings) and Ni (negative loading). None of these elements is strongly correlated with either of the others, and it probably includes the effects of more than one geological process.

With 9 factors, Mn (which is not adequately explained by 8 factors) enters a factor of its own, possibly reflecting deposition of manganese oxides accompanying hydrothermal alteration.

R-mode factor analysis appears to be useful in indicating whether groups of rocks of similar bulk composition have been affected by different geological processes, such as hydrothermal alteration, greisenization, etc. In particular, it may indicate the nature of the chemical changes which accompany such processes. The tin-bearing granites and non-stanniferous granites differ mainly in that the former are more strongly fractionated and more likely to have been affected by greisenization and other late-magmatic processes. Li and Sn are positively correlated only in the tin-bearing granites. The intrusive and extrusive rocks differ in that the former show relatively strong fractionation. The volcanics, however, show more extensive alteration and the most important constituents of ferromagnesian minerals (CaO, FeO, MgO, and Sr) do not correlate so strongly with Fe_2O_3, TiO_2, and Ni, which tend to be concentrated in opaque iron minerals. Th and U appear in a separate factor in the volcanics, suggesting secondary redistribution of these elements. Cu (and probably Zn) appears to a large extent to behave independently of other elements, possibly reflecting the action of mineralizing fluids, or alternatively the distribution of a sulphide phase.

RELATIONSHIP OF GEOCHEMISTRY TO MINERALIZATION

Tin

The tin-bearing Esmeralda, Elizabeth Creek, Mareeba, Cannibal Creek, Finlayson, and Altanmoui Granites are highly fractionated granites or adamellites in which greisenization is comparatively widespread. They are generally low in FeO, MgO, CaO, TiO_2, Cr, Co, and Ni, and high in SiO_2 and K_2O (Tables 3, 5, 10). Niggli k values are relatively high (>0.4), particularly in the Esmeralda Granite, whereas mg values tend to be low (generally less than 0.32) (Fig. 55). Neither of these factors seems to be, by itself, a significant indicator of potential tin mineralization, even in a single province, because high k and low mg values are also found in non-stanniferous granites (e.g. the Herbert River Granite and some phases of the Dumbano Granite). Trace elements that are concentrated during magmatic differentiation (notably Li and Rb, and in the case of the Elizabeth Creek Granite Y, Th, and U) are high, whereas Sr and Ba are generally low. K/Rb ratios are often considerably lower than the crustal average of 230 (Taylor, 1965) and Mg/Li ratios are also low (Figs 56, 58). Ba/Rb ratios are low in the Upper Palaeozoic tin-bearing granites, but not particularly so in the Esmeralda Granite (Fig. 57). Tauson & Kozlov (1973) have suggested that the Ba/Rb ratio may be useful indicator of the ore-bearing potential of granites. Ratios of less than 1 are generally found in late-stage highly fractionated granitic rocks that are often accompanied by economic deposits of tin, tungsten, molybdenum, etc. Both Ca and Sr are relatively low in the tin-bearing granites, but Ca/Sr ratios show little correlation with tin mineralization (Fig. 59). The importance of extreme fractionation and late-stage hydrothermal processes in the tin-bearing granites is confirmed by factor analysis.

Particularly noteworthy are the high concentrations of volatile elements in the granites, suggested by the abundance of fluorite or tourmaline, or both. Fluorite is common in the Elizabeth Creek Granite (average F content of 22 fluorite-containing samples is 2100 ppm) and tourmaline is a characteristic accessory mineral in the Esmeralda, Mareeba, and Finlayson Granites. The last two also have particularly high Li contents. Li and Sn are quite strongly correlated in the tin-bearing granites, but not the non-stanniferous granites (p. 120). The Elizabeth Creek, Altanmoui, and the single sample of Cannibal Creek Granite are also relatively high in Be.

The common association of tin deposits with late-stage leucocratic and generally potassic granites has been demonstrated by many authors (Gotman & Rub, 1961; Rattigan, 1963; Klominsky & Groves, 1970; Hesp & Rigby, 1974), and the importance of volatile elements in the formation of economic deposits has also been noted (Gotman & Rub, 1961; Lyakhovich, 1965; Hosking, 1967; Rub, 1972; Tischendorf et al., 1972). Greisenization may be an important factor in the concentration of tin (Gotman & Rub, 1961; Hosking, 1964; Hall, 1969) and Hesp & Rigby (1972) have suggested that post-magmatic processes are of considerable importance in the formation of cassiterite deposits. Tauson et al. (1968) have shown that a high level of volatiles is necessary for the enrichment of the apical parts of intrusions in rare elements such as Li, Be, Sn, W, Nb, and Ta. These authors consider that the highest potential for mineralization is shown by hypabyssal intrusions with high volatile contents.

With one exception, only the granitic rocks with which tin mineralization is associated have mean Sn contents significantly greater than the detection limit of 4 ppm (Fig. 12; Tables 3, 5). The exception is the Kalunga Granodiorite, which, as a result of a single high value of 17 ppm, has a mean Sn content of about 5 ppm. The Esmeralda and Elizabeth Creek Granites have average Sn contents of about 5 ppm, which, although significantly greater than values for the non-stanniferous granites of northeast Queensland, are considerably lower than values reported for many tin granites elsewhere (Rattigan, 1963; Ivanova, 1963; Lyakhovich, 1965; Mulligan, 1966; Hall, 1969; Ivanov & Narnov, 1970; Cotelo Neiva, 1972; Davy, 1972). The Mareeba, Finlayson, and Altanmoui Granites have rather higher mean Sn contents (9, 16, and 10 ppm, respectively). Tin-bearing granitic rocks often contain 20 to 30 ppm Sn, whereas non-stanniferous granites normally have Sn contents of about 3 ppm (Rattigan, 1963; Barsukov, 1967). Tauson et al. (1966), however, found that granitic rocks associated with tin deposits in eastern Transbaikaliya have a mean Sn content of 7.1 ppm, compared with 3.5 ppm for non-stanniferous granites from the same area. These are very similar to the average values found in the northeast Queensland rocks (Table 11).

None of the investigated tin-bearing granites (except possibly the Finlayson Granite) is uniformly high in Sn—individual samples may have relatively high or low concentrations. Sixty-seven percent of the analysed samples of the Esmeralda Granite contain 4 ppm or more Sn; the corresponding figures for the Elizabeth Creek, Mareeba, and Finlayson Granites are 60 percent, 69 percent, and 100 percent, respectively. Figure 60 shows the Sn contents of the Upper Palaeozoic granitic rocks plotted on a map of the area between Cooktown and Mount Surprise. The main concentrations of samples with high Sn contents (>6 ppm) include the Herberton/Mount Garnet area, the Annan River tinfield, and some of the Mareeba Granite intrusions. These correspond fairly closely to the most important areas of tin mineralization. The intrusion of Elizabeth Creek Granite east of Mount Surprise also has a moderately high Sn content. Most of the samples that are high in Sn occur near tin mines or prospects, whereas low values may be found anywhere. Similarly, Hosking (1971) found that the granitic dykes (elvans) in the vicinity of tin-bearing veins in Cornwall have variable Sn contents, whereas dykes not associated with tin deposits are always low in Sn; that is, all dykes with more than 10 ppm Sn occur in the vicinity of tin-bearing granites.

The necessity for a statistical approach to sampling has been emphasized by Beus & Sitnin (1968) and Bolotnikov & Kravchenko (1970). Beus & Sitnin (1968) found that in a random sample of tin-bearing granites, 80 percent of samples contained more than 10 ppm Sn and 3 percent had less than 5 ppm. Almost 90 percent of samples of barren granites contained less than 5 ppm Sn. Tauson & Kozlov (1973) have emphasized that even within a single intrusion, the Sn content can vary considerably—from 25 ppm in the apical part to only 5.8 ppm in the abyssal part of the Verkhneurmijsky granite massif. MacLeod et al. (1971) have shown that tin tends to be concentrated in the roof zones of the Younger Granite intrusions of Nigeria. It is apparent that sampling must be reasonably extensive if the tin-bearing potential of an intrusion is to be realistically assessed. A non-uniform distribution of Sn, with a high proportion of samples having contents significantly higher than background values, appears to be an important indicator of potential tin mineralization, although a uniformly high Sn content would also, of course, be significant. Similar arguments may be applied to the Sn contents of biotites from granitic rocks. Of the very limited number of results available, high Sn contents are found only in biotites from the Elizabeth Creek Granite, although not all such biotites are high in Sn. Rattigan (1963) found that Sn contents are higher in biotites from tin-bearing granites (75-325 ppm) than in those

TABLE 11. AVERAGE COMPOSITION OF THE UPPER PALAEOZOIC TIN-BEARING GRANITES (ELIZABETH CREEK, MAREEBA, CANNIBAL CREEK, FINLAYSON, AND ALTANMOUI GRANITES) COMPARED TO NON-STANNIFEROUS GRANITES

	Tin-bearing Granites					*Other Granites*				
	mean	*s.d.*	*max.*	*min.*	*r.s.d.*	*mean*	*s.d.*	*max.*	*min.*	*r.s.d.*
SiO_2	75.4	2.1	78.6	66.7	0.03	71.8	4.8	77.7	52.9	0.07
TiO_2	0.15	0.13	0.75	0.01	0.87	0.32	0.21	1.20	0.03	0.66
Al_2O_3	12.89	0.98	16.42	11.43	0.08	13.82	1.24	17.94	11.58	0.09
Fe_2O_3	0.32	0.22	1.19	0.00	0.69	0.70	0.55	3.40	0.01	0.79
FeO	1.17	0.66	4.05	0.20	0.56	1.90	1.27	8.30	0.26	0.67
MnO	0.04	0.02	0.11	0.00	0.50	0.05	0.03	0.16	0.01	0.60
MgO	0.19	0.22	1.45	0.00	1.16	0.83	1.04	6.65	0.02	1.25
CaO	0.87	0.56	3.41	0.18	0.64	2.25	1.69	9.22	0.22	0.75
Na_2O	3.53	0.51	5.0	1.55	0.14	3.43	0.60	4.6	0.46	0.17
K_2O	4.63	0.60	5.54	1.59	0.13	3.91	0.90	6.73	1.14	0.23
P_2O_5	0.05	0.07	0.36	0.00	1.40	0.07	0.05	0.24	0.00	0.71
H_2O	0.68	0.21	1.35	0.32	0.31	0.75	0.37	2.41	0.20	0.49
TOTAL	99.92					99.83				
Li	44	37	281	6	0.84	25	14	59	5	0.56
Be	5.0	3.1	100	1.0	0.62	3.3	1.6	9.5	1.0	0.48
F	—	—	4 500	500	—	—	—	4 500	400	—
Cr	$\sim$3	—	24	<3	—	9	—	81	<3	—
Co	$\sim$4	—	11	<3	—	7	—	18	<3	—
Ni	<3	—	8	<3	—	$\sim$4	—	40	<3	—
Cu	6	10	91	1	1.7	7	9	54	<1	1.3
Zn	37	25	161	9	0.68	37	19	134	9	0.51
Ga	18	4	40	12	0.22	16	2	23	11	0.13
Rb	404	167	1 170	76	0.41	219	96	563	65	0.44
Sr	42	51	331	3	1.21	124	79	357	2	0.64
Y	76	47	287	10	0.62	42	22	143	14	0.52
Zr	124	54	387	11	0.44	142	56	405	32	0.39
Sn	7	$\sim$7	47	<4	1	<4	—	18	<4	—
Ba	174	169	895	<3	0.97	420	250	1 480	7	0.60
La	41	38	240	<2	0.93	36	19	158	6	0.53
Ce	69	37	178	<7	0.54	64	24	196	<7	0.38
Pb	30	8	49	8	0.27	24	10	65	6	0.42
Th	37	21	81	<2	0.57	25	11	67	4	0.44
U	9	6	28	<2	0.67	5	4	20	<2	0.80
Mg/Li	26		190	1		200		3 300	3	
Rb/Sr	9.6		280	0.24		1.77		120	0.16	
K/Rb	95		244	31		148		321	68	
Ba/Sr	4.1		20	1.06		3.4		22	0.22	
Ba/Rb	0.43		5.0	0.006		1.46		14.4	0.028	
K/Ba	221		10 000	37		77		5 000	22	
Ca/Sr	148		1 600	41		130		1 200	46	
Ca/Y	82		2 400	13.2		380		2 500	11.2	
K/Pb	1 280		3 900	730		1 350		3 900	500	
Th/U	4.1		15	0.6		5.0		16	1.0	
K/U	4 300		22 000	1 200		6 500		22 000	1 900	
Al/Ga	3 800		5 400	1 720		4 600		6 600	2 700	
mg	0.18		0.43	0.00		0.37		0.56	0.03	
k	0.47		0.70	0.22		0.43		0.88	0.24	
No. of samples	106					140				

s.d.—standard deviation.

r.s.d.—relative standard deviation.

from non-stanniferous granites (5-30 ppm), and Bradshaw (1967) also found higher Sn contents in biotites from mineralized, as compared with non-mineralized stocks.

Whereas most granitic rocks with associated tin mineralization have anomalously high Sn contents, other genetically related acid igneous rocks, not themselves spatially associated with tin deposits, may also be relatively high in Sn (e.g. Kalunga Granodiorite and Walsh Bluff Volcanics). One sample of the Featherbed Volcanics (68490018B) contains 1000 ppm Sn. The Sn contents of granitic rocks are undoubtedly useful in defining tin provinces. Once the existence of such a province has been established, attention should be concentrated on the most highly differentiated (probably high-level) granitic rocks, particularly those which show evidence of high volatile contents (i.e., contain fluorite, tourmaline, etc.) and are extensively greisenized.

Copper

Several authors (e.g. Brownlow et al., 1967; Bradshaw, 1967; Brabec & White, 1971) have found little or no correlation between the Cu content of acid igneous rocks and copper mineralization. Other authors have reported that areas of copper mineralization are reflected in anomalously high Cu contents of rocks (Putman & Burnham, 1963) or, more particularly, biotites (Al-Hashimi & Brownlow, 1970; Lovering et al., 1970) from associated plutonic bodies, although Banks (1974) considered the high Cu contents of biotites near ore deposits to be probably the result of chloritization.

There is little apparent relationship between the Cu content and copper mineralization for the granitic rocks in northeast Queensland. The distribution of Cu in the various intrusive rocks is that expected for normal differentiation trends—the most fractionated rocks are, in general, lowest in Cu (Fig. 5). Copper mineralization does not show any preferential association with particular granitic rock types—granodiorite, adamellite, or granite—but may occur with any. Only minor copper mineralization is associated with the Esmeralda Granite, and Cu contents are close to those of average low-calcium granite (Turekian & Wedepohl, 1961) and average granite (Taylor, 1968). The Dumbano Granite and Dido Granodiorite are uniformly low in Cu, except for the quartz diorites. The three samples of quartz diorite from the Dido Granodiorite have relatively high Cu contents, but no known economic mineralization. The Forsayth Granite is generally low in Cu.

Some copper mineralization appears to be genetically related to the Elizabeth Creek and Herbert River Granites, but these are very low in Cu. A few samples of Elizabeth Creek Granite have relatively high Cu contents (>15 ppm), which may reflect the action of late-stage hydrothermal fluids. Factor analysis suggests that copper behaves as a geochemically independent variable, which may account for the difficulties in relating Cu abundances to those of other elements. Muscovitization of biotite during greisenization can lead to the release of copper and zinc, which may consequently become significantly concentrated (Hosking, 1964). Copper mineralization is associated with the Mareeba Granite near Mount Molloy but, although the mean Cu content is slightly higher than that of the Elizabeth Creek Granite, it is close to the average low-calcium granite of Turekian & Wedepohl (1961). The Almaden Granite, which appears on field evidence to have been responsible for the most important copper mineralization in the area—the contact replacement deposits around Chillagoe—tends to have a rather lower Cu content than the average granodiorite (Table 9). The areal distribution of Cu in the Upper Palaeozoic granitic rocks is shown in Figure 61. A few relatively high values (>15 ppm) occur in the Elizabeth Creek Granite of the Herberton/Mount Garnet area, but there is little obvious correlation with areas of copper mineralization. The granitic rocks of the Chillagoe area are conspicuous in not having anomalously high Cu contents. Cu contents of the analysed biotites are generally lower than values reported for biotites from granitic rocks with associated copper mineralization in the United States (Al-Hashimi & Brownlow, 1970; Lovering et al., 1970) but comparable with biotites from various British granites (Bradshaw, 1967). Slightly higher values occur in some of the Elizabeth Creek biotites, and in the single biotite from the Nymbool Granite.

Lead and zinc

A number of authors have noted the absence of any systematic relationships between lead-zinc deposits and the Pb and Zn contents of associated granitic rocks (Tauson, 1967; Barsukov, 1967; Blaxland, 1971; Brabec & White, 1971). Bradshaw (1967), however, found that the Pb contents of muscovites, biotites, and feldspars from the mineralized granites of southwest England are significantly higher than those of non-mineralized granites from Scotland. Only the feldspars from the granites of southwest England are higher in Zn.

Minor lead and zinc deposits are related to the Elizabeth Creek, Herbert River, and Esmeralda Granites; the major lead-zinc mineralization of the Chillagoe area is spatially associated with the Almaden Granite. However, isotopic data for the contact metasomatic deposits of the Chillagoe area preclude a direct relationship between the Almaden Granite and the nearby lead deposits (Black & Richards, 1972b). Zn contents of the various granites show little systematic variation, although they tend to be lower in the more fractionated granites (Elizabeth Creek and Herbert River Granites), compared with the granodiorites (Almaden Granite and Dido Granodiorite) (Fig. 6). Pb varies more systematically, being higher in the more acid rocks (e.g. Elizabeth Creek Granite) (Fig. 16). Gavrilin et al. (1972) have shown that lead, but not zinc, may accumulate in the apical parts of intrusions. The Esmeralda Granite is relatively rich in both Zn and Pb, compared with the other granitic rocks and the average granite of Taylor (1968).

All these distribution patterns may be related to magmatic differentiation trends, and there is no evidence for either significant enrichment or depletion of Pb or Zn in the mineralized, as compared with the non-mineralized, granitic rocks or their biotites. There is, however, some evidence for depletion of Pb during post-magmatic alteration of volcanic rocks (see p.) and a few samples have high Pb (68490018B, 68590062) or Zn (68590062, 70571210) contents.

Source of ore metals

The difficulties involved in any attempt to relate the abundances of ore metals in acid intrusives to the occurrence of economic deposits of these metals have been outlined in detail by Krauskopf (1967). There are two opposing viewpoints: the formation of economic deposits is favoured when the magma has an unusually high metal content; or, ore formation causes the depletion of the magma in metals (Krauskopf, 1967; Tilling et al., 1971). Either enrichment or depletion of a granite in ore metals could thus be taken as evidence of a genetic relationship between intrusive and ore deposit and could be used as a possible indicator of potential mineralization. Krauskopf (1967, p. 6), however, has pointed out that 'only slight enrichment from fairly modest volumes need be assumed to account for the metal, even in large deposits. For example, to concentrate a million tons of metal in an ore-body—which would constitute a sizable deposit for such metals as copper, lead, and zinc—requires only that the amount of metal in 100 km^3 of granite be diminished by about 3 ppm'. Such a decrease would not be significant compared with the average 10 to 70 ppm of these metals in normal granites. Even if it is assumed that the magma was the main source of ore metals, the apparent lack of correlation between the geochemistry of the granitic rocks of northeast Queensland and lead-zinc or copper mineralization is hardly surprising.

The question of the ultimate source of ore metals has been the subject of considerable discussion. The Esmeralda Granite was probably derived by anatexis of sialic crustal rocks, which may well have been the source of the tin and other ore metals. However, isotopic evidence suggests that the Upper Palaeozoic tin-bearing and other granitic rocks, with their associated ore metals, may be of deeper origin. Magma generation associated with a subduction zone is considered to be the most likely mechanism in this case. The formation of ore deposits in relation to subduction zones has been discussed by several authors (Mitchell & Garson, 1972; Guild, 1972; Sawkins, 1972; Sillitoe, 1972; Wright & McCurry, 1973). Mitchell (1973) has related the type of mineral deposit to angle of dip of the Benioff zone. Tin-tungsten-bismuth-fluorite deposits were considered to have been emplaced above gently dipping Benioff zones and porphyry copper deposits above steeply dipping zones. According to most of these authors, metals such as copper, lead, and zinc were probably derived from subducted oceanic crust, although Noble (1970, 1974) in his investigation of the distribution of metal provinces in the western United States concluded that these metals have a mantle origin. Noble considered the role of igneous intrusion in mineralization to be one of structural control rather than a source of ore metals. If the mineralizing fluids associated with igneous bodies do not develop by magmatic crystallization processes, but are regarded as independent by-products of magma generation (Wright & McCurry, 1973), there is no reason why acid intrusives with which lead, zinc, or copper mineralization is associated should contain anomalous abundances of these metals. This would, of necessity, be the case if a large part of the ore metals originated in subducted oceanic crust or in the mantle overlying the subduction zone and, as is suggested for the Upper Palaeozoic rocks of northeast Queensland, the acid magmas were derived by melting of the lower crust. Possible support for such a concept has come from the isotopic studies of Black & Richards (1972b), who found that the lead deposits which are spatially associated with the Almaden Granite are not directly related to it.

The importance of source rock composition in the formation of tin-bearing granites has been emphasized by Flinter (1971) and Hesp (1971), and Wright & McCurry (1973) proposed that 'geochemical culminations may exist in the deep crust or upper mantle'. Schuiling (1967) has argued that the restriction of the economic tin deposits of the earth to well defined 'tin provinces' indicates an inhomogeneous distribution of the metal in the crust. As the ages of mineralization vary within tin belts, it was suggested that the main source of tin must be within the crust itself. Mitchell (1973) has concluded that since there is no obvious source of tin in either the downgoing oceanic crust or in the overlying mantle, a crustal source is probable for this and other metals, such as tungsten and bisthmuth. It would be more difficult to explain the distribution of tin in the continents if the metal is assumed to originate in the mantle, because the process of continental drift would be expected to have produced a more even distribution than is actually found. It is not possible to entirely rule out a derivation of tin from the mantle, however. Data on the Sn contents of possible source materials, such as oceanic crust sediments, are, at present, inadequate for the probability of such an origin to be assessed. Volatiles such as fluorine, probably expelled from subducted oceanic crust, would be instrumental in the transportation of tin and other ore metals into the upper crust (Mitchell & Garson, 1972; Mitchell, 1973).

The existence of a region of anomalously high Sn content, either in the upper mantle or, more probably, in the lower crust, would explain the presence of tin granites with ages covering a period of over 1000 m.y. in northeast Queensland. Such a concept would also explain the high Sn contents of granites associated with tin mineralization compared with granites from areas which do not contain tin deposits. Not all granitic rocks (or even fractionated granites) within a tin province have associated tin mineralization, however, and it is apparent that a combination of factors, including tin-rich source rocks, well advanced magmatic differentiation, and the presence of volatiles, are necessary if economic deposits of tin are to be formed.

CONCLUSIONS

At least four petrographically and geochemically distinct groups of acid igneous rocks are present in northeast Queensland.

The Precambrian Esmeralda Granite and comagmatic Croydon Volcanics are characterized by relatively high K_2O, FeO (total), Zn, Rb, Y, Zr, Sn, Pb, Th, and U, and low Na_2O and MgO contents. Tourmaline and almandine-rich garnet are characteristic accessories. Both geochemical and isotopic evidence suggest an origin for the magmas by anatexis of potash-rich sialic crustal rocks. The Esmeralda Granite crystallized under conditions of low water pressure (<1000 bars), consistent with the observed shallow depth of emplacement.

The Forsayth Granite includes a geochemically heterogeneous suite of mostly synkinematic, catazonal or mesozonal granitic rocks. The granites and adamellites of the Forsayth area are probably not genetically related to the granodiorites of the Forsayth batholith. The former group, at least, show evidence of extensive alkali metasomatism, as well as redistribution of U and Th. The granodiorites from the intrusions southeast of Forest Home homestead form a chemically distinct group. At least three unrelated parent magmas therefore appear to have been involved in the formation of the Forsayth Granite, and it is probable that intrusions of a wide range of ages occur within the Forsayth batholith. Rocks originally regarded as Robin Hood Granite may be divided into two groups—adamellites and granites (now assigned to the Digger Creek Granite) and granodiorites (Robin Hood Granite s.s.).

The Siluro-Devonian Dumbano Granite and Dido Granodiorite also form a relatively heterogeneous group. Most of the rocks have relatively low Fe/Mg and K/Na ratios. Probably at least three magmas were involved in the formation of these rocks. The Dumbano trondhjemites, with particularly low K/Na ratios, do not appear to be chemically related to the group which includes the granites, adamellites and granodiorites, as well as the Dido tonalites. Parent magmas for both of these groups were relatively potash-poor and may have been derived by anatexis of materials of igneous origin. The Dido quartz diorites form another chemically distinct group; they lie on a fractionation trend which is characterized by relatively high K/Na ratios and either represent a primary intermediate magma type or were derived by differentiation of mafic magma.

The Upper Palaeozoic igneous rocks consist of an extensive and typically calc-alkaline suite of high-level intrusive rocks (mostly adamellite, with subordinate granite and granodiorite, and minor diorite and gabbro) with associated volcanics (mainly rhyodacite welded tuff sheets and flows, with subordinate rhyolite, dacite, andesite, and basalt). The extrusive and intrusive rocks exhibit similar variation trends and element abundances, although the volcanics have a greater range of alkali ratios, attributable to post-consolidational metasomatism. The dacites and microgranodiorites of the Cumberland Range Cauldron Subsidence Area are geochemically distinct from the other rocks, having relatively low K/Na ratios. Many of the granitic rocks, notably the Elizabeth Creek Granite, show highly fractionated element abundances, that is, low TiO_2, FeO, MgO, CaO, Ni, Cr, Co, Sr, Ba, K/Rb, Ba/Rb, and Mg/Li and high SiO_2, K_2O, Li, Be, Rb, Y, Sn, Th, and U. The Elizabeth Creek and Lochaber Granites commonly contain fluorite, and tourmaline is a characteristic accessory mineral in the Mareeba and Finlayson Granites. The intrusive rocks as a group have higher than average abundances of Sn, Th, and U.

The majority of the Upper Palaeozoic acid igneous rocks are considered to have been derived by anatexis of rubidium-poor deep crustal material in association with a subduction zone. Isotopic data are not consistent with an origin by partial melting of normal sialic crustal rocks, and the scarcity of basic to intermediate rock types points strongly against a derivation by differentiation of mafic magma. A hybrid origin for the Almaden Granite is not considered likely—the chemical variations can best be explained if the Almaden Granite and other acid rocks are regarded as members of the same magmatic differentiation series. It is possible that intrusion of andesitic or basaltic magma, generated by melting of subducted oceanic crust, may have caused melting of the lower crustal rocks. Such a process would be facilitated by rising volatiles, such as fluorine, lithium, and phosphorus pentoxide, from the subduction zone. Anatexis of relatively anhydrous, high-grade metamorphic rocks would be expected to yield fairly dry granitic magmas, capable of rising to high crustal levels. This is consistent with estimated water pressures during crystallization of less than 1000 bars. The amount of melting would have to be rather restricted to produce granitic to granodioritic liquids significantly enriched in K and Rb relative to the parent material, although not limited to the extent that only water-saturated melts were produced. The chemistry of the more siliceous rocks can only be explained by a process of fractional crystallization and it is probable that the lower levels of the intrusions are predominantly of less fractionated granodioritic composition, possibly similar to the Hammonds Creek Granodiorite, which is relatively low in Rb, Th, and U and has a high K/Rb ratio. The temporal progression of Palaeozoic igneous activity from southwest to northeast may be related to migration of a Benioff zone away from the continental margin, associated with opening of the marginal Hodgkinson Basin.

Granitic rocks with associated tin mineralization (the Esmeralda, Elizabeth Creek, Mareeba, Cannibal Creek, Finlayson, and Altanmoui Granites) have well defined chemical characteristics. Like tin-bearing granites from many other parts of the world, they are high-level strongly fractionated granites or adamellites, enriched in volatile elements such as B, Be, Li, and F. Li and Sn are highly correlated in the tin-bearing granites, but not in the other acid rocks. Sn contents are significantly higher than those of non-stanniferous granites, but lower than values reported for many tin-bearing granites elsewhere. A distribution of Sn in which a high proportion of samples have Sn contents significantly higher than background values appears to be a characteristic feature of granitic rocks with associated tin mineralization. Most of the higher Sn values occur in the vicinity of known tin mines or prospects. The occurrence in northeast Queensland of two groups of tin-bearing granites, of widely different ages and possibly different origins, may be explained by the existence of a region of anomalously high Sn content, either in the upper mantle, or, probably, the crust. Such a concept would also explain the difference in Sn content between tin-bearing and non-stanniferous granitic rocks.

There is a notable lack of correlation between granite geochemistry and lead-zinc or copper mineralization. Granites associated with such mineralization do not show significant enrichment in Pb, Zn, or Cu. The geochemical behaviour of copper (and probably zinc) appears to be largely independent of those of the other studied elements, possibly reflecting the action of mineralizing fluids or the distribution of sulphide phases, or both. It is probable that the Upper Palaeozoic acid magmas were derived by melting of the lower crust, whereas a large part of the ore metals (including lead, copper, and zinc) may well have been derived from subducted oceanic crust or the overlying mantle. We follow Wright & McCurry (1973) in regarding mineralization as an independent by-product of magma generation rather than a direct result of magmatic differentiation processes. Thus, the general lack of correlation between the Cu, Pb, and Zn contents of intrusive bodies and their association with economic deposits of these metals is explicable.

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APPENDIX

ANALYTICAL METHODS

Si, Ti, Al, Fe (total), Mn, Mg, Ca, Na, K, P, Ga, Rb, Sr, Y, Zr, Ba, La, Ce, Pb, Th and U were determined in the BMR laboratories, using a Philips PW-1210 automatic X-ray spectrometer (analysts, J. W. Sheraton, J. C. Weekes). Major elements (except for Na_2O) were determined on fusion discs, using the technique of Norrish & Hutton (1969). Na_2O was measured on pressed powder pellets. Trace elements were also determined on powder pellets, with direct measurement of the mass absorption coefficients of each sample (Norrish & Chappell, 1976). Empirical interfering element corrections were made where necessary. Detection limits (Table A) were calculated at the 95 percent confidence level for detection of peak above background, using the relation given by Jenkins & de Vries (1967):

TABLE A. DETECTION LIMITS

Oxide	*%*	*Element*	*ppm*
SiO_2	0.02	Li	1
TiO_2	0.004	Be	0.5
Al_2O_3	0.03	Cr	3
Fe_2O_3	0.01	Co	3
MnO	0.005	Ni	3
MgO	0.11	Cu	1
CaO	0.006	Zn	1
Na_2O	0.11	Ga	2
K_2O	0.002	Rb	1
P_2O_5	0.006	Sr	0.5
		Y	1
		Zr	2
		Sn	4
		Ba	3
		La	2
		Ce	7
		Pb	2
		Th	2
		U	2

$$\text{Detection limit} = \frac{3c}{(Rp\text{-}Rb)}\sqrt{\frac{Rb}{t}},\ \text{where } Rp$$

= peak count rate (counts/sec); Rb = background count rate (counts/sec); t = background counting time (secs); and c = concentration of element.

Li, Be, Cr, Co, Ni, Cu, Zn, and Sn, together with FeO, MgO and Pb in the biotites, were determined by atomic absorption spectroscopy in the BMR laboratories (analysts, B. I. Cruikshank, R. W. Powell, G. Willcocks). H_2O, CO_2, F, and ferrous iron were determined by the Australian Mineral Development Laboratories.

TABLE B. COMPARISON OF STANDARD ROCK ANALYSES

	G2 Recommended	*XRF*	*AGVI Recommended*	*XRF*
SiO_2	69.19	69.16	59.00	59.27
TiO_2	0.53	0.50	1.08	1.09
Al_2O_3	15.35	15.30	17.01	17.15
†Fe_2O_3	2.77	2.68	6.80	6.86
MnO	0.04	0.03	0.10	0.10
MgO	0.78	0.80	1.49	1.61
CaO	1.99	1.93	4.98	4.98
Na_2O	4.16	4.18	4.33	4.10
K_2O	4.51	4.43	2.90	2.91
P_2O_5	0.14	0.13	0.49	0.50
TOTAL	99.46	99.14	98.18	98.57
Cr	9	11*	13	
Co	5	9*	16	
Ni	6	3*	18	
Cu	11	13*	64	
Ga	20	22	18	20
Rb	174	168	75	65
Sr	463	492	657	661
Y	12	13	25	20
Zr	320	333	230	241
Ba	1 950	1 836	1 340	1 205
La	104	95	40	41
Ce	166	168	76	68
Pb	29	29	35	34
Th	25	31	7.0	8
U	2.0	1.5	1.9	2.5

† Total iron as Fe_2O_3.
* Atomic absorption results.

Precision and accuracy

Precision of the X-ray fluorescence technique is generally good. The effects of all but very short term drift in machine conditions were practically eliminated by ratioing each measurement to a reference standard. Each determination was carried out in duplicate (using the same sample) and, in cases where significant differences occurred between duplicates, the determination was repeated. Replicate sample precision was checked by running duplicate samples, and was found to be within acceptable limits (±1% for fusion discs and considerably better for powder pellets).

Accuracy was assessed by analysing international rock standards. Comparisons of XRF and AA results with recommended values for two USGS standard rocks (G2 and AGVI) are given in Table B. Data for the USGS standards are from Flanagan (1969). For several trace elements, means were recalculated after rejecting some obviously spurious values. In most cases, this was found to give a much more reasonable value than the averages given by Flanagan (1969, p. 109). Thus for Rb in G2, the very high value of 513 ppm was rejected and the mean of the remaining values was calculated. In cases where individual reported values are themselves means of two or more determinations, the values were taken only once. Replicate analyses from the same laboratory are liable to the same systematic errors and there seems no reason to weight the final average in favour of these values. The recalculated mean Rb content for G2 is 174 ppm, which compares much more favourably with the majority of the quoted values than the average of 234 ppm given by Flanagan. For AGVI, recalculated and published means for Rb are 75 and 89 ppm, respectively.

For most major elements, agreement between recommended and XRF results is good (i.e. within ±3%). For Na_2O and most trace elements (except near the detection limit), accuracy is of the order of ±5 to 10 percent. Uncertainties in the compositions of the international standards, particularly for trace elements, means that estimates of accuracy can only be approximate, however.

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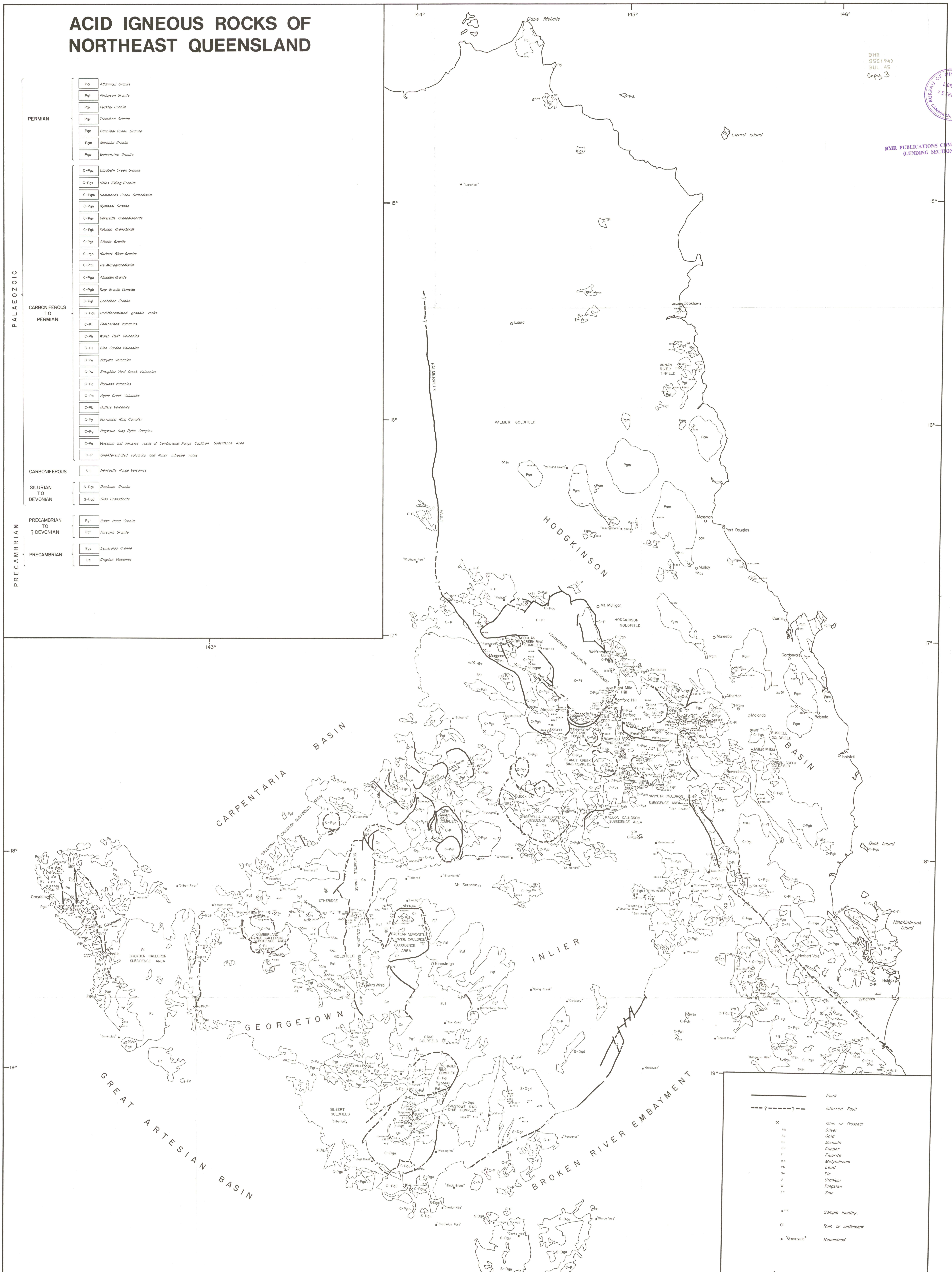
ACID IGNEOUS ROCKS OF NORTHEAST QUEENSLAND

PALAEOZOIC	PERMIAN	Pgi	*Altanmoui Granite*
		Pgf	*Finlayson Granite*
		Pgk	*Puckley Granite*
		Pgv	*Trevethon Granite*
		Pgc	*Cannibal Creek Granite*
		Pgm	*Mareeba Granite*
		Pgw	*Watsonville Granite*
	CARBONIFEROUS TO PERMIAN	C-Pgz	*Elizabeth Creek Granite*
		C-Pgs	*Hales Siding Granite*
		C-Pgm	*Hammonds Creek Granodiorite*
		C-Pgn	*Nymbool Granite*
		C-Pgv	*Bakerville Granodioriorite*
		C-Pgk	*Kalunga Granodiorite*
		C-Pgt	*Atlanta Granite*
		C-Pgh	*Herbert River Granite*
		C-Pmi	*Ixe Microgranodiorite*
		C-Pga	*Almaden Granite*
		C-Pgb	*Tully Granite Complex*
		C-Pgl	*Lochaber Granite*
		C-Pgu	*Undifferentiated granitic rocks*
		C-Pf	*Featherbed Volcanics*
		C-Ph	*Walsh Bluff Volcanics*
		C-Pl	*Glen Gordon Volcanics*
		C-Pn	*Nanyeta Volcanics*
		C-Pw	*Slaughter Yard Creek Volcanics*
		C-Po	*Boxwood Volcanics*
		C-Pa	*Agate Creek Volcanics*
		C-Pb	*Butlers Volcanics*
		C-Py	*Gurrumba Ring Complex*
		C-Pg	*Bagstowe Ring Dyke Complex*
		C-Pu	*Volcanic and intrusive rocks of Cumberland Range Cauldron Subsidence Area*
		C-P	*Undifferentiated volcanics and minor intrusive rocks*
	CARBONIFEROUS	Cn	*Newcastle Range Volcanics*
	SILURIAN TO DEVONIAN	S-Dgu	*Dumbano Granite*
		S-Dgd	*Dido Granodiorite*
PRECAMBRIAN	PRECAMBRIAN TO ? DEVONIAN	Pgr	*Robin Hood Granite*
		Pgf	*Forsayth Granite*
	PRECAMBRIAN	Pge	*Esmeralda Granite*
		Pc	*Croydon Volcanics*



━━━━	*Fault*
━ ━ ? ━ ━ ━ ? ━ ━	*Inferred Fault*
⚒	*Mine or Prospect*
Ag	*Silver*
Au	*Gold*
Bi	*Bismuth*
Cu	*Copper*
F	*Fluorite*
Mo	*Molybdenum*
Pb	*Lead*
Sn	*Tin*
U	*Uranium*
W	*Tungsten*
Zn	*Zinc*
● 1173	*Sample locality*
○	*Town or settlement*
■ "Greenvale"	*Homestead*

0 — 50
kilometres

M (G) 487