THE DYKES OF ANVERS ISLAND AND ADJACENT ISLANDS

By P. R. Hooper*

Abstract. The petrology of over 50 dykes collected from the Anvers Island area is recorded and 24 of these have been analysed for the major elements with the exception of sodium, water and carbon dioxide.

Two groups of dykes can be distinguished in the field and under the microscope. Those of the younger and smaller group are easily weathered, contain pyroxene and are usually propylitized. They intrude the Cape Monaco Granite and are assumed to be of Tertiary age. Those of the older and larger group are hard compact rocks with a monotonous mineralogy of acicular hornblende and basic oligoclase, and they are probably older than the Cape Monaco Granite. These are called amphibolite dykes because their texture is demonstrably secondary in many examples. Some of the amphibolite dykes are hornfelsed by Andean intrusions and thus are pre-Andean in age, probably associated with the Upper Jurassic Volcanic Group. Other amphibolite dykes intrude the major Andean intrusions. The majority intrude the Upper Jurassic Volcanic Group and might be either pre- or post-Andean. The chemical analyses supported by the petrography have allowed a further subdivision of the pre-Andean amphibolite dykes into a dominant group of basic composition and a group of rhyolitic composition which includes breccia dykes. Diagnostic differences between the pre-Andean basic amphibolite dykes and the post-Andean amphibolite dykes have not been found.

A clear mineralogical and chemical distinction is demonstrated between the normal propylitized pyroxene-bearing dykes and two, later, non-propylitized pyroxene-bearing dykes. A study of the chemical analyses indicates a higher K_2O and SiO_2 content of the pyroxene-bearing dykes of the Cape Monaco area compared to the Börgen Bay area and a generally higher K_2O content of all the Anvers Island dykes relative to those of the Argentine Islands.

It is concluded (i) that the identical mineralogy of the pre-Andean and post-Andean amphibolite dykes is due to deep burial and elevated temperatures during the period of Andean intrusions; (ii) that the metasomatic phase in south-west Anvers Island was very prolonged, affecting Tertiary dykes intruded into the cold Cape Monaco Granite, itself a product, in part at least, of the metasomatism.

Anvers Island is the largest and most southerly member of the Palmer Archipelago which fringes the north-west coast of Graham Land. A description of the geology of Anvers Island and adjacent islands has already been published (Hooper, 1962), and the reader is referred to this report for maps of the area and localities. The oldest exposed rocks are a volcanic sequence of andesitic and rhyolitic composition of Upper Jurassic age. These were intruded by gabbros and tonalites belonging to the Andean Intrusive Suite, which locally compressed and thermally metamorphosed the volcanic rocks. Later a wide-scale metasomatic phase gave rise to the Altered Assemblage on the south-west side of Anvers Island, mainly by the introduction of Si, K and Na to volcanic rocks. The development of the Cape Monaco Granite is associated with this metasomatism and is believed to represent its final product. On the north-eastern corner of Anvers Island a succession of Tertiary volcanic rocks fills an ancient valley eroded in the Andean intrusions.

Dykes are common throughout the area, but they are particularly abundant in the Upper Jurassic Volcanic Group and the Altered Assemblage. Other than dykes clearly hornfelsed by Andean intrusions and the breccia dykes of the Joubin Islands (Hooper, 1962, p. 18, 24, 26), these dykes have not yet been described.

That the dykes belong to at least three age groups was recognized in the field. Early dykes cutting the Upper Jurassic volcanic rocks are hornfelsed by Andean intrusions. These demonstrably pre-Andean dykes are probably closely associated with the Upper Jurassic volcanic rocks in which they are found. A second group intrudes the Andean intrusions but these are probably older than the Cape Monaco Granite. These dykes are probably closely associated in time with the major Andean intrusions.

These two groups cannot be distinguished in the field when they are found within the volcanic rocks or the Altered Assemblage at some distance from the Andean intrusions. Subsequent examination in the laboratory has shown them to have an identical mineralogy of basic oligoclase and acicular hornblende which is demonstrably secondary in many examples. All these dykes are described as amphibolites. A third group of dykes, distinguished in the field by their easily weathered surfaces and in the laboratory by the pyroxene they contain, is

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later than the amphibolite dykes, intrudes the Cape Monaco Granite and is assumed to be Tertiary in age.

Virtually all the dykes dip steeply, usually at an angle greater than 80°. In the Cape Monaco–Joubin Islands area the trends of a large number of these dykes have been recorded and are illustrated in Fig. 1. Both the amphibolite dykes and the pyroxene-bearing dykes show a strong maximum about 070° (Fig. 1a and b), with secondary maxima at approximately 030° and 130°. It would appear that the same planes of weakness remained available for dyke intrusion from Upper Jurassic to Tertiary times. A similar, but less marked maximum, in joints and faults has a similar trend and, indeed, the occupation of joint planes by the pyroxene-bearing dykes was often noted in the field. In contrast to this, the aplite veins in the Andean intrusions on the Joubin Islands show a very different maximum about 150°, which is presumably related to tension planes in the cooling body. The post-Andean amphibolite and pyroxene-bearing dykes appear to have been controlled by regional rather than such local structures.

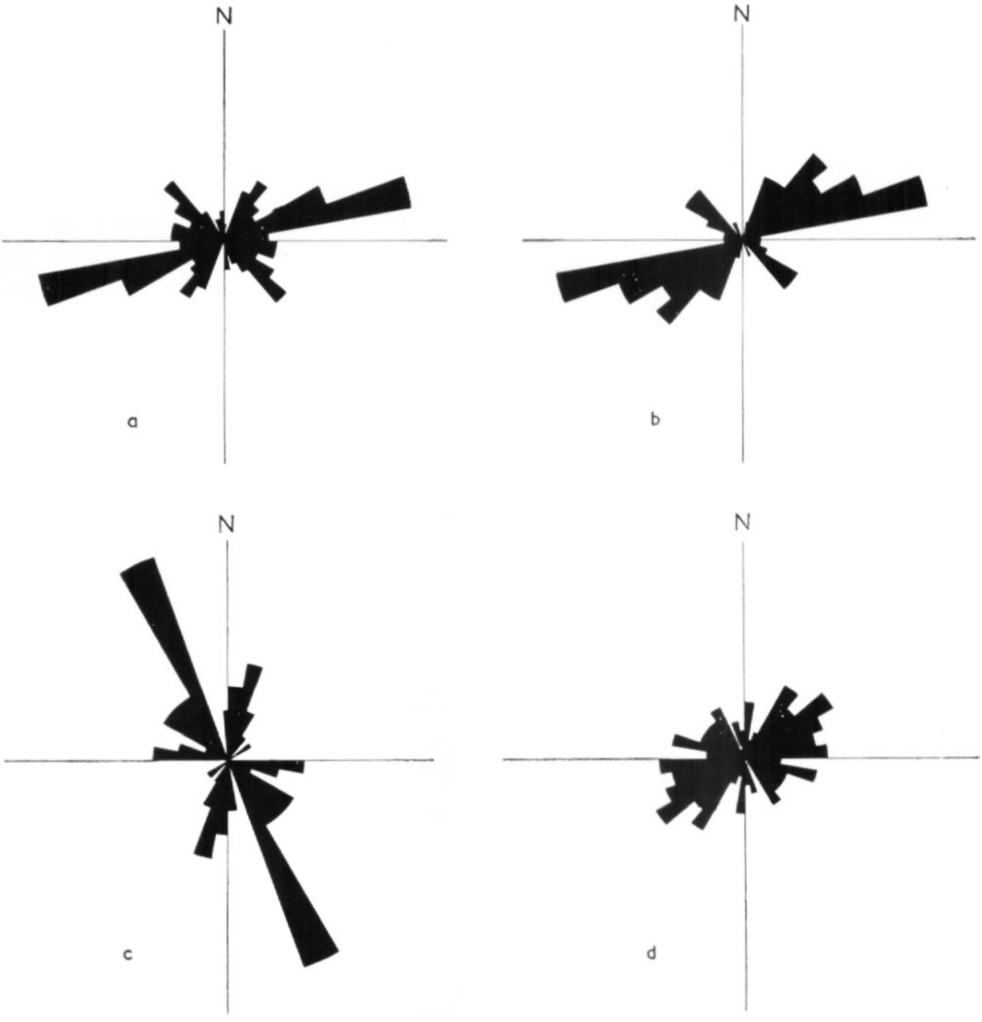

Fig. 1. Rose diagrams of the trend of basic dykes, aplite dykes, joints and faults from the Cape Monaco—Joubin Islands area. a. 127 amphibolite dykes; b. 44 pyroxene-bearing dykes; c. 37 aplite dykes within the Andean intrusions, Joubin Islands; d. 107 joints and faults.

Earlier geological reports on the north-west and west coasts of Graham Land emphasized the abundance of dykes found over this area. Pelikan (1909) described dolerites. Gourdon (1908, 1914) mentioned dykes of basalt, diabase and andesite cutting gabbro on Adelaide Island and microdiorite and hornblende-andesite dykes from the Anvers Island area; he also published numerous chemical analyses of these rocks. Barth and Holmsen (1939) gave a detailed description and seven chemical analyses of pyroxene-bearing diabases and dolerites and pyroxene-free rhyolitic breccia dykes, from the South Shetland Islands and the Anvers Island area. Tyrrell (1945), in an exhaustive review of rocks collected up to that date, mentioned many dykes and drew attention to the presence of spessartite dykes, composed of hornblende and andesine with a typical panidiomorphic texture, in the Adelaide Island area and at Cape Roquemaurel, in addition to the more typical pyroxene-bearing diabases and dolerites. Tyrrell (1945, p. 72) said that "this group of lamprophyres appears to be abundant in the Graham Land peninsula and the adjacent archipelagos".

More recently Goldring (1962) has described pyroxene-bearing andesite- and hornblende-microdiorites which he asserts are associated with the Upper Jurassic Volcanic Group, and post-Andean basalt and dolerite dykes carrying pyroxene. From the Basement Complex of the Neny Fjord area Hoskins (1963) has described pyroxene-bearing dykes which are probably younger that the Basement Complex. Dykes described by Hawkes (1961) from King George Island, South Shetland Islands, are thought to be of Tertiary age and contain either a single clinopyroxene or two pyroxenes. A chemical analysis is quoted.

Elliot (1964) has given a detailed account of the petrography and eight chemical analyses of dykes collected from the Argentine Islands by W. L. S. Fleming in 1934–37 and G. J. Roe in 1958–59. Elliot distinguished pre-Andean microdiorites and metamorphosed microdiorites, many of which contain pyroxene and certain hydrothermal alteration products; post-Andean altered microgabbros, basaltic andesites, augite-microdiorites and porphyritic microdiorites, most of which contain some pyroxene; porphyritic andesites and porphyritic augite-microdiorites which have been assigned to the Tertiary because of their fresh appearance. The variation in the chemistry of the eight rocks analysed is very limited.

In the present paper such terms as dolerite, diabase, microdiorite and basalt have been avoided because all these terms are to some extent ambiguous and because on Anvers Island, at least, one type grades into another and frequently a dyke margin would be placed under a different heading from the centre of the same dyke. The Anvers Island dykes are described as basic or rhyolitic on chemical grounds and amphibolites or pyroxene-bearing dykes on their petrography. None of the younger pyroxene-bearing dykes possess an ophitic texture, but relict ophitic textures do occur in some of the recrystallized amphibolites. Most dykes of all ages carry some phenocrysts or relict phenocrysts. The size and abundance of these, and the degree to which they form glomeroporphyritic aggregates, varies within each group.

Pyroxene-bearing Dykes

Pyroxene-bearing dykes have been collected from the Börgen Bay area, Cape Monaco and the Joubin Islands. They are relatively soft rocks, easily weathered and eroded. Fresh specimens show much less recrystallization than the amphibolite dykes. Where they are seen in contact, they are younger than the amphibolite dykes. The pyroxene commonly forms small glomeroporphyritic groups and it only rarely occurs in the groundmass. Pseudomorphs, probably after orthopyroxene or olivine, occur in most of the dykes, but fresh examples of these minerals have not been identified. Calcic plagioclase occurs in some dykes showing only modest alteration, but more typically the plagioclase is albite-oligoclase, liberally spattered with grains of calcite, chlorite and epidote.

Amphibole is typically present in two generations. A yellow-brown hornblende can occur as quite large euhedral phenocrysts, but it occurs more typically as subhedral prisms. A later green amphibole may form narrow margins to the yellow-brown hornblende, but more typically it forms a mesh of tiny needles throughout the groundmass. Amphibole is absent from only two pyroxene-bearing dykes examined.

Most of these dykes have suffered various degrees of propylitization with the development of calcite, chlorite and epidote. Areas of clear quartz, the alteration of cubes of titanomagnetite to tiny aggregates of leucoxene or sphene, and the occasional occurrence of prehnite-bearing veinlets may be associated with the propylitization. Two dykes of this group are not propylitized. The petrology of the pyroxene-bearing dykes is summarized in Table I.

The colour of the pyroxene varies between a very pale green and colourless. A slight pleochroism was noted in N.143.2.* It always appears colourless in thin section. Twinning is typical. Slight zoning both of the hour-glass type and oscillatory marginal type is present in most examples. The extinction angle $\gamma : c = 35° \pm 5°$. The optic axial angles and refractive indices of the pyroxenes from five dykes have been measured, using standard Universal Stage and oil immersion techniques, respectively, and a crude estimate of their chemical compositions has been derived (Deer, Howie and Zussman, 1963, figs. 22 and 41). All the pyroxenes fall within the salite field of the diopside-hedenbergite series. The variation in the Mg/Fe ratio indicated by refractive indices is rather large (Table I) and it does not appear to be reflected in the chemical analyses of the rocks in which they occur (Table II). As the crystals are seen to be quite extensively zoned, the variation in iron content found may reflect zoning in individual crystals rather than a difference between the dykes, indicating that the number of samples measured from each dyke was too small.

Many of the pyroxenes have a reaction rim of yellow-brown hornblende, which may in turn be rimmed by a late clear green actinolite. The earlier hornblende ($\alpha' = 1 \cdot 654 \pm 0 \cdot 003$, pale yellow; $\gamma' = 1 \cdot 677 \pm 0 \cdot 003$, olive-brown; $2V\alpha = 78–90°$; $\gamma : c = 16° \pm 2°$) forms euhedral to subhedral crystals and is a primary mineral. Its optical properties correspond to common hornblende with approximately equal proportions of the iron and magnesium molecules (Deer, Howie and Zussman, 1963, fig. 76). The later amphibole ($\alpha' = 1 \cdot 647$, pale green to yellow; $\gamma' = 1 \cdot 657$, colourless to green; $2V\alpha = 72–87°$; $\gamma : c = 14° \pm 2°$) corresponds to actinolite with approximately equal proportions of the iron and magnesium molecules (Deer, Howie and Zussman, 1963).

Plagioclase is always the most abundant mineral. In the few dykes in which it develops as phenocrysts, in addition to occurring in the groundmass, the phenocrysts have cores of basic bytownite while the groundmass laths are strongly zoned from An_{75} to andesine or oligoclase. In the coarse centres of the wider dykes the larger plagioclase laths are usually basic labradorite zoned to andesine or oligoclase.

With one exception, all the dykes collected in the vicinity of Cape Monaco, cutting the Cape Monaco Granite *or* the Altered Assemblage, have well-developed subhedral laths of oligoclase (An_{10-20}), speckled with grains of epidote, chlorite and calcite.

The alteration of the original calcic plagioclase crystals appears to have been independent of the propylitization of the pyroxenes and groundmass material. A particularly clear example of this is seen in the wide dyke represented by specimens N.233.7 (margin) and N.233.8 (centre) which occurs in rocks of the metasomatized Altered Assemblage near Cape Monaco. The centre of the dyke is so extensively propylitized that the pyroxenes are almost completely replaced by calcite, but the feldspar remains a fresh labradorite zoned normally from An_{70} to An_{30}. At the dyke margins the pyroxenes are fresh but the feldspar is completely altered to albite-oligoclase.

Chlorite is absent in only two dykes of this group (N.70.1, 84.2). Both also lack epidote, quartz and sphene but they contain a zeolite and biotite. Calcite is absent in the first but it is present in the second. As all the other pyroxene-bearing dykes are propylitized with the extensive development of calcite, chlorite and epidote and one of the non-propylitized dykes (N.84.2) intrudes a propylitized dyke, these two dykes appear to represent a slightly younger sub-group.

In the propylitized dykes the chlorite is usually abundant in areas interstitial to the plagioclase laths. It also forms blebs along the lengths of oligoclase crystals and fills cleavage cracks in the pyroxenes of some dykes. Its colour in thin section varies from virtually colourless, through a very pale green with no observable pleochroism to a distinct green with faint pleochroism (α' = pale yellow-green, γ' = pale green). In form, it varies from relatively large platy masses through smaller wavy platy crystals to radiating fibres. The larger crystals usually show a slate-grey interference colour with a birefringence of approximately $0 \cdot 005$ and positive

* Numbers refer to specimens in the British Antarctic Survey collection housed in the Department of Geology, University of Birmingham.

Specimen Number	General Area	Country Rock	Texture	Clinopyroxenes							Plagioclase			Amphibole†‡		Chlorite‡			Other Minerals						Pseudomorphs
				2Vγ†	α‡	γ‡	Composition	Colour	Zoning	Alteration	Form	Composition	Alteration	Earlier‡	Later‡	Colour	Sign	Interference Colours	Calcite	Quartz	Epidote	Ore	Sphene		
N.70.1*	Börgen Bay	Tonalite	Fine crystalline, with odd vesicles	Very small rectangular crystals with large extinction angle				Colourless	—	Altering to green biotite	Small laths	Basic labradorite zoned to andesine	Slight	Absent	A few small green needles		Absent		x	?	—	x	—	Biotite, zeolite	—
N.84.1*	Börgen Bay	Tonalite	Slightly porphyritic, small pyroxene phenocrysts	55°	1·695	1·720	$Mg_{30}Fe_{24}Ca_{46}$	Green	—	Fresh; hornblende reaction rim	Phenocrysts and groundmass	An_{85-10}	Fresh, with oligoclase containing a little calcite	α = 1·659 (yellow) γ = 1·677 (brown-green) 2V = 90° $\gamma : c$ = 16° ± 2°	α = yellow-brown γ = colourless 2Vα = 87° $\gamma : c$ = 14° ± 2°	Pale green	−ve	Blue (fibrous)	x	x	x	x	—	—	—
N.84.2*	Börgen Bay	Tonalite and N.84.1	Plagioclase and pyroxene in very fine matrix. Flow texture				Small grains		—	Fresh	Small laths	Basic labradorite	Green biotite	Absent	Mat of tiny green needles		Absent		—	—	—	x	—	Green biotite, natrolite, glass	—
N.141.3	Gossler Islands	Cape Monaco Granite	Glomero-porphyritic groups of pyroxene					Colourless	Hour-glass	Fresh; hornblende reaction rim	Stout laths in groundmass	An_{10-20}	Epidote, chlorite, calcite	α = pale yellow γ = green-brown; subhedral prisms	Tiny green needles	Colourless	+ve −ve	Brown, blue	x	x	x	x →	x		—
N.143.2*	Gossler Islands	Cape Monaco Granite and N.143.3	Porphyritic phenocrysts of pyroxene	55° to 60° (margin)	1·678	1·703	$Mg_{44}Fe_{10}Ca_{46}$	Green, slight pleochroism	Slight marginal	Fresh; hornblende reaction rim	Small laths in groundmass	An_{10-20}	Epidote	α = yellow γ = pale brown; subhedral prisms	Tiny green needles	Pale green	−ve	Berlin blue	x	x	x	x →	x	Haematite	Epidote, calcite, antigorite
N.143.3	Gossler Islands	Cape Monaco Granite	Coarse, feldspathic					Colourless	—	Little chlorite	Coarse laths	An_{10}	Epidote, chlorite, calcite	Absent	Absent	Strong green	−ve	Blue-grey	x	x	x	x →	x		—
N.233.3	Cape Monaco	Tonalite	Small phenocrysts (pyroxene and olivine pseudomorphs)					Green tinge	—	Chlorite	Small laths in groundmass	An_{20}	Epidote, chlorite	α = yellow γ = green-brown; subhedral prisms	Tiny green needles	Pale green	−ve	Berlin blue	x	x	x	x →	x	Prehnite in vein	—
N.233.4	Cape Monaco	Tonalite	Small phenocrysts (pyroxene and olivine pseudomorphs)	Small grains in groundmass also				Colourless	Slight marginal	Fresh	Small laths in groundmass	An_{10-20}	Epidote, chlorite	α = pale yellow-green γ = brown-green	Tiny green needles	Very pale green	−ve	Pale grey	x	—	x	x →	x		Chlorite, epidote
N.233.5 (centre)	Cape Monaco	Tonalite	Coarse phenocrysts of plagioclase, pyroxene and hornblende					Pale green	Slight marginal	Calcite; hornblende reaction rim	Coarse laths (phenocrysts)	An_{10-20}	Epidote, chlorite	α = pale yellow γ = olive-brown; stout subhedral prisms	Absent	Very pale green	−ve	Isotropic to Berlin blue	x	—	x	— →	x		Chlorite, epidote
N.233.6 (margin)	Cape Monaco	Tonalite	Few phenocrysts (pyroxene) in fine groundmass					Pale green	—	Calcite	Small laths in groundmass	An_{10-20}	Epidote, chlorite	Absent	Absent	Very pale green	−ve	Isotropic to Berlin blue	x	x	x	x →	x		Epidote
N.233.7 (margin)	Cape Monaco	Tonalite and N.233.5, 6	Small phenocrysts (pyroxene and olivine pseudomorphs) in flow-textured groundmass					Pale green	Slight marginal	Fresh	Small orientated laths in groundmass	An_{20}	Epidote, chlorite	α = pale yellow γ = brown-green orientated laths	Gradation to finer green laths				x	—	x	x →	x		Calcite, chlorite
N.233.8 (centre)	Cape Monaco	Tonalite and N.233.5, 6	Coarse, slightly porphyritic (pyroxene)					Pale green	—	Almost complete to calcite	Coarse laths	An_{70-50}	Fresh; very little epidote	α = yellow γ = brown-green; stumpy phenocrysts	Absent	Very pale green	−ve	Blue-grey	x	x	tr	x →	tr	Haematite	?
N.267.5*	Cape Monaco	Altered Assemblage and amphibolite dyke	Phenocrysts of pyroxene	55°	1·687	1·713	$Mg_{37}Fe_{17}Ca_{46}$ Small grains in groundmass also	Colourless	Hour-glass and oscil-latory marginal	Fresh	Small laths in groundmass	An_{20}; slight normal zoning	Fresh; very little epidote	α = yellow γ = brown-green; small subhedral prisms	Tiny green needles	Pale green	−ve n' = 1·596	Berlin blue	x	(?)	x	x	x	Iddingsite (?)	Epidote, calcite-chlorite
N.289.1*	Joubin Islands	Meta-somatized volcanic rocks	Fine; small phenocrysts of plagioclase and pyroxene					Colourless	Oscil-latory marginal	Fresh	Larger crystals Groundmass laths	Oligoclase An_{50-40}	Epidote	A few small laths of green amphibole		Very pale green	Microcrystalline		—	—	x	x	—	Zeolite, glass	Antigorite-chlorite
N.299.3	Joubin Islands	Hornfelsed volcanic rocks	Glomero-porphyritic pyroxene and plagioclase	52°	1·686	1·716	$Mg_{37}Fe_{19}Ca_{44}$	Colourless	Hour-glass and oscil-latory marginal	Fresh	Phenocrysts Groundmass laths	Labradorite An_{40}	Slight	Possibly present as tiny olive needles		Very pale green	−ve	Berlin blue	x	x	—	x	x		Antigorite
N.416.2	Joubin Islands	Tonalite	Coarse, with large crystals of pyroxene, plagioclase, hornblende and olivine pseudomorphs	52°	1·681	1·709	$Mg_{44}Fe_{12}Ca_{44}$	Colourless	Slight marginal	Fresh; hornblende reaction rim	Phenocrysts Smaller laths	An_{82} An_{74-20}	Slight	α = 1·560 (yellow) γ = 1·565 (brown) 2Vα = 78° $\gamma : c$ = 16° ± 2° Core of phenocrysts	α = 1·647 (pale green) γ = 1·657 (green) 2Vα = 72° Margin of phenocrysts and groundmass	Very pale green	−ve	Grey	—	x	tr	x	—		Antigorite-ore
N.44.3	Iliad Glacier	Acid intrusion (? Andean)	Plagioclase phenocrysts embedded in devitrified glass	No pyroxene present							Phenocrysts (A)	An_{44}; normal oscillatory zoning	Fresh	No hornblende present		Colourless	?	Blue	x	—	—	x	—	Biotite, formed from devitrified glass	Biotite-ore
											Phenocrysts (B)	—	Completely pseudomorphed by sericite												
N.278.1*	Joubin Islands	Meta-somatized volcanic rocks and amphibolite dykes	Coarse, intergranular	No pyroxene present							Laths	Labradorite (zoned)	Calcite but relatively fresh	Euhedral brown-green hornblende		Green pleochroic (radiating fibres)	+ve	Brown	x	x	—	x	—		Chlorite, calcite

* Chemically analysed (see Table II). † 2V values ± 3°. ‡ Refractive index values ±0·003. x Mineral present.

elongation (optically negative). Smaller crystals appear to have a lower birefringence and deep Berlin-blue interference tints, but still with positive elongation. There are a few examples of isotropic chlorite and in one rock areas of chlorite have centres showing Berlin-blue interference tints and positive elongation surrounded by a narrow margin with brownish interference tints and negative elongation (optically positive). A single measurement of refractive index gave $n' = 1 \cdot 596$.

The correspondence between the change in the tint of the anomalous interference colours with change in optic sign agrees well with the work of Albee (1962). The rather low refractive index at which this change occurs is unusual for the majority of chlorites, but it is typical of chlorites occurring in vesicles and veins of basic igneous rocks. Albee has tentatively suggested that in such cases it is the optic sign which is anomalous due to some aluminium in six-fold co-ordination being balanced by an H deficiency. If this is true, the chlorites in the pyroxene-bearing dykes are pycrochlorites in Hey's (1954) classification. If it is not true, then these chlorites would fall within Hey's diabantite group.

Many of these dykes contain areas of epidote, epidote and calcite, epidote and chlorite, calcite and chlorite, antigorite, antigorite and chlorite, and antigorite and iron ore. Some could represent original vesicles, but many have fairly definite crystal form and are probably pseudomorphs after orthopyroxene or olivine.

Two dykes (N.44.3, 278.1) which do not contain pyroxene are grouped with the pyroxene-bearing dykes and they are believed to be of the same general age, because of their fresh unaltered appearance, the presence of abundant chlorite in both and of euhedral olive-green hornblende crystals in N.278.1 (Table I). These last two features are not found in the amphibolite dykes.

The age of the pyroxene-bearing dykes is not known exactly. They appear to have been intruded some considerable time after the crystallization of the Andean intrusions and the Cape Monaco Granite, which are generally regarded as being late Cretaceous or early Tertiary in age (although accurate dating is lacking). Thus the dykes can be assigned to the Tertiary with reasonable certainty. Whether they are related to the post-Andean (Tertiary) volcanic rocks which crop out on the north-east corner of Anvers Island is much less certain, but this would seem possible.

Amphibolite Dykes

Petrography

The great majority of dykes on Anvers Island and adjacent islands belong to this group. They are characterized by the absence of pyroxene and the presence throughout of an acicular hornblende associated with a basic oligoclase. Their mineralogy is remarkably consistent. They occur in greatest abundance in the Upper Jurassic Volcanic Group and the Altered Assemblage but they are well distributed within the various Andean intrusions. One example occurs within the margin of the Cape Monaco Granite on the Joubin Islands, a unique occurrence the significance of which is discussed below. From their field occurrence there is little doubt that many of these dykes are closely associated in time with the Jurassic extrusions (p. 75), while others are post-Andean, and are therefore late Cretaceous or early Tertiary in age.

The texture of these dykes is dominated by the sheaves and individual needles of hornblende with a pleochroism α = very pale yellow, β = pale green and γ = clear bluish green. The smaller individual needles are found throughout the rock, penetrating the feldspar and quartz phases. The hornblende appears identical all through the group and it is distinct from both the coarser hornblende phase and the acicular actinolite phase of the pyroxene-bearing dykes. The plagioclase is typically oligoclase with a composition between An_{20} and An_{30}. A general lath or tabular form can be distinguished in a number of cases, but the margins are always irregular, pierced by hornblende needles which, with biotite, occur all through the crystals. Twinning is poorly developed and usually simple. In approximately one-third of the dykes examined a more basic plagioclase forms the cores of the crystals. This is usually andesine but labradorite has been recorded in a few cases. These cores exhibit a better developed lamellar twinning than the oligoclase.

The two minerals, amphibole and plagioclase, form over 95 per cent by volume of most of these dykes. Plagioclase phenocrysts are common and large coherent sheaves of hornblende, sometimes associated with iron ore, suggest that in such cases this mineral is pseudomorphing an earlier ferromagnesian mineral. In at least two cases a ghost ophitic texture is seen, indicating original pyroxene. Dyke N.293.1, associated with the Upper Jurassic volcanic rocks on the Joubin Islands, has a well-developed trachytic texture and it is distinctive in the abundance of quartz, the presence of an iron epidote and clinozoisite, and a green biotite. Chemical analysis (Table II) proves it to be rich in SiO_2 and K_2O. Two other dykes (N.267.3, 4) have developed a hornfelsic texture in the plagioclase phase, the new interlocking oligoclase grains showing a little twinning. The hornblende is similar to that in the other members of the group, except that in specimen N.267.3 pyroxene cores occur in the larger sheaves of hornblende.

A biotite, pleochroic from almost colourless to a medium brown, occurs as small crystals in most of these dykes, although its abundance varies considerably. It appears to be in equilibrium with the small hornblende needles. Small cubic grains of iron ore are typical and they may be quite fresh or partially altered to tiny grains of leucoxene or sphene. Small grains of quartz occur in the more acid members.

Iron epidote, chlorite and occasionally albite and clinozoisite occur in small quantities in many dykes, apparently associated with more quartz than would be expected from the chemical analysis. In some cases the earlier hornblende-oligoclase-biotite-titanomagnetite assemblage has been completely replaced by an iron epidote-quartz assemblage along narrow veins which stand out in the field as yellow streaks typically developed along joint planes.

This assemblage appears to represent a very localized retrograde metamorphism, although some metasomatism must also have occurred. Development of a similar mineralogy along the margins of some major Andean intrusions has already been described (Hooper, 1962, p. 15) and it was suggested that it is associated with a late shearing along intrusive contacts.

Origin of the amphibolite dykes

The mineral assemblage hornblende-oligoclase-biotite corresponds to that of the amphibolite facies, while relict ophitic textures imply that the assemblage is secondary. A hornfelsic texture is confined to a few dykes within the contact aureoles of the Andean intrusions and a tectonic fabric has never been observed. The amphibolitization of the post-Andean dykes might be explained by a process of uralitization by the late phases of the Andean magma. In view of the identical assemblages developed in the pre-Andean and post-Andean dykes, the earlier dykes must have been recrystallized under the same conditions. Conditions of deep burial and elevated temperature over much of the Anvers Island area during the final stages of the Andean intrusive period would appear to be the most satisfactory explanation.

The amphibolite dykes described above are very similar to those rocks collected from Cape Roquemaurel and from dredgings off Adelaide Island, and described by Tyrrell (1945) as spessartites. This term has not been applied to the amphibolite dykes from Anvers Island, because true hornblende phenocrysts are not seen and in many the texture is clearly secondary.

Geochemistry of the Dykes

Twenty-four dykes collected in the Anvers Island area have been analysed for all major elements with the exception of sodium, water and carbon dioxide (Table II). The analyses were made by X-ray fluorescence techniques as described by Hooper (1964), except that a chromium target tube was used for phosphorus and magnesium, thus increasing the precision and accuracy of the analyses for these elements.

In Table II the analyses have been arranged according to the field and microscopic evidence. The pyroxene dykes are separated from the amphibolite dykes and three of the latter are grouped as pre-Andean. Only one of these (N.267.3), in fact, is pre-Andean beyond all doubt, because it is hornfelsed by an Andean intrusion. The other two are assumed to be pre-Andean, because they are cut by many other amphibolite dykes and a breccia dyke. The majority of the amphibolite dykes cannot be described as either pre- or post-Andean and they have not been used in Figs. 2 and 3.

A study of Table II and Figs. 2 and 3 reveals no clear distinction between the three pre-

TABLE II. CHEMICAL ANALYSES OF DYKES FROM ANVERS ISLAND

	Amphibolite Dykes																
	Probably Pre-Andean										Unknown Age						
	Rhyolitic and Breccia Dykes							Basic Dykes			Basic Dykes						
	N.420.1	N.420.6	N.293.1	A	B	C	D	N.267.3	N.277.1	N.277.2	N.289.4	N.290.3	N.290.4	N.293.3	N.295.5	N.420.2	N.277.3
SiO_2	70·5	73·8	74·5	77·7	74·8	71·9	63·4	50·5	50·2	53·0	53·9	53·4	47·5	55·0	50·6	58·5	47·8
TiO_2	0·47	0·35	0·37	0·25	0·29	0·60	0·92	0·68	0·94	1·69	0·52	1·28	1·04	0·92	0·67	1·15	2·22
Al_2O_3	14·55	13·65	12·95	11·55	13·29	14·77	18·88	15·75	15·35	15·15	15·75	15·00	19·40	17·75	15·55	16·10	14·75
Total Fe (as Fe_2O_3)	3·94	3·02	2·28	1·89	2·29	3·82	5·36	9·08	10·15	11·66	12·10	9·07	10·97	8·00	7·66	9·18	15·14
Fe_2O_3	1·43	0·52	0·84	1·40	nil	0·40	1·43	2·30	3·61	4·63	3·91	3·82	5·14	2·17	2·82	4·19	6·80
FeO	2·44	2·43	1·48	0·44	2·06	3·08	3·54	6·37	6·16	6·60	7·64	5·00	5·52	5·47	4·54	4·76	7·91
MnO	0·08	0·04	0·04	—	—	—	—	0·41	0·25	0·23	0·22	0·13	0·11	0·11	0·13	0·16	0·24
MgO	1·15	0·63	0·25	0·02	0·04	0·07	1·22	8·00	7·23	3·75	3·90	2·48	4·42	3·90	8·50	2·42	5·80
CaO	2·45	1·50	2·10	4·79	1·93	2·97	4·10	7·60	9·45	7·50	7·25	5·45	6·50	6·55	7·80	10·55	4·90
Na_2O	—	—	—	1·13	4·06	3·12	5·34	—	—	—	—	—	—	—	—	—	—
K_2O	3·38	3·39	3·33	2·15	2·34	1·44	0·97	2·61	0·58	0·16	0·39	1·55	4·95	1·46	1·04	0·17	3·42
P_2O_5	0·06	0·22	0·06	0·01	—	—	—	0·15	0·23	0·82	0·53	0·30	0·22	0·21	0·13	0·39	0·74
$Fe_2O_3/(Fe_2O_3+MgO)$ (per cent)	78·26	83·64	90·84	98·95	98·28	98·20	81·46	53·97	59·14	76·13	76·07	79·07	71·83	67·90	48·04	79·66	72·88

	Pyroxene-bearing Dykes													
	Post-Andean					Propylitized					Unpropylitized		Associated Rocks	
	Basic Dykes					Basic Dykes					Basic Dykes			
	N.44.4	N.60.1	N.60.2	N.238.1	N.238.2	N.143.2	N.267.5	N.289.1	N.84.1	N.278.1	N.84.2	N.70.1	N.44.1	N.239.1
SiO_2	53·7	55·0	57·0	49·1	48·3	52·6	50·0	48·1	48·3	56·5	51·4	51·8	78·5	75·3
TiO_2	0·67	0·57	0·65	0·88	0·88	0·86	0·65	1·66	0·78	0·61	0·55	0·57	0·05	0·21
Al_2O_3	18·10	18·35	17·2	16·20	16·60	14·50	15·40	15·70	17·50	16·05	18·35	17·75	12·60	13·10
Total Fe (as Fe_2O_3)	7·28	6·90	6·28	8·20	9·67	7·70	7·56	7·05	8·31	6·21	8·51	8·39	1·08	1·58
Fe_2O_3	2·14	3·30	3·52	2·99	4·64	3·19	2·62	4·02	3·68	2·13	5·61	3·54	0·47	0·72
FeO	4·90	3·51	2·75	4·96	4·80	4·33	4·72	3·00	4·44	3·76	2·88	3·19	0·64	0·86
MnO	0·13	0·10	0·10	0·17	0·17	0·13	0·14	0·09	0·12	0·13	0·16	0·16	0·02	0·02
MgO	5·00	3·40	2·60	8·63	7·90	7·92	9·60	8·58	8·65	4·95	3·10	3·10	0·10	0·50
CaO	7·55	5·60	6·60	8·85	8·70	9·20	5·00	7·00	9·20	7·40	8·40	7·85	0·50	1·90
Na_2O	—	—	—	—	—	—	—	—	—	—	—	—	—	—
K_2O	1·76	2·33	1·03	1·22	1·79	1·49	3·58	2·38	0·58	0·33	0·42	0·82	4·48	3·04
P_2O_5	0·12	0·17	0·24	0·52	0·21	0·25	0·15	0·14	0·18	0·23	0·26	0·23	0·04	0·08
$Fe_2O_3/(Fe_2O_3+MgO)$ (per cent)	62·40	67·92	71·68	49·62	55·79	50·25	45·02	46·14	49·88	56·04	73·97	73·71	92·19	77·06

N.420.1, 6. Breccia dykes, Island G_1, Joubin Islands.
N.293.1, 3. Island F_4, Joubin Islands.
A. Quartz-porphyrite boulder, Port Lockroy (Barth and Holmsen, 1939).
B. Prehnitized rock fragment in breccia, Joubin Islands (Barth and Holmsen, 1939).
C. Igneous breccia, Joubin Islands (Barth and Holmsen, 1939).
D. Igneous breccia, Peltier Channel (Barth and Holmsen, 1939).
N.267.3, 5. Opposite Dream Island, near Cape Monaco.
N.277.1, 2, 3. Island G_1, Joubin Islands.
N.89.4. Island F_1, Joubin Islands.
N.290.3, 4. Island F_1, Joubin Islands.
N.295.5. Island D_1, Joubin Islands.

N.420.2. Island G_1, Joubin Islands.
N.44.1. Major intrusive body, north-east side of Iliad Glacier.
N.44.4. Dyke in N.44.1, north-east side of Iliad Glacier.
N.60.1, 2. Gateway Ridge, Börgen Bay.
N.238.1, 2. Outcast Islands (1).
N.143.2. Gossler Islands.
N.289.1. Island F_1, Joubin Islands.
N.84.1, 2. Billie Peak, Börgen Bay.
N.70.1 Copper Peak, Börgen Bay.
N.239.1. Aplite vein, Outcast Islands (1).

[*face page 80*

Andean dykes and those known to be post-Andean. A possible exception is the apparent higher iron and manganese of the earlier dykes. This distinction is not observed in Elliot's (1964) analyses of the Argentine Islands dykes. Certainly the analyses of all the amphibolite dykes clearly fail to separate into two distinct groups when plotted on various diagrams and it can only be concluded at present that no petrological or chemical criteria have yet been

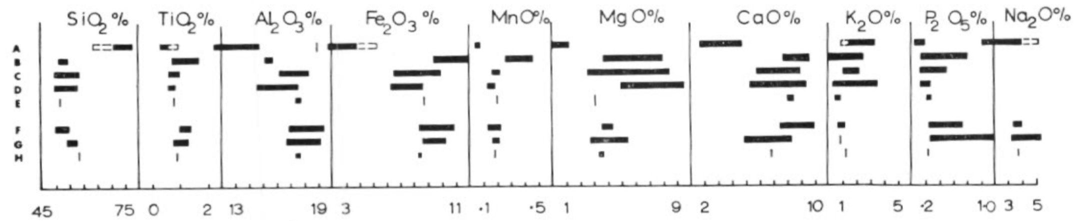

Fig. 2. The range in chemical composition of the five groups of dykes on Anvers Island and the three groups from the Argentine Islands.

A. 6 rhyolite (breccia) dykes, Anvers Island.
B. 3 basic pre-Andean amphibolite dykes, Anvers Island.
C. 5 basic post-Andean amphibolite dykes, Anvers Island.
D. 5 pyroxene-bearing (Tertiary) dykes (propylitized), Anvers Island.
E. 2 pyroxene-bearing (Tertiary) dykes (non-propylitized), Anvers Island.
F. 3 pre-Andean dykes, Argentine Islands (Elliot, 1964).
G. 3 post-Andean dykes, Argentine Islands (Elliot, 1964).
H. 2 Tertiary dykes, Argentine Islands (Elliot, 1964).

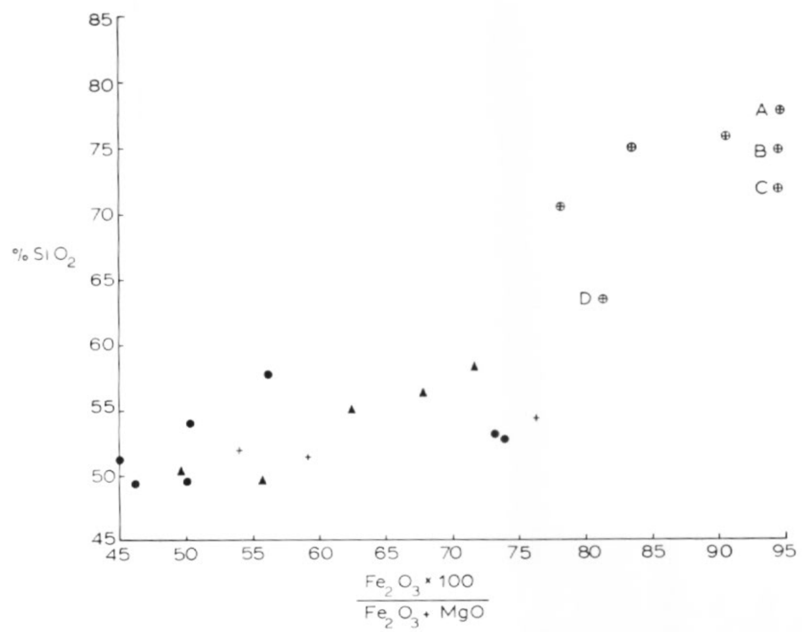

Fig. 3. Plot of SiO_2 against $(Fe_2O_3 \times 100)/(Fe_2O_3 + MgO)$ for Anvers Islands dykes.

● Pyroxene-bearing dykes.
▲ Post-Andean amphibolite dykes.
\+ Pre-Andean amphibolite dykes (basic).
⊕ Pre-Andean amphibolite dykes (rhyolitic and breccia dykes).
A, B, C and D refer to Table II.

established to distinguish the pre-Andean amphibolite dykes from the post-Andean amphibolite dykes. It is also impossible to distinguish between the much later pyroxene-bearing dykes and the amphibolite dykes on chemical grounds, despite clear differences in the field and in their petrography (Figs. 2 and 3). A basic magma of much the same composition appears to have been available in this area from Upper Jurassic until Tertiary times.

There is, on the other hand, a marked chemical difference between a small group of amphibolite dykes, including the breccia dykes (Hooper, 1962, p. 26) which have a rhyolite composition, and the typical basic amphibolite dykes. Four of the analyses published by Barth and Holmsen (1939) fall into the rhyolite group and they are quoted in Table II. They have high silicon and potassium, and low titanium, iron, manganese, magnesium and calcium. Even if the analyses are recalculated to 100 per cent without SiO_2, these dykes are still significantly lower in iron, manganese, magnesium and calcium, and very much higher in potassium. The igneous breccia from the Peltier Channel (Barth and Holmsen, 1939, p. 32, analysis 13), while retaining the characteristic features noted above, is less extreme and may represent a gradation between the rhyolitic and basic dykes. All six rhyolitic dykes analysed and the other breccia dykes recorded in the field occur in the Upper Jurassic volcanic rocks, are usually cut by a number of later amphibolite dykes and have a composition similar to many of the extrusions which they intrude. The tentative correlation of these dykes with the Cape Monaco Granite previously made (Hooper, 1962) therefore seems unlikely and all are now assigned to the Upper Jurassic.

Fig. 3 is a plot of SiO_2 against (Fe_2O_3+MgO). A significant feature of this diagram is the separation of the two non-propylitized pyroxene-bearing dykes which are known to be later than the propylitized dykes. Two is a very small sample, but it might be possible to separate other Tertiary dykes in this part of Graham Land into two such groups. This diagram also shows a general increase in the SiO_2 content with an increase in the $Fe_2O_3/(Fe_2O_3+MgO)$ ratio within each group, and this may represent some degree of normal calc-alkaline differentiation.

When the potash content of the pyroxene-bearing dykes is plotted against their silica content (Fig. 4), it is found that those collected from the Cape Monaco area, in which the plagioclase is altered to albite-oligoclase, contain a wide variation in these two oxides and higher values than do the dykes of the Börgen Bay area in which the plagioclase is unaltered. The lack of correlation between the alteration of the plagioclase and the propylitization has been noted (p. 78). The evidence suggests that these comparatively recent dykes which intrude the Cape Monaco Granite, which is a result, in part at least, of a regional metasomatism, have themselves been affected by the metasomatism. As the dykes have straight chilled contacts, the metasomatic process must have been active when the Cape Monaco Granite was brittle and relatively cold.

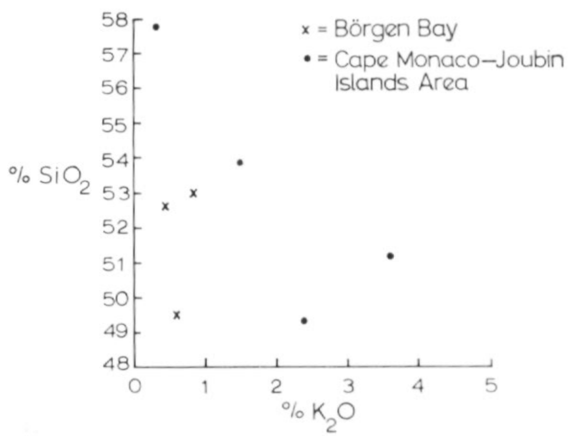

Fig. 4. Plot of SiO_2 against K_2O for the pyroxene-bearing dykes.

A comparison between the analyses of dykes from the Anvers Island area by X-ray fluorescence and analyses of dykes from the Argentine Islands (20 miles (32 km.) to the south) by chemical methods (Elliot, 1964) emphasizes the apparent lack of dykes with a rhyolitic composition from the Argentine Islands. The basic dykes show a general similarity but slight and probably significant differences occur in Al_2O_3, MgO and K_2O (Fig. 2).

Al_2O_3. The Argentine Islands results are higher. The possibility of getting high Al_2O_3 results by classical methods of analysis are well known (Hooper, 1964) and the differences between the two groups of analyses in this element are best explained by the different techniques used.

MgO. The Anvers Island dykes show a much greater variation in this element, with a tendency towards higher results. This is the least satisfactory element attempted by the X-ray technique, but checks against chemical analyses* show a slight bias in the X-ray results towards lower values than those obtained chemically.

K_2O. The Anvers Island dykes show a larger range and tend towards a higher value than the Argentine Islands rocks. Both X-ray and chemical techniques (assuming a colorimetric technique was used by Elliot) must be considered reliable for this element. The higher K_2O values of the Anvers Island dykes can be correlated with the regional metasomatism known to have affected the Anvers Island rocks.

Discussion and Conclusions

On field, petrographic and chemical data five groups of dykes can be distinguished in the Anvers Island area. These are set out in Table III together with their diagnostic properties.

The relative ages of the rhyolitic dykes (including the breccia dykes) and the basic amphibolite dykes of Upper Jurassic age has not been established, though they are probably contemporaneous. It is stated in Table III that all the amphibolite dykes are older than the Cape Monaco Granite, but a unique exception to this has already been mentioned (p. 79) and

Table III. Classification of the Anvers Island Dykes

Field Identification (General Petrography)	*Age*	*Group (Detailed Petrography)*	*Characteristic Features of Each Group*
Pyroxene-bearing Dykes	Tertiary (intrude Cape Monaco Granite)	Non-propylitized (younger)	Easily weathered. Pyroxenes occur as fine intergranular crystals. Zeolites but little or no chlorite and epidote. High $Fe_2O_3/(Fe_2O_3+MgO)$ ratio
		Propylitized (older)	Easily weathered. Pyroxene occurs as phenocrysts. Abundant chlorite, epidote and calcite. Low $Fe_2O_3/(Fe_2O_3+MgO)$ ratio
Amphibolite Dykes	Andean	Basic	Cuts Andean intrusions but not Cape Monaco Granite. Oligoclase–acicular hornblende–biotite–titanomagnetite assemblage
	Upper Jurassic	Basic	Hornfelsed by Andean intrusions or cut by rhyolitic (breccia) dykes. Oligoclase–acicular hornblende–biotite–titanomagnetite assemblage
		Rhyolitic	Often forms breccia dykes and usually cut by basic amphibolite dykes. Some with trachytic texture. Oligoclase–acicular hornblende–biotite–titanomagnetite assemblage with quartz and sometimes potash feldspar. High SiO_2, K_2O; low Al_2O_3, Fe_2O_3, MnO, MgO and CaO relative to basic dykes

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it needs an explanation. The dyke N.295.5 is a normal amphibolite type with subhedral prismatic to acicular hornblendes and it occurs within the margin of the Cape Monaco Granite on the Joubin Islands. It is possible that the complete absence of amphibolite dykes from Cape Monaco, in the centre of the granite mass and elsewhere, is a coincidence and that some amphibolite dykes were intruded after the formation of the granite. There is, however, another possibility which is consistent with the metasomatic origin of this granite previously suggested (Hooper, 1962) and supported by evidence from the dykes themselves. This is that the dyke is Andean in age and was intruded into Andean tonalite which is in close proximity. The metasomatic transformation of the marginal phase of this tonalite to granite has been described and illustrated (Hooper, 1962, p. 46, pl. IIIb). On the same island there are basic "inclusions" strung out in distinct bands, and it has been suggested from the field evidence that these represent earlier basic dykes which the granitization process had found more difficult to digest than the tonalite. This view is accepted in Table III for dyke N.295.5.

The main problem in classifying the dykes of Anvers Island has been the lack of obvious field, mineralogical or chemical differences between dykes of different ages, except in a relatively few examples. Earlier workers who have attempted to classify dykes from other areas of Graham Land have found similar difficulties (Goldring, 1962). However, on Anvers Island all the dykes of Andean age and older lack pyroxene, due to recrystallization, so they can be distinguished clearly in the field from the Tertiary dykes. In other parts of the west Graham Land coast, pre-Andean dykes apparently contain pyroxenes and many of the other features typical of the Tertiary dykes on Anvers Island (Goldring, 1962; Elliot, 1964). On the Joubin Islands and on Wiencke Island a group of rhyolitic dykes is present, often in the form of breccia dykes, associated with the Upper Jurassic volcanic rocks. Similar rocks have not yet been described from other parts of the west coast of Graham Land. A method of distinguishing basic dykes of Upper Jurassic age from basic dykes of Andean age on Anvers Island, and dykes of any age in the rest of the west coast of Graham Land, when field evidence is lacking has not been found. Indeed, the very similar basic lava that was available for intrusion as dykes from Upper Jurassic until Tertiary times is remarkable.

Amphibolitization of Andean and earlier dykes is attributed to deep burial and high temperatures in the Anvers Island area during the intrusion of the major Andean masses. Similar conditions did not apparently exist in the South Shetland Islands, the Argentine Islands or the Loubet Coast, but they may have existed at Cape Roquemaurel and on Adelaide Island from where Tyrrell (1945) has described similar amphibolite dykes.

Study of the Anvers Island dykes, in addition to providing further petrological and chemical evidence of the metasomatism most of the rocks of Anvers Island have undergone, has also indicated the prolonged nature of the metasomatism, continuing to affect dykes intruded into the Cape Monaco Granite, itself a product of that process.

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