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ABSTRACT

PREVIOUS exploration and geological investigations in areas adjacent to and including the central Black Coast, Palmer Land, are summarized.

Several rock groups have been established from field, petrographic and geochemical evidence and these are compared with similar rocks from other areas in the Antarctic Peninsula as well as elsewhere in the circum-Pacific orogenic belt.

The metamorphic complex, which probably represents the oldest rocks, is discussed by areas and subdivided into homogeneous and heterogeneous varieties. Particularly in the Welch Mountains, these rocks are inferred as being *ortho*gneisses and *para*gneisses, respectively. In the latter, metamorphism has proceeded towards the amphibolite facies and local retrograde effects have been recognized. It is noted that the lithological units of the metamorphic complex resemble those of the "Basement Complex" (Adie, 1954) exposed elsewhere in the Antarctic Peninsula and therefore they may be of similar age.

A sequence of metavolcanic and metasedimentary rocks termed the Mount Hill Formation is critically compared with the Upper Jurassic Latady Formation of the Lassiter Coast and the (?) Carboniferous Trinity Peninsula Series. The structural, lithological and metamorphic features of the Mount Hill Formation seem to show similarities closer to those of the Latady Formation. The dominantly metapelitic rocks and associated metavolcanic rocks have been subjected to an early low-grade regional or possible dynamic metamorphism and a later thermal metamorphism during and after which further deformation occurred.

Minor sheared, coarse, unstratified (?) epiclastic rocks associated with similarly unstratified vitric tuffs and dacitic lavas are cut by gabbroic hypabyssal rocks and probably by a gabbro thought to belong to the intrusive rock group. These rocks are correlated with the Upper Jurassic Volcanic Group by comparison with previous observations.

The intrusive plutonic rocks which cut all the major stratigraphical units are further subdivided into five lithological types; an apparently older metagabbroic suite of rocks in the upper Murrish Glacier area intrudes the Mount Hill Formation but it is cut by the youngest member of the intrusive rock group (the main granodiorite). A highly variable gabbro containing olivine appears to intrude Upper Jurassic volcanic rocks and represents the only occurrence of this rock type in the central Black Coast. The diorite at Marshall Peak has no observed relationship with other intrusive rocks or major stratigraphical units in the central Black Coast but it has petrographic and some geochemical affinities with similar rocks described from Cape Bryant (Adie, 1955). A garnetiferous tonalite at the head of Lamplugh Inlet is also isolated but it is chemically similar to the main granodiorite which was intruded in Lower Cretaceous times. Geochemical differences between the metagabbroic and main granodioritic suites are thought to reflect their possible derivation from different sources.

Five groups of hypabyssal rocks, ranging in composition from basic to acidic, are noted but they also include granodioritic and aplitic apophyses. Some basic and acidic dykes cut the main granodiorite and therefore represent the youngest rocks on the central Black Coast. It is thought that the acidic dykes were genetically related to the main granodiorite at some stage in their evolution.

The conclusions and regional correlations include suggestions for the genesis of each stratigraphical unit in terms of rigid plate tectonics.

CONTENTS

I. INTRODUCTION

1. *Location and previous investigations*

The central Black Coast is that part of Palmer Land between lat. 70° 50′ and 71° 30′S, and long. 64° and 61°W (Fig. 1); this area was mapped geologially by the author during the two austral summers of 1972–73 and 1973–74. The work was undertaken from the British Antarctic Survey scientific station at Stonington Island (lat. 68° 11′S, long. 67° 01′W).

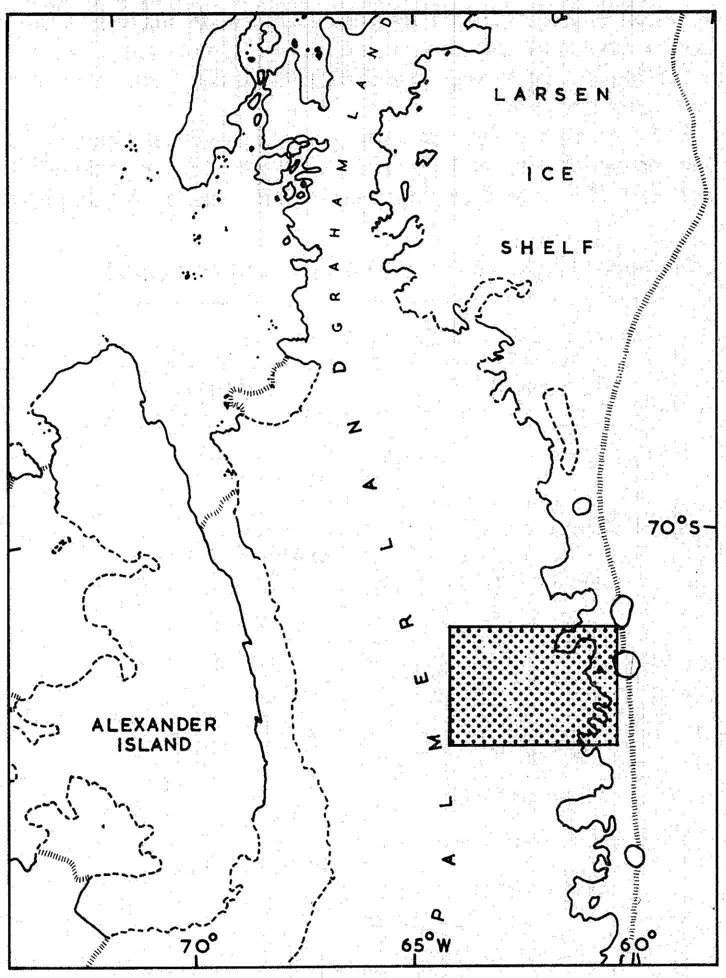


FIGURE 1
Map of the Antarctic Peninsula showing the position of the area mapped.

This area was first visited by a sledge party of the United States Antarctic Service Expedition (USAS), 1939–41, when geological samples were collected from the Welch Mountains which then were thought to be the Eternity Range (Black, 1945; Knowles, 1945). In November 1940, this expedition pioneered an overland route from the west coast to the east coast of the Antarctic Peninsula and made a full reconnaissance along the Larsen Ice Shelf as far south as lat. 71° 48′S. This ground work was further supplemented by air photographs and observations during aircraft flights; the photographs extended over the area discussed here and led to the first mapping of Mount Jackson.

The combined sledging operations of the Falkland Islands Dependencies Survey and the Ronne Antarctic Research Expedition (RARE), 1946–48, resulted in a further survey of the east coast which extended the previous observations southward to lat. 70° 42′S (Ronne, 1948). Valuable information was obtained from the trimetrogon air-photograph cover taken during this period.

Since that time, the western fringes of this area have been visited by personnel of the Falkland Islands Dependencies Survey and the British Antarctic Survey during the systematic topographical and geological mapping of Palmer Land.

In October 1972, the author, an assistant and two dog teams reached the area overland to commence the reconnaissance geological mapping. In the following year a similar party was flown into the area and the geological mapping was extended.

2. *Scope of the present study*

This work represents a continuation of reconnaissance geological surveys carried out on the eastern side of Palmer Land by Fraser and Grimley (1972) and Davies (1976). During the summer season of 1972–73 the survey of the Welch Mountains and nunataks, extending eastward towards Mount Hill, was completed. In 1973–74, geological work was continued southward to Mount Jackson and eastward towards the cape areas including Mount Hill and Marshall Peak.

A plane-table map, at a scale of 1 : 100 000, was constructed of the area covered in 1973–74 and this has been extended at the same scale (Fig. 2) by a controlled sketch map of the area covered in 1972–73.

3. *Physiography*

The central Black Coast (Fig. 2) is bounded on the west by the 2 000–3 000 m plateau demarcated by the Welch Mountains and Mount Jackson (3 178 m), the highest point on the Antarctic Peninsula. The terrain extends eastward from this scarp for 35–45 km to the Larsen Ice Shelf; the area is gently undulating and there are many nunataks with occasional steep slopes into the glaciers flowing towards the inlets.

A detailed account of the physiography of this area has already been given by Singleton (1980).

II. GENERAL STRATIGRAPHY

THE stratigraphy of the central Black Coast is compared with that of the nearby Lassiter Coast in Table I. Five rock groups are recognized but some of them are of a questionable age.

Mainly in the Welch Mountains and the Mount Jackson massif but also in some of the eastern areas, the metamorphic complex is only seen to be cut by granodioritic rocks of Lower Cretaceous age.

The metavolcanic and metasedimentary rocks of the Mount Hill Formation are generally intruded by the main granodiorite but their exposed relationships with other rock units are limited. The occurrence of thermally metamorphosed rocks adjacent to predominantly regionally metamorphosed porphyroblastic gneisses in the Mount Jackson area precludes correlation of the Mount Hill Formation with the older metamorphic complex. This is substantiated by the random spatial field relationships between the metamorphic complex and the Mount Hill Formation, and further demonstrates that there are no gradational zones of metamorphism between them. The Mount Hill Formation is comparable with the Upper Jurassic Latady Formation of the Lassiter Coast, which is overlain by volcanic rocks of a similar age, but it also exhibits some features which are similar to those of the Upper Palaeozoic Trinity Peninsula Series of Graham Land and Alexander Island.

Sheared and faulted extrusive rocks occur in isolation on a small nunatak 2 km south of Mount Jackson and these are associated with similarly structured unstratified (?) epiclastic rocks. They are apparently cut by an olivine-gabbro and are intruded by hypabyssal rocks of possible Andean or earlier affinity. Here they are correlated with the widespread Upper Jurassic Volcanic Group by petrographic comparison as their limited exposure on the central Black Coast precludes the establishment of further possible field relationships with other stratigraphical units.

It is recognized that the main granodiorite is the youngest of the intrusive rocks and has been assigned a K-Ar radiometric age of 122±3 Ma (see Appendix). The tonalite of Lamplugh

TABLE I

A COMPARISON BETWEEN THE STRATIGRAPHIES OF THE CENTRAL BLACK COAST AND THE LASSITER COAST

	Central Black Coast		*Lassiter Coast*	
Age	*Rock types*	*Rock group*	*Rock types*	*Rock group*
Tertiary	Felsite dykes Granite-porphyry dykes Microtonalitic dykes Microdioritic dykes Microgabbroic rocks Granodiorite and aplite apophyses	Minor intrusive rocks	Diabase dykes Lamprophyres	Dykes and sills
Mesozoic	Main granodiorite Garnetiferous tonalite of Lamplugh Inlet Diorite of Marshall Peak Gabbro from the plateau edge Metagabbro	Intrusive rocks	Granite Quartz-monzonite Granodiorite Quartz-diorite	Plutonic rocks
	Vitric tuffs, dacitic lavas and associated (?) epiclastic rocks	Upper Jurassic Volcanic Group	Dacitic lavas, volcanic sedimentary rocks and tuffs	Jurassic rocks
	Metasedimentary (pelitic) and metavolcanic rocks	Mount Hill Formation	Siltstones, mudstones, minor sandstones and their metamorphosed equivalents	Jurassic rocks (Latady Formation)
Palaeozoic	Amphibolitic dykes *Ortho*gneisses and *para*gneisses plus minor schists	Metamorphic complex	—	—

Inlet and the diorite of Marshall Peak are probably of a similar age to the main granodiorite but other members of this plutonic rock group may be older.

Dyke rocks of varying compositions cut all rock units, including the main granodiorite, and these are the youngest rocks in this area. Microtonalitic and microdioritic rocks, which are not found intruding the main granodiorite, may possibly be older.

Although relative ages of individual rock units are available from the field evidence, their absolute positions within the stratigraphical column have been determined by comparison with other areas in the Antarctic Peninsula (Adie, 1964) and by reference to radiometric ages obtained by Grikurov and others (1966, 1967), Halpern (1971), Rex (1971), Mehnert and others (1975), and most recently by R. J. Pankhurst (see Appendix).

III. THE METAMORPHIC COMPLEX

Two main sequences of rocks have been recognized in the metamorphic complex: the banded and heterogeneous gneisses of the north-eastern Welch Mountains and the eastern part of the Mount Jackson massif, and the more prevalent homogeneous, foliated to weakly foliated granodioritic gneisses which crop out in the central to western Welch Mountains, the western part of the Mount Jackson massif and the Guard Glacier area.

A distinctly hornblendic metagabbro in the western Parmelee Massif and an occurrence of migmatitic gneisses on the south side of Dana Glacier are minor exceptions to this general pattern.

The heterogeneous gneisses include highly quartzitic varieties in close association with mafic biotitic types and these are thought to represent a metasedimentary sequence.

In contrast, some of the more homogeneous, weakly foliated gneisses either resemble intrusive rocks or possess relict igneous characteristics.

Altered hypabyssal dyke rocks have been observed within the heterogeneous and the homogeneous gneisses.

Both groups of metamorphic rocks are frequently cut by dominantly quartzo-feldspathic veins, clearly offshoots of the later intrusive episodes which culminated during the Andean orogeny and are distinct from similar rocks and veins within the metamorphic complex.

Further field relationships and petrography of the metamorphic complex are discussed by areas under the broad parameters set out above.

A. Metamorphic Complex of the Welch Mountains

1. *Heterogeneous gneisses*

These are mainly exposed at the northern end of the eastern ridge of the Welch Mountains but they also occur on nunataks forming the low-lying extensions of these ramifying ridges.

a. *Field relations.* The heterogeneous gneisses constitute only a small part of the metamorphic complex and they comprise homogeneous, augen, porphyroblastic and banded types.

The banded varieties may represent an original sedimentary sequence, now consisting of closely foliated biotite-gneisses and gneisses which contain varying proportions of biotite, quartz, plagioclase and potash feldspar. At station E.4010, a large exposure of almost pure quartzitic gneiss is conformable with a contrasting biotitic, quartz lenticular to augen, banded gneiss. The contact is gradational through a number of contrasting compositional layers of varying thicknesses and may represent original interbedding (Fig. 3).

Figure 3
Quartzitic gneiss interbedded with banded gneiss (E.4010). The hammer shaft is 60 cm long.

This sequence extends towards station E.4045, where distinct augen are present and there is an apparent gradation towards a porphyroblastic gneiss (Fig. 4). The porphyroblasts are not preferentially orientated except in the rock types transitional between the banded and porphyroblastic forms. Farther north in Palmer Land, to the east of the Eternity Range, similar feldspar-gneisses are seen to have intruded black irregularly banded basic gneisses in a *lit-par-lit* fashion (Davies, 1976). A rock fragment found on the scree slopes at station E.4045 consists of a porphyroblastic gneiss similar to that observed *in situ* but here it

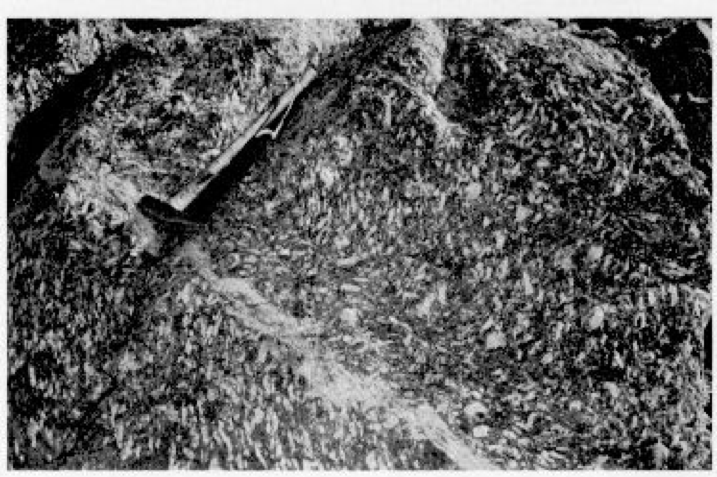


Figure 4
Porphyroblastic gneiss (E.4045). The hammer shaft is 60 cm long.

appears to have brecciated two small fragments of a laminated metamorphite. This is the only evidence which suggests an intrusive mode of formation for this rock. At station E.4017, the porphyroblastic gneiss is in contact with a homogeneous biotite-gneiss through a 20–30 cm distinctly biotite-rich zone. The relationship between this homogeneous biotite-gneiss and the granodiorite to the south was not seen. However, at the southern tip of the eastern main ridge of the Welch Mountains (E.4020) a complex series of gneisses is intruded by a granodiorite presumably consanguineous with the "main granodiorite".

On the low nunataks, extending from the north-eastern Welch Mountains, a gradation away from this porphyroblastic habit occurs but the banded genisses persist as far east as station E.4048. At stations E.4040 and 4043 the mafic bands are quartz-biotite-schists and biotite-muscovite-schists, respectively. These are interspersed with various quartzofeldspathic gneisses. Schists, which crop out farther south (E.4081), have an apparent porphyroblasticity and they contain some laminated quartzite bands. However, the main rock types forming the eastern extremities of the Welch Mountains are medium-grained quartzofeldspathic biotite-gneisses, whose texture ranges from porphyroblastic to augen to virtually homogenous.

b. *Petrography*. The heterogeneous (?) *para*gneiss sequence is discussed under four textural sub-divisions:

i. *Banded biotite-gneisses*. In the hand specimen (E.4010.2, 4045.15 and 4046.1) these rocks consist of alternating closely foliated mafic layers and coarser quartzitic bands, of which both are variable in thickness.

The mafic bands (E.4010.2) consist mainly of small brown biotite flakes, most of which are preferentially orientated though some are discordant. The significant amount of associated sillimanite also has an elongated form but with some cross fractures caused by crystal bending. Muscovite is present but mainly around small anhedral crystals of garnet which are sometimes fractured and replaced by biotite (E.4045.15). In these mafic bands, plagioclase occurs in minor quantities relative to quartz, and it is polysynthetically twinned and occasionally normally zoned. Some myrmekitic intergrowths occur in the plagioclase crystals. Common accessory minerals within the biotite layers are elongated iron ore grains and scattered minor epidote.

The leucocratic bands consist essentially of large elongated quartz crystals with sutured terminal margins. In addition, bands in specimen E.4045.15 contain a significant amount of potash feldspar as well as plagioclase. Potash feldspar is intergrown with vaguely polysynthetically twinned plagioclase producing braid antiperthite (Fig. 5a) in the leucocratic bands of specimen E.4010.2. At station E.4010, the larger leucocratic gneissic bands are more composite; the finer-grained groundmass around the coarser quartz lenses is a mosaic of quartz with some plagioclase, which have triple-point junctions as well as interlobate boundaries. The enclosed coarser bands and lenses of quartz show only sutured to interlobate grain boundaries which suggests that greater recrystallization has occurred in the groundmass.

ii. *Augen- and homogeneous biotite-gneisses*. These gneisses are transitional towards the porphyroblastic biotite-gneiss described later but they also include more homogeneous gneisses which are exposed elsewhere and may be related.

These rocks have a general uniform appearance consisting of continuous and discontinuous foliated layers of biotite broken by lenses or elongated zones of aggregated quartz and feldspar. They have a variable microscopic texture due to a contrast between coarse lenses, porphyroblasts and the finer interstitial material.

Quartz, which is present in most rocks, has irregular interlobate to sutured margins in its coarse form but finer polygonal to granoblastic varieties occur interstitially.

Plagioclase occurs both as small porphyroblasts and in the groundmass. It is commonly polysynthetically twinned in the porphyroblasts and the groundmass but in the latter pericline types also occur (E.4011.1). Twin lamellae are sometimes discontinuous. In the more homogeneous rocks, crystals (E.4006.1, An_{25-31}; E.4011.1, An_{30-35}) are occasionally normally zoned but rare oscillatorily zoned forms occur (E.4011.1). In a similar homogeneous gneiss (E.4011.2), some polysynthetic twins are deflected at the rim of a simple-zoned crystal. This may reflect some movement at zone boundaries during the subsequent early formation of twinned crystals (Fig. 5b). Plagioclase porphyroblasts are invariably altered to sericite and saussurite, and in some examples (E.4047.1) this alteration is almost complete (Fig. 5c). The alignment of the majority of plagioclase twin trends with the metamorphic fabric suggests that these porphyroblasts developed syntectonically. However, there are examples (E.4047.1) which demonstrate a discordancy of twin development with the foliation trends. This suggests that some porphyroblasts may be pre-tectonic and is further supported by the occurrence of some rare oscillatorily zoned varieties (E.4047.4).

Potash feldspar is present but not in as great a quantity as that observed in the porphyroblastic biotite-gneisses. Microcline is dominant and invariably contains plagioclase inclusions. Incipiently formed porphyroblasts are less distinct and are masked by dusty alteration products which probably include some fine sericite. Potash feldspar sometimes occurs interstitially in the groundmass (E.4044.5). The margins of small microcline porphyroblasts are often myrmekitically intergrown and are occasionally internally altered to saussurite as well as sericite (E.4050.1). String and patch perthitic intergrowths are common in some gneisses (E.4047.7 and 4050.1). These are believed to have resulted from exsolution rather than direct replacement (Alling, 1938). The microcline porphyroblasts of specimen E.4050.5 have been fractured and replaced by quartz which would support their pre- or syntectonic origin.

Widespread green-brown biotite generally defines the foliation of the rocks. In the porphyroblastic to augen varieties, biotite flakes are bent around the larger crystals, are frequently altered to chlorite and epidote, and contain some prehnite* lenses.

* Prehnite interleaved with biotite is a common association not only in the metamorphic rocks but also in the intrusive rocks of the central Black Coast. It is colourless with moderate relief and has a lens-shaped form which bows the enclosing mica cleavages. Although the associated biotite is invariably partly or wholly chloritized, the lenses also occur in unaltered flakes. Prehnite lenses have been described from elsewhere in Palmer Land (Rowe, 1973) but also farther north in Graham Land (Hoskins, 1963; Elliot, 1964; Fraser, 1965) and as far north as the South Orkney Islands (Thomson, 1974). Further more widespread reports of this type of "intergrowth" have been discussed by

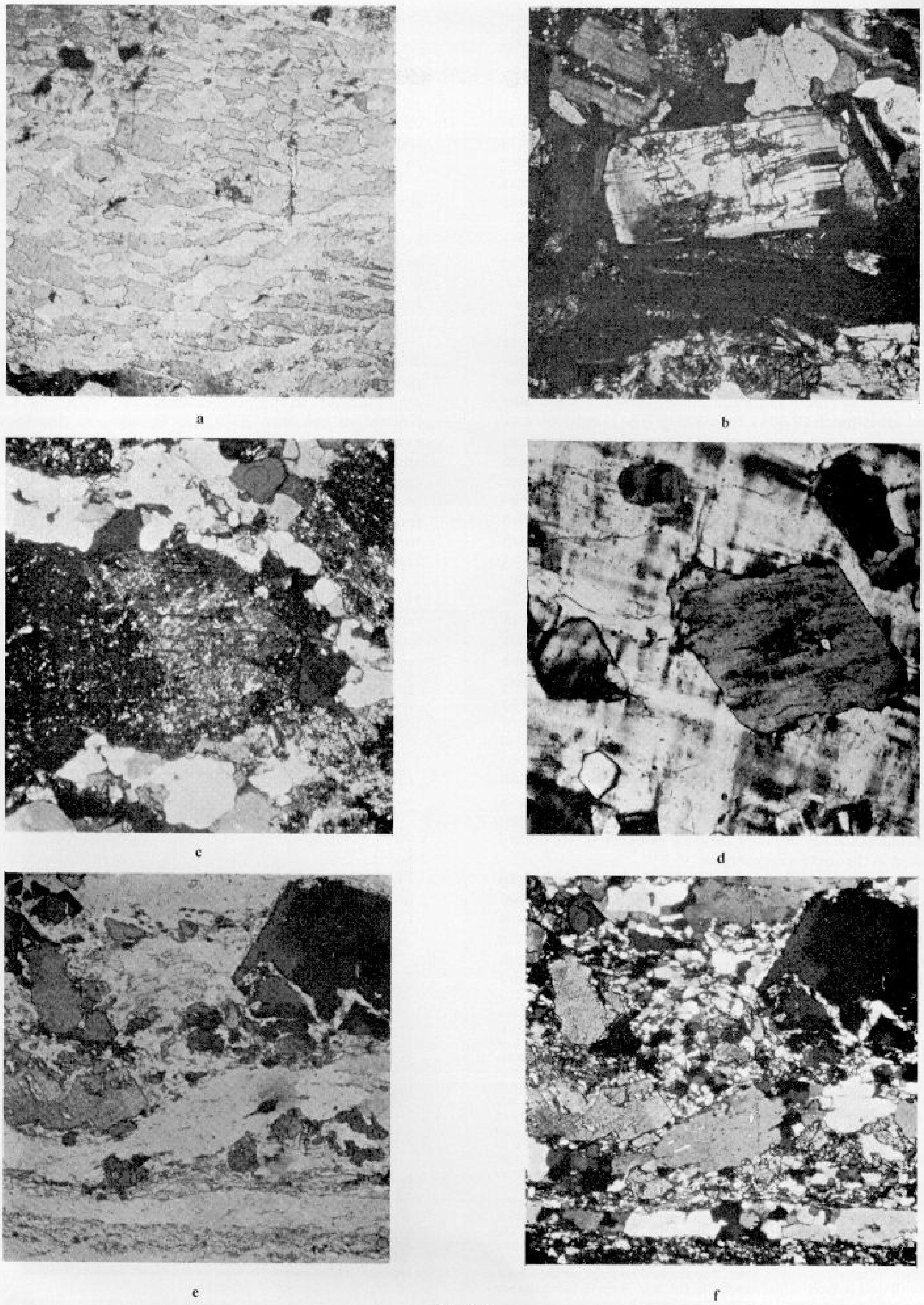


FIGURE 5

a. Braid antiperthite in banded biotite-gneiss. (E.4010.2: X-nicols ×80)
b. Deformation of twin planes at a simple zone boundary in plagioclase. (E.4011.2; X-nicols; ×50)
c. Almost complete sericitization of plagioclase in a quartzo-feldspathic gneiss. (E.4047.1; X-nicols; ×65)
d. Inclusions of orthoclase and microcline in a large microcline porphyroblast. (E.4017.1; X-nicols; ×65)
e. Fragmented tourmaline crystals with associated bending of a clear quartz band. (E.4071.4; ordinary light; ×65)
f. The same thin section under X-nicols.

Hornblende is the subdominant mafic mineral and is generally found in association with biotite (E.4050.1). Colourless muscovite and, to some degree, iron ore also occur with biotite (E.4047.7 and 4050.5). The presence of muscovite is occasionally equal to that of biotite (E.4044.5). Apatite is a common accessory in these rocks.

iii. *Porphyroblastic biotite-gneisses.* At station E.4050, the growth of potash feldspar porphyroblasts has resulted in the complete disruption of the fabric of the biotite-gneiss. They commonly exceed 1 cm in length, are almost idioblastic, white in colour and show no preferred orientation. However, the mineral and textural relationships of the host are similar to those described for the augen and homogeneous biotite-gneisses. The potash feldspar is microcline which displays Carlsbad, rudimentary (E.4045.1) and also good gross-hatch (E.4017.1) twinning. The porphyroblasts contain some inclusions of smaller microcline crystals (Fig. 5d) but normally plagioclase and some minor quartz. Small patch and string perthitic intergrowth areas occur in some of the porphyroblasts. Smaller, less distinct porphyroblasts of invariably heavily sericitized plagioclase are subdominant to those of potash feldspar. In specimen E.4047.10, the growth of plagioclase occurred probably at a late syntectonic stage, when the surrounding groundmass was sufficiently pliable to arch around them but the pressure was sufficiently reduced to prevent deformation of the porphyroblasts. The discontinuous nature of the bands around these further suggests syntectonic growth. Some twin planes have developed normal to the metamorphic fabric. Apatite is a common accessory in the porphyroblastic biotite-gneisses.

iv. *Schists and associated quartzites.* The schists exposed at stations E.4040 and 4043 in the augen to homogeneous gneisses are coarser than those rocks farther south (E.4081). Also, the schists in the north show kink bands and crenulation folds, whereas vague lineations on first-cleavage plane surfaces are the only evidence of secondary folding in the southern examples.

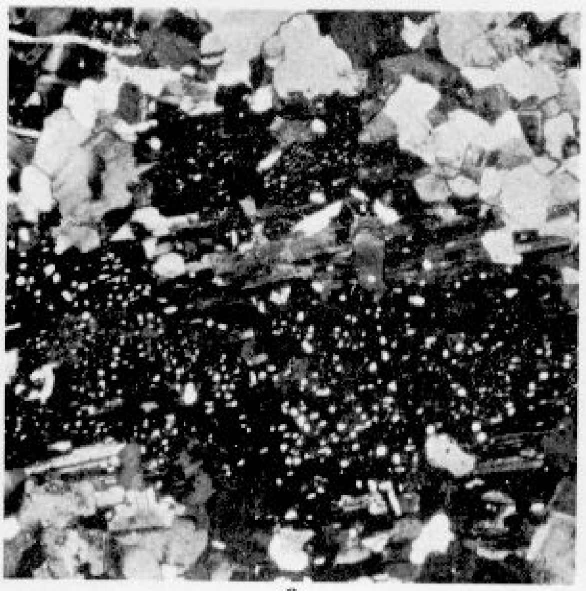
The northern schists consist of dominant granoblastic to idiotopic quartz with scattered biotite, some of which is discordant to the foliation trend. Elongated muscovite shreds in association with similarly elongated iron ore occur in the mafic bands (E.4040.1). The micas are more prevalent in specimen E.4043.5 in which the biotite contains many opaque inclusions. Large garnet crystals also present in this specimen are slightly corroded and replaced by quartz along small fractures.

The southern schists (E.4081.6) have decussate ovoid-shaped areas of fine recrystallized quartz which contain less mica than the surrounding host and probably represent local recrystallization or possibly complete pseudomorphs of an earlier mineral. The texture of the quartzitic host rock is granoblastic or polygonal with some elongated grains. Interstitial and foliated biotite is sometimes altered to chlorite and in patches to an unidentifiable yellow mineral.

The fine-grained quartzites have a granoblastic to elongate-granoblastic inequigranular texture with some fine polycrystalline layers. Biotite and muscovite are present in minor quantity in specimen E.4081.4 but they are more significant in specimen E.4071.5. In addition, the former example contains fragmented tourmaline crystals (Fig. 5e and f), which have a dichroism scheme from colourless to orange-brown. Some of the fractures in these crystals are occupied by muscovite, quartz and occasional calcite. This fragmented nature, accompanied by the arching of the surrounding quartz bands, suggests an early origin for these crystals. Although magnesian tourmalines or dravites are usually found in metamorphic rocks (Deer and others, 1966), it is thought from the marked dichroism and moderate birefringence to be schorl, a more iron-rich tourmaline.

FIGURE 6
Early quartz vein sheared during intrusion of a quartz-pegmatitic vein. The hammer shaft is 60 cm long.

Phillips and Rickwood (1975). Elliot (1964) believed that the prehnite was released during the retrograde chloritization of biotite. Rowe (1973) has suggested that the occurrence of interleaved prehnite in biotite could indicate that low-grade metamorphism (prehnite-pumpellyite facies) affected the metamorphic complex at a late stage. The presence of traces of pumpellyite as well as interleaved prehnite in the metamorphic complex rocks of the South Orkney Islands also led Thomson (1974) to postulate a metamorphic origin. The fact that the growth of prehnite appears to have caused the dilation of the biotite cleavage planes rather than having resulted from their alteration, and also because the composition of biotite and prehnite are too dissimilar for one to have been produced from the other led Hall (1965*a*) to suggest a possible primary origin. Hall (1965*a*) thought that the biotite and prehnite had formed simultaneously from the surrounding hornblende within the rocks studied as a result of low-temperature potash metasomatism. However, experimental evidence has indicated that prehnite is unstable above 393°C at 5 kbar, which implies that a primary origin is unlikely (Phillips and Rickwood, 1975). The slight undulatory extinction of the surrounding biotite in most cases on the central Black Coast (E.4624.1), particularly when the lenses are very dilatory, suggests that the biotite grew first. Thus, it seems that evidence for the formation of interleaved prehnite is not conclusive but it is likely to be secondary after biotite and possibly related to deuteric reactions (Phillips and Rickwood, 1975).



a

b

FIGURE 7

a. Plagioclase with sieve texture in granitic gneiss. (E.4014.4; X-nicols; ×80)
b. Chloritized biotite with a central zone of prehnite in quartzo-feldspathic biotite-gneiss. (E.4034.1; ordinary light; ×65)

2. *Homogeneous gneisses*

These occupy the main central zone of the Welch Mountains, including the northern half of the western ridge, part of the eastern ridge and the east–west ridge joining the two.

a. *Field relations*. They are massive, generally foliated, mesocratic xenolithic rocks consisting of white plagioclase, quartz, biotite, some hornblende and potash feldspar.

The homogeneous gneisses of the central western ridge of the Welch Mountains appear variable because of the extensive presence of the random massive quartz veins and dykes within them. Quartz veins, which are probably related to the main granodiorite farther south, are seen cutting these earlier bands and on the eastern side of this central western ridge they appear to have been accompanied by shearing (Fig. 6). The contact between the gneisses on the central western ridge and the main granodiorite to the south seems to be gradational on the western side but more abrupt on the eastern side where there is an extensive area of re-mobilization in the gneisses.

The relationship between the heterogeneous and homogeneous gneisses was not seen in the Welch Mountains.

b. *Petrography*. Thin-section examinations show that the composition of the plagioclase in these granodioritic to granitic gneisses is similar to that of the augen-gneisses (E.4013.1; An_{27-38}). The plagioclase characteristics are also very similar. Some fracturing with associated displaced twins has occurred in specimens E.4021.6 and 4029.1. Two generations of twinned plagioclase are occasionally evident; the younger generation in one example (E.4014.4) is poikiloblastically included with feldspar and quartz forming sieve-textured crystals (Fig. 7a).

The potash feldspar present in most samples is generally microcline and is invariably altered to dusty probable sericite. Larger areas of potash feldspar in specimen E.4019.1 have marginal intergrowths of myrmekite.

Inequigranular quartz and feldspars dominate this rock group. Occasionally quartz is undulose (E.4021.6 and 4029.1) and when present in the interstitial areas it is invariably granoblastic to polygonal.

Biotite, which is also present in all the examined sections, is generally brown-green with a pleochroism scheme: α = light brown-green, $\beta = \gamma$ = dark green. The colour of the biotite has been largely attributed to the relative amounts of titania and ferric iron present. Intermediate proportions of Ti and Fe^{3+} result in greenish brown colorations, whereas high amounts of ferric iron give a green colour (Hall, 1941; Hayama, 1959; Deer and others, 1966). The distinct association of sphene aggregates with biotite in these rocks (E.4019.1, 4021.6, 4029.1, 4031.1 and 4038.4) may be explained by the presence of excess titania not taken up by the biotite. Common alteration products are epidote and chlorite with interleaved prehnite (Fig. 7b).

Green hornblende is the minor mafic mineral and is occasionally partly altered to epidote (E.4034.1).

Iron ore, sphene aggregates and epidote are common accessories. Prismatic apatite is widespread in specimen E.4038.4. Minor and simple-zoned allanite* also occurs in these rocks.

The fine-grained and mafic xenoliths examined have a composition similar to that of the host rock and therefore have been well assimilated.

B. METAMORPHIC COMPLEX OF GUARD GLACIER AND THE SOUTH SIDE OF DANA GLACIER

1. *Metagabbro*

a. *Field relations*. The outcrop of the metagabbro extends from Guard Glacier northward along the ridges projecting into Lehrke Inlet. On the extreme western tip of this massif (E.4074), it is sharply intruded by the "main granodiorite". The relationship between the metagabbro to the east (E.4073) and a distinctly leucocratic granodioritic gneiss is gradational over a

* Allanite is a rare accessory in most rock groups of the central Black Coast. The unusually simple-zoned crystals are distinctive with a dark brown core and a lighter orange or deep orange rim. Their pleochroism is strong and negative 2V large. One twinned crystal has been observed and it is also simple-zoned with a narrow outer rim. Rare allanite has been reported by other Antarctic work (Fraser, 1965; Rowe, 1973; Thomson, 1974) from a variety of rock groups.

crude inter-zoned contact. This granodioritic gneiss resembles the homogeneous *ortho*gneisses exposed at stations E.4071 and 4072. It is also similar to the host rock of the mafic xenolithic zone which marks the immediate contact with the metagabbro. The metagabbro on the summit area at station E.4073 appears particularly melanocratic due to the predominance of coarse hornblende, and in the contact area with the "main granodiorite" a high proportion of mafic xenoliths relative to host rock. Finer metagabbroic to dioritic equivalents are exposed in melanocratic zones towards the base of the ridge.

b. *Petrography*. The coarse gabbroic areas on the summit of station E.4073 consist essentially of large, occasionally twinned hornblende crystals, which have been partially epidotized along fractures and contain plagioclase inclusions. The minor interstitial areas are filled with almost completely sericitized, polysynthetically twinned plagioclase.

The medium-grained gabbro, which occurs towards the contact with "main granodiorite", contains similar hornblendes but they have irregular margins and are only slightly dominant over deep brown late biotite. Alteration of polysynthetically and pericline-twinned plagioclase (An_{42-58}) is not so extreme; slight deformation of twin lamellae is evident and crude patchy zoning occurs in some crystals. Apatite is a common accessory mineral.

The mafic xenoliths near the contact with the main granodiorite (E.4073.2) have a markedly altered appearance in comparison with the host rock. Sutured quartz predominates over sericitized and sutured plagioclase. Minor green biotite blades have formed as small aggregates but they are subordinate to green and broken irregularly formed hornblende crystals. The amphibole, and to a certain extent biotite, is sometimes altered to epidote which also masks the whole xenolith as scattered aggregates. Some anhedral sphene and small cubes of iron ore are present.

The immediate host rock to these xenoliths is less altered and, although finer-grained, it resembles the granodioritic to granitic gneiss (E.4073.5) at the base of the ridge and can be petrographically correlated with granodioritic gneisses (E.4071 and 4072) farther east. The plagioclase shows some deformation, occasional oscillatory zoning and widespread marginal development of myrmekite. In this example, a large area of potash feldspar adjacent to the xenolith contains many inclusions of euhedral and twinned hornblende, and also plagioclase. The hornblende occurring outside this area still has ragged and irregular margins. Minor green-brown biotite is partly altered to epidote. Interstitial quartz occasionally has sutured and almost granulitized margins which are mostly irregular. The host rock farthest from the contamination area of the xenoliths has a similar composition; oscillatorily cored plagioclase is more common with superimposed twins. Larger ragged green-brown flakes of biotite with inclusions of plagioclase are more widespread than the smaller hornblende crystals. Sphene, prismatic apatite and iron ore are accessory minerals common to both host rocks.

The finer-grained equivalents of the metagabbro which crop out towards the base of the ridge have an igneous texture consisting mainly of dark green hornblende with intervening white patches of quartz and feldspar (E.4073.6). The hornblende in this metatonalite is almost euhedral (up to 1.5 mm in length) and contains epidote veins, chloritized biotite and iron ore inclusions. Minor biotite outside the hornblende is also completely chloritized in most examples. In some areas of the rock, the interstitial plagioclase (An_{26-44}) is completely altered to sericite and saussurite.

2. *Homogeneous gneisses*

a. *Field relations*. Varieties of gneiss exposed on the south side of Guard Glacier are homogeneous but they have a well-developed foliation. They grade eastward into the porphyroblastic gneisses exposed at station E.4108 on the east side of Murrish Glacier and are intruded by the "main granodiorite" to the west. The contact was obscured by snow but the granodiorite-gneiss close to this point is finely laminated and contains quartz bands. These tonalitic to granodioritic gneisses contain abundant mafic elongated xenoliths parallel to the main foliation.

Similar xenolithic but more leucocratic granodioritic gneisses are exposed on the north side of Guard Glacier. To the east they are in contact with a dark amphibolitic gneiss (E.4071.2). Here, a small marginal mafic xenolith zone, in which the granodioritic gneiss appears to be the host rock, suggests an intrusive contact. This dark amphibolitic gneiss contains a small linear zone of banded quartzitic gneiss, a separate 7 m zone of the granodioritic gneiss and a small grey laminated gneiss band before making contact with the metavolcanic rocks of the Mount Hill Formation.

b. *Petrography*. The rock on the south side of Guard Glacier (E.4067.1) is medium-grained, mesocratic to leucocratic in colour and consists of elongated patches of dark hornblende and biotite set in a quartzo-feldspathic groundmass.

Microscopically, the more prevalent hornblende contains inclusions of plagioclase and biotite. Epidote and sometimes twinned euhedral sphene are present in association with the mafic minerals. Plagioclase in the andesine range (An_{30-36}) has occasionally discontinuous deformed twin lamellae and some normal-zoned crystals have sericitic cores. Myrmekitic intergrowths are common, occasionally between adjacent plagioclase crystals, suggesting that any original potash feldspar here has been replaced. Unaltered potash feldspar occurs in small amounts interstitially and this is defined by embryonic or rudimentary cross-hatch twinning or by its association with myrmekite. Quartz is subdominant to plagioclase, occasionally has an undulose extinction and is generally found in the interstitial areas. Apatite is again present.

The laminated gneisses observed near their contact to the west with the "main granodiorite" have a texture comprising sutured quartz and feldspar with widespread biotite formed as scattered blades and as random clotted aggregates. The colour of biotite varies between layers from brown to green and is associated with large amounts of small iron ore granules. Muscovite is also widespread but is subordinate to biotite, and the whole rock is masked by what appears to be fine sericite. The laminated texture in the hand specimen is largely the result of a number of fine quartzo-feldspathic veins which have formed parallel to the foliation. These veins do not contain iron ore crystals but the feldspars are sericitized.

The homogeneous gneisses on the north side of Guard Glacier (E.4071.1) are granodioritic and differ from those on the south side in having coarser plagioclase feldspars which exhibit patch, normal and oscillatory zones with superimposed polysynthetic twinning. The presence of microcline is more significant and it sometimes contains inclusions of plagioclase and hornblende.

The contained xenoliths examined have a general dioritic composition. Those at station E.4072 have an almost granoblastic texture of occasionally normal-zoned plagioclase, interstitial green hornblende and dark straw-brown biotite. Minor quartz occupies some small areas. In contrast, the xenolith from the granodioritic gneisses of station E.4071 has a porphyroblastic texture. The porphyroblasts are mostly irregularly margined, oscillatorily zoned plagioclase that has discontinuous polysynthetic twinning as well as some Carlsbad and pericline varieties. Others are occasionally twinned large anhedral crystals of hornblende, which contain plagioclase inclusions and sparse ragged crystals of brown biotite with plagioclase and quartz inclusions. The oscillatory zoning of the plagioclase porphyroblasts suggests that they may have developed prior to metamorphism and their irregular margins are the result of later recrystallization. The groundmass around these porphyroblasts contrasts in grain-size but it is of a similar mineralogy, i.e. mainly decussate laths of twinned plagioclase which appear to have flowed around some porphyroblasts, small broken crystals of hornblende and minor interstitial quartz and potash feldspar. Apatite has formed interstitially and occasionally occurs as inclusions in the larger plagioclase crystals.

The dark amphibolite-gneiss on the north side of Guard Glacier (E.4071.2) contains polysynthetically and pericline-twinned plagioclases which have all been significantly deformed. The dominant hornblende is present as a xenomorphic interstitial mass between the larger plagioclase crystals and occasionally has formed triple-point junctions with adjacent amphibole crystals or recrystallized interstitial quartz and feldspar.

The porphyroblastic gneiss present at a station E.4108 also occurs at the eastern extremity of station E.4071 and is distinguished from the Mount Hill Formation metavolcanic rocks of the eastern part of Parmelee Massif by the differing nature of the porphyroblasts and the contrast in rock texture. Specimen E.4071.8 demonstrates that the porphyroblasts are growth structures which have a distinct poikilitic sieve-type texture partially obliterating polysynthetic twins. The granoblastic quartz matrix contains plagioclase and is broken by elongated laths of biotite.

The widespread occurrence of random oscillatorily to normal-zoned plagioclases within these homogeneous gneisses suggests that they may be *ortho*gneisses.

3. *Migmatitic gneisses and agmatites south of Giannini Peak*

a. *Field relations*. This complex sequence of metamorphic rocks contrasts with others within the metamorphic complex and is exposed on the south side of Dana Glacier (E.4084 and 4092). The contact with the "main granodiorite" to the south appears to be fairly abrupt. At the north-western end of station E.4084 and also at station E.4092 the generally leucocratic quartz-feldspar-biotite-gneiss contains random complex folds and contortions which could represent flow structures and were possibly developed during its melting and intrusion. Distorted augen or ball-shaped structures occur within these gneisses and they appear to consist essentially of quartz with some epidote (Fig. 8). Farther west, this leucocratic gneiss appears to have brecciated a small area of amphibolitic rock (Fig. 9). The resultant agmatite is also evident to the south (E.4092).

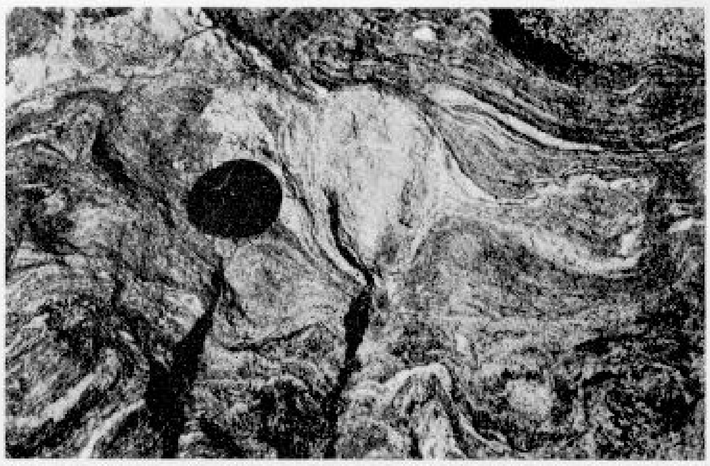


FIGURE 8
Deformed augen structure in contorted gneisses (E.4084). The diameter of the lens cap is 4 cm.

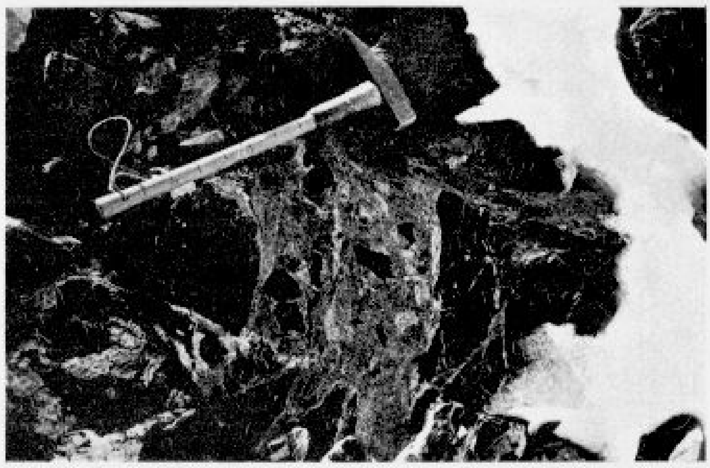


FIGURE 9
Amphibolite brecciated by an intrusion of more acidic material (E.4084). The hammer shaft is graduated at 5 cm intervals.

b. *Petrography*. The contorted migmatitic gneisses (E.4084.2) consist primarily of quartz and plagioclase, which possesses normal to vague oscillatory zones in most crystals and, in larger types, slight patchiness. Strained quartz with irregular to interlobate margins contrasts with finer presumably recrystallized varieties which have straight grain boundaries and some triple-point junctions in association with the plagioclase. Sphene has formed as small aggregates close to green-brown biotite which is the only mafic mineral present. Apatite is a minor accessory mineral.

The non-brecciated amphibolite (E.4084.7 and 4092.4) has a close lenticular texture. This has resulted through the arrangement of brown biotite flakes around pod-shaped aggregates of mainly subhedral hornblende. Polygonal quartz, subordinate polygonal plagioclase and iron ore are associated with the biotite flakes. Small euhedral crystals of hornblende are sometimes found as inclusions in the larger anhedral types.

The brecciated amphibolite (E.4084.4) consists of partially assimilated areas of mainly hornblende with straight to irregular margins and minor biotite. Radiating green fibrous actinolite is sometimes associated with hornblende which also shows slight epidotization. Quartz and some plagioclase provide the greater part of the polygonally textured intrusive matrix. The matrix of specimen E.4084.5 also contains large amounts of possibly late-formed quartz with inclusions of biotite, hornblende and plagioclase. The amphibolitic areas in this example are more obviously polygonal. These mafic areas also contain highly deformed small leucocratic lenses which were originally thought to represent remnant amygdaloidal structures as they appear to belong to an earlier generation than the leucocratic brecciating host rock. Their mineralogy is primarily polygonal quartz and plagioclase. The central areas sometimes consist of coarser more irregular crystals and occasionally crystal aggregates of epidote (E.4084.5). However, discontinuity of their margins suggests that they may represent local metamorphic segregation.

C. Metamorphic Complex of the Mount Jackson Area

The general foliation of these rocks dips at moderate angles towards the west (Fig. 10).

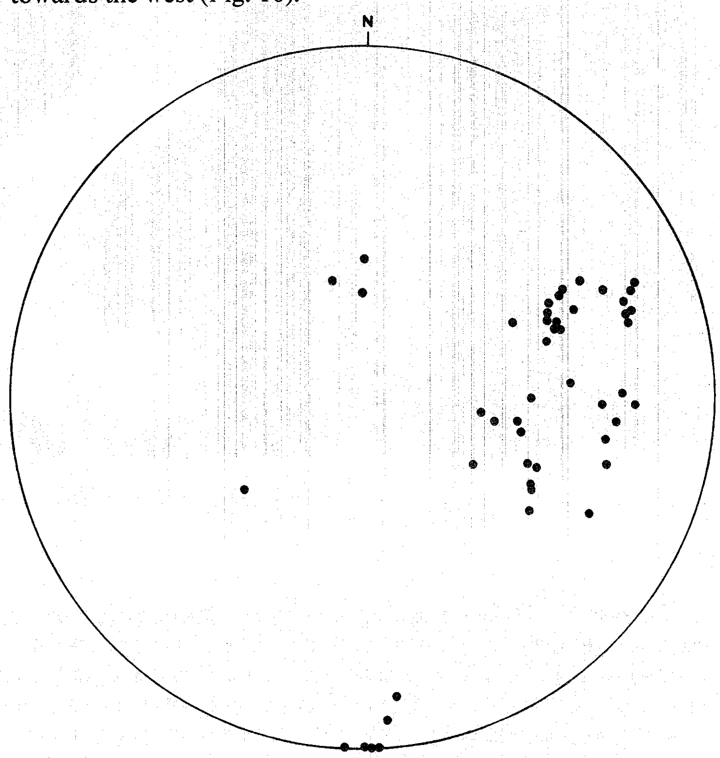


FIGURE 10
Stereogram of poles to foliation planes in the metamorphic complex of the Mount Jackson area.

1. *Heterogeneous and banded gneisses*

These are exposed on the ridges and nunataks on the eastern side of Mount Jackson and are cut by the "main granodiorite".

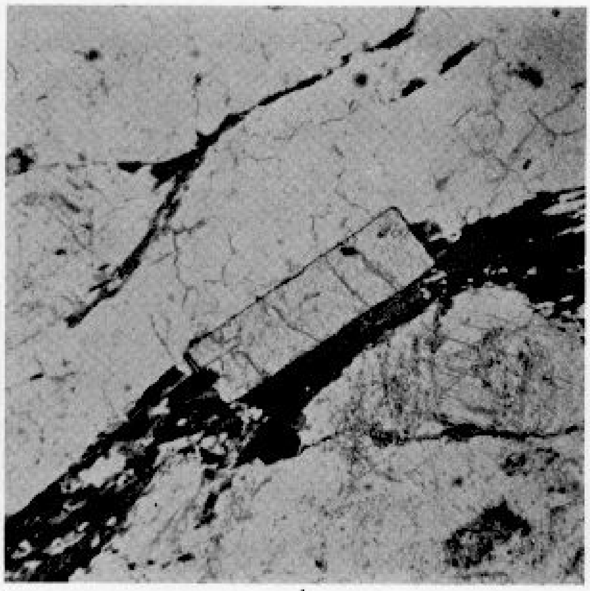
Variably banded gneisses occur at stations E.4171, 4172, 4197 and 4200. At the northern stations, melanocratic to mesocratic fine-grained biotite-gneisses are intruded both concordantly and discordantly by leucocratic veins. These veins consist of sericitized plagioclase and potash feldspar porphyroblasts, of which some are deformed, surrounded by recrystallized polygonal quartz. This mineralogy closely resembles that of the porphyroblastic gneisses at stations E.4174 and 4200, suggesting a *lit-par-lit* intrusive relationship between the fine-grained biotite-gneisses and the porphyroblastic types. The mesocratic gneissic bands adjacent to these veins consist mainly of elongated brown biotite shreds which alternate with or are enclosed by sericite and subordinate colourless muscovite. The mica shreds enclose lenses and ribbons of quartz with irregular margins. Also at this station the banded gneisses are discordantly cut by quartz-feldspar-gneisses (E.4171.2) on a much larger scale. These are similarly porphyroblastic to their presumably smaller-scale equivalents, the veins described above. Potash feldspar is the commonest type of porphyroblast and it is invariably altered to string microperthite. Small-scale faulting and deformation is evident in some plagioclase porphyroblasts. The larger mafic zones of the heterogeneous gneisses have an indistinct lenticular to augen texture (E.4171.3); strands of red-brown biotite are bent around presumably earlier syntectonic plagioclase, now deformed, sericitized and corroded by a later fine recrystallized, polygonal quartz matrix. Some poorly zoned accessory allanite is present in association with the biotite.

An equally zoned and banded sequence appears farther south on the distal half of the ridge branching due east from Mount Van Buren (E.4603 and 4604). A leucocratic micaceous quartzo-feldspathic gneiss (E.4603.2) alternates with zones of a finer grey laminated gneiss (E.4603.3) and these may represent the extreme eastern end members of the heterogeneous gneiss. The leucocratic zones occasionally pinch out towards the east (E.4603.2). They consist of large irregular sutured to rounded quartz crystals and some xenomorphic microcline, surrounded interstitially by polygonal quartz, plagioclase and some potash feldspar which occasionally has been altered to string microperthite and is cut by irregular quartz veins. Scattered minor flakes of biotite are subordinate to muscovite. Small crystals of fine sillimanite and rutile are also present in addition to an unusually large amount of apatite. The grey laminated gneiss (E.4603.3) is largely quartzitic with scattered elongated zones and rounded aggregates of green-brown biotite which define the rock foliation. The quartz is mainly polygonal and surrounds isolated lenticular to elongated areas of coarser crystals which have irregular to sutured margins. The small rounded aggregates of decussate biotite give the rock a speckled appearance. Minor late hornblende with inclusions is also present.

In some areas (E.4171 and 4200) the banded gneisses grade westward into a mesocratic porphyroblastic gneiss (E.4170.1). The porphyroblasts are of heavily sericitized and saussuritized plagioclase (E.4170.1). However, some occasionally fractured potash feldspar porphyroblasts are also present (E.4200.4). The surrounding groundmass is predominantly polygonal to coarser undulose quartz which is occasionally marginally polygonized (E.4200.4). The porphyroblastic to augen-gneisses at station E.4174 are more closely foliated. Their texture has resulted from the bending of elongated streaks and fine flakes of biotite with subordinate hornblende around untwinned and twinned plagioclase porphyroblasts, which are mostly sericitized and surrounded by dominantly polygonal quartz associated with partly polygonized coarse crystals. One porphyroblast with irregular to sutured margins has a twinned plagioclase core, is mantled by potash feldspar (Fig. 11a) and represents the inverse relationship to that observed in similar feldspars of Rapakivi-textured rocks (Hatch and others, 1972).

The banded gneisses at station E.4197 may represent the western end members of the heterogeneous gneisses as they seem to grade into more homogeneous types. Here, they contain

a



b

FIGURE 11

a. A plagioclase porphyroblast mantled by potash feldspar in an augen-gneiss. (E.4174.1; X-nicols; ×65)
b. Large apatite crystal. (E.419.2; ordinary light, ×30)

a zone of coarse to fine, sometimes xenolithic, tonalitic gneiss which also occurs farther west (E.4198) and compares with the homogeneous group of gneisses described later. It has a coarse texture consisting of thick layers of quartz and feldspar, separated by preferentially orientated thin, undulating discontinuous layers of coarse black biotite, speckled by yellow-green epidote. The feldspar is largely polysynthetically twinned oligoclase-andesine (An_{31-43}), which is sometimes oscillatorily zoned and has irregular grain margins (E.4198.1). The twins are invariably discontinuous and include lamellar, pericline and Carlsbad forms (E.4197.2). The biotite sometimes contains prehnite lenses and is also deformed. An unusually euhedrally formed apatite crystal (0.85 mm in length) is distinguished from more corroded forms (Fig. 11b).

2. *Homogeneous gneisses*

These gneisses occupy the central to western areas of the Mount Jackson massif, mainly on the high plateau, and the contact with the heterogeneous types farther east is thought to be gradational (E.4197 and 4608). To the south (E.4617), they are exposed adjacent to the massive slates of the Mount Hill Formation and occur as sub-rounded blocks in the coarse epiclastic rocks (E.4619) of the "Upper Jurassic Volcanic Group".

The extreme western outcrops of this group contain random irregular quartzitic intrusions (E.4610, 4611 and 4612) similar to those observed in the homogeneous gneisses of the western Welch Mountains.

Their coarse texture and generally more leucocratic appearance bear little resemblance to the gneisses in the heterogeneous group. At station E.4613, the foliation is well developed and the gneissic sequence is banded. Discontinuous and continuous zones of leucocratic feldspar-augen-gneisses alternate with slightly finer mafic micaceous equivalents containing similar feldspar augen (Fig. 12). They exhibit some secondary small kink folds which are sometimes sheared. However, there is little difference in mineralogy between the dark and light bands. It is therefore thought that they were derived by some form of metamorphic differentiation rather than that they represent original variations in lithology.

The leucocratic feldspar-augen-gneiss is common farther north (E.4067). Here, the porphyroblasts are microcline, of which some are Carlsbad twinned and partially altered to string microperthite. Most of these are orientated parallel to the plane of foliation. Individual groups of interlobate quartz crystals form coarse lenses and elongated ribbons. These, and the larger feldspar porphyroblasts, are mainly surrounded by polycrystalline quartz and plagioclase. The foliation is enhanced by the bending of brown biotite and muscovite shreds around the larger porphyroblasts. Farther south the polygonal groundmass contains significant amounts of microcline (E.4613.2) in addition to the minerals present in specimen E.4607.1. Apatite occurs throughout. Even farther south these gneisses appear to be more leucocratic (E.4615.1); less significant biotite has been

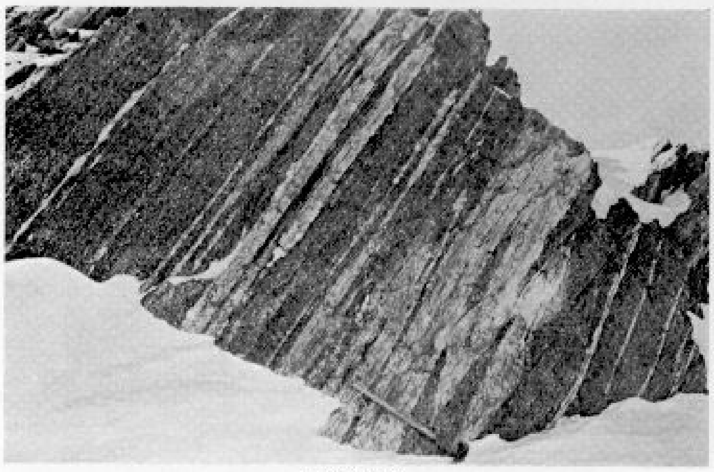


FIGURE 12
An alternating series of gneisses at station E.4613. The hammer shaft is 60 cm long.

completely chloritized, leaving some relict pleochroic haloes, and polygonized quartz is prevalent.

A feldspar-porphyroblastic gneiss (E.4611.1) appears to be very similar in mineralogy. However, the general texture is more homogeneous and the Carlsbad-twinned microcline porphyroblasts are randomly orientated but they contain similar quartz, plagioclase and occasional biotite inclusions. Muscovite flakes are notably larger and appear to have been late in formation but are still deformed. To the west (E.4612), a leucocratic porphyroblastic gneiss strongly resembles this. The porphyroblasts (E.4612.4) are similar in composition but they contain more inclusions and appear to have suffered marginal and internal corrosion by the partly recrystallized quartzo-feldspathic groundmass. Microcline also occurs interstitially with straight or curved margins and triple-point junctions. Occasionally, larger oligoclase crystals are marginally replaced by water-clear albite. Biotite occurs randomly in association with large muscovite flakes. Scattered small crystals of apatite are particularly significant.

D. Amphibolitic and Other Old Intrusive Rocks

Mafic dykes and bands are distinguishable from the later hypabyssal rocks by their foliation, and other probable intrusive rocks may also belong to the metamorphic complex.

The distinct foliation generally parallel to the surrounding metamorphite in some examples probably developed after their emplacement during the later stages of metamorphism. An earlier minor phase of dyke intrusion is inferred from the composite dyke (Fig. 13) observed parallel to the foliation trends in the gneisses at station E.4009.

Schistose amphibolitic rocks cutting homogeneous and heterogeneous gneisses are well illustrated in the metamorphic complex near Mount Jackson (E.4174, 4200 and 4613). An interwoven mass of dominantly elongated pale green actinolite and some brown biotite surrounds small decussate corroded plagioclase ($An_{>20}$) and minor quartz crystals. Much of the biotite is chloritized. The amphibolitic dyke suite, cutting the distinctly foliated augen-gneisses of station E.4613, has a more clearly defined schistosity (E.4613.3). The elongated amphiboles (actinolite) are coarser but they are still predominant over the minor interstitial quartz and sometimes deformed plagioclase. Old hypabyssal rocks with a poor foliation also occur in the metamorphic complex of the Welch Mountains and Guard Glacier. In the former they vary in thickness from approximately 15 to 70 cm and are sometimes laterally discontinuous. They have also been observed here to contain boudinaged quartzo-feldspathic veins (Fig. 14), which are older than the post-metamorphic veins cutting them. Their microscopic texture (E.4004.5) is xenomorphic to granoblastic. A large amount of green hornblende and some brown biotite has formed

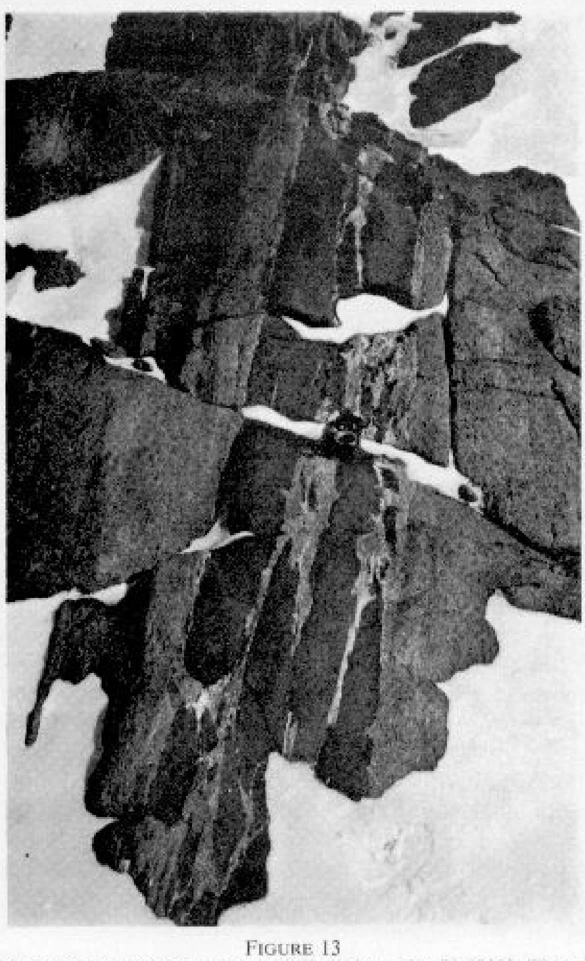


Figure 13
A composite dyke intruding quartzo-feldspathic gneiss (E.4009). The compass dial is 5 cm in diameter.

Figure 14
A boudinaged quartzo-feldspathic vein in an amphibolite band (E.4004). The hammer shaft is 60 cm long.

interstitially to quartz and twinned, sometimes normal-zoned, plagioclase. The preferentially orientated mafic minerals give this generally tonalitic rock a vague penetrative fabric. A more homogeneous example cutting gneisses at station E.4612 is very fine-grained and has a granoblastic texture. Quartz, in association with minor plagioclase, prevails in this rock but interstitial areas consist of partly chloritized brown biotite. Other minerals include some possible clinozoisite and a colourless hair-like aggregated mineral which has parallel extinction, is length fast and thought to be rutile.

An extensive area of what is possibly a blasto-amygdaloidal hypabyssal rock makes irregular sharp contact with an homogeneous quartz-biotite-gneiss in the north-eastern Welch Mountains (E.4009). Some rock fragments of a composition similar to the surrounding gneisses are present within this rock. This (?) hypabyssal rock is sufficiently old to have been metamorphosed, resulting in its complete recrystallization accompained by some deformation and replacement of the (?) amygdales which are occasionally linked by narrow quartz veins. If these ovoid cavities were not originally amygdales, it is difficult to explain their mode of formation but, if they were amygdales, their lack of extreme deformation (in view of the ensuing metamorphism) is equally puzzling. This metamorphism has created a general foliation trend similar to that in the adjacent rocks but it has not destroyed scattered polysynthetically twinned and oscillatorily zoned plagioclase crystals thought to be pre-tectonic.

The rocks described below from the metamorphic complex are without dyke form, occur over larger areas but are believed to have had igneous origins.

A massive amphibolitic semi-schistose rock occurs within the heterogeneous gneisses of the south-eastern Welch Mountains (E.4081 and 4082). The fibrous amphiboles are much coarser and are marginally altered to actinolite-ferroactinolite (E.4081.7). The groundmass consists of decussate crushed laths of plagioclase and small flakes of biotite.

Larger areas of a mafic dioritic rock occur within the same heterogeneous gneisses but its metamorphic fabric is not apparent (E.4083.4 and 5). Major differences between these specimens are apparent from an examination of the alteration state of the mafic minerals. Pyroxene is altered to green hornblende (E.4083.5) but in specimen E.4083.4 it has been replaced by tremolite (Fig. 15a), which in turn has been locally altered to granular sericite accompanied by exsolution of iron ore. Large biotite flakes are present in specimen E.4083.4 but they have been completely chloritized and epidotized in specimen E.4083.5. The textural characteristics of this rock suggest an igneous origin and the plagioclase in specimen E.4083.4 shows oscillatory and patchy zones.

Specimen E.4048.11, found even farther north in the banded gneisses, could be related to the above mafic dioritic rock but it has a completely different texture of essentially almost euhedral hornblende with interstitial fringing intergrown twinned plagioclase (Fig. 15b).

It is thought that the amphibolitization of the more typical dykes occurred during the waning stages of metamorphism.

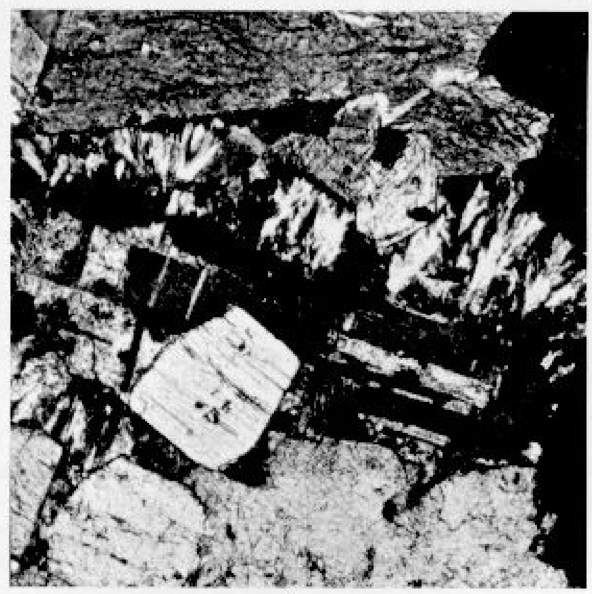
E. Metamorphism

The common association of hornblende and plagioclase ($An_{>20}$), particularly in the gneisses of the Guard Glacier area but also in some of the amphibolitic rocks, suggests that regional metamorphism approached the amphibolite facies as defined by Turner (1968).

This is supported locally by mineral assemblages observed in the banded gneisses of the north-eastern Welch Mountains; the association of quartz, potash feldspar, plagioclase, garnet and biotite in specimen E.4045.15 suggests that metamorphism occurred within the sillimanite zone of the amphibolite facies. This is also inferred from other pelitic assemblages (E.4010.2; quartz, sillimanite, muscovite, garnet and plagioclase) within the same rock group.

The complete dissemination of sericite throughout the plagioclase (oligoclase-andesine) crystals observed in some of the por-

a



b

Figure 15

a. Replacement of pyroxene by tremolite in the core and hornblende at the margins. (E.4083.4; X-nicols; ×65)

b. Fringing intergrown plagioclase in an amphibolite. (E.4048.11; X-nicols; ×80) phyroblastic gneisses of the north-eastern Welch Mountains has been suggested as a characteristic of middle to higher grades of regional metamorphism (Engel and Engel, 1960).

Later stresses are thought to have occurred locally from the shattered garnet crystals observed in specimen E.4045.15 and partly from the widespread occurrence of deformed plagioclase. The occasional partial replacement of garnet by biotite along fractures seen in some examples probably marked the onset of early high-temperature retrograde effects (Harker, 1950). The development of alkali-feldspar porphyroblasts and the marginal replacement of some plagioclase porphyroblasts by potash feldspar in the heterogeneous gneisses of the western part of this area suggest that alkali metasomatism may have occurred at least on a local scale. Possible late-stage metasomatic exchange of alkalis is further evident through the widespread observations of myrmekite in the metamorphic complex.

It has been appreciated that a range of temperature and pressure conditions can exist in metamorphic terrains and these may be too wide to be definitive of a single metamorphic facies (Miyashiro, 1961). However, there are other more conclusive accounts of metamorphism up to the amphibolite facies in metamorphic complex rocks from areas farther north on the Antarctic Peninsula (Hoskins, 1963; Fraser and Grimley, 1972; Davies, 1976).

F. Regional Correlation

Possible equivalents of the metamorphic complex occur elsewhere in the Antarctic Peninsula but no farther north than lat. 67°S (Adie, 1954; Hoskins, 1963; Fraser, 1965; Marsh, 1968; Stubbs, 1968; Fraser and Grimley, 1972; Rowe, 1973; Skinner, 1973; Smith, 1977) and these have been grouped together as the "Basement Complex". "Basement Complex" fragments have been observed as infrequent xenoliths in tonalites and granodiorites on the Loubet Coast (Goldring, 1962). Craddock and others (1964) have suggested that part of the Eights Coast is underlain by high-grade metamorphic rocks and intrusive plutonic rocks formed during the same orogenic event that affected the quartz-diorite-gneisses exposed there. A minimum age of 280 Ma (Upper Palaeozoic) has been derived for the time of formation of biotite in these gneisses. This represents the only outcrop of possible metamorphic complex rocks in the Antarctic Peninsula south of the central Black Coast area, although similar rocks have been recorded in Marie Byrd Land (Wade and Wilbanks, 1971).

The "Basement Complex" (Adie, 1964) rocks, like their central Black Coast correlatives, are also dominated by *ortho*gneisses and are generally associated with banded gneisses or *para*gneisses. Adie (1954) has concluded that the original "Basement Complex" was relatively poor in sediments and that most of the gneisses were derived from intermediate and acid igneous rocks. This has been further emphasized by other workers (Hoskins, 1963; Fraser, 1965; Stubbs, 1968; Rowe, 1973; Skinner, 1973) during the more detailed systematic mapping of the Antarctic Peninsula.

Only one phase of regional metamorphism has been identified in the central Black Coast area but up to three phases have been recorded in the "Basement Complex" rocks elsewhere (Hoskins, 1963; Adie, 1964; Smith, 1977). The first of these reached the lower stages of the almandine-amphibolite facies (Hoskins, 1963) and this is believed to be equivalent to that stage identified in the central Black Coast metamorphic complex. During this metamorphism extensive potash metasomatism occurred (Hoskins, 1963). A retrograde stage of the albite-epidote-amphibolite facies is superimposed on this metamorphism and there is vague evidence for an earlier metamorphism, prior to the first major one, in gneisses of the Marguerite Bay area (Hoskins, 1963).

The essentially *para*schistose and *para*-amphibolitic metamorphic complex rocks reported from the South Shetland Islands (Hobbs, 1968) and South Orkney Islands (Thomson, 1968) are in complete contrast to those of the Antarctic Peninsula. Lithological differences between the two metamorphic groups have previously prevented their correlation and reflect a contrast in the physical conditions of metamorphism. The rocks of the Antarctic Peninsula are believed to have been metamorphosed under high-temperature low-pressure conditions (Stubbs, 1968), whereas those of the off-lying islands were formed in low-temperature high-pressure conditions (Smellie and Clarkson, 1975).

From this evidence, it has recently been proposed that a paired metamorphic belt exists in western Antarctica (Smellie and Clarkson, 1975). This proposal, that the two metamorphic belts are related in time, is supported by a radiometric date (187 ± 5 Ma) obtained from the metamorphic complex of the South Orkney Islands (Miller, 1960) which is similar to those obtained from the Antarctic Peninsula.

G. Age of the Metamorphic Complex

A relative age for the metamorphic complex of the central Black Coast has been derived by correlation with rocks of the "Basement Complex", originally described by Adie (1954) as tentatively early Palaeozoic but more probably Archaean. Other Antarctic workers have agreed with this conclusion but they have provided little further evidence in support (Goldring, 1962; Hoskins, 1963; Fraser, 1965).

K-Ar determinations on hornblende from an amphibolite and a hornblende-biotite-gneiss from the Oscar II Coast, Graham Land, have given dates of 243 ± 10 and 237 ± 9 Ma (Permian), respectively (Marsh, 1968). Also, whole-rock "Basement Complex" *ortho*gneisses (Adie, 1954) have been dated by Rb-Sr methods (Halpern, 1971) as late Triassic (200 ± 10 Ma).

The above radiometric dates led some workers to believe that the main (or last major) metamorphism occurred in the mid- to late-Palaeozoic (Rowe, 1973; Skinner, 1973) or even the Mesozoic (Dalziel and Elliot, 1973).

The data available are still very limited and caution should be observed in their interpretation (Moorbath, 1967). However, it does seem likely that the "Basement Complex" and its paired equivalent in the South Shetland Islands were probably of early to mid-Palaeozoic age and that their last major metamorphism occurred during the mid- to late Palaeozoic prior to the early Mesozoic igneous activity (Rex, 1971).

IV. THE MOUNT HILL FORMATION

THE *Mount Hill Formation* represents a sequence of unfossiliferous sedimentary and volcanic rocks, which have suffered probable dynamic and thermal metamorphism and occur throughout the central Black Coast. A formation name is justifiable in view of the absence of definite stratigraphical relationships with similar rocks both to the north and south of this area. The name is derived from the Mount Hill area where vague primary sedimentary structures are still visible in the metapelitic rocks and also where there remains some hint of an original texture. Although they are never seen in contact with the metasedimentary rocks, the metavolcanic rocks have had a similar metamorphic history and are thought to be part of the same formation. Because of its extreme comminution (Fig. 16) and metamorphism, the thickness, base and tops of the composite rock sequences are not yet clearly known.

FIGURE 16
Extremely comminuted outcrop of the Mount Hill Formation at the type locality.

Its stratigraphical position is puzzling in that similar rocks have been described from Cape Bryant and Cape Christmas as part of the (?) Carboniferous Trinity Peninsula Series, which extends intermittently throughout the length of the Antarctic Peninsula to the north (Adie, 1957). Also, metamorphosed sediments similar to those of the Mount Hill Formation have been reported from the Lassiter Coast and southern Black Coast but they are Upper Jurassic in age and contain a varied fauna and flora (Williams and others, 1971). The random spatial relationship between the metamorphic complex and the Mount Hill Formation precludes any attempt to demonstrate gradational zones of metamorphism between the two successions.

The sediments are believed to have been deposited in a back-arc basin and possibly on continental crust during the evolution of the Antarctic Peninsula in Upper Mesozoic times.

The Mount Hill Formation is described below as two rock sequences (metavolcanic and metasedimentary) and is then critically compared with the Trinity Peninsula Series and the Latady Formation in order to assess its stratigraphical position.

A. METAVOLCANIC ROCKS OF THE MOUNT HILL FORMATION

The metavolcanic rocks consist of massive grey porphyroblastic to laminated rocks together with minor fine-grained laminated siltstones or ashes which are usually found in association with a sequence of greenstones. The latter contain undeformed blasto-amygdaloidal structures of a presumed volcanic origin. Also, various volcanic features of the porphyroblasts and the characteristic microscopic texture of the massive grey rocks has led to the possibility that these may represent a sequence of acidic porphyritic volcanic rocks.

1. *Field relations*

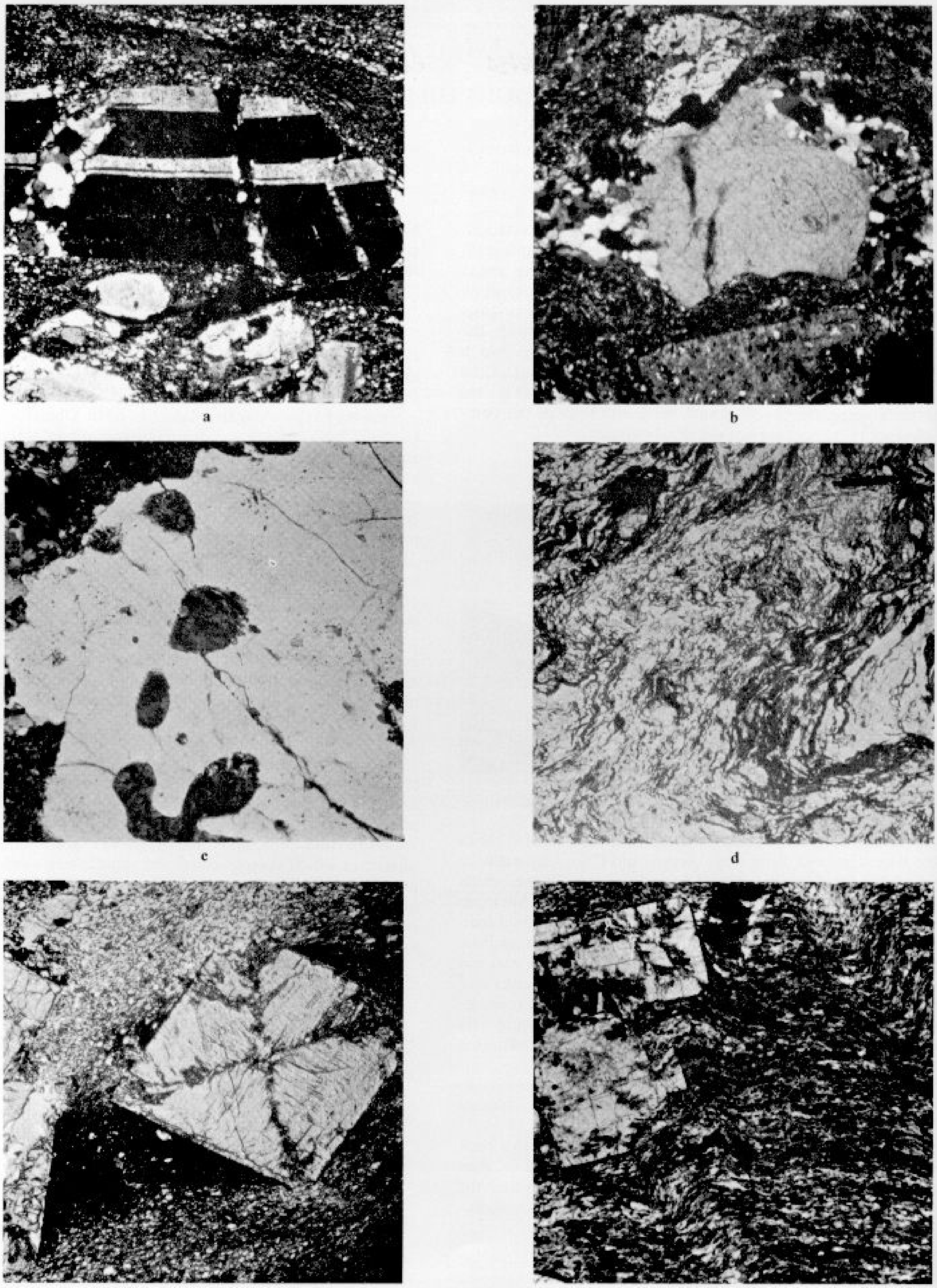
The grey metavolcanic rocks sometimes have a distinct cleavage (E.4099 and 4141) but the greenstones are always massive and well jointed. The contact between them shows no consistent pattern; at station E.4103 it appears sharp and the greenstone has an elongated dyke-like form. Observations in the Giannini Peak area revealed a more gradational trend (E.4051 and 4057) which could be attributed to the thermal metamorphism. The immediate contact rock adjacent to the granodiorite at station E.4051 is a massive fine-grained hornfels which becomes laminated and contains small irregular leucocratic patches a short distance away. The gradation then continues eastward into the more typical porphyroblastic metavolcanic rocks. At station E.4057 this trend is reversed and the porphyroblastic rock has a fairly sharp contact with a greenstone through a massive grey hornfels. Farther south (E.4059), there is a similar pattern but the porphyroblastic metavolcanic component is absent and the distance between the granodiorite and the greenstone is much reduced. The porphyroblastic metavolcanic rocks are particularly well exposed in the Giannini Peak area but they do occur elsewhere (E.4098, 4104 and 4141).

The massive greenstones are also exposed farther south at station E.4133, where they contain large bleached areas as well as quartz-epidote amygdales. They predominate over other metavolcanic rocks at Abendroth Peak. Typically associated with this rock are dyke and finger-like areas of laminated quartzites which usually consist of rapid alternations of mafic and leucocratic, continuous and discontinuous bands. These are interpreted as metasiltstones or fine-grained ashes and they are comparable with similar rocks described by Davies (1976) from farther north.

2. *Petrography*

The porphyroblasts in the massive grey rocks are two-fold in composition: pairs, groups or single plagioclase crystals up to 2.55 mm in length (An_{29-36}) prevail in most sections and show twinning of albite-type but pericline varieties also occur (E.4066.1). Where the metamorphic fabric is better developed, the porphyroblasts are cloudy and sericitized (E.4097.1). The normally sub-rounded crystal margins are sometimes sutured to irregular and they are occasionally embayed (E.4140.1). Andesine is commonly deformed and broken; the fractures have been replaced synkinematically (Misch, 1969) by polygonal quartz (Fig. 17a).

Quartz, the subordinate megacryst, occurs as single crystals and also as composite clasts with irregular margins. It is widely undulose and locally enclosed in a penetrative fabric with the development of pressure-shadow areas (Fig. 17b). Partial polygonization of some undulose quartz has occurred. Embayments



a b c d e f

FIGURE 17

a. Fractures in plagioclase replaced synkinematically by quartz. (E.4141.1; X-nicols; ×70)
b. The pressure shadow area of recrystallized quartz around a quartz porphyroblast in a metavolcanic rock. (E.4097.1; X-nicols; ×70)
c. An embayed quartz porphyroblast in a metavolcanic rock. (E.4066.1; X-nicols; ×80)
d. Complex folding in a slate. (E.4054.12; ordinary light; ×70)
e. Chiastolite in a slate. (E.4190.1; X-nicols; ×55)
f. Chiastolite which has grown across a crenulation cleavage. (E.4075.2; ordinary light; ×30

in quartz crystals (E.4066.1) could represent features of a volcanic origin (Fig. 17c) and they are thought to have formed through resorption by the magma, perhaps shortly before eruption (Pettijohn and others, 1972). The original aphanitic and glassy blebs have been completely replaced by the groundmass which consists mainly of fine polycrystalline quartz and variably of some fine green-brown biotite flakes, muscovite and chlorite (E.4066.1). Large elongated to lenticular areas of epidote are sometimes present (E.4141.1) and minor calcite is seen occasionally (E.4097.1). Epidote not only occurs as large individual aggregates but also as fine granules together with some plagioclase in the groundmass (E.4140.1). Iron ore occurs throughout as granules but also as elongated streaks (E.4141.1) where the penetrative fabric is better developed.

The homogeneous greenstones are dark green to black in colour and contain leucocratic blasto-amygdaloidal structures of irregular to ovoid form. These amygdales are confined to specific areas locally and are not ubiquitous. The melanocratic appearance of these rocks is due to the presence of a large amount of fibrous amphibole, usually actinolite, which occasionally (E.4058.2) has dark green margins and can attain a crystal length of 4 mm. Hornblende sometimes dominates over other amphiboles as anhedral crystals (E.4059.6) and may form an intricate elongated web-like texture. Chlorite flakes are also present in most specimens. Biotite is usually scarce (E.4052.5 and 4102.1) but may also predominate (E.4060.2) and is occasionally altered to chlorite. Epidote and sphene are common as scattered aggregates but sometimes may be more significant (E.4102.1, 4103.1 and 3). Quartz occurs in minor quantity interstitially to the amphiboles in all specimens together with indistinct polysynthetically twinned plagioclase in some of them. The amphibole-chlorite-epidote assemblage described above has been attributed, in other areas, to the low-grade regional metamorphism of basic to intermediate igneous rocks (Aitkenhead, 1964).

The amygdales are mainly occupied by quartz and epidote which generally show no differentiation in grain-size or composition between the margin and the core. However, some of them contain epidote at the margins and large polygonal to sutured quartz centrally (E.4060.2). In contrast, the amygdales of specimens E.4110.1 and 4133.2 consist of heavily sutured plagioclase crystals with some fine polysynthetic twins, epidote, fine decussate blades of actinolite, sphene and iron ore.

The massive homogeneous grey hornfelses which crop out over a small area in the immediate contact zone at station E.4051 probably represent the metamorphic equivalent of an originally quartzo-feldspathic rock (Turner, 1968) and may represent the more highly thermally metamorphosed equivalents of the porphyroblastic metavolcanic rocks. They are very fine-grained and consist of granoblastic inequigranular quartz with minor plagioclase and scattered tiny green-brown biotite flakes, some of which are altered to chlorite and occasional muscovite. Minor late potash feldspar and micro-string perthite contains biotite and quartzitic inclusions (E.4052.4) and mark an area of contamination immediately adjacent to the granodiorite. The small irregular leucocratic patches observed in specimen E.4051.5 are slightly finer-grained but are of a similar mineralogy to the surrounding groundmass and contain parallel discontinuous darker ribbon-shaped areas of late muscovite and biotite which have enclosed quartz inclusions and are associated with late quartz containing some biotite inclusions.

The fine-grained laminated metasiltstones or ashes found in association with the greenstones are usually quartzitic but some epidote, sphene and muscovite may be present (E.4103.5). The darker bands (E.4060.4) contain lines of sericite flakes in a coarser inequigranular quartzitic groundmass which lacks biotite but has some plagioclase. The lighter quartzitic bands contain scattered green-brown biotite flakes together with fine sericite laths but with larger plagioclase crystals.

B. Metasedimentary Rocks

The majority of these rock types are typical of metamorphosed pelitic assemblages. The widespread occurrence of aluminous minerals such as andalusite in rocks of this kind has been suggested as indicative of a significant proportion of clay in the original sediment (Elliot, 1965).

1. *Field relations*

The metasediments show some relict primary laminations and cross beds, particularly in the extreme eastern areas, but they are spotted and slaty grading through to hornfelsic varieties elsewhere.

The rocks are mostly sandwiched between cupolas and consequently no regular pattern of aureole zoning occurs at any one place. In general, the rocks are more massive and hornfelsic towards the contact but it is not uncommon for the spotted slaty rocks to occur here (E.4179). This probably reflects a variable marginal pluton temperature at the time of intrusion.

Although the immediate contact was not visible in the field, it seems very likely that the metamorphic complex and the Mount Hill Formation are two distinct geological units.

The widespread occurrence of secondary quartz veins and gashes is a characteristic of this sequence of rocks as well as the metavolcanic rocks.

2. *Petrography*

The rocks are typically dark grey to black in colour though there are some leucocratic hornfelses (E.4128.4). However, the primary laminated metasediments (E.4096.2) of the eastern central Black Coast consist of microcrystalline inequigranular quartz with a small amount of larger twinned plagioclase. Biotite is scattered throughout but it is reduced in amount in the leucocratic laminae. Conversely, calcite is more prominent in the mafic layers.

A similar finer-grained rock (E.4628.1) from Cape Bryant also has laminations, the more mafic of which contain a higher proportion of iron ore. This very fine metasiltstone comprises scattered coarser, corroded quartz fragments in a finer groundmass of biotite, some muscovite, quartz and iron ore. The macro-folding observed at stations E.4054 and 4062 appears very complex (Fig. 17d) and may have developed because of its close proximity to the contact with the main granodiorite.

The metasediments in close contact with the main intrusive rocks are variably altered to slates, spotted hornfelses and hornfelses. Large spots are very common, attain crystal dimensions of up to 2.8 cm in length and up to 4 mm in cross-section and have the characteristic cruciform outline of chiastolite (Fig. 17e). Less altered idioblastic forms of andalusite occasionally show two-directional normal cleavage traces in cross-sections. Less distinct, very pale pink forms occur as web-like patches around the granoblastic largely quartzitic groundmass where it forms in some of the andalusite-biotite-hornfelses (E.4064). Rare rose-red andalusite is present (E.4111.1) and is pleochroic to pale green.

In the slates close to one pluton contact, chiastolite appears to have grown across a fabric containing one crenulation cleavage (Fig. 17f) but the origin of this secondary folding is not conclusive.

Retrograde alteration of chiastolite to sericite, muscovite and sometimes biotite is occasionally accompanied by deformation (Fig. 18a). The spots can be marginally corroded and, in some examples, fragmented and partly replaced by polygonal quartz (Fig. 18b).

Cordierite is less widespread and it usually occurs as irregular margined heavily included ovoid forms (E.4062.7 and 4149.1). The cordierite in specimen E.4062.7 has been elongated parallel to a possible original fabric which has peristed through to the stage of chiastolite formation.

Scattered very pale red, fragmented garnet crystals occur in some of the semi-laminated pelitic hornfelses (E.4131) and these are thought to have formed during the earlier regional metamorphism but could also have resulted from thermal events. The garnet may be spessartine, reflecting a high manganese content of the original rock (Tilley, 1926), or possibly almandine which depends upon the quantity of "free ferrous oxide" in the original rock (Jones and Galwey, 1964). Almandine results from the regional metamorphism of argillaceous sediments but it can also occur in some contact metamorphic aureoles which also contain white mica but lack potash feldspar. Adie (1957) believed that the garnets observed in the metamorphosed argillaceous sediments on the east coast of Palmer Land south of Three Slice Nunatak did not result from the earlier regional metamorphism.

The highest grade of thermal metamorphism is identified on the south side of Guard Glacier, where thin foliated layers of sillimanite are found in association with biotite in a hornfels also containing andalusite (E.4075.4). According to Turner (1968), sillimanite generally takes the place of andalusite, particularly in more aluminous pelitic assemblages of hornblende-hornfels facies, and therefore this relationship probably represents a transition between two grades. This biotite-sillimanite-hornfels grades laterally from the contact into chiastolite-slates.

The groundmass of the dark hornfelses is mainly composed of granoblastic to polygonal quartz with minor plagioclase, some muscovite, usually brown biotite, iron ore and occasionally chlorite. The biotite present in the more slaty rocks is of two generations: the earlier form, parallel to the foliation in most cases, possibly developed synkinematically during early thermal episodes and was followed by a more randomly orientated variety thought to have grown during a later phase of static crystallization. The less common leucocratic hornfelses contain a significant amount of scattered epidote in the groundmass as well as sparse amphibole (E.4128.4).

The slates and their spotted equivalents have a better-developed foliation but they are still composed of granoblastic quartz, some biotite and occasionally large amounts of granular iron ore. There is muscovite in some examples (E.4111.1).

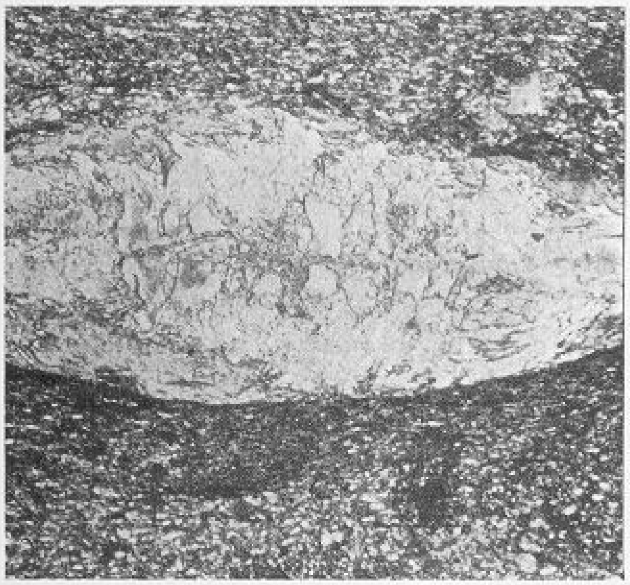
C. Metamorphism

The Mount Hill Formation appears to have suffered probable dynamic metamorphism prior to its thermal metamorphism. The results of K-Ar dating on rocks believed to be part of the main granodiorite suite (see Appendix) indicate a minimum age of 125 Ma for the pre-thermal deformation. There is evidence for syn- and post-kinematic deformation during the later thermal metamorphism.

1. *Evidence of pre-thermal metamorphism*

According to Spry (1969), rocks produced by low-grade regional metamorphism are mineralogically and texturally indistinguishable from those resulting from dynamic metamorphism and hence either could have affected the Mount Hill Formation.

There is evidence of pre-thermal deformation in both the metavolcanic and metasedimentary rocks of the Mount Hill Formation. The fact that the effects of this are not seen in the metamorphic complex reflects the low intensity of this metamorphism.



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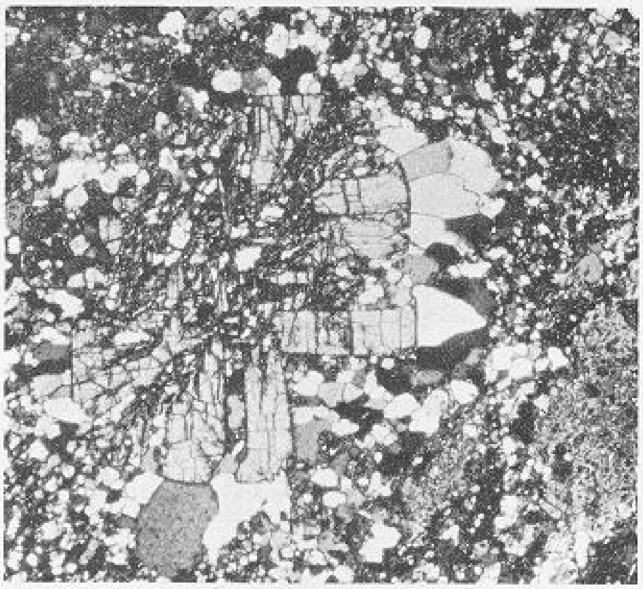


b

Figure 18

a. Deformed chiastolite altered marginally to chlorite and sericite. (E.4175.1; ordinary light; ×70)
b. Fragmented chiastolite, replaced by quartz adjacent to ovoid cordierite with unidentified inclusions. (E.4062.7; X-nicols; ×70)

The deformation of twinned plagioclase porphyroblasts in the acidic metavolcanic rocks could possibly have occurred prior to their fracturing and replacment by polygonal quartz during the later thermal metamorphism. The widespread occurrence of quartz porphyroblasts with an undulose extinction in these rocks is also thought to have resulted from an earlier dynamic or regional metamorphism. The pressure-shadow phenomenon observed around some porphyroblasts (E.4097.1) is further evidence of their pre-tectonic origin. The common occurrence of epidote in the metavolcanic greenstones could be due to retrograde re-adjustments associated with an earlier phase of metamorphism. Its formation is favoured by shearing stress and low temperature (Deer and others, 1966), more akin to dynamic conditions.

There have been several examples cited in the metapelites of relict penetrative fabrics. Adie (1957) has identified at least three cleavage directions in possible Trinity Peninsula Series rocks south of Three Slice Nunatak, on the east coast of Palmer Land. It appears that the pre-thermal metamorphism of the Mount Hill Formation consisted of at least one major phase of deformation.

2. *Thermal metamorphism*

The widespread occurrence of the characteristic rocks and constituent minerals expected in a thermal aureole indicates that contact metamorphism occurred.

The grade of metamorphism reached the hornblende-hornfels facies and the rare occurrence of sillimanite in some pelitic rocks suggests at least local attainment of the pyroxene-hornfels facies. Retrograde metamorphic effects identified as belonging to the albite-epidote-hornfels facies in the Latady Formation to the south (Plummer, 1974) have also been observed in the Mount Hill Formation.

a. *Synkinematic deformation.* Andalusite porphyroblasts formed during the thermal metamorphism have occasionally been deformed parallel to a foliation direction and could represent further deformation subsequent to the thermal metamorphism but they are thought to have been the result of synkinematic deformation. This has also been observed by Plummer (1974) in the Latady Formation. The fracturing and extension of the porphyroblasts in some metavolcanic rocks also possibly occurred during the thermal metamorphism.

b. *Post-kinematic deformation.* The polygonization of quartz porphyroblasts with an undulose extinction in some metavolcanic rocks may have resulted from post-thermal events but it could also have developed during a late syn-thermal stage. It is probable that the fragmentation and replacement of chiastolite by polygonal quartz could have occurred at a similar time.

Some quartzite lenses in the massive slates to the south of Neshyba Peak (E.4139.1) show sigmoidal deformation. These contain irregular sutured, inequigranular quartz crystals, whereas the less-deformed types contain polygonal quartz crystals and are indicative of more static conditions. The coexistence of both types indicates that shearing was not pervasive. It is thought that the quartz was introduced during thermal metamorphism and was deformed either late synkinematically or possibly post-kinematically.

c. *Retrograde effects after thermal metamorphism.* The effects of retrograde metamorphism in this area are similar to those described from the Latady Formation (Plummer, 1974). The chiastolite in some of the metapelites shows marginal alteration to sericite, muscovite and sometimes biotite. In the greenstones, brown biotite is commonly altered to chlorite (E.4060.2 and 4135.2).

The fragmentation of garnets in some of the metasedimentary rocks may be a retrograde effect that occurred after the regional metamorphism or it may have occurred prior to or during the later thermal events. However, if these garnets were formed during the thermal metamorphism, their later fracturing could have been due to retrograde processes.

D. Regional Comparisons

1. *The Trinity Peninsula Series and other late Palaeozoic sequences*

a. *Lithology, provenance and age.* Previous regional correlations of the Trinity Peninsula Series have been made on lithological as well as structural grounds (Adie, 1964; Aitkenhead, 1964; Elliot, 1965, 1966, 1967; Fleet, 1968; West, 1974).

The rocks are largely quartz-greywackes with shales and subordinate conglomerates, conglomeratic mudstones, arkoses, quartzites, siltstones, carbonaceous shales, limestones, cherts and greenschists. These have been variously metamorphosed to slates and hornfelses adjacent to younger plutons.

The provenance of the Trinity Peninsula Series is largely granitic though there is some evidence for derivation from sedimentary and metamorphic terrains. Evidence for contemporaneous volcanism is sparse; thick sequences of greenschists in northern Graham Land were believed to represent intermediate to basic hypabyssal and volcanic rocks and their clastic derivatives but "the nature of the original volcanism has not been proved" (Aitkenhead, 1964). Hobbs (1968) has reported bedded volcanic rocks in these sediments and rare volcanic detritus has also been found in cataclastic correlatives farther south on the Wilkins Coast (Fraser and Grimley, 1972).

The Trinity Peninsula Series rocks are unconformably overlain by Jurassic plant-bearing sediments in the extreme northern part of the Antarctic Peninsula (Adie, 1957). This unconformable relationship has also been observed in other areas of northern Graham Land (Aitkenhead, 1964; Bibby, 1966; Fleet, 1968). Although subject to recent criticism (Dalziel, 1971; Schopf, 1973), this "series" was originally assigned a late Palaeozoic age (Adie, 1957) and has since been compared with other believed late Palaeozoic–early Mesozoic formations.

The most distant comparison is with the sediments of the Madre de Dios basin of south-western Chile (Dalziel, 1971) which consist of a succession of marine sandstones, mudstones and massive limestones of Upper Carboniferous to Permian age (Dalziel and Elliot, 1971).

The Miers Bluff Formation of Livingston Island, South Shetland Islands, consisting of thin evenly bedded mudstones and sandstones (Hobbs, 1968; Dalziel, 1971), is a favoured correlative through its fossil characteristics, with an age later than Carboniferous and possibly Mesozoic (Schopf, 1972).

The Legoupil Formation of the north-western Antarctic Peninsula is similar to the Miers Bluff Formation and is now thought to be Triassic in age (Thomson, 1975). This conflicts with the previously proposed Cretaceous age, based on radiometric data (Halpern, 1964, 1965).

The Greywacke–Shale Series on Laurie and Fredriksen Islands in the South Orkney Islands group is of uncertain age but indeterminate fossil remains led Adie (1964) to suggest a Carboniferous age.

On the island of South Georgia, the Sandebugten Formation which comprises mainly quartz-rich greywackes has previously been tentatively assigned to the late Palaeozoic (Trendall, 1953, 1959; Adie, 1964; Skidmore, 1972) but recent workers have shown that this succession, although derived from a different source area, is synchronous with the Cumberland Bay Formation on the same island and is Lower Cretaceous in age (Dalziel and others, 1975).

A sequence of strongly sheared sedimentary and volcanic rocks has been described from southern Alexander Island (Bell, 1973) and this is believed to be part of the Upper Carboniferous to Permian Trinity Peninsula Series (Grikurov, 1971). This sequence has also been tentatively dated by spore-pollen analysis (Grikurov and Dibner, 1968) as Carboniferous. However, recent fossil discoveries have shown that this deformed sequence is late Palaeozoic to early Mesozoic and probably Triassic in age (personal communication from C. W. Edwards). One unusual characteristic, when compared with the typical Trinity Peninsula Series rocks of northern Graham Land, is that the main detrital constituents of these sediments are derived from contemporaneous volcanism (Bell, 1973).

b. *Structure and orogenesis*. The late Palaeozoic sequences of the Antarctic Peninsula are all strongly folded and show polyphase deformation. Their structure is dominated by folds with hinge lines parallel or sub-parallel to the length of the Antarctic Peninsula with some overturning from the Pacific side (Aitkenhead, 1964; Elliot, 1965, 1966, 1967; Fleet, 1968).

There is a similar north–south trend in the sedimentary rocks of the Madre de Dios basin (Dalziel, 1970).

The highly deformed Greywacke–Shale Series of the South Orkney Islands is reported to strike at a high angle to the trend of the south Scotia Ridge (Adie, 1964) but this has been attributed to late-stage "cross folds" (Dalziel, 1971).

The (?) Carboniferous sequence of Alexander Island has also undergone polyphase folding but in addition is polycataclastically deformed (Bell, 1974).

The age of deformation was thought to be pre-Jurassic (Adie, 1957) and is most certainly early Mesozoic in age (Miller, 1960; Aitkenhead, 1964; Hobbs, 1968; Dalziel, 1971). It was probably part of the much larger Gondwanian orogeny which affected the Antarctic sector of the Pacific margin of Gondwanaland (Elliot, 1973). Recent radiometric dating shows the existence of early Jurassic intrusive activity in the Antarctic Peninsula (Adie, 1971*a*) which may be related to the Gondwanian orogeny. Thus, these thick "late Palaeozoic" sediments probably accumulated in one or several discrete troughs along the continental margin of Gondwanaland and were compressed in the early Mesozoic, perhaps resulting from the development of a spreading ridge in the Pacific. The metamorphic grade reaches greenschist facies only in the Trinity Peninsula Series, which has also been correlated with rocks of a higher grade of metamorphism. Stubbs (1968) has tentatively suggested that the biotite-gneisses of the eastern Joerg Peninsula might be the metamorphic equivalents of the Trinity Peninsula Series. Also, banded gneisses have been considered by Marsh (1968) to be regionally metamorphic equivalents of geosynclinal sediments of a greywacke composition. In northern Graham Land there is a perceptible increase in regional metamorphism from north-east to south-west but the overall grade is low (Aitkenhead, 1964; Elliot, 1966). In areas farther south, such as the Nordenskjöld Coast (Elliot, 1966) and the northern part of the Oscar II Coast (Fleet, 1968), the regional metamorphism of the Trinity Peninsula Series is so low that there is little evidence for the maintenance of this southerly increase in metamorphic grade. Fraser and Grimley (1972) believed that the strong contrast provided by the progressive metamorphism and high-grade rocks of sedimentary origin in the area south of Mobiloil Inlet with the Trinity Peninsula Series type rocks farther north could be explained by differential conditions prevailing at the time of orogenesis and probably not simply that the higher-grade rocks are older.

After the early Mesozoic compression, the sediments of the Trinity Peninsula Series were finally uplifted and later intruded (Adie, 1957; Curtis, 1966) during the formation of the proto-Andean western Antarctic cordillera.

2. *Upper Jurassic Latady Formation*

a. *Lithology, provenance and age*. The Latady Formation consists of black siltstones, shales and mudstones with minor greywackes, quartzites, sandstones, and rare intraformational conglomerates and limestones (Williams and others, 1971). In contrast, the Jurassic succession of eastern Ellsworth Land contains polymictic conglomerates rich in volcanic pebbles and abundant intraformational conglomerates (Laudon, 1971). This difference is thought to reflect the relative proximity of each area to the sediment source (Williams and others, 1971).

Williams and others (1971) have not suggested contemporaneous volcanism, though this has been inferred by Laudon (1971) farther south and recorded in Jurassic strata elsewhere (Dewar, 1970; Fraser and Grimley, 1972; Skinner, 1973; Elliott, 1974). Volcanic quartz, which is common in the sandstones, indicates a provenance in part from a volcanic terrain.

A ternary QRF diagram has been used by Williams and Rowley (1972) to show that a comparison of sandstone composition is the most useful method for distinguishing between the Jurassic sediments of the Lassiter Coast and the Trinity Peninsula Series (Fig. 19a). This QRF plot can be expanded using the data of Laudon (1971) and Elliott (1974) for Jurassic sandstones and it partly blankets the Trinity Peninsula Series points from Elliot (1965) (Fig. 19b). When compared with the data of Aitkenhead (1975) and West (1974) for Trinity Peninsula Series sandstones, there is an almost complete overlap (Fig. 19c). Thus, in the broadest sense, the Jurassic sandstones may appear more lithic than the siliceous Trinity Peninsula Series types but diagrams of this kind based on sparse and widespread data for direct comparisons of sedimentary rock groups can appear particularly deceptive.

Kamenev (1973) believed that not all the sedimentary and volcanic rocks from the Lassiter Coast belong to the Jurassic formation and he has defined a western zone of possible Trinity Peninsula Series schists (Kamenev, 1975).

The Latady Formation contains abundant fossils of Jurassic

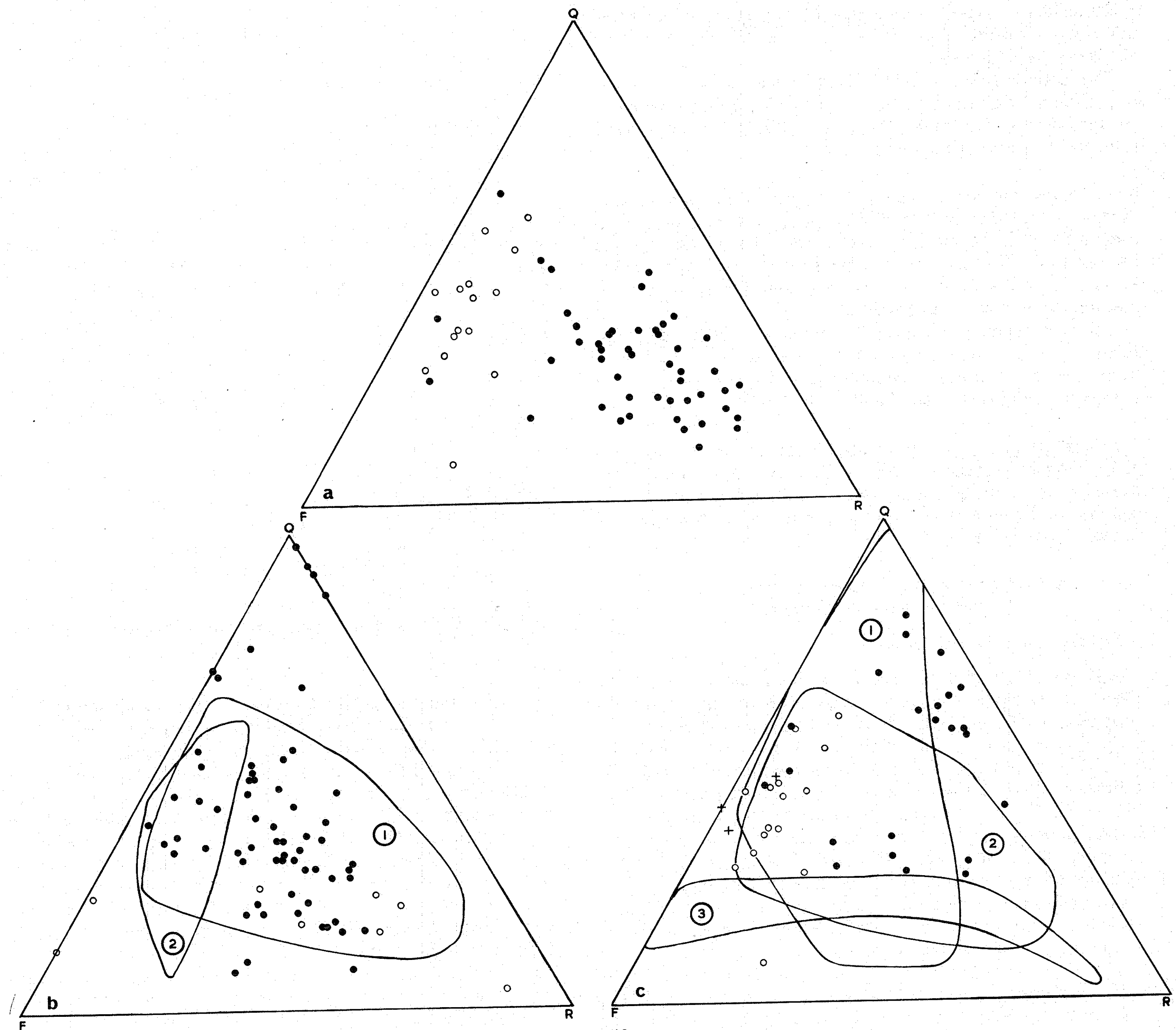


FIGURE 19
Modal triangles showing the relationship between Upper Jurassic sandstones and (?) Carboniferous Trinity Peninsula Series sandstones.

age and was probably deposited in a shallow-water environment.

b. *Structure and orogenesis*. These sediments and the overlying volcanic rocks display open to isoclinal folds with axial-planar cleavage. Fold axes trend north-east and are gently plunging to the north-east and south-west. A second period of folding, which caused displacement of the older folds, is confined to distances of less than 1 km from the pluton contact and is consequently attributed to the forceful intrusion of the plutons. This type of folding is commoner towards the north-east where plutonic rocks are more abundant (Kellogg and Rowley, 1974).

The most intensively thermally metamorphosed rocks are within the hornblende-hornfels facies, though some rocks possibly crystallized under conditions transitional between this and the amphibolite facies (Plummer, 1974). Recent K-Ar ages of plutonic rocks from the Lassiter Coast have indicated that the deformation occurred between the late Jurassic and the Middle Cretaceous. After this period, plutons were emplaced at about 119 Ma, causing the secondary deformation and thermal metamorphism (Mehnert and others, 1975).

3. *Review of the significant differences between the Trinity Peninsula Series and the Latady Formation*

a. *Structure and metamorphism*. The Jurassic and Cretaceous rocks have a simpler structural geometry and a less pronounced polyphase deformational history than the Trinity Peninsula Series and its equivalents.

The metamorphism of the Trinity Peninsula Series reached the grade of greenschist facies before contact metamorphism, whereas the pre-thermal folding in the Latady Formation only resulted in the development of a slaty cleavage.

b. *Lithology and provenance.* Pelitic assemblages predominate throughout the Latady Formation but they are secondary to psammitic rocks in the Trinity Peninsula Series. Attempts to demonstrate a difference between the Latady Formation and the Trinity Peninsula Series by a comparison of sandstone composition appear to be inconclusive.

Contemporaneous volcanism is much more widespread in the Jurassic strata. The derivation of the late Mesozoic sediments from a volcanic terrain certainly contrasts with that of the Palaeozoic sediments (Dalziel and Elliot, 1973).

c. *Fauna and flora.* The late Palaeozoic sequences are relatively unfossiliferous compared with the Latady Formation, which contains an abundant and varied marine fauna, including ammonites, belemnites and pelecypods as well as fragments of several types of land plants.

E. Conclusions and Correlations of the Mount Hill Formation

1. *Structure and metamorphism*

Analysis of the small amount of data available has revealed a series of folds which have axes striking approximately north–south. The wide scatter of poles to first cleavage planes is probably explained by secondary deflections resulting from the forceful intrusion of plutons, a phenomenon also observed in the sediments of the northern Lassiter Coast (Kellogg and Rowley, 1974) (Fig. 20). The metamorphism during this initial phase of folding appears only to have proceeded to the extent of the development of a slaty cleavage. Simple folding prior to thermal metamorphism also occurred in the Latady Formation, but the major polyphase deformational history observed in the Trinity Peninsula Series shows that the greenschist facies of metamorphism was attained before intrusion by the plutons.

The Mount Hill Formation has suffered a similar maximum grade of thermal metamorphism to that of the Lassiter Coast sediments (hornblende-hornfels facies) and both similar and higher grades of thermal metamorphism have been recorded in the Trinity Peninsula Series (Aitkenhead, 1964; Elliot, 1965).

Microscopically, the Mount Hill Formation shows retrograde and synkinematic mineralogical features of thermal metamorphism which are also apparent in the Latady Formation.

2. *Lithology and provenance*

The majority of the metasedimentary rocks of the Mount Hill Formation are metapelites. Slates and siltstones predominate in the Latady Formation but quartzitic greywackes with subsidiary shales are commoner in the Trinity Peninsula Series.

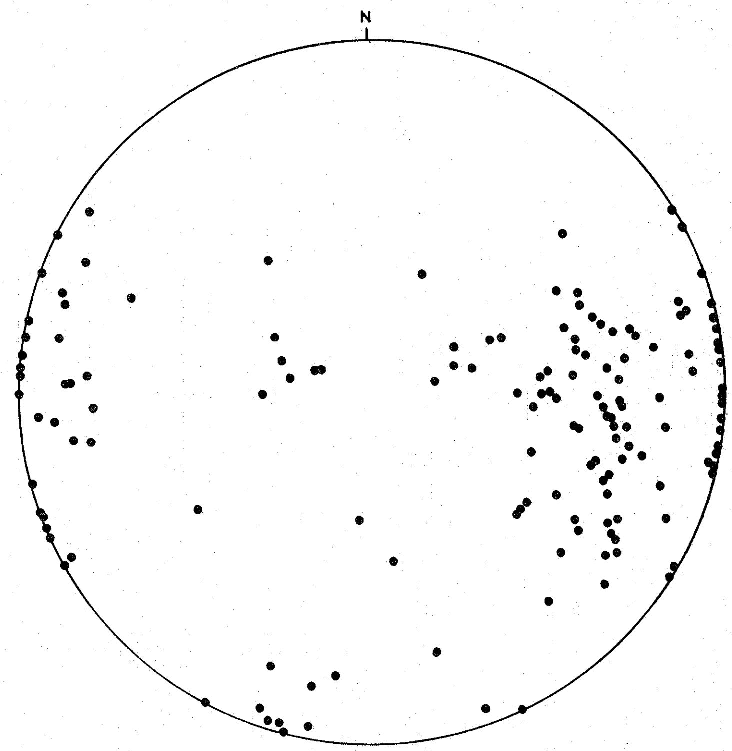


FIGURE 20
Stereogram of poles to first cleavage planes in metasediments of the Mount Hill Formation.

The metavolcanic rocks resemble metamorphosed basic lavas and porphyritic dacitic lavas or possibly tuffs. They were never found together with the metasediments but are believed to be contemporaneous with them. They do not have the same stratigraphical relationships as the intercalated metabasites described by Fraser and Grimley (1972) but their mineralogy is similar to the amphibole-bearing greenschists (Aitkenhead, 1964) and basic lavas (Davies, 1976) described from Trinity Peninsula Series rocks. The porphyroblasts observed in some of the metavolcanic rocks show some similarities in composition and alteration to those described by Plummer (1974) in volcanic rocks overlying the Latady Formation but the massive nature of the porphyroblastic metavolcanic rocks of the central Black Coast, as well as their association with the greenstones, makes further comparisons difficult. No rock fragments were identified in the metasedimentary rocks of the Mount Hill Formation and therefore their provenance is not known.

It is concluded particularly from the metasedimentary rocks that structural, petrographic and metamorphic features of the Mount Hill Formation are more closely similar to those of the Latady Formation rather than the Trinity Peninsula Series.

V. THE UPPER JURASSIC VOLCANIC GROUP

ALTHOUGH these volcanic rocks are probably representatives of the very widespread Upper Jurassic Volcanic Group, their exposure on the central Black Coast is limited to a small nunatak on the plateau edge 2 km south of Mount Jackson.

They consist of unstratified vitric tuffs associated with extensive deposits of unstratified and sheared probable epiclastic rocks. A nearby exposure of a porphyritic dacite is thought to be part of this same volcanic group.

FIGURE 21
A fragment of porphyroblastic gneiss in an (?) epiclastic rock (E.4619). The steel tape is 4 cm across.

A. FIELD RELATIONS

These volcanic rocks crop out at stations E.4619, 4620 and 4622. The sheared and faulted green probable epiclastic rocks are the commonest and they contain mainly sub-rounded to angular feldspar-porphyroblastic gneiss clasts (Fig. 21) up to 2 m in diameter. Vitric or ash-flow tuffs (Ross and Smith, 1961) occur in association with this "sedimentary" rock. Their relationship is puzzling in that some examples, including extremely leucocratic types (E.4619.5), occur as elongated irregular ribbons within the epiclastic rocks.

A small nunatak to the south, which is separated from the main area of volcanic rock outcrop, consists totally of a pink, porphyritic dacitic lava.

At stations E.4619 and 4620 the green (?) epiclastic rock appears to be cut by a very mafic microgabbroic rock which is probably related to the later hypabyssal intrusions of possible Andean affinity. Also, it is adjacent to and may be cut by the olivine-gabbro, described later under "intrusive rocks" (p. 29). These intrusions appear to have had little thermal effect.

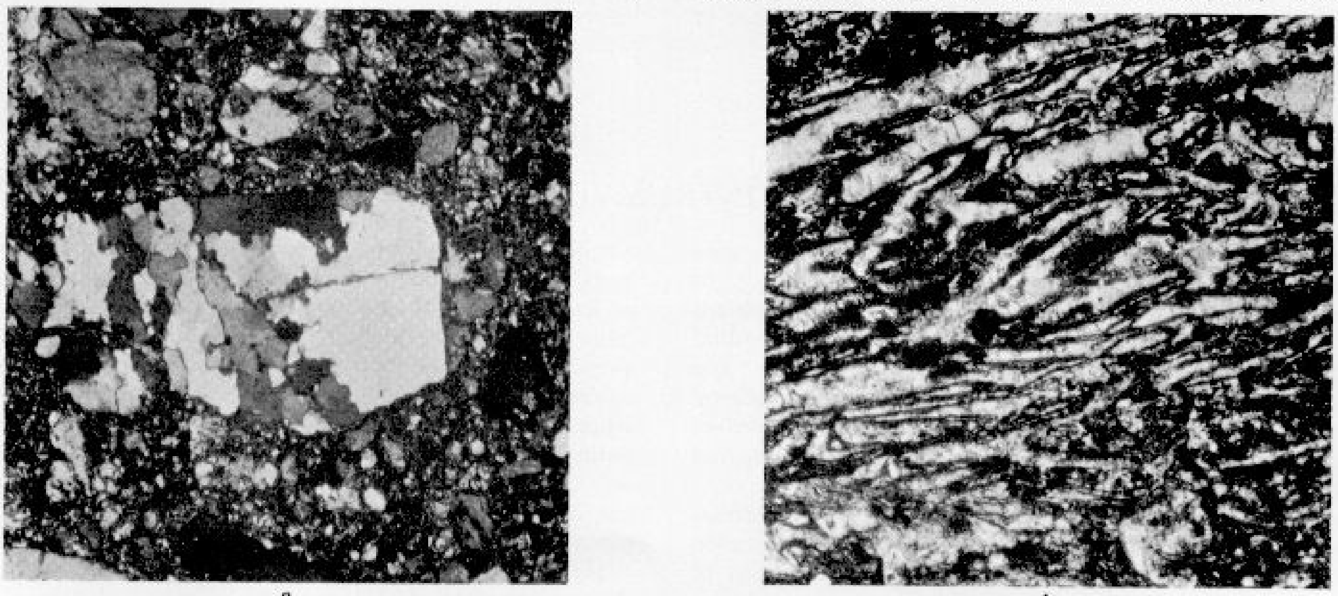
The relationship between this group of rocks and the nearby Mount Hill Formation is not known.

B. PETROGRAPHY

The green colour of the epiclastic rock is largely due to the presence of chlorite within the fine-grained cryptocrystalline matrix. This consists mainly of quartz but small discernible flakes and shreds of muscovite and some biotite are also present. The remainder of the rock is indeterminate. Although field observations show that the larger clasts are mainly of feldspar-porphyroblastic gneiss, the smaller interstitial ones comprise mainly angular to sub-angular quartz with subordinate microcline, some plagioclase and occasional allanite clasts. These clasts therefore appear to be poorly sorted.

The quartz fragments are mostly strained and sometimes partly recrystallized; this has resulted in the formation of composite quartzite clasts with sutured margins (Fig. 22a). The microcline, like the quartz, is sometimes fractured and veined by sericite and calcite.

The acid vitric tuffs are light brown to purple-brown in colour with a poorly developed fabric and they are characterized in thin section by a shard-rich matrix which is partly welded in



a b

FIGURE 22
a. A quartzite clast in an (?) epiclastic rock. (E.4619.1; X-nicols: ×80)
b. Welded shards in a vitric tuff. (E.4619.8; ordinary light; ×70)

specimen E.4619.8 (Fig. 22b) and in some cases has been moulded against the contained phenocrysts. These are largely of plagioclase and are invariably sericitized. However, possible potash feldspar (E.4619.5) and quartz varieties (E.4619.8 and 4620.2) also occur. The quartz is present both as composite clasts and also as single crystals which are sometimes broken and embayed by the shard-rich matrix. Ubiquitous grains of a brown amorphous substance occurring in the distinctly leucocratic tuffs (E.4619.5) sometimes have irregular shapes and may represent alteration products or they could even be a form of iron oxide replacing the shards. Lithic fragments are visible in the hand specimen (E.4020.2) and some have an almost identical composition to that of the host rock.

The porphyritic dacite or rhyodacite (E.4022.1) is distinctly irregularly flow-banded in the hand specimen but its composition is almost totally indeterminate in thin section. The phenocrysts are dominantly altered twinned plagioclase which still shows vague oscillatory zoning. The matrix is cryptocrystalline quartz and probably feldspar but it is largely indiscernible.

C. Regional Correlation

The origin of the (?) epiclastic rocks is problematical though very similar deposits have been recognized farther north (Davies, 1976) and they are thought to have formed from the weathering products of pre-volcanic igneous or metamorphic rocks. The large and sub-rounded boulders contained within this deposit suggest that transport before deposition was rapid and over a comparatively short distance.

The vitric tuffs and dacitic lavas can be more definitely correlated with the Upper Jurassic Volcanic Group, whose presence has been recorded in other areas of Palmer Land (Rowe, 1973; Skinner, 1973; Davies, 1976) and Graham Land (Goldring, 1962; Hooper, 1962; Curtis, 1966; Elliot, 1966; Fleet, 1968; Marsh, 1968; Stubbs, 1968; Dewar, 1970; West, 1974).

At Adelaide Island the volcanic rocks have been assigned to the Upper Jurassic through fossil evidence from the interbedded sedimentary rocks (Thomson, 1972). Although volcanic sequences can accumulate rapidly, the widespread distribution of the Upper Jurassic Volcanic Group in the Antarctic Peninsula and the localized thick successions (Adie, 1964; Dewar, 1970) suggest that these rocks may not be confined to the narrow time limits of the Upper Jurassic. Adie (1964) recognized that the volcanic phases were diachronous and, in fact, considerable quantities of penecontemporaneous volcanic debris have been discovered in the Lower Cretaceous sediments of Alexander Island (Horne and Thomson, 1972; Bell, 1974). If the radiometric ages obtained by Rex (1971) for similar volcanic rocks are representative, the Upper Triassic age of 186±8 Ma would indicate a minimum date for the deposition of the Upper Jurassic Volcanic Group. The volcanic rocks of this group comprise lava flows, agglomerates and tuffs of calc-alkaline affinity which have a compositional range from andesite to rhyolite. Re-worked epiclastic deposits are commonly interspersed with these volcanic rocks (Adie, 1971*b*). Individual vents are evidence of part of the active volcanic belt and they have been recorded along the west coast of Palmer Land (Ayling, 1966; Skinner, 1973; Wyeth, 1975; Smith, 1977).

In many parts of Graham Land and Palmer Land, intrusive rocks have been reported as being genetically associated with the volcanic rocks (Goldring, 1962; Elliot, 1966; Fleet, 1968; Marsh, 1968; Stubbs, 1968; Dewar, 1970; Rowe, 1973; Skinner, 1973; West, 1974). This syngenetic relationship is further supported by radiometric dating (Rex, 1971) which has enabled five phases of igneous activity to be identified, ranging from Lower Jurassic to early Tertiary, and thus they cover the time period so far suggested for the evolution of the Upper Jurassic Volcanic Group.

Over the entire length of the Antarctic Peninsula, the volcanic rocks are intruded by the gabbro–granite bodies of the Andean Intrusive Suite (Adie, 1971*b*), which corresponds to the last of the five intrusive phases identified by Rex (1971). As a result of this, the volcanic rocks have become highly altered and faulted but they show little deformation as most of the strata are either gently dipping or gently folded (Grikurov, 1971).

VI. THE INTRUSIVE ROCKS

The plutonic rocks underlie greater than one-third of the area studied (8 000 km^2). Their compositions vary from acidic to basic (Fig. 23) and they were probably emplaced at different times. Large individual bodies also have a range in composition which commonly trends towards a more felsic interior. The abundance of plutonic rocks relative to others along the central Black Coast marks a continuation of similar trends observed on the northern Lassiter Coast, 150 km farther south (Rowley and Williams, 1974).

The fresher-looking relatively undeformed homogeneous intrusive rocks, grouped as the main granodiorite were intruded in Lower Cretaceous times and marked the termination of igneous activity in this area (see Appendix). However, rocks such as the metagabbro are thought to be older, although they are younger than the Mount Hill Formation. Fragments of hornfelsed metasediments (assigned to the Mount Hill Formation), which are present in the garnetiferous tonalite at the head of Lamplugh Inlet, suggest a similar age relationship but the more altered metagabbro may be older than this tonalite. The diorite at Marshall Peak is tentatively correlated with the quartz-diorites at Cape Bryant which were thought to be part of the Andean Intrusive Suite (Adie, 1955). However, in the absence of radiometric dating, the existence of the Andean Intrusive Suite on the central Black Coast is not conclusive. At stations E.4619 and 4621, 2 km south of Mount Jackson, an unaltered olivine-gabbro occurs adjacent to sheared volcanic and epiclastic rocks.

Field evidence therefore suggests a wide range of ages for these rocks. Rex (1971), working on rocks elsewhere in the Antarctic Peninsula, has recognized five separate intrusive episodes ranging from the Lower Jurassic to the early Tertiary

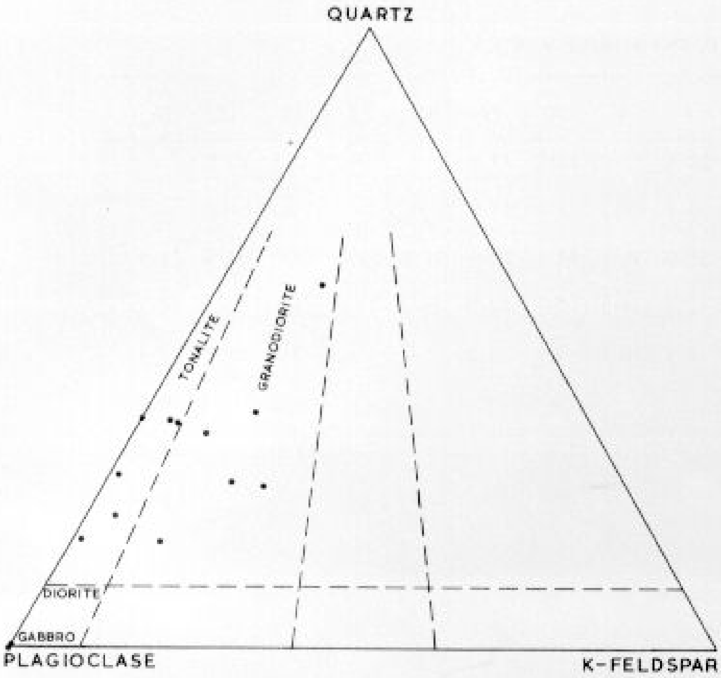


FIGURE 23
Diagram showing the modal composition of plutonic rocks in the central Black Coast area. Rock classification after Nockolds (1954).

and the last two episodes are allied to the Andean orogeny. The results of the radiometric dating carried out on intrusive rocks from the Lassiter Coast indicate a time span of about 20 Ma for the emplacement of plutons and their age range (99–119 Ma) falls within that of widespread Middle Cretaceous plutonism in the Andean province of the Antarctic Peninsula (Mehnert and others, 1975). The results of the radiometric dating achieved from this study are given in the Appendix.

Modal analyses of 16 specimens are given in Table II.

A. METAGABBRO

1. *Field relations*

The metagabbro is exposed on the ridges which form the eastern and western sides of the head of Murrish Glacier and also over a large area of the massif associated with Neshyba Peak.

It makes sharp contact with the metasediments of the Mount Hill Formation on the western side of the head of Murrish Glacier. On the eastern side of the same glacier it is separated from the main granodiorite by a contact breccia, which is discussed further with reference to the main granodiorite. Close to an obscured contact with the metasediments in the Neshyba Peak area (E.4143) the metagabbro is banded and gneissose.

Uralitized hornblende-gabbros have been recorded in association with and intruded by later quartz-diorites at Cape Bryant and these have been considered contemporaneous with similar rocks at Cape Christmas on the southern Black Coast (Adie, 1955).

2. *Petrography*

These rocks are readily distinguishable because of their heterogeneity and mesocratic to melanocratic appearance which can be attributed to the large proportion of hornblende within them. Their texture ranges from pegmatitic through banded varieties to finer-grained types, all of which can occur together.

Banded zones sometimes contain hornblende porphyroblasts. Rhythmic cumulate layering is also occasionally evident; the basal metallic ore bands consist essentially of coarse-grained magnetite, whose margins are partly defined by exsolved patches of possible ilmenite (Ramdohr, 1969) and whose interior is occasionally intergrown with probable ilmenite strings. A minor very hard grey anisotropic ore mineral, possibly chromite, is also present and this has myrmekitic-type intergrown margins which seem to have resulted from replacement by magnetite and ilmenite. Ramdohr (1969) has stated that chromite shows little intergrowth with other minerals, and exsolution and replacement are relatively rare. The nature of the cumulate layering above the metallic mineral bands is puzzling in that no crystals display their true form; cumulate hornblende appears to have formed first with intercumulus plagioclase but above this pyroxene occurs with intercumulus hornblende and plagioclase, representing the reverse of what would normally be expected. There is a general gradational trend towards a concentration of plagioclase higher in the cumulate sequence. Almost vertical alternating bands of large hornblende crystals up to 15 cm in length and similarly coarse quartzo-feldpathic minerals occur at station E.4105. Hornblende-pegmatitic phases are also present as irregular veins and these are cut by finer types of a similar composition (Fig. 24).

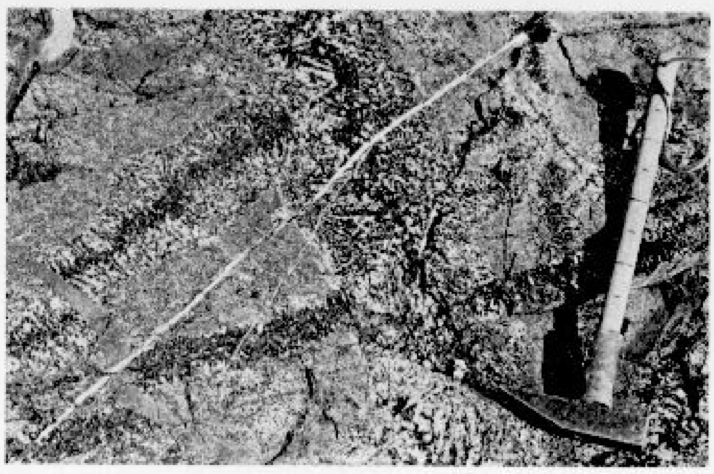


FIGURE 24
Hornblende-pegmatite veins cut by their fine-grained equivalents in a metagabbro (E.4143). The hammer shaft is graduated at 5 cm intervals.

The metagabbro ranges in composition from gabbro to quartz-diorite.

Plagioclase is the main leucocratic mineral and its polysynthetic twins are invariably distorted. This may be partially due to deformation during cooling but its common occurrence and occasional extreme nature suggest some modification through a possible later metamorphism. Fraser (1964) has described a similar phenomenon in a gabbro from the Anagram Islands; he has ascribed this to recrystallization controlled by strains set up in the crystal by the re-organization of the structure during the elimination of patchiness and zoning. Oscillatory zoning, which is rare in true metamorphic rocks, is quite common in the metagabbro and is invariably superimposed by

TABLE II

MODAL ANALYSES OF THE INTRUSIVE ROCKS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Quartz	26·4	31·5	51·3	23·4	23·0	56·8	16·0	22·8	12·6	18·2	33·8	–	–	0·3	29·5	–
Potash feldspar	7·5	3·7	5·1	19·6	14·9	13·6	11·4	0·1	1·1	3·4	11·2	–	–	–	–	–
Plagioclase	40·6	48·9	33·1	44·4	46·5	25·9	62·0	55·8	56·5	61·7	28·4	65·5	53·6	68·2	48·9	14·8
Hornblende	6·4	1·0	–	4·7	5·0	–	2·7	12·8	14·3	5·1	12·0	29·3	25·9	–	–	10·3
Biotite	17·5	12·1	9·2	3·5	7·6	1·9	7·3	6·6	10·9	9·4	14·3	–	–	3·8	19·7	1·1
Orthopyroxene	–	–	–	–	–	–	–	–	–	–	–	–	–	0·2	–	0·6
Clinopyroxene	–	–	–	–	–	–	–	–	–	–	–	–	–	23·0	–	62·1
Phlogopite	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0·5
Epidote	0·3	1·4	–	–	tr	0·5	tr	–	1·9	0·3	–	1·3	16·0	–	–	–
Sphene	tr	0·1	0·1	0·7	1·0	–	tr	0·9	0·6	tr	–	0·2	–	–	–	–
Zircon	–	–	–	–	–	–	–	–	–	–	–	–	–	–	tr	–
Iron ore	1·1	0·7	0·9	1·6	1·6	0·4	0·1	1·0	0·7	1·0	tr	3·7	4·5	4·5	0·1	–
Myrmekite	0·2	0·5	0·3	2·0	0·4	1·1	0·5	–	1·4	0·9	0·3	–	–	–	–	–
Apatite	–	0·1	–	tr	–	–	–	tr	–	tr	–	–	–	–	tr	–
Olivine	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	8·8
Garnet	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1·8	–
Chlorite	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1·8
Plagioclase composition	An_{39}	An_{47}	An_{40}	An_{41}	An_{38}	An_{26}	–	An_{52}	An_{42}	An_{42}	An_{39}	An_{64}	An_{62}	An_{47}	An_{41}	–

tr Trace. A dash indicates that the mineral percentage could not be determined.

1. E.4005.1 Granodiorite.
2. E.4035.1 Granodiorite.
3. E.4065.1 Granodiorite.
4. E.4074.1 Granodiorite.
5. E.4078.1 Granodiorite.
6. E.4093.1 Granodiorite.
7. E.4100.1 Granodiorite.
8. E.4113.4 Tonalite.
9. E.4176.1 Tonalite.
10. E.4181.1 Tonalite.
11. E.4193.1 Granodiorite.
12. E.4105.2 Gabbro.
13. E.4158.1 Gabbro.
14. E.4146.1 Diorite.
15. E.4150.1 Tonalite.
16. E.4621.1 Gabbro.

The locations of the geological stations are given in Fig. 2.

polysynthetic twinning (E.4122.1). Patchy zoning also occurs and it obliterates both the earlier zoning and twinning in the plagioclase by corrosion, giving a characteristic mottled appearance rather than the more coalesced patches discussed by Vance (1965). Plagioclase crystal margins appear to have suffered some recrystallization and are serrated and sutured (E.4123.1). The polygonal texture of some larger feldspars (Fig. 25a), although possibly the result of metamorphic effects, is more likely representative of magmatic crystallization under static pressure conditions.

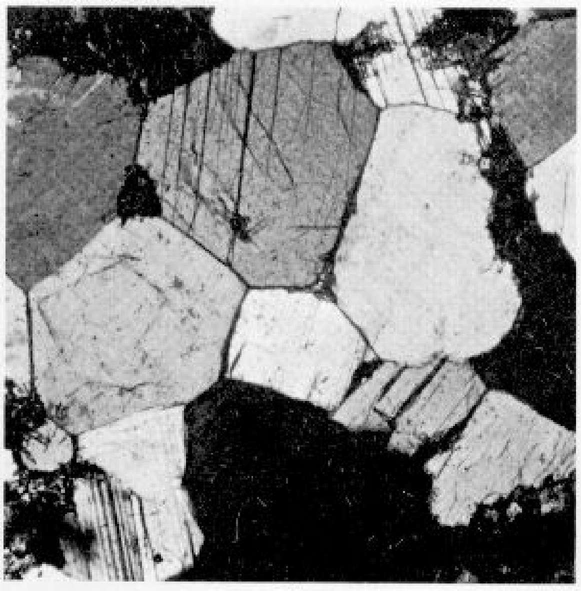
Alkali-feldspar occurs in very minor quantities and, like quartz, it is confined to interstitial areas.

Hornblende, the dominant mafic mineral, is partly the alteration product of pyroxene and was probably developed during the late magmatic stages. Augite may also occur as distinctly unaltered crystals within the same rock (E.4123.1). It is not uncommon for the amphibole and pyroxene to contain inclusions of plagioclase but also some iron ore and biotite (E.4160.1). The pleochroism scheme of the hornblende is sometimes differentiated between rim and core (E.4122.1):

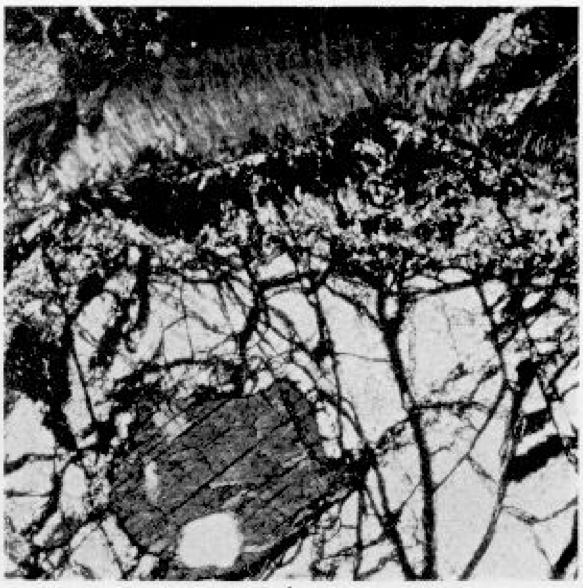
Core: α = straw-yellow,
β = light yellow-green,
γ = deep yellow-brown;
Rim: α = straw-yellow,
β = light blue-green,
γ = deep blue-green.

This probably reflects a marginal compositional change to actinolite-ferroactinolite and this more absorptive mineral would account for the deeper colours of the rim. The form of the amphibole ranges from good twinned types on (100) through various anhedral mosaics and interstitial habits to dispersed aggregates which are sometimes associated with biotite (E.4105.8).

Biotite occurs in two crystal forms: as larger ragged flakes or as anhedral interstitial types and is invariably the subordinate



a



b

FIGURE 25
a. Triple-point junctions of feldspars in metagabbro. (E.4158.1; X-nicols; ×70)
b. Fibrous chlorite and (?) tremolite marginal to olivine in a gabbro. (E.4621.1; X-nicols; ×80)

mafic mineral (E.4160.1). Exsolved iron ore at the margins of some biotites (E.4124.1) could possibly indicate that some alteration has occurred, producing a gradual replacement of Fe^{2+}, Mn and Fe^{3+} by Ti and Mg (Deer and others, 1966). This is further substantiated by the deep reddish brown colour of the larger exsolved biotites (Engel and Engel, 1960).

Anhedral and euhedral sphene is a common accessory mineral often found at the margins of iron ore grains (E.4105.2). Also, a colourless aggregated mineral with grey to blue-grey to yellow interference colours has a similar relationship to the iron ore and is thought to be an anomalous form of clinozoisite. In specimen E.4158.1 it is an alteration product of plagioclase and occurs with epidote which also surrounds the ore grains.

Apatite is also found scattered in these rocks.

B. Gabbro from the Plateau Edge South of Mount Jackson

1. *Field relations*

At station E.4621, the gabbro is adjacent to the green sheared epiclastic rocks, described as the Upper Jurassic Volcanic Group. It resembles a similar gabbroic rock observed at the base of the nearby ridge to the east, about 30 m away (E.4619).

2. *Petrography*

The gabbro (E.4621.1) is medium-grained and melanocratic. The latter is due to the greater mass of pyroxene minerals, interspersed with a few flakes of biotite, surrounded by a very small amount of white feldspar. Specimen E.4619.6 is of a similar grain-size and colour but it contains a larger proportion of the leucocratic minerals. Its slightly dark green hue is reflected in the large amount of tremolite-actinolite.

Microscopic observations on specimen E.4621.1 reveal the presence of olivine which is secondarily altered to magnetite along irregular fractures and peripherally to possible tremolite with subsidiary talc and calcite. Marginal green fibrous chlorite has formed probably through reaction with adjacent plagioclase (Fig. 25b). Partial corona structures similar to this are thought to be the result of the action of liquid residue at high temperatures (Hatch and others, 1972). In one instance, olivine has been completely pseudomorphed by this tremolite and chlorite, leaving the iron ore as remnants in the centre. However, clinopyroxenes, partly replaced by hornblende prevail, although some hypersthene does occur. A very small amount of biotite is accompanied by a few cleavage flakes of pale light yellow-brown phlogopite which has a very good negative biaxial interference figure with a small axial angle. Minor plagioclase is polysynthetically twinned, although some pericline types have been observed.

In view of the known variability of gabbroic rocks within one intrusion, it is difficult to correlate specimen E.4619.6 with E.4621.1 but, because of their close proximity, it is quite likely that they may be related. Specimen E.4619.6 contains more biotite and phlogopite is absent. It appears that the large amount of pyroxene has been pseudomorphed by fibrous tremolite-actinolite, which is colourless to pale green in the centres of the crystal aggregates and darker green at the outer edges. Some clinopyroxene is still present and this is altered to hornblende. Distinct iron-rich areas contain a colourless, highly birefringent aggregate which could probably be associated with the tremolite mineral replacing olivine in specimen E.4621.1 Fibrous chlorite is still present in association with this. Plagioclase is more significant and, as well as polysynthetic twinning, patchy and normally zoned crystals also occur. The minor quartz present has an undulose extinction which might be expected in this slightly more altered rock.

C. Diorite of Marshall Peak

1. *Field relations*

This rock crops out over the entire Marshall Peak massif. Its relationship with the garnetiferous tonalite at Lamplugh Inlet is questionable; therefore, it is discussed here separately but it could be of a similar age. The rock is fairly homogeneous though there is evidence of some flow-banding in the nunataks farther east.

2. *Petrography*

The diorite is medium-grained and mesocratic. In thin section, clinopyroxenes are the main mafic minerals and have a pleochroism scheme α = colourless, β = very pale red-brown, γ = light green, with multiple twinning on (100) and (001) (γ:c = 45°; 2V large). The orthopyroxene present is a very pale green to pink, slightly pleochroic hypersthene. Both pyroxenes are altered marginally and in fractures to a green pleochroic amphibole.

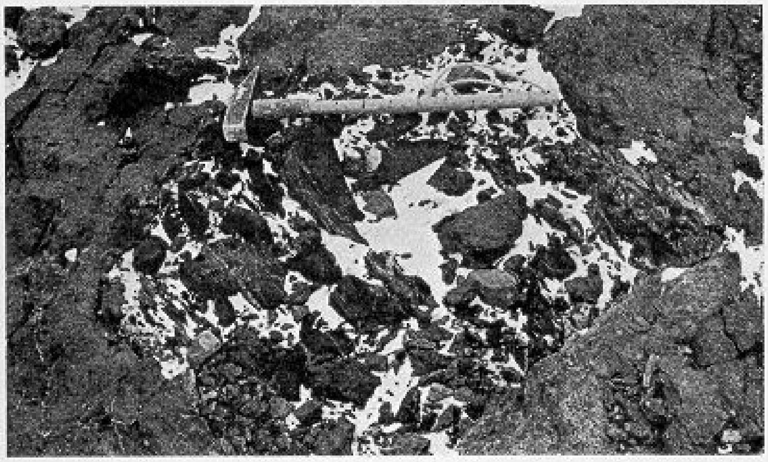


FIGURE 26
A large metasedimentary fragment in a garnetiferous tonalite at Lamplugh Inlet. The hammer shaft is 60 cm long.

Plagioclase (An_{40}) comprises the majority of the rock with the more basic feldspars (An_{47}) having formed interstitially. This is explained by the fact that the megacrysts were possibly not derived from the same magma source. A small amount of plagioclase occurs as inclusions within the clinopyroxene. The andesine is nearly always twinned according to the albite law though there are some Carlsbad types and the lamellae are often bent.

Brown biotite is present in small quantity, usually enclosing or marginal to iron ore grains.

A very small amount of quartz is found in association with the interstitial feldspar which shows some triple-point crystal junctions.

D. GARNETIFEROUS TONALITE OF LAMPLUGH INLET

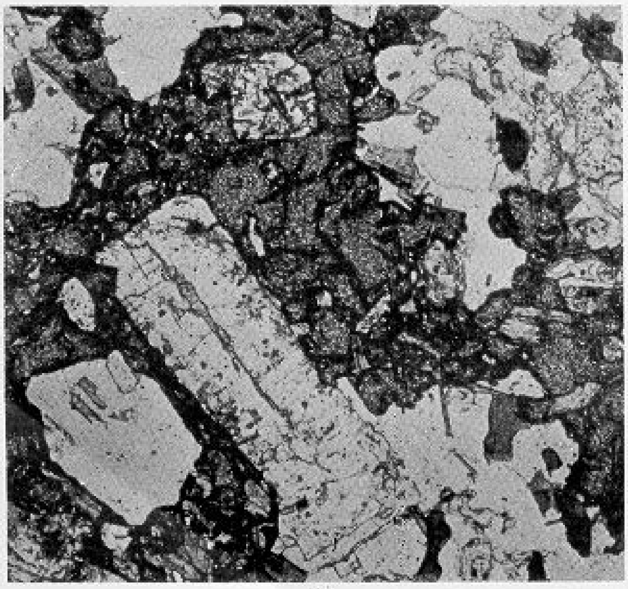
1. *Field relations*

The small weathered outcrop is randomly cut by granodioritic dykes, up to 70 cm in width, which have a similar mineralogy to the main granodiorite. The inclusion of large metasedimentary fragments of hornfelsic grade within this garnetiferous tonalite (Fig. 26) suggests that it was partly responsible for the thermal metamorphism of the Mount Hill Formation.

2. *Petrography*

The purplish fine-grained rock (E.4150.1) is speckled by small flakes of biotite set in an indistinct quartzo-feldspathic matrix. In thin section, the mafic mineral is biotite altered along the cleavage planes to penninite. The small amount of garnet is partly altered to penninite but it contains inclusions of quartz and plagioclase (Fig. 27a). Large areas of interstitial quartz also contain inclusions but of biotite and feldspar. Accessory minerals include zircon, apatite and iron ore.

It is believed that igneous garnets develop through the enrichment of magma in manganese (Hall, 1965*b*) which could be brought about through contamination by the country rock containing this element (Brammall and Harwood, 1923; Tilley, 1926; Deer and others, 1966). Therefore, it could be inferred that the metasedimentary rocks provided a source of manganese when intruded by this rock.



a

b

FIGURE 27
a. Garnet with inclusions of quartz and plagioclase in a tonalite at Lamplugh Inlet. (E.4150.1; ordinary light; ×80)
b. Patchy zoned plagioclase in a granodiorite. (E.4090.7; X-nicols; ×80)

E. Main Granodiorite

1. *Field relations*

The main granodiorite appears to underlie most of the area between the high plateau and the Larsen Ice Shelf, and it extends to the north and south beyond the central Black Coast. It clearly intrudes the Mount Hill Formation, although its relationship with the higher-grade rocks of the metamorphic complex is not consistent; on the south-eastern flanks of Mount Jackson the granodiorite sharply cuts the metamorphic complex rocks (E.4193). The effects of this contact are limited to vague banding and a very narrow chilled margin within the intrusive rock. Banding observed at margins of the batholiths in central Peru is believed not to be due to cataclasis but to recrystallization when the intrusive rock was still hot (Cobbing and Pitcher, 1972). Similar sharp contacts with metamorphic complex rocks are seen elsewhere (E.4074, 4601 and 4624). However, the relationship between this intrusive rock and the western zone of the metamorphic complex, in the Welch Mountains, is apparently gradational over a small area (E.4038). On the eastern flank of the head of Murrish Glacier, the main granodiorite cuts the metagabbro but they are separated from each other by a grey quartzitic brecciated rock. The latter contains fragments of both intrusive rocks but those of the metagabbro are commoner. The host to these fragments consists of large relict quartz, oscillatorily zoned plagioclase and perthitic microcline crystals with minor hornblende and biotite set in an even finer recrystallized groundmass of quartz. This mortar texture presumably developed through late-stage marginal fragmentation and recrystallization, producing grains with sutured boundaries and quartz with a marked undulose appearance. A 5 m wide granodiorite apophysis thought to be related to the main granodiorite encloses some metagabbroic xenoliths at station E.4105. This relationship also suggests that the main granodiorite is probably the younger intrusive rock.

2. *Petrography*

The texture of these rocks ranges from medium to coarse but the medium-grained ones are the commonest. In most examples, they are identified through their typically leucocratic and homogeneous appearance mottled by the presence of large amounts of dark vitreous quartz which invariably has a purple hue. Half of the rock is formed by white plagioclase with subsidiary opaque quartz and this agrees with observations on granodiorites farther north (Davies, 1976). The mafic minerals are dark green hornblende and consistently larger flakes of brown biotite. Variations within the main granodiorite are largely reflected in the significance of one mafic mineral relative to the other, an increase in the total amount of mafic minerals or an increase in potash feldspar.

The main intrusive rock has a compositional range from diorite to granodiorite. Rocks of more basic composition (E.4113.4; An_{52}) are generally to be found at the pluton margins. Compositional changes are thought to be gradational within the same pluton.

The typical granodiorite contains a large proportion of plagioclase, mainly in the andesine range (e.g. E.4005.1, An_{39}; E.4105.7, An_{32}). It is twinned according to the Carlsbad, albite and pericline laws which generally seem to supersede zoning. Emmons and Mann (1953) have stated that polysynthetic twinning replaces and is consequent on zoning. In the main granodiorite, a whole range is evident from poorly twinned well-zoned crystals through to vaguely zoned well-twinned crystals. In all cases, except one (E.4188.1), twin planes have formed parallel to zone directions and confirm some probable deformational relationship between the two. It is thought that these twins, which do not coincide with zone directions as in specimen E.4188.1, may be early forms. There are all types of zoning but oscillatorily zoned cores with normally zoned rims are the commonest. In specimen E.4027.1, the core to rim compositional range is from An_{40} to An_{27}. According to Vance (1962), oscillatory zoning is a response to recurrent supersaturation of the melt adjacent to the crystals and the abrupt change to normally zoned rims is due to late-stage saturation of the residual melt in volatiles through the rise of magma with a consequent fall in pressure. There are fewer examples of completely normally zoned crystals and simple types with twins are rare (E.4624.1). The sharp transition between relatively basic corroded cores and normally zoned rims accompanied by discordant twin directions between these two phases in plagioclases of some tonalitic rocks (E.4134.1) suggests contamination or some mixing of more sodic magmas locally. Patchy zoning is quite common (Fig. 27b) and is firmly believed by Vance (1965) to be a feature of magmatic origin. However, it may be due to lower temperatures or deformation, or both, though others have stressed exsolution or even partial melting (Pitcher and Berger, 1972). It consists of corroded cores filled and surrounded in crystalline continuity by plagioclase of a more sodic composition. Crystals are commonly altered to sericite and sometimes saussurite, particularly in the more basic cores of zoned varieties. Sericitization of plagioclase in Donegal granites is thought to be a late-stage process (Pitcher and Berger, 1972). Plagioclase crystals are generally to be found as incomplete laths occupying the main body of the rock but also as inclusions in the alkali-feldspars, biotite and hornblende. In many cases, plagioclase crystals present in the alkali-feldspars show corrosion, as shown by the rounded and sutured nature of their margins.

Myrmekitic intergrowths frequently occur between plagioclase and alkali-feldspars as well as between adjacent crystals. The form of myrmekite is generally restricted to two varieties: discontinuous or continuous rim and a more lobate form. Sometimes plagioclases are completely intergrown producing an irregular mass of myrmekite. Myrmekite formed as a partial rim around plagioclase inclusions within alkali-feldspar megacrysts is usually restricted to undeformed rocks (Phillips, 1974) and is typical of the main granodiorite. Although other theories have been put forward suggesting origins for myrmekite (Deer and others, 1966; Hatch and others, 1972), it is thought that deuteric alteration along intercrystal boundaries is most probable in the main granodiorite.

Alkali-feldspars are minor in quantity in most cases and consist of microcline and orthoclase which occur both separately and together. Microcline is variably cross-hatch twinned from poor (E.4193.1) to fair (E.4002.1) and orthoclase occasionally displays Carlsbad twins (E.4075.9). Potash feldspar in the intrusive rocks of the Lassiter Coast only becomes grid twinned in the more northerly plutons towards the Black Coast (Rowley and Williams, 1974). They are usually late stage and contain inclusions of plagioclase but also biotite, hornblende and sphene. Perthitic intergrowths between the alkali-feldspars and more sodic types are present but they are poor examples and are commonly of the string variety. It has been suggested by Gates (1953) that the occurrence of string and film perthite indicates a local origin for the sodic material. Also, according to Marmo (1971), perthitic intergrowths will be finer if the temperature of crystallization of material of composition corresponding to albite and potash feldspar is relatively high. At these temperatures the ability of the potash feldspar to take albite into solid solution increases.

Hornblende is the only amphibole present and it is generally subordinate to biotite. It has a pleochroism scheme α = yellow-green, β = olive-green, γ = dark green (E.4059.1), its 2V is approximately 80° and $\gamma{:}c$ = 28°. Twinned euhedral forms occur but anhedral crystals are commoner. In specimen E.4609.1, the hornblende is peculiarly mottled and contains inclusions of biotite, chlorite, plagioclase and epidote. Hornblende is also found as inclusions but within potash feldspars.

The generally large ragged brown biotite flakes are invariably altered to chlorite along cleavage planes and sometimes to the anomalous blue birefringent form, penninite (E.4100.1). Epidote has often formed along the partings of cleavage traces and is commonly found as granular aggregates in association with biotite. Similar partings are produced by lenticular prehnite. Rod-like and sometimes small hexagonal inclusions, believed to be apatite, are frequently observed within biotite and in specimen E.4131.5 they form a concentric arrangement which may correspond to the original crystal growth of the biotite. Deformation of some biotite cleavage planes could possibly be accounted for by cooling processes, causing differential stress during the later stages of the intrusion (E.4012.1 and 4059.1).

The undulose and patchy extinction frequently observed in quartz crystals is believed to be indicative of lattice transformations (Spry, 1969). Larger crystals are commonest and sometimes contain inclusions of hornblende and plagioclase. When it occurs interstitially, quartz occasionally shows triple-point crystal junctions.

Accessory minerals include iron ore, sphene, calcite, epidote, some simple-zoned allanite (E.4059.1) and apatite.

Mafic to mesocratic xenoliths are a characteristic of the main granodiorite and they vary in shape from ovoid through subangular to elongated ovoid forms up to 1.5 m in length. The commonest xenoliths, mainly those occurring away from the margins of the pluton, are of two types which differ only in that one is finer-grained and porphyritic. The porphyritic areas consist of possibly synneusis aggregates of large plagioclase crystals which are invariably oscillatorily zoned and polysynthetically twinned (E.4188.2). The sericitization of the plagioclase in these aggregates is greater than in the groundmass. Some of the xenoliths (E.4005) contain large feldspar phenocrysts which have been explained as a late development due to the thermal influence of the granodiorite host (Didier, 1973). Occasionally at pluton margins, less well-assimilated xenoliths occur and may have later origins than the common variety (E.4179). Xenolith/host-rock boundaries are generally sharp but there is little evidence of chilling. This suggests a long history for their development with sufficient assimilation at depth to have resulted in a composition very similar to that of the host rock. This is further substantiated by the roundness of xenoliths and the increase in saussuritization and sericitization of plagioclase within them compared with the main granodiorite (E.4609.2). Occasionally, the beginnings of disintegration of large xenoliths are evident where granodiorite material has penetrated across their margins, a migration which may have resulted in its almost complete enclosure within the xenolith (E.4005). Xenoliths largely consist of green hornblende and brown, sometimes chloritized, biotite which has formed late in an otherwise quartzo-feldspathic granodiorite rock. The plagioclases are simple and normally zoned with some oscillatory types, whereas in the host intrusive rock oscillatorily zoned cores with normal rims are commoner (E.4188.2 and 4609.2) A predominance of normally zoned plagioclase is typical of recrystallized feldspars formed in roof and wall rocks (Emmons and Mann, 1953). Polysynthetic twinning is poor in xenolith plagioclase and Carlsbad-twinned types are more widespread.

F. GEOCHEMISTRY

Sixty-four plutonic rocks have been analysed for the major oxides and 13 trace elements (Tables III and IV).

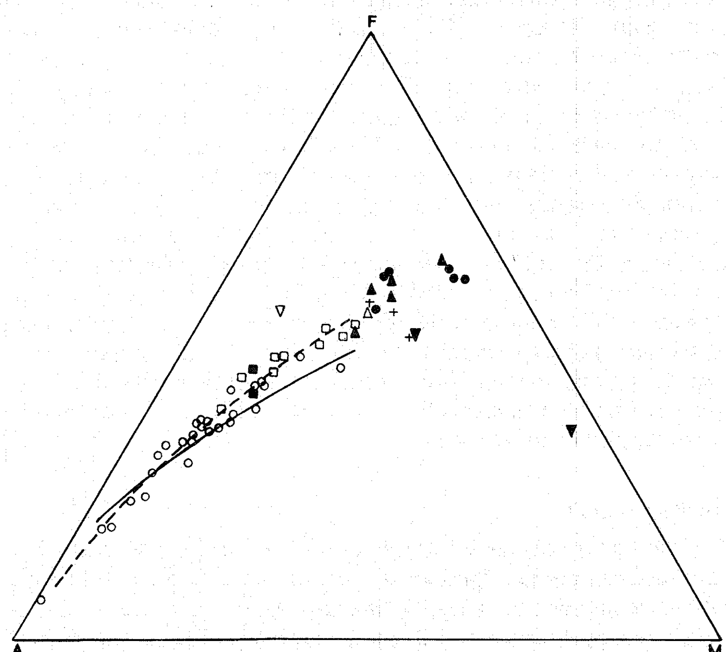


FIGURE 28
Triangular A–F–M diagram for the central Black Coast plutonic rocks.

When plotted on the A–F–M diagram (Fig. 28), these analyses fall on an almost straight line extending from the Fe–Mg side to the alkali apex and they do not show iron enrichment. This pattern is typical of calc-alkali rocks (Nockolds and Allen, 1953; Best, 1969) and is broadly comparable with the findings of previous workers in the Antarctic Peninsula (Adie, 1955; Marsh, 1968; West, 1974; Davies, 1976). These comparisons have been made with respect to the confines of variation inevitable from the examination of data which have been derived by differing analytical techniques. This probably explains the slight deviations of the characteristic trends obtained by Adie (1955) from those of this study (Fig. 28). Similar deviations are also apparent in the K–N–Ca diagram (Fig. 29), which shows the associated alkali-enrichment trend of calc-alkali rocks. A further fundamental of this rock association is that their chondrite-normalized Ce/Y ratios are greater than unity,

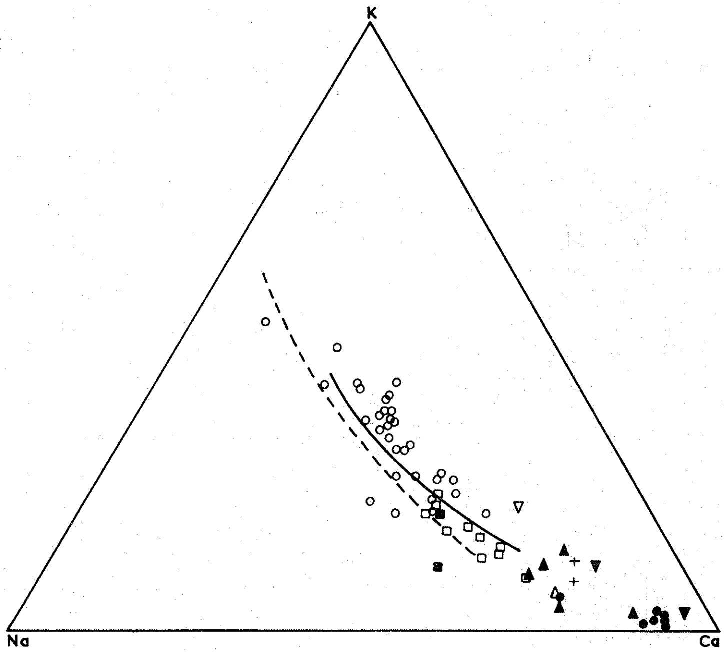


FIGURE 29
Triangular K–Na–Ca diagram for the central Black Coast plutonic rocks.

assuming for this purpose that yttrium behaves as a heavy rare-earth element (Lambert and Holland, 1974; Drake and Weill, 1975) (Fig. 30). Also, those rocks of the high-silica range (56–75%) have the expected ratio values of K_2O/Na_2O (0.6–1.1) and $FeO+Fe_2O_3/MgO$ (greater than 2) for calc-alkali rocks of continental margins (Jakes and White, 1972).

The numerous suggestions which have been made for the evolution of the plutonic rocks in the Antarctic Peninsula are consistent with the processes operating at an Andean-type continental margin. Hooper (1962) found that the variation trends of the probable Andean Intrusive Suite plutonic rocks from Anvers Island could be explained by regional metasomatism of primary rocks. Adie (1955) has suggested that fractional crystallization was significant and this has been further emphasized by Marsh (1968), who has also shown that partial melting of sediments has occurred during the emplacement of some of the plutonic rocks in eastern Graham Land. Studies of rocks from the Danco Coast, Graham Land (West, 1974), have revealed that the plutonic rocks are primary and probably derived from the mantle or lower crust but that the intermediate rocks are products of magma contamination. Davies (1976) has suggested that the plutonic rocks of northern Palmer Land are primary and possibly derived by melting of the sialic crust. It is considered that magmatic differentiation and crystal fractionation occurred during the emplacement of the central Black Coast intrusive rocks.

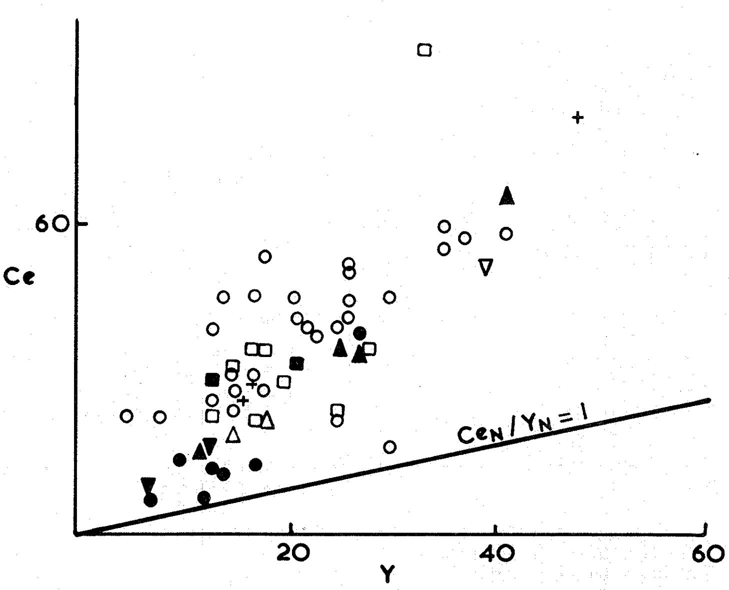


FIGURE 30
A plot of cerium against yttrium for the analysed plutonic rocks.

The linear variation diagrams (Fig. 31) for oxides, trace elements and element ratios plotted against the modified Larsen factor ($\frac{1}{3}Si \times K$) – (Ca+Mg) (Nockolds and Allen, 1953) show the range of concentrations of elements of particular rock groups and also their measure of acidity. Their curvilinear trends suggest that fractionation could have occurred but not necessarily as one series from a basic magma. These trends compare with those for other areas of the Antarctic Peninsula (West, 1974; Davies, 1976) and with other calc-alkali suites (Nockolds and Allen, 1953). With increasing modified Larsen factor, the rocks show a progressive increase in silica, soda and potash together with a general decrease in titania, alumina (gentle), manganese, magnesia, lime and iron oxide. Amongst the trace elements, yttrium, niobium, barium, lanthanum, cerium, lead, thorium and rubidium increase with increasing modified Larsen factor, whilst chromium, nickel and strontium decrease. Zirconium and phosphorus increase but decrease at the acid end. The fall in the K/Rb and Ba/Rb ratios with increased modified Larsen factor (Fig. 31) can be explained in terms of fractionation (Taylor, 1965; Hahn-Weinheimer and Johanning, 1968; Gill, 1970). This is further supported by the consistent behaviour of other element ratios and inter-element relationships presented later in the discussion on emplacement (p. 36). It seems that the evolution of the central Black Coast intrusive rock group at least in part involved the fractionation of a more basic magma at some stage during emplacement.

1. *Metagabbro*

The range in composition of this rock group is from gabbro to tonalite, although the majority of the rocks have basic affinities. The scatter of element concentrations on some of the linear variation diagrams makes assessment of trends difficult and it is attributed to their partial metamorphism already inferred from the petrographic study. However, with increasing modified Larsen factor, the general behaviour of these metagabbros–metatonalites is as described for the general calc-alkali rock association. The strong chemical similarities of the group of six true metagabbros is good stratigraphical evidence for correlating the rocks of the Neshyba Peak area and upper Murrish Glacier area. The metagabbro with a distinctly higher modified Larsen factor which plots away from this group can be explained by the effects of the nearby main granodiorite (Turner and Verhoogen, 1960). The two metatonalites sampled from these separate areas are also closely related.

The average of 15 of the analysed metagabbros has a similar major-oxide geochemistry to Nockolds' (1954) hornblende-gabbro and also to that of Marsh (1968) from Seligman Inlet, Foyn Coast (Graham Land), although the average metagabbro

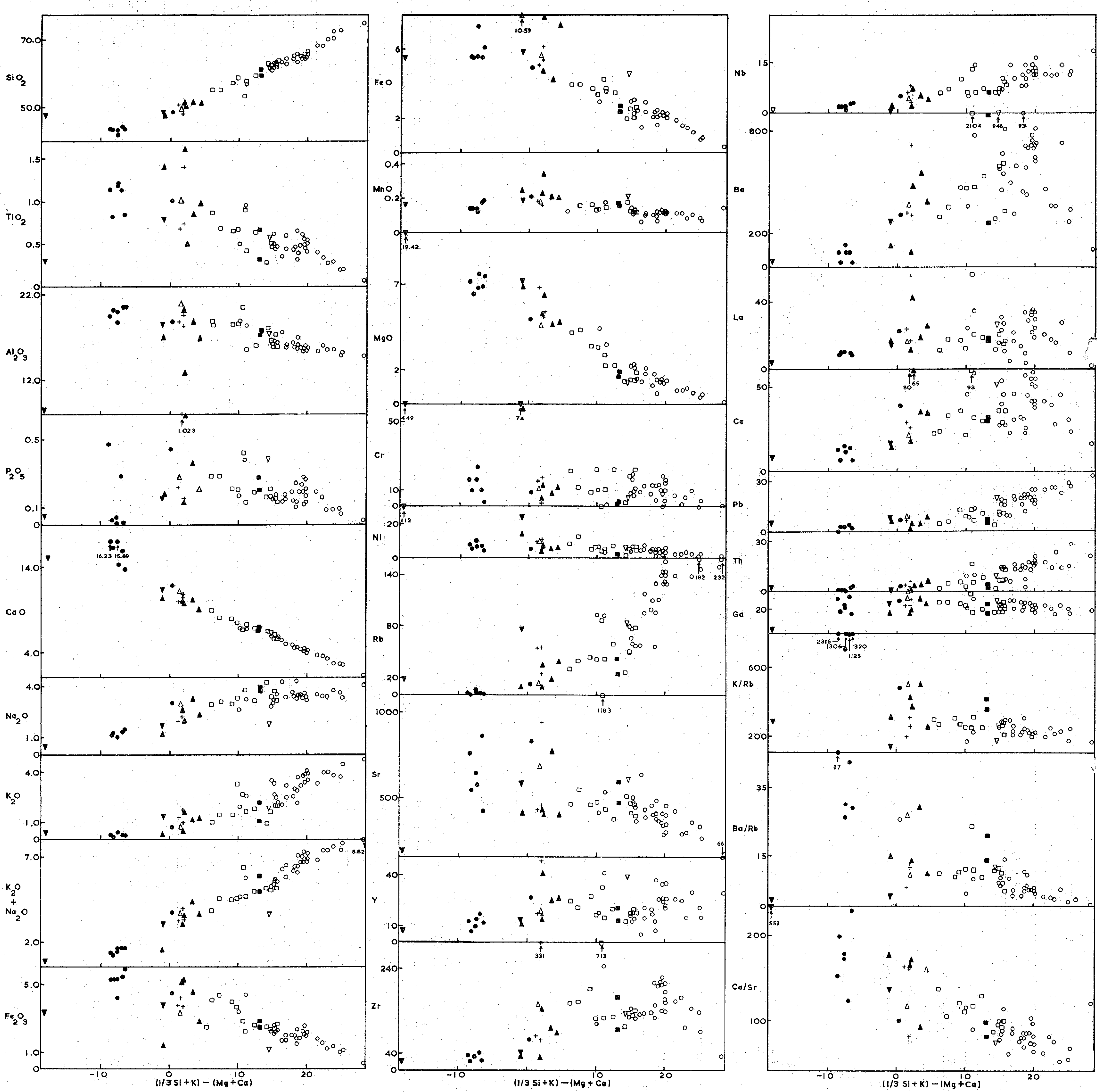


FIGURE 31
Plots of the major oxides, trace elements and inter-element ratios against the modified Larsen factor ($\frac{1}{3}$Si+K)–(Mg+Ca) for the plutonic rocks.

from the central Black Coast has a slightly higher Fe^{3+}/Fe^{2+} ratio of 0.76.

Field and petrographic evidence suggests that these rocks could possibly be older within the intrusive rock group. It appears from Fig. 32 that the ratio Zr/Y is generally lower in the

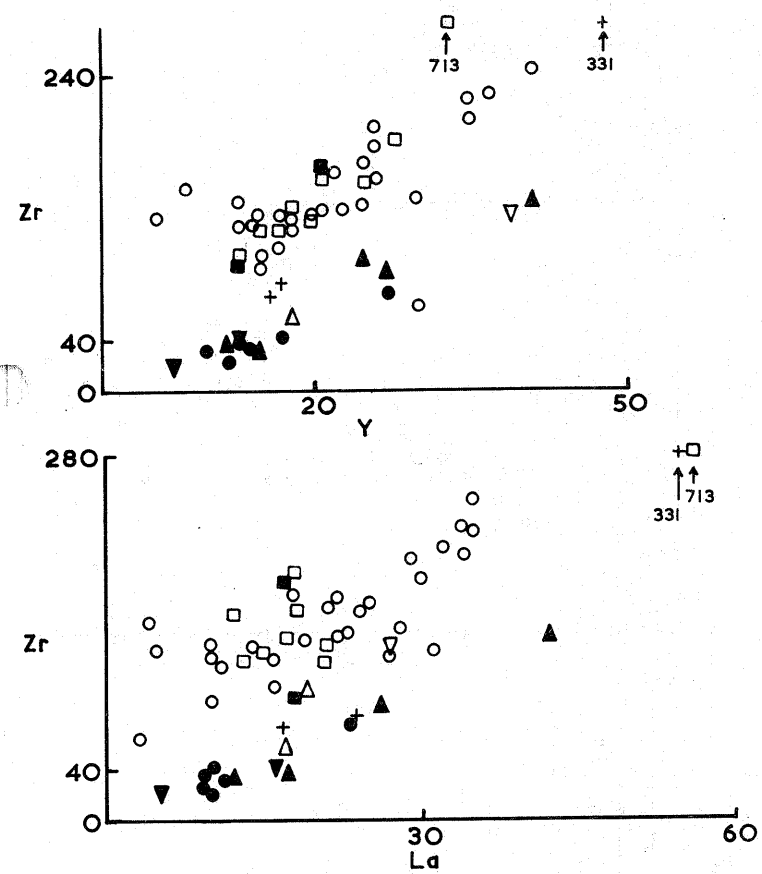


FIGURE 32
Plots of zirconium against yttrium and lanthanum for the plutonic rocks.

metagabbroic rocks than in the main granodiorite suite. As both of these elements are generally considered incompatible (Pearce and Cann, 1973), they would normally gradually concentrate in the melt during fractionation or a similar process and hence their ratio at any time would remain constant. If this situation is expressed graphically, the line representing Zr/Y at any point would be expected to pass through the origin and show a linear increase as the concentrations of the two elements increase. It therefore seems that the observed differences in Zr/Y and possibly Zr/La (Fig. 32) between the metagabbro and the main granodiorite suites can only be explained in terms of derivation from different sources. The derivation of the metagabbroic rocks from a different source could support the general view that they are probably older rocks.

2. *Gabbro from the plateau edge south of Mount Jackson*

The differentiation index plots show that the olivine-gabbro (E.4621.1) has a markedly lower modified Larsen factor than its petrographically related and altered equivalent (E.4619.6). Its high magnesia content would suggest that the olivine present is forsteritic and therefore may represent early cumulate crystallization. This is further supported by the high chromium and nickel concentrations in the rock. Specimen E.4619.6 appears to fall within the field of other metagabbroic rocks, probably because of its alteration but it has not been correlated with them because of its petrographical associations with the olivine-gabbro. Also, the similar Zr/Y and Zr/La ratios of this rock within the metagabbro range to those of the olivine-gabbro suggest a close relationship and a common source area (Fig. 32).

3. *Diorite of Marshall Peak*

The one analysed specimen of this rock is in accord with trends of the other rock types on the central Black Coast. The major oxide concentrations are similar to those of the quartz-biotite-diorite at Cape Bryant (Adie, 1955) but the concentrations of rubidium, strontium, zirconium and barium are low. The petrography has precluded correlation of the Marshall Peak diorite with the diorites of the main granodiorite suite, although it occurs in close proximity to them on the linear variation diagrams. In contrast, the low Zr/Y and Zr/La ratios would suggest a source area different from that of the main granodiorite (Fig. 32). It has already been suggested that some contamination may have occurred during emplacement of the Marshall Peak diorite.

4. *Garnetiferous tonalite of Lamplugh Inlet*

In all respects this rock is geochemically akin to the tonalite of the main granodiorite suite. Its contrastingly high concentration of yttrium is believed to be contained within the secondary garnet (Arth and Hanson, 1975) and may have replaced some manganese. The slightly higher amounts of ferrous oxide relative to that in other tonalites suggests that the garnet is probably almandine ($Fe_3Al_2Si_3O_{12}$), of which a common alteration product is the chlorite observed in thin section. The significant presence of manganese supports the general belief that spessartine molecules are also contained in almandine of igneous rocks found in thermal aureoles (Deer and others, 1966). It is therefore thought from field and geochemical evidence that the garnetiferous tonalite of Lamplugh Inlet was cogenetic with the main granodiorite but during emplacement it was secondarily contaminated by the argillaceous sediments of the Mount Hill Formation. However, the extent of this contamination is probably limited as the alumina values for this rock are not particularly high.

5. *Main granodiorite*

The main granodiorite may have been emplaced as one pluton or as a series of cupolas similar to that observed on the Lassiter Coast (Williams and others, 1971). The compositional range is from diorite at the pluton(s) margin(s) to granodiorite centrally though the majority of rocks sampled lie within the field of the latter. The most acidic member (E.4093.1) is geochemically and geographically situated to possibly represent an extremely fractionated central area of a pluton.

A comparison of element concentrations using the Gribble (1969) distribution curves for a normal calc-alkaline suite shows that the main granodiorite is significantly high in alumina and low in nickel and niobium. However, the major-oxide values are very similar to those of Nockolds' (1954) average granodiorite. Compared with Graham Land (West, 1974) and northern Palmer Land (Davies, 1976), the average central Black Coast granodiorite shows differences in some of the trace elements (Ba, La, Ce and Cr) and these could easily be explained by the differences in calibrations used during their analysis.

The strong linear trend of the main granodiorite suite in all variation diagrams, plus the geochemical evidence for crystal fractionation and its spatial compositional field relationships, suggests that differentiation occurred *in situ* after emplacement in the upper crust. The contrastingly higher Zr/Y and Zr/La ratios (Fig. 32) in conjunction with the field and petrographic evidence imply that the main granodiorite originated from a source different from that of the metagabbro and therefore would justify the belief that it is probably younger.

6. *Emplacement*

All the rocks of this study are unquestionably part of a calc-alkaline association and therefore one would expect them to have had a similar origin. However, the petrogenetic theories and hypotheses proposed for the origins of such associations have so far been variable (Green and Ringwood, 1969; Taylor, 1969; Moorbath, 1975).

It has already been suggested that the contrasting Zr/Y and Zr/La ratios of the main granodiorite suite could suggest derivation from a different source.

The concentration of a given element at the surface is a function of (Gast, 1968):

i. Concentration in the source liquid.
ii. Extent of chemical fractionation during melting.
iii. Extent of chemical fractionation during the ascent and crystallization of the magma.

It is thought that fractionation has occurred within the intrusive rock group, although the less scattered plots for the main granodiorite are more convincing than those of the basic members. The fall in K/Rb ratio with increased modified Larsen factor reflects the concentration of rubidium (Rb^+) in the felsic fractions relative to potassium (K^+). Their difference in ionic radii (Rb^+, 1.47Å; K^+, 1.33Å) accounts for the preferential entry of Rb^+ into potassic minerals such as biotite in preference to feldspars by replacement of potassium at a later stage. This difference in ionic size becomes important under conditions of extreme fractionation. The Ba/Rb ratio, which also apparently decreases with magmatic differentiation (Gill, 1970), shows a similar trend to that of the ratio K/Rb (Fig. 31). The large ionic radius (1.34Å) causes Ba^{2+} to have generally low mineral/liquid partition coefficients for most minerals (Arth and Hanson, 1975) and is therefore not depleted in the magma until late in the differentiation sequence. This enrichment of Ba^{2+} in the melt is not as marked as Rb^+, and Ba^{2+} will enter K-feldspar more readily than biotite (Taylor, 1965) even though the partition coefficients are relatively high for both of these minerals (Arth and Hanson, 1975).

The Sr/Ba ratio in the melt compared to that of the parent magma is lowered by plagioclase (Arth and Hanson, 1975; Drake and Weill, 1975), and this is clear in Fig. 33. Sr^{2+}, which is intermediate in size between Ca^{2+} (0.099A) and K^+, is particularly compatible with intermediate plagioclase (Drake and Weill, 1975) and hence will be depleted after this stage (Fig. 33).

The strong linear trend observed for CaO in Fig. 31 probably also reflects feldspar fractionation and, because of their difference in size and the fact that Sr replaces Ca in plagioclase, the ratio Ca/Sr will decrease in the melt (Fig. 31) (Taylor, 1965; Hahn-Weinheimer and Johanning, 1968).

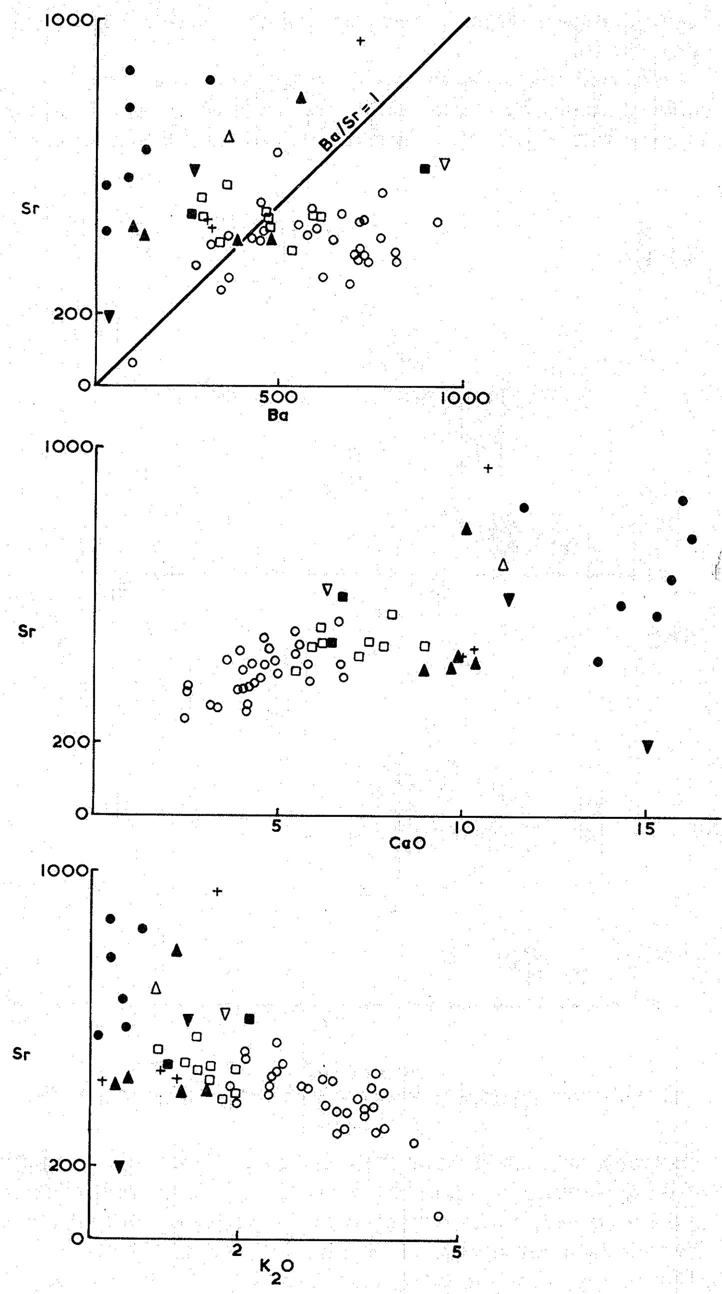


FIGURE 33
Plots of strontium against barium, lime and potash for the plutonic rocks.

The relationship between Sr^{2+} and K^+ is evident from Fig. 33, in which the decrease of Sr^{2+} in the acidic rocks is explained by its strong partitioning by intermediate plagioclase, and the corresponding increase in K^+ is due to its concentration in biotite and potash feldspars.

Ni^{2+} and Cr^{2+} are highly compatible in basic melts and therefore they are removed by the fractionation of pyroxene, hornblende and olivine (Gast, 1968) (Fig. 34). The low concentration of Ni^{2+} and Cr^{3+} relative to an increasing Fe^{2+} + Fe^{3+}/Mg ratio is a function of the absence of available partitioning minerals beyond the basic stage of fractionation and also because the minor concentrations of these elements have already been almost completely depleted in the melt by early fractionation. The fact that Mg^{2+} is concentrated

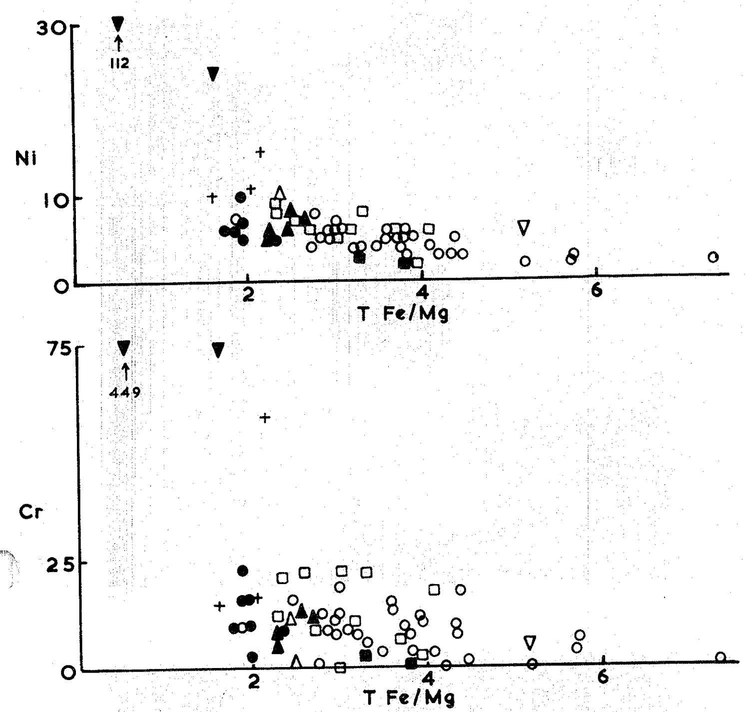


FIGURE 34
Plots of nickel and chromium against the total iron to magnesia ratio for the plutonic rocks.

in early crystal precipitates (mainly by olivine and pyroxene but also amphibole and micas) relative to the total iron accounts for the steady increase in the $Fe^{2+} + Fe^{3+}/Mg$ ratio (Fig. 34).

It therefore seems that chemical fractionation provides a common explanation for the distribution of the elements chosen for discussion but, except for the main granodiorite, the stage at which this occurred is not yet clear. It must also be appreciated that the same element distribution could be obtained by the gradual melting of a crustal segment, though this would not explain the *in situ* fractionation of the main granodiorite suite.

The evolution of plutonic rocks in the Antarctic Peninsula has been further complicated after or during their emplacement; the process of alkali metasomatism and possible magma contamination, inferred from the petrographic study as possibly having occurred during the emplacement of the main granodiorite, are not reflected in the geochemistry and therefore are considered to be minor in effect as observed by other workers (Winkler, 1974). However, metasomatic addition of silica, sodium and potassium to primary tonalites and gabbros is believed to have occurred during the formation of the acid and intermediate plutonic rocks on Anvers Island (Hooper, 1962). The scatter observed on some variation diagrams for the metagabbro suite has been attributed to the effects of the alteration observed in thin section. A similar scatter, but for intermediate plutonic rocks, observed in variation diagrams for the Danco Coast rocks, is believed to have been a product of magma contamination but this is further supported by field and petrographic evidence (West, 1974). However, this is not the case on the central Black Coast.

It is therefore concluded from petrographic and geochemical evidence that the main granodiorite suite originated as an essentially tonalitic differentiate and after migration to a relatively high level within the continental crust, it suffered fractionation *in situ* to an almost adamellitic central core.

There is also petrographic evidence to suggest that differentiation had occurred on a smaller scale within the metagabbro in the form of minor cumulate layering and static polygonal crystallization patterns.

VII. MINOR INTRUSIVE ROCKS

THESE hypabyssal rocks are generally commoner in the southern part of the central Black Coast and they consist of basic to intermediate types though there are altered equivalents and some acidic examples.

Of all the rocks examined in detail, it is apparent that the intermediate ones (microtonalites and microdiorites) have not been observed cutting the main granodiorite and therefore could be older. However, as stratigraphical evidence is poor for the main rock units and because cross-cutting relationships between the dykes were never seen in the field, it is especially difficult to derive age relationships for them in this area.

One aplitic and one granodioritic apophysis are described here and these are believed to be related to the main granodiorite as are the felsitic dykes.

A. GROUPING OF THE MINOR INTRUSIVE ROCKS

The hypabyssal rocks of the central Black Coast have been subdivided into five groups on the basis of petrographical and chemical character but this does not necessarily reflect their age.

1. *Microgabbro dykes*

Distinctly green to grey, sometimes porphyritic, microgabbroic dyke rocks intrude metamorphic complex rocks in the Welch Mountains (E.4032) and the Mount Jackson area (E.4193). They are common within the main granodiorite (E.4000, 4020, 4024, 4100 and 4112) but they also cut the Mount Hill Formation (E.4100).

These rocks are usually fine-grained though their microscopic texture is variable. The green varieties have generally been chloritized and epidotized. The latter process has involved the replacement of the mafic minerals of specimen E.4020.1. Chlorite usually occurs in the interstitial areas of the predominant decussate mass of dusty plagioclases, which are occasionally associated with calcite. The porphyritic microgabbros contain phenocrysts of euhedral and sometimes twinned hornblende (E.4000.4), which contrast with the smaller laths associated with the plagioclase microlites of the groundmass.

Similar but coarser microgabbroic rocks intrude the Upper

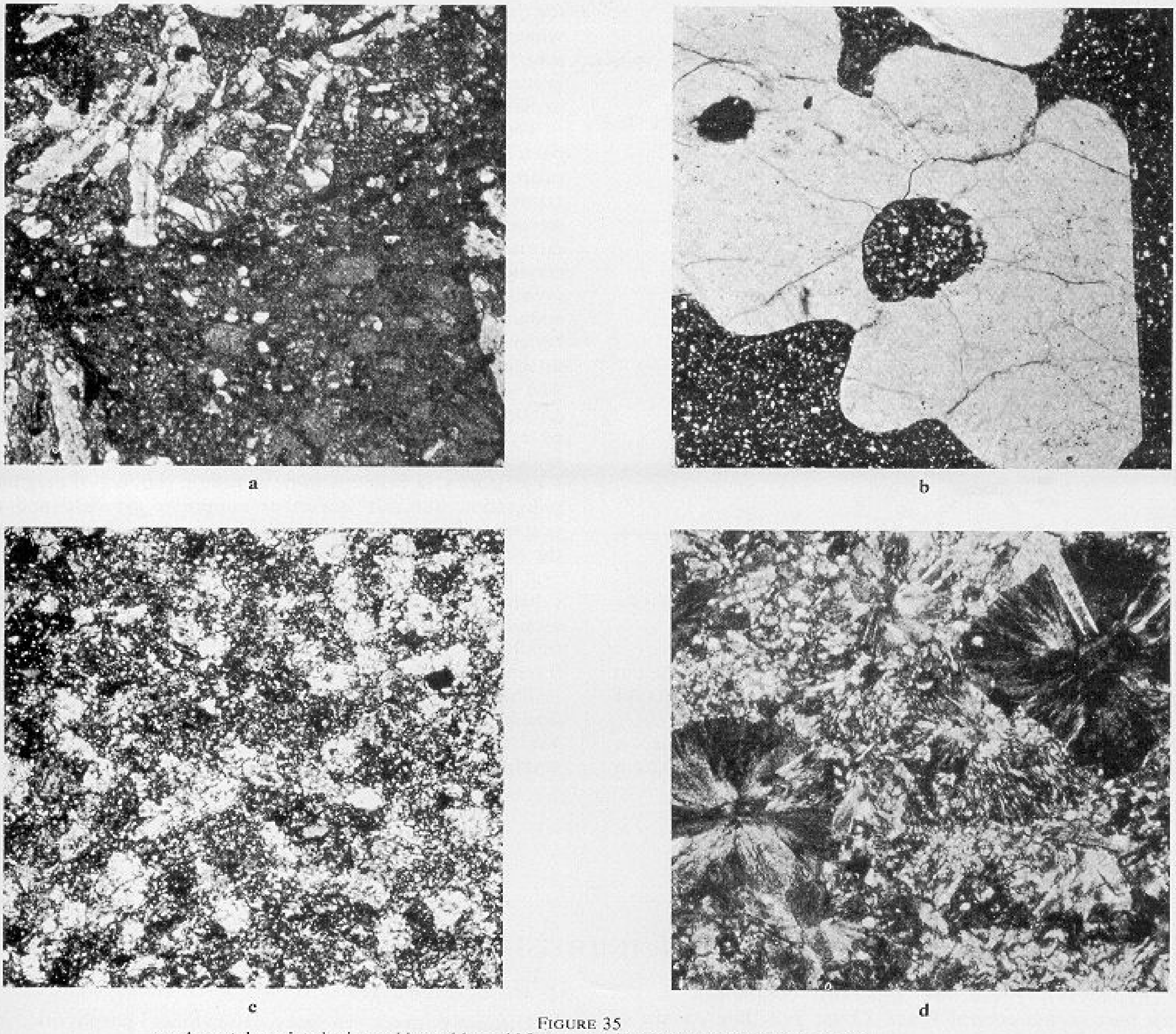


FIGURE 35
a. An autobrecciated microgabbro with ovoid fragments. (E.4620.4; ordinary light; ×80)
b. Embayed quartz in a granite-porphyry dyke. (E.4005.2; X-nicols; ×70)
c. Patchy devitrification of a felsitic dyke. (E.4174.2; X-nicols; ×80)
d. Spherulitic devitrification in a felsitic dyke. (E.4130.1; X-nicols; ×70)

Jurassic Volcanic Group at stations E.4619 and 4620. However, a green amorphous mass of actinolite prevails and this is interstitial to decussate laths of twinned and normally zoned labradorite (An_{46-66}). Isolated small areas of aggregated green-brown biotite are associated with iron ore grains. At station E.4620 this rock appears to have been brecciated and partially resorbed (E.4620.4), resulting in the observed partially epidotized ovoid gabbroic forms enclosed within a matrix of similar composition but with a significant amount of presumed actinolite (Fig. 35a). This autobrecciation probably occurred during the later stages of intrusion, possibly through a sudden increase in pressure causing migration of the gabbroic mass.

2. *Microtonalitic and microdioritic dykes*

The dyke rocks of intermediate composition intrude all the main rock units excluding the main granodiorite and the relatively small outcrop of the Upper Jurassic Volcanic Group.

They are fine-grained grey rocks with some green varieties. In thin section, it is clear that hornblende is the major mafic mineral (E.4072.5) and, as phenocrysts in the porphyritic varieties, it is invariably twinned with a maximum crystal length of 1.2 mm (E.4070.2). The latter is the common form set in a quartzo-feldspathic matrix and occasionally (E.4146.2) it is unusually simply zoned with a differential pleochroism scheme between core (α = light yellow-green; β = dark olive-green; γ =

dark green) and rim (α = very light yellow; β = greenish yellow; γ = dark greenish yellow). Some pale green possible augite phenocrysts also occur in this example. Biotite is rare in the microdiorites but is commoner in the microtonalites and is generally associated with the amphibole (E.4174.3) which in specimen E.4167.1 is rare actinolite. The hornblende phenocrysts of specimen E.4604.4 have been secondarily cut by biotite both as crystals and as veins. Occasionally, biotite may dominate the mafic minerals (E.4184.3) and a green variety forms almost 50% of the groundmass in specimen E.4147.1.

Plagioclase is widespread in the groundmass in most examples, particularly in the microdiorites. Plagioclases as phenocrysts are commonly polysynthetically twinned, sometimes oscillatorily or normally zoned (E.4147.1) and invariably altered to sericite. Secondary calcite is present in most of the specimens together with epidote and some chlorite.

3. *Granite-porphyry dykes*

The granite-porphyry dykes cut all the major rock units (E.4005, 4032, 4121 and 4193) and, although broadly scattered, they are not very common.

These light grey to brown rocks are mottled by many phenocrysts of mainly sub-rounded plagioclase, up to 3 mm long, sometimes oscillatorily zoned and having discontinuous polysynthetic twins (E.4005.2). The distinctly rounded and sometimes embayed quartz phenocrysts (Fig. 35b) are larger than the chloritized and epidotized biotite megacrysts. Smaller phenocrysts include subhedral hornblende (E.4121.1) and scattered minor rhombs of sphene. The groundmass consists of indistinguishable polycrystalline quartz and some feldspar.

4. *Felsite dykes*

The felsite dykes are particularly common along the southern margins of the upper reaches of the head of Murrish Glacier where they intrude the Mount Hill Formation and the main granodiorite (E.4130, 4131, 4132 and 4136) but they also cut the metamorphic complex of the Mount Jackson area (E.4174) and the main granodiorite of the Welch Mountains (E.4015 and 4022).

Their pink to cream colour contrasts with that of the other dyke rocks. They are speckled with small phenocrysts of epidotized and sericitized plagioclase, chloritized biotite, subangular quartz with embayments, some sphene and potash feldspar (E.4174.2). The groundmass in specimen E.4174.2 shows patchy devitrification (Fig. 35c) and is highly quartzitic. This devitrification is almost spherulitic in some examples (Fig. 35d). These radiating fibrous areas occasionally contain small colourless mineral inclusions (E.4022.2) of low refractive index which are probably albite.

5. *Granodioritic and aplitic apophyses*

The granodiorite apophyses (E.4150.2) cut the garnetiferous tonalite at the head of Lamplugh Inlet. These dykes have a similar mineralogy and texture to that of the main granodiorite, except for the minor presence of muscovite subordinate to biotite and occasional pleochoic green to light green chlorite. Because of the geochemical affinities of the Lamplugh Inlet tonalite with the main granodiorite, these apophyses must have been intruded at a very late stage.

A number of aplitic apophyses have been observed cutting the Mount Hill Formation in the upper Guard Glacier area (E.4072). Their mineralogy differs from that of the granodiorite apophysis in that the amount of potash feldspar is large and the mafic minerals (biotite) are reduced in amount and dominated by scattered rounded to subhedral garnet crystals (E.4075.8). The latter could possibly have originated through contamination by the argillaceous metasediments, although spessartine is a common garnet in granitic pegmatites (Deer and others, 1966).

B. Geochemistry

All of the 39 hypabyssal rocks analysed (Table V) plot in a manner similar to that of the intrusive rocks on the A–F–M and K–Na–Ca diagrams (Figs 36 and 37). The microgabbroic and some of the microdioritic dykes differ only in their slight enrichment in magnesia which could possibly reflect their derivation from a more primitive magma. The gradual decrease in K/Rb and Ba/Rb ratios from the basic to the acidic dykes is comparable with the trends obtained from the intrusive rocks and this means that differentiation of the magma by fractional crystallization had probably occurred before its later intrusion as dykes. This is further supported by the plots of the element concentrations against the modified Larsen factor. All the major oxides show trends and concentrations similar to those of their equivalents in the plutonic rocks except for alumina, which appears to be low in concentration for the microgabbroic and microdioritic dykes (Fig. 38). This seems to be concomitant with the higher magnesia and slightly higher iron oxide values. The trace elements are also similar in their comparative concentrations, although there is considerable scatter of rubidium and barium for particular examples and the general trends for concentrations of yttrium, zirconium, cerium and lanthanum are quasi-horizontal (Fig. 38). The scatter of some of the trends in contrast with the majority partly agrees with the findings of

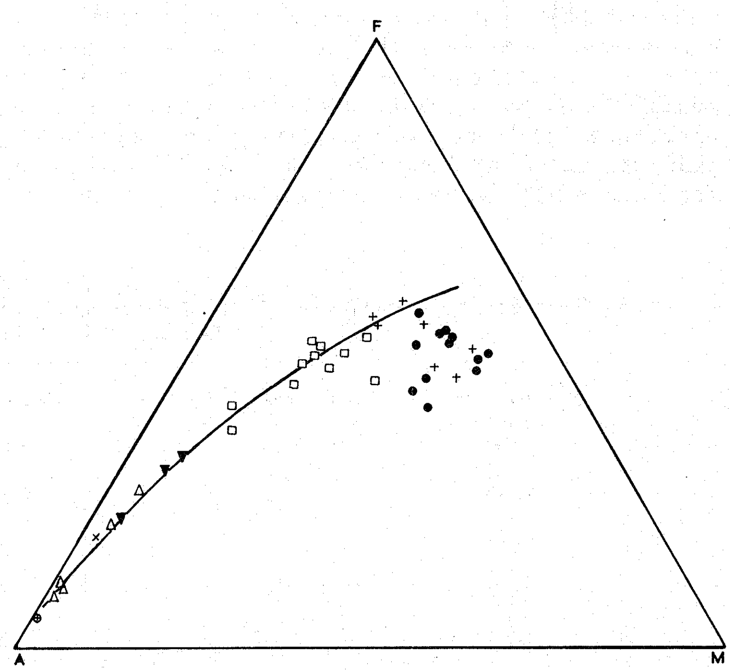


Figure 36
Triangular A–F–M diagram for the minor intrusive rocks of the central Black Coast.

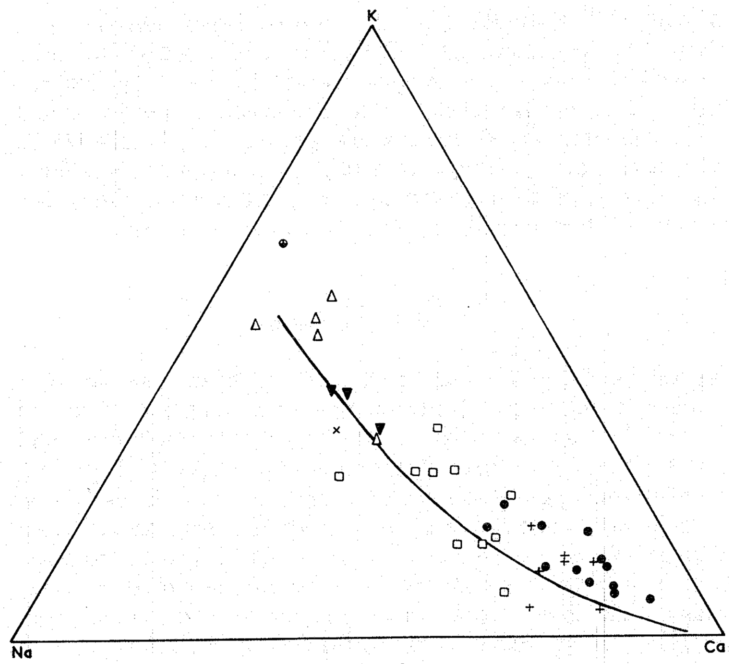


FIGURE 37
Triangular K–Na–Ca diagram for the minor intrusive rocks of the central Black Coast.

Davies (1976) but only for the microgabbroic and microdioritic hypabyssal rocks of northern Palmer Land.

The acidic dykes have distinctly higher modified Larsen factors and contrastingly higher Nb/Y and Nb/La ratios (Fig. 39). These Nb/Y and Nb/La discrimination diagrams for the dyke rocks differ from those for the plutonic rocks in that the acidic dykes are separated from the microtonalites, which plot with the microgabbroic varieties and have consistently lower Nb/Y and Nb/La ratios. In similar diagrams for the plutonic rocks, the tonalites plot between the granodiorites and the basic rocks and reflect a gradation of niobium concentrations from basic to acidic rocks for given Y and La ranges. The plots of Zr–Y and to a certain extent Zr–La (Fig. 39) show that generally for all dyke rocks the ratios of these elements are of a similar range but do not have the separate group of higher Zr/Y ratios seen in the acid plutonic rocks (Fig. 39). When considering relatively immobile elements such as yttrium and lanthanum, which also appear to show no variation in range of concentration with modified Larsen factor for both the plutonic and the hypabyssal rocks, it is apparent that their inter-element ratio is only slightly higher for all the dyke rocks and very similar for the acidic ones (Table VI). This is the only viable comparison that can be made between the dyke rocks and the plutonic rocks when differentiation can be considered constant. Thus it is possible that the source magma for the dyke rocks and the plutonic rocks contained similar ratios of concentrations of lanthanum to yttrium. However, the state of differentiation of the magma source was different at the time of pluton emplacement compared with that for intrusion of the dyke rocks; apart from the low-alumina trend, this is also particularly clear in the horizontal plots of cerium, yttrium, zirconium and lanthanum against the modified Larsen factor for the dyke rocks compared with the plots for equivalent plutonic rocks and also in their contrasting inter-element ratios, particularly for Zr/Y, Zr/La, Nb/Y and Nb/La (Table VI; Figs 38 and 39). However, a close correlation between the acid dykes and main granodiorite for all the element ratios in Table VI, except for Nb/Y and Nb/La, suggests some genetic relationship. Most of the acidic dykes, containing Q+Ab+Or>80%, occur in association with the granodioritic plutonic rocks of a similar composition close to and mainly within the field of maximum concentration for normal granites (Fig. 40). This further confirms that there is some magmatic evolutionary relationship between the acidic dykes and the main granodiorite which also involved similar water pressures. One felsitic dyke appears to be more enriched in orthoclase but still it lies within the field containing 86% of all the granites considered by Winkler (1974).

A possible suggestion for the tectonic setting of at least the basic dykes can be made by comparing the elements titanium, zirconium, niobium and yttrium (Pearce and Cann, 1973), which have been considered by Pearce (1975) to be generally stable during weathering and metamorphism below the amphibolite facies. As with the work of Pearce and Cann (1973), only basic dykes with a compositional range of MgO+CaO>12–20% have been used. The scaling factors for titanium and yttrium in Fig. 41 serve to bring the points into the centre of the triangle without altering their relative positions. It is interesting that, in a geographical position so close to a continental margin, all the basic dykes should plot as "within-plate" types. However, a comparison of the absolute concentrations of

TABLE VI
A COMPARISON OF RATIOS OF CERTAIN TRACE ELEMENTS IN THE DYKE ROCKS WITH THOSE IN THE PLUTONIC ROCKS OF THE CENTRAL BLACK COAST

Element ratio	*Main granodiorite*	*Metagabbro*	*Hypabyssal rocks*	*Acid dykes*
Zr/Y	6·86	3·87	5·66	6·28
Zr/La	7·19	4·15	4·62	7·85
Ce/Y	1·73	1·36	1·59	1·67
La/Y	0·96	0·93	1·22	0·80
Nb/Y	0·35	0·20	0·27	0·60
Nb/La	0·48	0·22	0·22	0·75

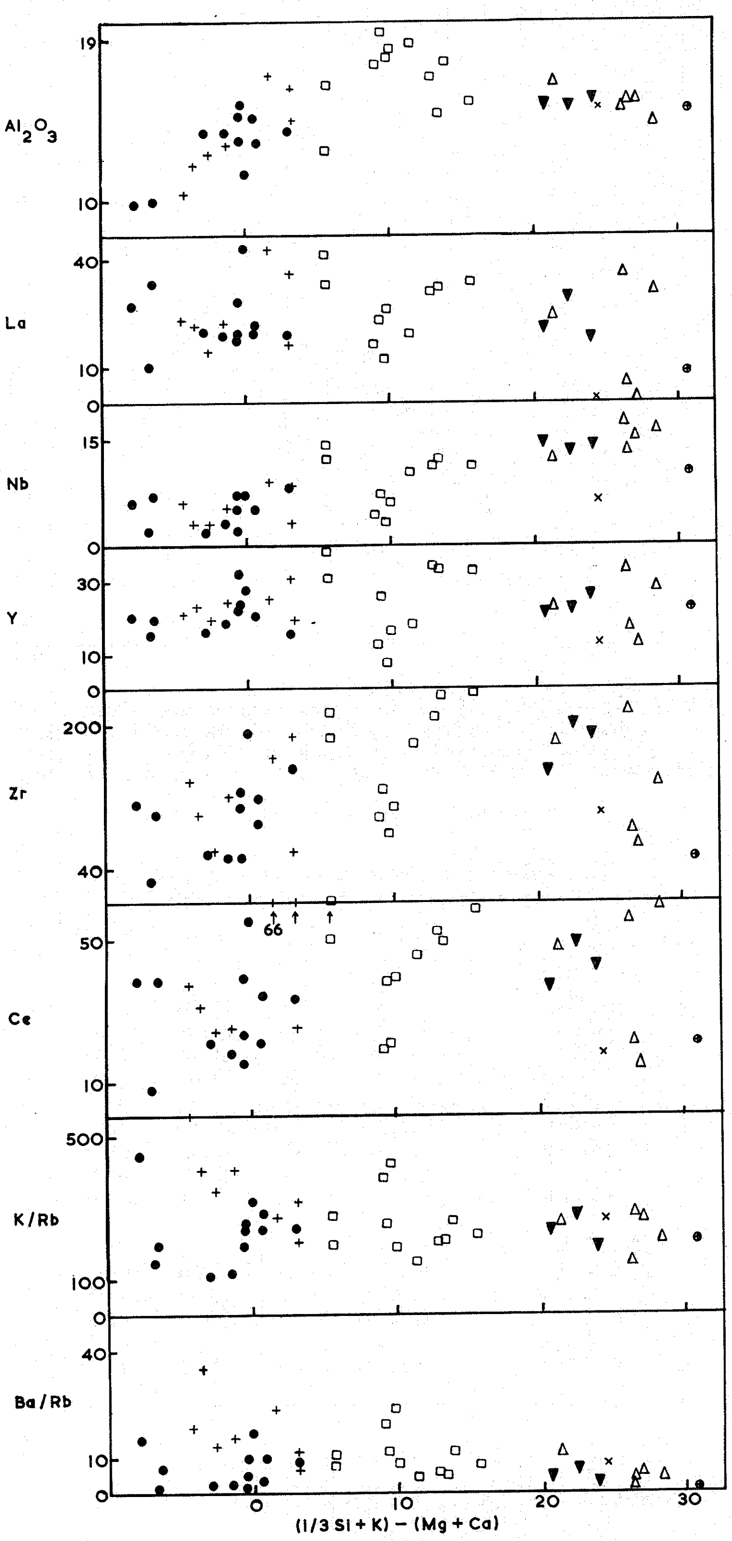


FIGURE 38
Plots of some major oxides, trace elements and inter-element ratios against the modified Larsen factor for the minor intrusive rocks.

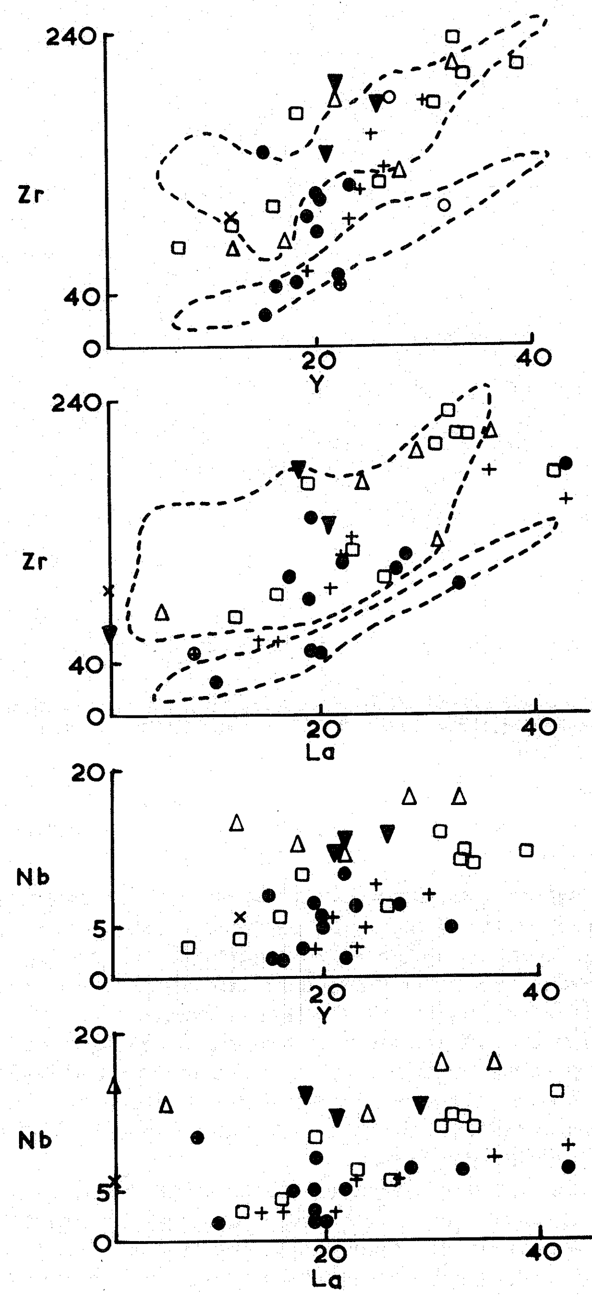


FIGURE 39
Plots of zirconium and niobium against yttrium and lanthanum for the minor intrusive rocks.

titanium, zirconium and yttrium obtained in this study with those for each tectonic province considered by Pearce and Cann (1973) shows that the values for yttrium and zirconium are generally low for "within-plate" basalts and the titanium values are slightly low but too high for calc-alkali or low-potash tholeiites. The gabbro (E.4619.3) and its presumed autobrecciated equivalent (E.4620.4), distinguished petrographically from the other basic hypabyssal rocks, plot as "low-potash tholeiites". The distinctly high Y/Nb ratios for these rocks (Fig. 41) indicate that they are generally of tholeiitic character (Pearce and Cann, 1973).

The aplitic apophysis (E.4075.8) is markedly acidic but it has an unusually low amount of barium considering the amount of

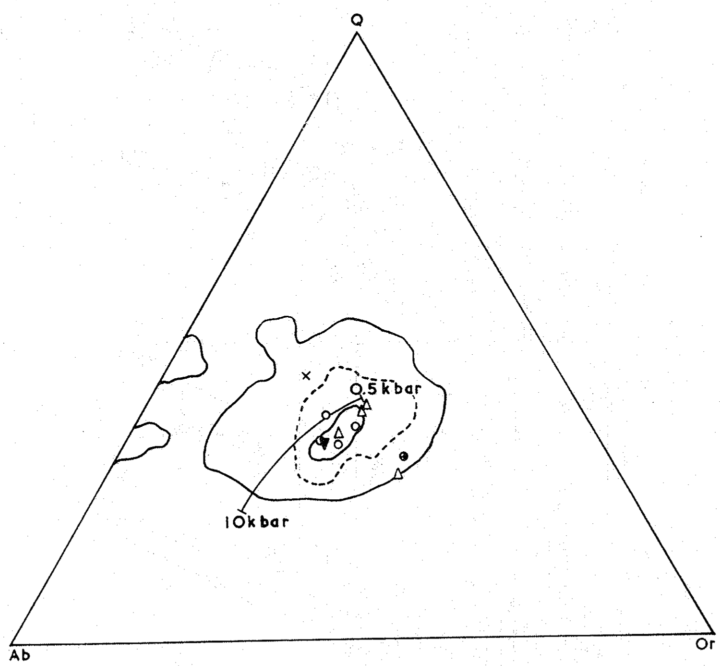


FIGURE 40
A plot of normative quartz, albite and orthoclase for the minor intrusive rocks and plutonic rocks which contain normative Q+Ab+Or>80%.

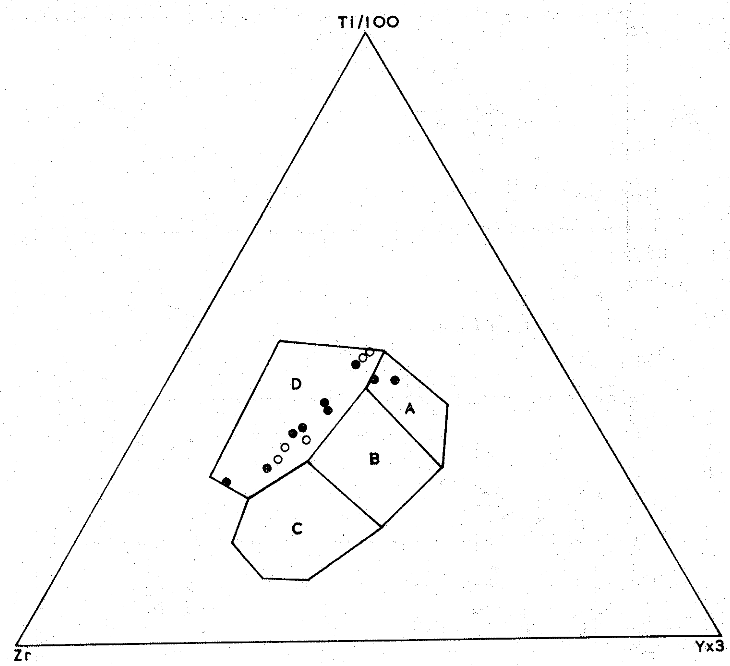


FIGURE 41
Tectonic setting of the basic hypabyssal rocks from the central Black Coast, Palmer Land, using the discrimination diagrams proposed by Pearce and Cann (1973). The fields represented are low-potassium tholeiites (A and B); calc-alkaline basalts (C and B); "within-plate" basalts, ocean island or continental (D).
Microgabbros (●), microdiorites (○).

potash feldspar within the rock. However, the amounts of barium in some of the acidic plutonic rocks are also low, although there is considerable variation in concentration for these rocks. In view of the general lack of mafic and opaque minerals, it is thought that the slightly higher iron oxide concentration for this apophysis is contained in the garnets. This apophysis plots outside the main concentration for true aplites in the Q–Ab–Or diagram of Luth and others (1964) but it is still contained within the field of granitic rocks (Winkler, 1974) as is the granodiorite apophysis.

The geochemistry of the granodiorite apophysis (E.4150.2) is similar to that of the main granodiorite except that strontium is higher and niobium, rubidium and potash are lower in concentration. Although the strontium value for the apophysis within the acid dyke group appears normal, the concentrations of rubidum, niobium and potash are still low.

The broader chemical similarities of these apophyses would suggest that they are related to the main granodiorites.

Coordinates of triangular diagram and symbols

	Ti/100	Zr	Y×3	Y/Nb
Microgabbros				
E.4000.4	26.56	56.58	16.86	1.88
E.4020.1	35.42	41.44	23.21	3.29
E.4024.2	39.75	35.99	24.26	4.00
E.4032.4	34.47	43.32	22.21	4.00
E.4113.3	28.96	49.80	21.23	3.86
E.4169.2	38.19	36.27	25.54	7.67
E.4193.3	45.98	28.47	25.55	6.40
E.4619.3	43.29	27.26	29.44	6.00
E.4620.4	43.22	24.47	32.31	11.00
Microdiorites				
E.4070.2	46.96	26.98	26.06	6.33
E.4096.4	32.02	45.89	22.09	3.75
E.4122.2	47.61	26.19	26.19	6.33
E.4160.2	33.54	41.54	24.92	4.80
E.4178.4	30.09	47.79	22.12	2.78

VIII. CONCLUSIONS AND REGIONAL CORRELATIONS

A. METAMORPHIC COMPLEX

The oldest rocks exposed on the central Black Coast are the homogeneous and heterogeneous, acid to intermediate gneisses and minor schists of the metamorphic complex. These have been tentatively correlated with the "Basement Complex" (Adie, 1954; Hoskins, 1963), which is exposed throughout northern Palmer Land and Graham Land but no farther north than lat. 67°S.

The heterogeneous gneisses of the north-eastern Welch Mountains are thought to represent a metasedimentary sequence in which the presence of sillimanite and garnet within the inferred pelitic bands suggests that regional metamorphism approached the amphibolite facies. This is believed to be equivalent to the first major phase of the three phases of metamorphism recognized in "Basement Complex" rocks (Hoskins, 1963). A similar grade of metamorphism is inferred for the homogeneous (?) *ortho*gneisses found in association with the heterogeneous varieties. Later retrograde processes have been operative, at least on a local scale and include the partial replacement of some cracked garnets by biotite in the metasediments and a widespread occurrence of deformed plagioclases. Retrograde alteration is not uncommon in the "Basement Complex" rocks of the Antarctic Peninsula. It is probable from the development of alkali-feldspar porphyroblasts and the marginal replacement of some plagioclase porphyroblasts by potash feldspar in the heterogeneous gneisses that alkali metasomatism also occurred on a local scale. A more widespread abundance of alkali-feldspar porphyroblasts in the gneisses of the Bowman and Wilkins Coasts led Fraser and Grimley (1972) to suggest that alkali metasomatism was regional in effect and was related to the emplacement of the granitic bodies which cut them. However, this is probably not the case on the central Black Coast.

As with the "Basement Complex", the central Black Coast metamorphic complex contains a preponderance of *ortho*-gneisses associated with subordinate banded gneisses or *para*gneisses. In this respect, they contrast with the belt of *para*schistose and *para*-amphibolitic rocks exposed in the South Shetland and South Orkney Islands. It is also clear that the "Basement Complex" and its correlatives were formed under contrasting physical conditions and they represent the high-temperature low-pressure zone of a paired metamorphic belt in which the South Shetland Islands rocks form the outer high-pressure member. It is thought that this paired metamorphic belt of western Antarctica has a similar origin to those which occur elsewhere around the Pacific Ocean and therefore it provides evidence for pre-Jurassic subduction (Smellie and Clarkson, 1975). The significant occurrence of *ortho*gneisses in the "Basement Complex" rocks suggests that some of them may be equivalent to the granitic rocks typically associated with the low-pressure members of paired metamorphic belts (Miyashiro, 1961). It is thought that this pre-Jurassic metamorphism of the Basement Complex rocks occurred in mid to late Palaeozoic times after their emplacement and deposition during the early to mid-Palaeozoic.

B. The Mount Hill Formation

The Mount Hill Formation represents an unfossiliferous metavolcanic and metasedimentary sequence of rocks which is exposed throughout the central Black Coast. The metasedimentary pelitic rocks, although never seen in contact with the metavolcanic basic lavas and porphyritic dacites or possible tuffs, are believed to be contemporaneous with them.

These rocks had suffered an early probable dynamic metamorphism prior to their thermal metamorphism caused by the intrusion of Upper Jurassic to at least mid-Cretaceous plutonic rocks. The pre-thermal metamorphism created a series of folds with approximately north–south axes, defined by the widespread development of a slaty cleavage particularly in the metapelites. The growth of chiastolite porphyroblasts across the early penetrative fabrics confirms that these rocks were subsequently thermally metamorphosed. The common mineral assemblage of quartz-muscovite-biotite-andalusite and cordierite in the metasediments suggests that this thermal metamorphism attained the hornblende-hornfels facies. A local slightly higher grade is inferred from the occasional presence of sillimanite. It is also evident that further deformation occurred both during and after this thermal metamorphism. The marginal alteration of the chiastolite porphyroblasts to sericite, muscovite and sometimes biotite indicates that retrograde processes were operative during the waning stages of thermal metamorphism.

The structural, lithological and metamorphic features of the Mount Hill Formation are more similar to those of the Upper Jurassic Latady Formation of southern Palmer Land than those of the (?) Upper Palaeozoic Trinity Peninsula Series of Graham Land and Alexander Island. Also, equivalents of the Latady Formation have been recorded on the southern Black Coast (Rowley, 1973). It has recently been suggested that these Upper Mesozoic marine deposits are part of a belt extending from eastern Ellsworth Land to at least Crabeater Point in northern Palmer Land and they may represent the western remnants of an originally more extensive marine assemblage deposited in a back-arc basin which possibly formed part of a proto-Weddell Sea (Suárez, 1976). Suárez (1976) has compared these back-arc sediments with those of Patagonia and he has suggested that they are possibly linked through the Scotia arc. However, it has been argued that the exposures of definite Upper Jurassic–Lower Cretaceous back-arc sediments do not seem to extend into Graham Land. Also, the Upper Mesozoic sediments which are present on the east coast of Graham Land are not strongly folded like the back-arc sediments of Palmer Land whose tectonic setting is little known (personal communication from R. B. Wyeth). Therefore, it is not entirely conclusive that these sediments were deposited in a marginal basin partly floored by oceanic crust and hence deposition could have occurred totally on continental crust (personal communication from R. B. Wyeth).

C. The Upper Jurassic Volcanic Group

This relatively small and isolated group of rocks, consisting of sheared coarse unstratified (?) epiclastic rocks associated with unstratified tuffs and dacitic lavas of unknown thickness, is intruded by hypabyssal and plutonic rocks. It has been compared with the more widespread Upper Jurassic Volcanic Group (Adie, 1971*b*) which extends into northern Graham Land.

The stratigraphical relationship with the Mount Hill Formation is not clear on the central Black Coast. However, on the Lassiter Coast, 1 000 m of dacitic and andesitic lavas and ash-flow tuffs apparently overlie the Latady Formation, a correlative of the Mount Hill Formation. The preponderance of pyroclastic deposits suggests that the volcanic activity in this part of Palmer Land occurred under subaerial conditions. The (?) epiclastic rocks are probably the rapid-weathering products of a pre-volcanic igneous or metamorphic terrain.

Radiometric dating by other workers has shown that the Upper Jurassic marked the climax in volcanicity which initially commenced much earlier. It has been suggested that the Upper Jurassic Volcanic Group represents an ensialic volcanic arc which at some stage may have developed into a volcanic peninsula (Suárez, 1976) and this has been attributed to an eastward-dipping subduction zone beneath the Antarctic continental margin (Williams and others, 1971). It is thought that some intrusive rocks of the Antarctic Peninsula are genetically related to the Upper Jurassic Volcanic Group (Adie, 1971*b*) and therefore they can also be explained in terms of this subduction.

D. The Intrusive Rocks

The plutonic rocks, which cut all the major stratigraphical units, underlie most of the central Black Coast and range in composition from basic to acidic, although the intermediate to acidic varieties are the commonest. The predominance of intermediate plutonic rocks in various parts of the Antarctic Peninsula has been noted by other authors (Adie, 1955; Davies, 1976) and has also been observed elsewhere in the circum-Pacific belt (Hamilton and Myers, 1967; Cobbing and Pitcher, 1972). However, there are local exceptions (West, 1974). The abundance of plutonic rocks relative to other rock units in this area represents a continuation of similar trends observed on the southern Black Coast (Rowley, 1973).

Except for the main granodiorite, only relative ages of the intrusive rocks have been derived using field, petrographic and geochemical evidence. It is probable that plutonism occurred over a long period from the Upper Jurassic to at least the Lower Cretaceous. The widely exposed and undeformed main granodiorite has intruded the altered metagabbro, the Mount Hill Formation and the metamorphic complex. Radiometric dating has suggested that this occurred in Lower Cretaceous times. Geochemical evidence indicates some relationship between the garnetiferous tonalite at the head of Lamplugh Inlet and the main granodiorite but it does not wholly confirm the petrographical similarities between the diorite at Marshall Peak and the quartz-biotite-diorite of Andean affinity described by Adie (1955) from Cape Bryant. The gabbro at the plateau edge, south of Mount Jackson, intrudes the epiclastic rocks thought to be part of the Upper Jurassic Volcanic Group but its relationship with other plutonic rocks is not known. It is also recognized that the metagabbro could be older but it is still younger than the Mount Hill Formation.

It is known, that over the entire Antarctic Peninsula, plutonic activity covered a time span from the Lower Jurassic to the early Tertiary and involved at least five separate episodes, of which the last two are believed to represent the Andean orogeny (Rex, 1971). The origin of this calc-alkaline suite has been attributed to an east-dipping subduction zone beneath the continental margin (Williams and others, 1971; Suárez, 1976). Some of the earlier intrusive phases may be coeval with the volcanicity resulting in the Upper Jurassic Volcanic Group. There appears to be no general migration of magmatic foci over geological time as observed in other parts of the circum-Pacific orogenic belt (Farrar and others, 1970) but this may reflect the present poor distribution and availability of radiometric data for the Antarctic Peninsula. A similarly poor dating pattern has been derived by Halpern (1973) for the plutonic rocks in southern Chile.

It is thought that the plutonic rocks of the central Black Coast were probably intruded as discrete phases. The various processes, such as alkali metasomatism, which occurred during this emplacement seem to have been minor and local in effect. The field, petrographic and geochemical evidence suggests that differentiation of the main granodiorite occurred *in situ* after its emplacement in the crust. The extreme heterogeneity of the metagabbroic suite, further complicated by its inferred metamorphism, precludes any firm possibility that differentiation has occurred on a large scale during its evolution.

The rocks are undoubtedly members of a calc-alkaline association and have been favourably compared with similar rock associations elsewhere in the Antarctic Peninsula and in the circum-Pacific belt. Unfortunately, because this study involved a comparison of rocks of variable acidity, it has not been possible to apply the chemical criteria used by West (1974) for distinguishing plutonic rocks of various ages on the Danco Coast. However, a comparison of the ratios of relatively immobile elements, such as zirconium and yttrium, has revealed a possible source difference between the main granodiorite and metagabbroic suites and this lends support to their age difference inferred from field and petrographic work.

E. Minor Intrusive Rocks

The numerous acidic to basic hypabyssal rocks of the central Black Coast have been described but it has not been possible to establish their relative age relationships conclusively.

All of the dykes are calc-alkaline and follow trends very close to those of the plutonic rocks on the A–F–M and K–Na–Ca diagrams. It seems that the acidic dykes show strong chemical affinities with the main granodiorite and they can be distinguished from other hypabyssal rocks of a more basic composition. This relationship between the acidic dykes and the acidic plutons agrees with the observations of Davies (1976) for similar dykes in northern Palmer Land. It is thought that these acidic dykes and also the microgabbroic dykes, which cut the main granodiorite, are probably the youngest rocks on the central Black Coast. However, the microtonalitic and microdioritic dykes, which do not intrude the main granodiorite, may be older.

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X. REFERENCES

ADIE, R. J. 1954. The petrology of Graham Land: I. The Basement Complex; early Palaeozoic plutonic and volcanic rocks. *Falkland Islands Dependencies Survey Scientific Reports,* No. 11, 22 pp.

——. 1955. The petrology of Graham Land: II. The Andean Granite–Gabbro Intrusive Suite. *Falkland Islands Dependencies Survey Scientific Reports,* No. 12, 39 pp.

——. 1957. The petrology of Graham Land: III. Metamorphic rocks of the Trinity Peninsula Series. *Falkland Islands Dependencies Survey Scientific Reports,* No. 20, 26 pp.

——. 1964. Geological history. (*In* PRIESTLEY, R. E., ADIE, R. J. *and* G. DE Q. ROBIN, *ed. Antarctic research.* London, Butterworth and Co. (Publishers) Ltd., 118–62.)

——. 1971*a*. Recent advances in the geology of the Antarctic Peninsula. (*In* ADIE. R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget. 121-24.)

——. 1971*b*. Evolution of volcanism in the Antarctic Peninsula. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 137-41.)

AITKENHEAD, N. 1964. *The Trinity Peninsula Series of northeast Graham Land.* Ph.D. thesis, University of Birmingham, 168 pp. [Unpublished.]

——. 1975. The geology of the Duse Bay–Larsen Inlet area, north-east Graham Land (with particular reference to the Trinity Peninsula Series). *British Antarctic Survey Scientific Reports,* No. 51, 62 pp.

ALLING, H. L. 1938. Plutonic perthites. *J. Geol.,* **46,** No. 2, 142–65.

ARTH, J. G. *and* G. N. HANSON. 1975. Geochemistry and origin of the early Precambrian crust of north-eastern Minnesota. *Geochim. cosmochim. Acta,* **39,** No. 3, 325–62.

AYLING, M. E. 1966. *The geology of the "St. Valentine's" area, and related observations in the Batterbee Mountains, Palmer Land.* M.Sc. thesis, University of Birmingham, 119 pp. [Unpublished.]

BELL, C. M. 1973. The geology of southern Alexander Island. *British Antarctic Survey Bulletin,* Nos. 33 and 34, 1–16.

——. 1974. *The geology of parts of Alexander Island.* Ph.D. thesis, University of Birmingham, 125 pp. [Unpublished.]

BEST, M. G. 1969. Differentiation of calc-alkaline magmas. (*In* MCBIRNEY, A. R., *ed.* Proceedings of the andesite conference. *Bull. Ore. St. Dep. Geol. miner. Ind.,* No. 65, 65–75.) [International Upper Mantle Project, Scientific Report 16.]

BIBBY, J. S. 1966. The stratigraphy of part of north-east Graham Land and the James Ross Island group. *British Antarctic Survey Scientific Reports,* No. 53, 37 pp.

BLACK, R. B. 1945. Geographical operations from East Base, United States Antarctic Service Expedition, 1939–41. *Proc. Am. phil. Soc.,* **89,** No. 1, 4–12.

BRAMALL, A. *and* H. F. HARWOOD. 1923. The Dartmoor granite: its mineralogy, structure and petrology. *Mineralog. Mag.,* **20,** No. 101, 39–53.

COBBING, E. J. *and* W. S. PITCHER. 1972. The coastal batholith of central Peru. *J. geol. Soc. Lond.,* **128,** Pt. 5, 421–51.

CRADDOCK, C., GAST, P. W., HANSON, G. N. *and* H. LINDER. 1964. Rubidium-strontium ages from Antarctica. *Geol. Soc. Am. Bull.,* **75,** No. 3, 237–40.

CURTIS, R. 1966. The petrology of the Graham Coast, Graham Land. *British Antarctic Survey Scientific Reports,* No. 50, 51 pp.

DALZIEL, I. W. D. 1970. Structural studies in the Scotia arc: the Patagonian and Fuegian Andes. *Antarct. Jnl U.S.,* **5,** No. 4, 99–100.

——. 1971. Large-scale folding in the Scotia arc. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 47–55.)

——. *and* D. H. ELLIOT. 1971. Evolution of the Scotia arc. *Nature, Lond.,* **233,** No. 5317, 246–52.

——, *and*——, 1973. The Scotia arc and Antarctic margin. (*In* STEHLE, F. G. *and* A. E. M. NAIRN, *ed. The ocean basins and their margins. I. The South Atlantic.* New York, Plenum Publishing Corporation, 171–246.)

——., DOTT, R. H., WINN, R. D. *and* R. L. BRUHN. 1975. Tectonic relations of South Georgia island to the southernmost Andes. *Geol. Soc. Am. Bull.,* **86,** No. 7, 1034–40.

DAVIES, T. G. 1976. *The geology of part of northern Palmer Land, Antarctica.* Ph.D. thesis, University of Birmingham, 152 pp. [Unpublished.]

DEER, W. A., HOWIE, R. A. *and* J. ZUSSMAN. 1966. *An introduction to the rock-forming minerals.* London, Longmans, Green and Co. Limited.

DEWAR, G. J. 1970. The geology of Adelaide Island. *British Antarctic Survey Scientific Reports,* No. 57, 66 pp.

DIDIER, J. 1973. *Developments in petrology. Vol. 3. Granites and their enclaves.* Amsterdam, London, New York, Elsevier Publishing Company.

DRAKE, M. J. *and* D. F. WEILL. 1975. Partition of Sr, Ba, Ca, Y, Eu^{2+}, Eu^{3+} and other REE between plagioclase feldspar and magmatic liquid: an experimental study. *Geochim. cosmochim. Acta,* **39,** No. 5, 689–712.

ELLIOT, D. H. 1964. The petrology of the Argentine Islands. *British Antarctic Survey Scientific Reports,* No. 41, 31 pp.

——. 1965. Geology of north-west Trinity Peninsula, Graham Land. *British Antarctic Survey Bulletin,* No. 7, 1–24.

——. 1966. Geology of the Nordenskjöld Coast and a comparison with north-west Trinity Peninsula, Graham Land. *British Antarctic Survey Bulletin,* No. 10, 1–43.

——. 1967. The geology of Joinville Island. *British Antarctic Survey Bulletin,* No. 12, 23–40.

——. 1973. Gondwana basins of Antarctica. (*In* CAMPELL, K. S. W., *ed. Gondwana geology.* Canberra, Australian National University Press, 493–536.)

ELLIOTT, M. H. 1974. Stratigraphy and sedimentary petrology of the Ablation Point area, Alexander Island. *British Antarctic Survey Bulletin,* No. 39, 87–113.

EMMONS, R. C. *and* V. MANN. 1953. A twin-zone relationship in plagioclase feldspar. (*In* EMMONS, R. C., *ed.* Selected petrogenic relationships of plagioclase. *Mem. geol. Soc. Am.,* No. 52, 41–54.)

ENGEL, A. E. J. *and* C. G. ENGEL, 1960. Progressive metamorphism and granitization of the major paragneiss, northwest Adirondack Mountains, New York. Part II: Mineralogy. *Bull. geol. Soc. Am.,* **71,** No. 1, 1–57.

FARRAR, E., CLARK, A. H., HAYNES, S. J., QUIRT, G. S., CONN, H. *and* M. ZENTILLI. 1970. K-Ar evidence for the post-Paleozoic migration of granitic intrusion foci in the Andes of northern Chile. *Earth planet. Sci. Lett.,* **10,** No. 1, 60–66.

FLEET, M. 1968. The geology of the Oscar II Coast, Graham Land. *British Antarctic Survey Scientific Reports,* No. 59, 46 pp.

FRASER, A. G. 1964. Banded gabbros of the Anagram Islands, Graham Land. *British Antarctic Survey Bulletin,* No. 4, 23–38.

——. 1965. The petrology of Stonington and Trepassey Islands, Marguerite Bay. *British Antarctic Survey Scientific Reports,* No. 52, 51 pp.

——. *and* P. H. GRIMLEY. 1972. The geology of parts of the Bowman and Wilkins Coasts, Antarctic Peninsula. *British Antarctic Survey Scientific Reports,* No. 67, 59 pp.

GAST, P. W. 1968. Trace element fractionation and the origins of tholeiitic and alkaline magma types. *Geochim. cosmochim. Acta,* **32,** No. 10, 1057–86.

GATES, R. M. 1953. Petrogenetic significance of perthite. *Mem. geol. Soc. Am.,* No. 52, 55–69.

GILL, J. B. 1970. Geochemistry of Viti Levu, Fiji, and its evolution as an island arc. *Contr. Miner. Petrol.* (*Beitr. Miner. Petrogr.*), **27,** No. 3, 179–203.

GOLDRING, D. C. 1962. The geology of the Loubet Coast, Graham Land. *British Antarctic Survey Scientific Reports,* No. 36, 50 pp.

GREEN, D. H. *and* A. E. RINGWOOD. 1969. High pressure experimental studies on the origin of andesites. (*In* MCBIRNEY, A. R., *ed.* Proceedings of the andesite conference. *Bull. Ore. St. Dep. Geol. miner. Ind.,* No. 65, 21–42.) [International Upper Mantle Project, Scientific Report 16.]

GRIBBLE, C. D. 1969. Distribution of elements in igneous rocks of the normal calc-alkaline sequence. *Scott. J. Geol.,* **5,** No. 4, 322–27.

GRIKUROV, G. E. 1971. Tectonics of the Antarctandes. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 163-67.)

——. *and* A. F. DIBNER. 1968. Novye dannye o Serii Triniti (C_{1-3}) v zapadnoy Antarktide [New data on the Trinity Series (C_{1-3}) in west Antarctica]. *Dokl. Akad. Nauk SSSR,* Geology, **179,** No. 2, 410–12. [English translation: More information on the Trinity Series (C_{1-3}) of western Antarctica. *Dokl. (Proc.) Acad. Sci. U.S.S.R.,* Geological sciences sect., **179,** 39–41.]

——., KRYLOV, A. YA. *and* YU. I. SILIN. 1966. Absolyutunyy vozrast nekotorykh porod iz rayona zaliva Margerit Antarkticheskiy poluostrov [Absolute age of certain rocks in the Marguerite Bay region of the Antarctic Peninsula]. *Dokl. Akad. Nauk SSSR,* Geology, **171,** No. 6, 1399–401. [English translation: *Dokl. (Proc.) Acad. Sci. U.S.S.R.,* Geological sciences sect., **171,** 127–30.]

——., ——. *and* ——. 1967. Absolyutnyy vozrast nekotorykh porod dugi Skotiya i Zemli Aleksandra I (Zapadnaya Antarktika) [Absolute age of some rocks from the Scotia arc and Alexander I Land (western Antarctica)]. *Dokl. Akad. Nauk SSSR,* Geology, **172,** No. 1, 168–71. [English translation: *Dokl. (Proc.) Acad. Sci. U.S.S.R.,* Geological sciences sect., **172,** 19–22.]

HAHN-WEINHEIMER, P. *and* H. JOHANNING. 1968. Geochemical investigation on differentiated granite plutons in the Black Forest. (*In* AHRENS, L. H., *ed. Origin and distribution of the elements.* Oxford, London, Edinburgh, New York, Toronto, Sydney, Paris, Braunschweig, Pergamon Press, 777–93.)

HALL, A. 1965*a*. The occurrence of prehnite in appinitic rocks from Donegal, Ireland. *Mineralog. Mag.,* **35,** No. 269, 234–36.

——. 1965*b*. The origin of accessory garnet in the Donegal granite. *Mineralog. Mag.,* **35,** No. 272, 628–33.

HALL, A. J. 1941. The relation between colour and chemical composition in the biotites. *Am. Miner.,* **26,** No. 1, 29–33.

HALPERN, M. 1964. Cretaceous sedimentation in the "General Bernardo O'Higgins" area of north-west Antarctic Peninsula. (*In* ADIE, R. J., *ed. Antarctic geology.* Amsterdam, North-Holland Publishing Company, 334–47.)

——. 1965. The geology of the General Bernardo O'Higgins area, northwest Antarctic Peninsula. (*In* HADLEY, J. B., *ed. Geology and paleontology of*

the Antarctic. Washington, D.C., American Geophysical Union, 177–209.) [Antarctic Research Series, Vol. 6.]
——. 1971. Rb-Sr total-rock and mineral ages from the Marguerite Bay area, Kohler Range and Fosdick Mountains. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 197–204.)
——. 1973. Regional geochronology of Chile south of 50° latitude. *Geol. Soc. Am. Bull.*, **84**, No. 7, 2407–22.
HAMILTON, W. *and* W. B. MYERS. 1967. The nature of batholiths. *Prof. Pap. U.S. Geol. Surv.*, No. 554-C, 30 pp.
HARKER, A. 1950. *Metamorphism: a study of the transformations of rock-masses*. 3rd edition. London, Methuen and Co. Ltd.
HATCH, F. H., WELLS, A. K. *and* M. K. WELLS. 1972. *Textbook of petrology Vol. I: Petrology of the igneous rocks*. 13th edition. London. Thomas Murby and Company.
HAYAMA, Y. 1959. Some considerations on the color of biotite and its relation to metamorphism. *J. geol. Soc. Japan*, **65**, No. 1, 21–30.
HOBBS, G. J. 1968. The geology of the South Shetland Islands: IV. The geology of Livingston Island. *British Antarctic Survey Scientific Reports*, No. 47, 34 pp.
HOOPER, P. R. 1962. The petrology of Anvers Island and adjacent islands. *Falkland Islands Dependencies Survey Scientific Reports*, No. 34, 69 pp.
HORNE, R. R. *and* M. R. A. THOMSON. 1972, Airborne and detrital volcanic material in the Lower Cretaceous sediments of south-eastern Alexander Island. *British Antartic Survey Bulletin*, No. 29, 103–11.
HOSKINS, A. K. 1963. The Basement Complex of Neny Fjord, Graham Land. *British Antarctic Survey Scientific Reports*, No. 43, 49 pp.
JAKES, P. *and* A. J. R. WHITE. 1972. Major and trace element abundances in volcanic rocks of orogenic areas. *Geol. Soc. Am. Bull.*, **83**, No. 1, 29–39.
JONES, K. A. *and* A. K. GALWEY. 1964. A study of possible factors concerning garnet formation in rocks from Ardara, Co. Donegal, Ireland. *Geol. Mag.*, **101**, No. 1, 76–93.
KAMENEV, E. N. 1973. Geological investigations at McMurdo station, 1972–1973. *Antarct. Jnl U.S.*, **8**, No. 6, 338–39.
——. 1975. Skladchatye osadochnye i intruzivnye obrazovaniya Berega Lassitera i Berega Bleka (Antarkticheskiy Poluostrov) [Folded sedimentary and intrusive rocks of the Lassiter and Black Coasts (Antarctic Peninsula). *(In Trudy Sovetskoy Antarkticheskoy Ekspeditsii Tom 65, Semnadtsataya Sovetskaya Antarkticheskaya Ekspeditsiya. Zimovochnye issledovaniya 1971–1973 gg*. Leningrad, Gidrometeoizdat, 215–22).
KELLOGG, K. S. *and* P. D. ROWLEY. 1974. Structural geology of the Lassiter Coast. *Antarct. Jnl U.S.*, **9**, No. 5, 224–25.
KNOWLES, P. H. 1945. Geology of southern Palmer Peninsula, Antarctica. *Proc. Am. phil. Soc.*, **89**, No. 1, 132–45.
LAMBERT, R. ST. J. *and* J. G. HOLLAND. 1974. Yttrium geochemistry applied to petrogenesis utilizing calcium-yttrium relationships in minerals and rocks. *Geochim. cosmochim. Acta*, **38**, No. 9, 1393–1414.
LAUDON, T. S. 1971. Stratigraphy of eastern Ellsworth Land. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 215–23.)
LUTH, W. C., JAHNS, R. H. *and* O. F. TUTTLE. 1964. The granite system at pressures of 4 to 10 kilobars. *J. geophys. Res.*, **69**, No. 4, 759–73.
MARMO, V. 1971. *Developments in petrology. Vol. 2. Granite petrology and the granite problem*. Amsterdam, London, New York, Elsevier Publishing Company.
MARSH, A. F. 1968. *Geology of parts of the Oscar II and Foyn Coasts, Graham Land*. Ph.D. thesis, University of Birmingham, 291 pp. [Unpublished.]
MEHNERT, H. H., ROWLEY, P. D. *and* D. L. SCHMIDT. 1975. K-Ar ages of plutonic rocks in the Lassiter Coast area, Antarctica. *J. Res. U.S. geol. Surv.*, **3**, No. 2, 233–36.
MILLER, J. A. 1960. Potassium-argon ages of some rocks from the South Atlantic. *Nature, Lond.*, **187**, No. 4742, 1019–20.
MISCH, P. 1969. Paracrystalline microboundinage of zoned grains and other criteria for synkinematic growth of metamorphic minerals. *Am. J. Sci.*, **267**, No. 1, 43–63.
MIYASHIRO, A. 1961. Evolution of metamorphic belts *J. Petrology*, **2**, Pt. 3, 277–311.
MOORBATH, S. 1967. Recent advances in the application and interpretation of radiometric age dates. *Earth Sci. Rev.*, **3**, No. 3, 111–33.
——. 1975. The geological significance of early Precambrian rocks. *Proc. Geol. Ass.*, **86**, Pt. 3, 259–79.
NOCKOLDS, S. R. 1954. Average chemical compositions of some igneous rocks. *Bull. geol. Soc. Am.*, **65**, No. 10, 1007–32.
——. *and* R. ALLEN. 1953. The geochemistry of some igneous rock series. *Geochim. cosmochim. Acta*, **4**, No. 3, 105–42.
PEARCE, J. A. 1975. Basalt geochemistry used to investigate post-tectonic environments on Cyprus. *Tectonophysics*, **25**, No. 1, 41–68.
——. *and* J. R. CANN. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth planet. Sci. Lett.*, **19**, No. 4, 290–300.
PETTIJOHN, F. J., POTTER, P. E. *and* R. SIEVER. 1972. *Sand and sandstone*. New York, Springer-Verlag.
PHILLIPS, E. R. 1974. Myrmekite—one hundred years later. *Lithos*, **7**, No. 3, 181–94.
——. *and* P. C. RICKWOOD. 1975. The biotite-prehnite association. *Lithos*, **8**, No. 4, 275–81.
PITCHER, W. S. *and* A. R. BERGER. 1972. *The geology of Donegal: a study of granite emplacement and unroofing*. New York, Wiley.
PLUMMER, C. C. 1974. Contact metamorphism of the Latady Formation, southern Lassiter Coast, Antarctic Peninsula. *Antarct. Jnl U.S.*, **9**, No. 3, 82–83.
RAMDOHR, P. 1969. *The ore minerals and their intergrowths*. Oxford, London, Edinburgh, New York, Toronto, Sydney, Paris, Braunschweig, Pergamon Press.
REX, D. C. 1971. K-Ar age determinations on volcanic and associated rocks from the Antarctic Peninsula and Dronning Maud Land. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 133–36.)
——. 1976. Geochronology in relation to the stratigraphy of the Antarctic Peninsula. *British Antarctic Survey Bulletin*, No. 43, 49–58.
RONNE, F. 1948. Ronne Antarctic Research Expedition, 1946–48. *Geogrl Rev.*, **38**, No. 3, 355–91.
ROSS, C. S. *and* R. L. SMITH. 1961. Ash-flow tuffs: their origin, geologic relations, and identification. *Prof. Pap. U.S. geol. Surv.*, No. 366, 81 pp.
ROWE, P. J. 1973. The geology of the area between Riley and Bertram Glaciers, Palmer Land. *British Antarctic Survey Bulletin*, No. 35, 51–72.
ROWLEY, P. D. 1973. Geologic observations on the northern Lassiter Coast and southern Black Coast. *Antarct. Jnl U.S.*, **8**, No. 4, 154–55.
——. *and* P. L. WILLIAMS. 1974. Plutonic rocks of the Lassiter Coast. *Antarct. Jnl U.S.*, **9**, No. 5, 225–26.
SCHOPF, J. M. 1973. Plant material from the Miers Bluff Formation of the South Shetland Islands. *Rep. Inst. polar Stud. Ohio State Univ.*, No. 45, 45 pp.
SINGLETON, D. G. 1980. Physiography and glacial geomorphology of the central Black Coast, Palmer Land. *British Antarctic Survey Bulletin*, No. 49, 21–32.
SKIDMORE, M. J. 1972. The geology of South Georgia: III. Prince Olav Harbour and Stromness Bay areas. *British Antarctic Survey Scientific Reports*, No. 73, 50 pp.
SKINNER, A. C. 1973. Geology of north-western Palmer Land between Eureka and Meiklejohn Glaciers. *British Antarctic Survey Bulletin*, No. 35, 1–22.
SMELLIE, J. L. *and* P. D. CLARKSON. 1975. Evidence for pre-Jurassic subduction in western Antarctica. *Nature, Lond.*, **258**, No. 5537, 701–02.
SMITH, C. G. 1977. The geology of parts of the west coast of Palmer Land, Antarctica. Ph.D. thesis, University of Birmingham, 193 pp. [Unpublished.]
SPRY, A. 1969. *Metamorphic textures*. Oxford, London, Edinburgh, etc., Pergamon Press.
STUBBS, G. M. 1968. *Geology of parts of the Foyn and Bowman Coasts, Graham Land*. Ph.D. thesis, University of Birmingham, 244 pp. [Unpublished.]
SUÁREZ, M. 1976. Plate-tectonic model for southern Antarctic Peninsula and its relation to southern Andes. *Geology*, **4**, No. 4, 211–14.
TAYLOR, S. R. 1965. The application of trace element data to problems in petrology. (*In* AHRENS, L. H., PRESS, F., RUNCORN, S. K. *and* H. C. UREY, *ed. Physics and chemistry of the Earth*, **6**. Oxford, London, Edinburgh, New York, Paris, Frankfurt, Pergamon Press, 133–213.)
——. 1969. Trace element chemistry of andesites and associated calc-alkaline rocks. (*In* MCBIRNEY, A. R., *ed.* Proceedings of the andesite conference. *Bull. Ore. St. Dep. Geol. miner. Ind.*, No. 65, 43–63.) [International Upper Mantle Project, Scientific Report 16.]
THOMSON, J. W. 1968. The geology of the South Orkney Islands: II. The petrology of Signy Island. *British Antarctic Survey Scientific Reports*, No. 62, 30 pp.
——. 1974. The geology of the South Orkney Islands: III. Coronation Island. *British Antarctic Survey Scientific Reports*, No. 86, 39 pp.
THOMSON, M. R. A. 1972. New discoveries of fossils in the Upper Jurassic Volcanic Group of Adelaide Island. *British Antarctic Survey Bulletin*, No. 30, 95–101.
——. 1975. New palaeontological and lithological observations on the Legoupil Formation, north-west Antarctic Peninsula. *British Antarctic Survey Bulletin*, Nos. 41 and 42, 169–85.
TILLEY, C. E. 1926. On garnet in pelitic contact-zones. *Mineralog. Mag.*, **21**, No. 113, 47–50.
TRENDALL, A. F. 1953. the geology of South Georgia: I. *Falkland Islands Dependencies Survey Scientific Reports*, No. 7, 26 pp.
——. 1959. The geology of South Georgia: II. *Falkland Islands Dependencies Survey Scientific Reports*, No. 19, 48pp.
TURNER, F. J. 1968. *Metamorphic petrology, mineralogical and field aspects*. New York, San Francisco, St. Louis, London, Toronto, Sydney, McGraw-Hill Book Company.
——. *and* J. VERHOOGEN. 1960. *Igneous and metamorphic petrology*. 2nd edition. New York, Toronto and London, McGraw-Hill Book Company, Inc.
VANCE, J. A. 1962. Zoning in igneous plagioclase: normal and oscillatory zoning. *Am. J. Sci.*, **260**, No. 10, 746–60.

——. 1965. Zoning in igneous plagioclase: patchy zoning. *J. Geol.*, **73**, No. 4, 636–51.

WADE, F. A. *and* J. R. WILBANKS. 1971. Geology of Marie Byrd and Ellsworth Lands. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 207–14.)

WEST, S. M. 1974. The geology of the Danco Coast, Graham Land. *British Antarctic Survey Scientific Reports,* No. 84, 58 pp.

WILLIAMS, P. L. *and* P. D. ROWLEY. 1972. Composition of Jurassic sandstones, Lassiter Coast. *Antarct. Jnl U.S.*, **7,** No. 5, 145–46.

——., SCHMIDT, D. L., PLUMMER, C. C. *and* L. E. BROWN. 1971. Geology of the Lassiter Coast area, Antarctic Peninsula: preliminary report. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 143–48.)

WINKLER, H. G. F. 1974. *Petrogenesis of metamorphic rocks*. 3rd edition. Berlin, Heidelberg, New York, Springer-Verlag.

WYETH, R. B. 1975. *The geology of the southern Fallières Coast, Antarctic Peninsula*. M.Sc. Qual. thesis, University of Birmingham, 204 pp. [Unpublished.]

APPENDIX

Radiometric Dating

By

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Five samples of the main granodiorite unit were selected for K-Ar mineral dating in order to set a mimimum age for the termination of igneous activity within the central Black Coast area. Three of these samples had undeformed igneous textures with black platy biotite and (in two of the three) euhedral hornblende. The two remaining samples were of the marginal facies with a crude foliation defined by the alignment of biotite and hornblende. The ferromagnesian minerals appeared fresh in all samples, although in thin section all were found to contain minute inclusions of quartz, feldspar and/or magnetite.

Separated biotites and hornblende were analysed at the Institute of Geological Sciences, London. Potassium was determined in duplicate by flame photometry, and ^{40}Ar by vacuum fusion and mass spectrometric isotope dilution. Results and calculated ages are given in Table VII. Comparative replicate analyses of international standards (BCR-1 basalt, Bern 4M muscovite and GL-0 glauconite) indicate that systematic errors are no worse than the quoted experimental precision.

The hornblende–biotite pairs from the undeformed samples (E.4012.1 and 4021.1) yield concordant ages averaging 122±3 Ma. This is regarded as the best estimate of the age of crystallization of the intrusion. Calculated ages for the foliated samples are slightly lower, especially in the case of the biotites which average 112 Ma. Biotite from the most granitic sample (E.4065.1), which contains no hornblende, gives the lowest age of all, 104±4 Ma. Since there is no evidence for prolonged intrusive episodes within the main granodiorite pluton, these younger dates must be regarded as reflecting significant loss of radiogenic Ar subsequent to crystallization. In view of the fact that the rocks dated represent the last major igneous event in this area, the Ar loss cannot be related to degassing during a specific geological event.

It is concluded that plutonic igneous activity on the Black Coast terminated with intrusion of the main granodiorite during Lower Cretaceous times. At present no correlation is possible with Andean plutons in Graham Land to the north where Rex (1976) has recognized major groupings of K-Ar ages at 45–75, 90–110, 130–140 and 160–180 Ma. The proposed age appears to be slightly older than the Middle Cretaceous age assigned to similar rocks from the Lassiter Coast, 200 km farther south, by Mehnert and others (1975). These authors reported K-Ar ages for hornblende–biotite pairs from five separate plutons, ranging

Table VII

K-Ar DATA

Sample	K (%)	$^{40}Ar^*$ (nl/g)	$^{40}Ar^*$ (%)	*Age* (Ma)
E.4065.1 biotite	6·89	29·470	87·7	104±4
E.4012.1 biotite	6·42	31·901	90·3	121±4
hornblende	0·823	4·218	79·7	124±4
E.4021.1 biotite	7·08	34·583	87·0	119±4
hornblende	0·305	4·576	61·7	123±4
E.4178.1 biotite	6·61	31·347	88·5	115±4
hornblende	0·609	2·948	59·2	118±5
E.4193.1 biotite	4·61	20·428	83·8	108±4
hornblende	0·664	3·091	61·6	113±4

Precision: K%±2%, ^{40}Ar±1·5%.
Atmospheric argon correction assumes $^{40}Ar/^{36}Ar = 287\pm2$, as determined on the equipment used.
All errors quoted at $2-\sigma$ level.
Decay constants: $\lambda_\beta = 4 \cdot 72\times10^{-10}\ a^{-1}$;
$\lambda_e = 0 \cdot 584\times10^{-10}\ a^{-1}$.
$^{40}K/K = 1 \cdot 19\times10^{-4}$ atom %.

from 99 to 119 Ma. Only in one case was there evidence of discordance between hornblende and biotite, and the results were interpreted as showing significant differences in age between the earliest diorites and later granodiorites and quartz-monzonites. Since a comparable range has been obtained from a single pluton in the present study, the possibility must be considered that the Lassiter Coast ages are also affected by some argon loss, and that all intrusions in both areas are at least 120 Ma old. On the other hand, if plutonic activity outside the area sampled here genuinely continued to about 100 Ma ago, this could have been the cause of thermal resetting of K-Ar ages in the analysed minerals. These alternatives can only be distinguished by more intensive radiometric study, preferably including Rb-Sr dating.