THE GEOCHEMISTRY AND AGE OF THE DANGER ISLANDS PLUTON, ANTARCTIC PENINSULA

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Abstract. The geology of the Danger Islands is described in detail for the first time. They comprise a cogenetic suite of mainly leucocratic gabbroic rocks with minor alkali-rich differentiates. Rb–Sr dating indicates a late Cretaceous age of emplacement (89 ± 11 Ma) with an initial ^{87}Sr/^{86}Sr ratio of 0.7040 ± 0.0001.

Introduction

The Danger Islands (63°26′S, 54°41′W) are a chain of seven islands, trending north-east to south-west, situated 25 km east-south-east of Joinville Island at the tip of the Antarctic Peninsula (Fig. 1). The largest island in the group, Darwin Island (Fig. 2), is roughly circular in outline, 1 km in diameter and is surrounded by steep cliffs 80 m high. Dixey Rock, an isolated sea stack 35 m high, is the smallest island (Fig. 2). Scud Rock and Brash Island, lying half way between the Danger Islands and Joinville Island, are included in this study because of their proximity and geological similarity to the Danger Islands (Fig. 2).

Previous geological investigation of the islands was limited to a three-day visit to Beagle Island (Fig. 2) by P. H. H. Nelson, in December 1960 (Aitkenhead and Nelson, 1962). Heavy pack ice prevented further field study, although the remarkable layering of Comb Island (Figs. 2 and 3) was observed from both Beagle Island and from abroad RRS *Shackleton*. The exact nature of these layered rocks and their relationship to the gabbroic rocks, found on Beagle Island by Nelson, was unknown (Aitkenhead and Nelson, 1962). Elliot (1967) speculated that they were ither layered gabbros or volcanic rocks or even bedded sedimentary strata.

The area is notoriously difficult of access due to the large number of tabular icebergs grounded in the shallow waters. However, an opportunity to extend the study presented itself in January 1979 during a three-week period of logistical support by two Wasp helicopters from HMS *Endurance*. Scud Rock, Brash, Earle and Platter islands were examined by G. Hyden. Dixey Rock, Heroine and Comb islands were examined by R. D. Hamer. Both parties visited Darwin Island independently.

Field Relationships

Basic rocks crop out at all the localities examined with the exception of Comb Island, where a syenitic vein cuts layered microdiorite. No other rock types were seen throughout the island group. Leucocratic gabbro and olivine gabbronorite are the main rock types present and typically display spheroidal weathering in outcrop (Fig. 4). They are coarsely crystalline and homogeneous although, at a number of localities, for example on the west coast of Beagle Island (Aitkenhead and Nelson,

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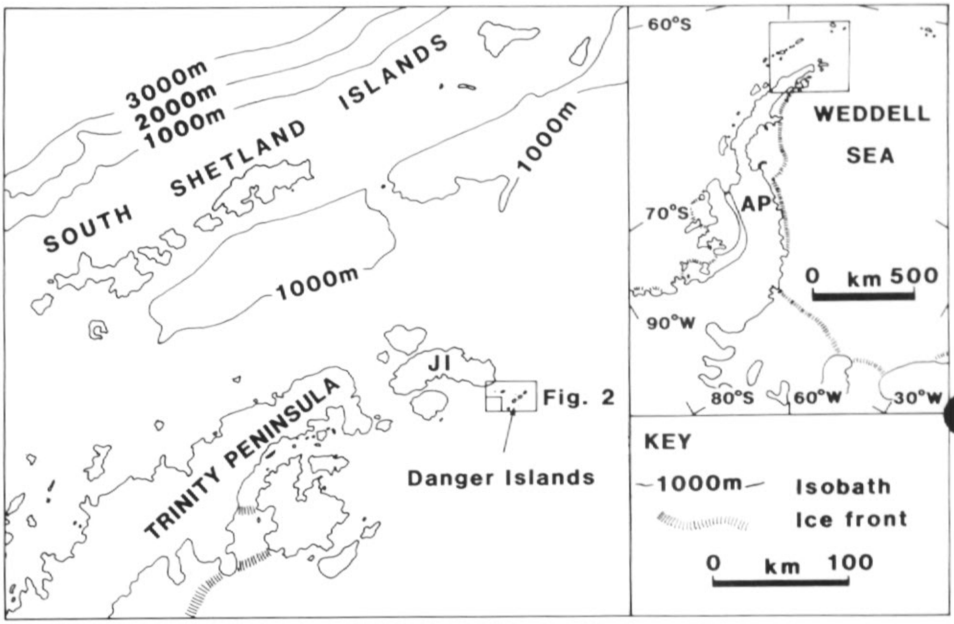

Fig. 1. Sketch map of the northern Antarctic Peninsula showing the location of the Danger Islands. AP, Antarctic Peninsula; JI, Joinville Island.

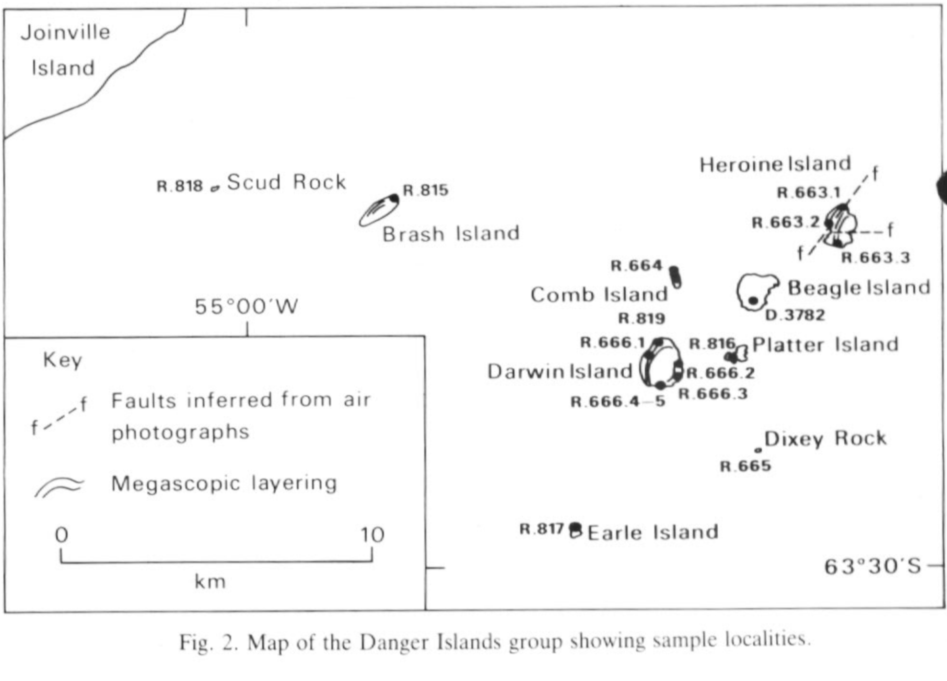

Fig. 2. Map of the Danger Islands group showing sample localities.

Fig. 3. Oblique air photograph of Comb Island from the south-east illustrating the spectacular layering.

Fig. 4. Spheroidal weathering in leuco-gabbro; northern tip of Heroine Island (R.663). Adélie penguins for scale are approximately 76 cm in height.

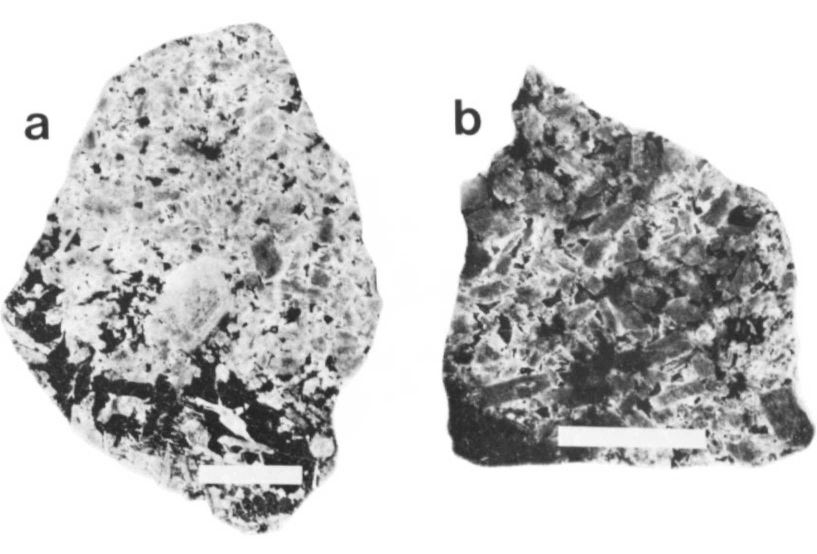

Fig. 5. Hand specimens showing features typical of the gabbroic rocks. (a) Mineral layering of augite (dark) and plagioclase (light) in a leuco-gabbro; Darwin Island (R.666.5B). (b) Cumulate texture in a leuco-gabbro; Darwin Island (R.819.1). Scale bar is 2 cm.

Fig. 6. Comb Island viewed from the north showing the stepped outline. In the background 2 km away is the north coast of Darwin Island.

1962) and on the north coast of Darwin Island, the rocks show mineral layering due to varying proportions of plagioclase, clinopyroxene and ilmenite (Fig. 5a). Mesocumulate textures are sometimes well-developed (Fig. 5b) with plagioclase as the major cumulate phase.

As noted by Nelson (Aitkenhead and Nelson, 1962), the rocks of Comb Island are conspicuously layered (Fig. 3). The layers are horizontal, subparallel, laterally continuous and 1.5–2.0 m thick. A total of 22 layers was observed at the southern end of the island. Each layer comprises a basal, dark coloured unit, overlain by a lighter coloured more friable unit. The contact between these two units appears to be gradational and contrasts with the sharp contacts between adjacent layers. Preferential weathering of the more friable upper units produces a stepped outline (Fig. 6). Both units are composed of fine- to medium-grained porphyritic microdiorite and no obvious differences in grain size or mineral content could be detected within each layer. Similar features have been described from Upper Tertiary basic intrusions in the South Shetland Islands, e.g. the Neogene sill at Williams Point, Livingston Island, and have been interpreted as the result of multiple intrusion (Smellie, 1979).

A small irregular vein of dull pinkish alkali-feldspar quartz syenite cuts the layering at the north end of the island. No other rock type is exposed and the relationship of the Comb Island rocks to the leucocratic gabbro of the other islands is unclear. However, porphyritic microdiorite, petrographically similar to that of

Comb Island, has been described from the summit of Beagle Island (Aitkenhead and Nelson, 1962). The contact between this rock and the surrounding gabbro is poorly exposed, although textural evidence led Nelson to suggest that it was probably the remains of a sill that once covered the whole island (Aitkenhead and Nelson, 1962). These latter rocks are volumetrically subordinate to the gabbroic rocks and together form less than 5% of the total outcrop.

PETROGRAPHY

The Danger Islands rocks range from gabbro to alkali-feldspar quartz syenite (based on the IUGS modal classification scheme of Streckeisen, 1973). However, they contain very low-grade metamorphic mineral assemblages associated with late-stage hydrothermal alteration. In some cases this makes precise classification difficult although, in general, the igneous mineralogy is clearly recognizable. In view of the problems associated with the modal classification of partially altered rocks an alternative scheme, based on chemical composition, is also considered (De la Roche and others, 1980).

The gabbroic rocks are all feldspar-rich, with plagioclase frequently forming more than 75% of the mode (Table I). They are mainly leuco-gabbro, together with lesser amounts of leuco-olivine gabbronorite. Using De la Roche and others' (1980) scheme, the gabbroic rocks fall into the gabbro-diorite field. In thin section, plagioclase forms large (2 cm maximum in length), tabular, euhedral crystals, which sometimes define a mesocumulate texture (Figs. 5b and 7a). In the non-cumulate gabbroic rock (e.g. R.665.1), plagioclase exhibits marked oscillatory zoning and is typically of labradorite to andesine composition. In the mesocumulate leuco-gabbro (e.g. R666.5), however, plagioclase crystals, ophitically enclosed by pyroxene, exhibit large cores of bytownite composition surrounded by a weakly zoned rim of

Table I. Modal analyses.

Sample number	*R.663.1*	*R.663.3*	*R.665.1*	*R.666.4*	*R.664.2B*
Rock type	*Leuco-gabbronorite*	*Leuco-gabbro*	*Leuco-olivine gabbronorite*	*Leuco-olivine gabbronorite*	*Alkali-feldspar quartz syenite*
Quartz	–	–	–	–	6.91
Alkali feldspar	–	–	–	–	90.65
Plagioclase feldspar	67.52	83.84	78.68	83.32	+
Olivine	–	–	6.38	1.45	–
Orthopyroxene	1.86	2.60	+	–	–
Clinopyroxene	14.60	9.50	9.00	9.44	1.00
Biotite	–	–	0.42	–	–
Fe-oxide	1.66	0.30	2.40	0.27	1.10
2° biotite	0.06	–	–	–	–
2° amphibole	0.04	–	1.30	3.52	–
Chlorite	13.88*	0.64	1.00	1.48	0.14
Apatite	0.20	0.09	0.82	0.08	0.14
Prehnite	0.18	3.03	–	0.44	–
Carbonate	+	+	–	+	0.06

* Largely altered orthopyroxene.
– Not recorded.
+ Present.

labradorite-andesine. They contain inclusions of acicular apatite together with rare ilmenite and, in specimen R.665.1, small serpentine pseudomorphs after olivine. Plagioclase is usually fresh, although often traversed by fine cracks filled by chlorite and calcite. In more altered samples plagioclase is frequently sericitized and in a few instances the margins of plagioclase crystals adjacent to altered intercumulus minerals are extensively replaced by fibrous prehnite (Fig. 7b).

Clinopyroxene is the main mafic phase and is usually fresh. It occurs as anhedral crystals containing inclusions of apatite and ilmenite. In the mesocumulate leuco-gabbro, clinopyroxene is the most abundant intercumulus mineral and subophitically encloses plagioclase. Alteration to an admixture of fibrous ferro-hornblende (Fig. 7c), biotite, chlorite and prehnite is seen in specimen R.666.1. Olivine and orthopyroxene also occur, but they are more susceptible to alteration and in most rocks are completely replaced by chlorite and serpentine or iddingsite (Fig. 8b). In altered samples it is frequently difficult to distinguish between irregularly shaped pseudomorphs after olivine and orthopyroxene. Small amounts of skeletal ilmenite, occasionally showing signs of alteration to biotite and containing elongate inclusions of apatite, also occur.

The less basic representatives of the complex are confined to Comb Island. Samples from the basal units of three consecutive layers at the north end of the island (R.664.1–3) are petrographically similar, comprising plagioclase phenocrysts up to 1.5 cm set in a fine- to medium-grained subequigranular groundmass of

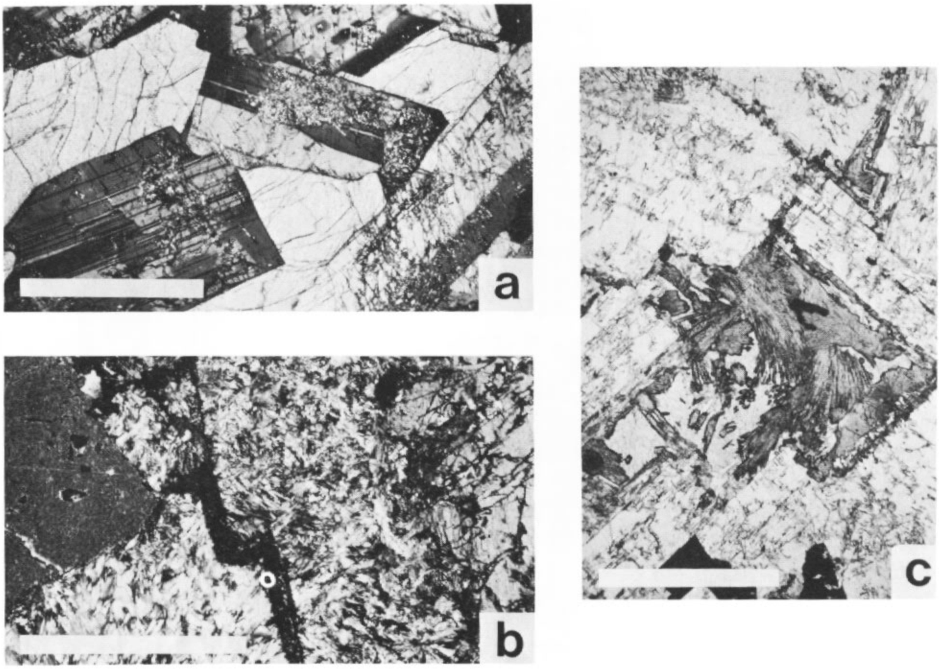

Fig. 7. Photomicrographs showing characteristic features of the gabbroic rocks. (a) Cumulate texture with plagioclase laths partially enclosed by augite in a leuco-gabbronorite (c.p.l.); Darwin Island (R.666.4). (b) Prehnite replacing plagioclase in an altered leuco-gabbronorite (c.p.l.); Heroine Island (R.663.1). (c) Amphibole replacing intercumulus augite in an altered leuco-gabbronorite (p.p.l.); Darwin Island (R.666.1). Scale bar is 1 mm.

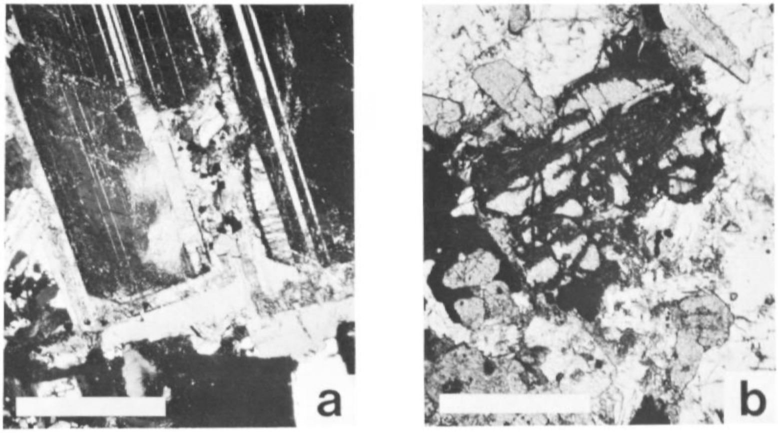

Fig. 8. (a) Photomicrograph of a labradorite phenocryst with an andesine-oligoclase rim in a porphyritic microdiorite (c.p.l.); Comb Island (R.664.1). (b) Photomicrograph of olivine altering to iddingsite in a leuco-olivine gabbronorite (p.p.l.); Dixey Rock (R.665.1). Scale bar is 1 mm.

clinopyroxene, plagioclase, alkali feldspar, quartz and Fe-oxide, together with accessory apatite and biotite. The porphyritic texture and altered state of some of the groundmass phases precludes modal classification. Applying De la Roche and others' (1980) chemical classification, these rocks fall into the syenodiorite field. Henceforth, the general term 'porphyritic microdiorite' is used to describe these rocks.

The plagioclase phenocrysts are tabular and subhedral with prominent euhedral cores of labradorite surrounded by narrow rims of andesine-oligoclase, intergrown with the groundmass phases (Fig. 8a). Smaller subhedral plagioclase crystals of andesine to oligoclase composition occur in the groundmass. Clinopyroxene is the most abundant mafic phase occurring as small subhedral crystals (0.5 mm) scattered throughout the groundmass and as inclusions in the rims of plagioclase phenocrysts. The groundmass clinopyroxene crystals sometimes show partial narrow rims of pale brownish green amphibole.

The dull pinkish acidic vein (R.664.2B), which cuts the layered porphyritic microdiorite of Comb Island, is composed almost wholly of alkali feldspar with smaller amounts of interstitial quartz, clinopyroxene, Fe-oxide and rare apatite. Modal data indicate that this rock is an alkali-feldspar quartz syenite and this agrees well with the chemical classification of syenite (De la Roche and others, 1980). The alkali feldspar that forms more than 90% of the mode (Table I), is highly turbid but sometimes exhibits a patch microperthitic texture. The clinopyroxene is pale greenish in colour and is frequently rimmed by a pale brownish green amphibole similar to that in specimens R.664.1–3.

ORDER OF CRYSTALLIZATION

The sequence of crystallization, in the magma from which these rocks were derived, is not entirely clear because of the state of alteration. Apatite and ilmenite were the first minerals to crystallize. Plagioclase was probably the first of the major phases to appear, followed closely by clinopyroxene. It is not clear whether olivine crystallized before or contemporaneously with plagioclase. Orthopyroxene was probably next, followed by Fe-oxide. Interstitial quartz, low-An plagioclase and alkali feldspar were the last minerals to crystallize. The amphibole in the gabbroic samples is a secondary alteration product but in the Comb Island rocks it is possible that the amphibole, rimming the pyroxene crystals, may have crystallized as a late-stage magmatic phase in response to an increase in the P_{H_2O} of the magma.

MINERALOGY

Representative analyses of the major rock-forming minerals in the suite have been obtained using the energy dispersive electron microprobe at the University of Cambridge.

Olivine

Partially altered olivine (Fo_{50-54}) occurs in only one sample (R.665.1), a leuco-olivine gabbronorite from Dixey Rock (Fig. 2). Elsewhere it is completely pseudomorphed by chlorite and serpentine. In sample R.665.1 the olivine is highly fractured and shows only minor alteration to orange–brown iddingsite. Representative analyses are given in Table II and plotted in Fig. 9.

Table II. Representative analyses of selected mineral phases.

Sample number	*R.665.1*	*R.666.5A*	*R.664.1*	*R.664.2B*	*R.666.1*	*R.664.1*	*R.664.1*
Mineral	*Olivine*	*Pyroxene*	*Pyroxene*	*Pyroxene*	*Plagioclase*	*Plagioclase*	*Plagioclase*
Analysis number	*OL2.1*	*CPX1.1*	*PX3.1*	*PX3.3*	*PL2.1*	*PL1.2*	*PLR1.2*
SiO_2	35.73	51.30	52.61	50.38	49.79	53.17	61.29
TiO_2	–	1.46	0.67	0.26	–	0.12	–
Al_2O_3	–	2.56	1.95	0.69	31.33	30.05	24.12
FeO	40.91	9.31	9.82	25.75	0.51	0.42	0.33
MnO	0.91	0.26	0.20	0.94	–	–	–
MgO	0.71	13.99	13.27	3.84	–	–	–
CaO	22.73	20.98	21.04	17.81	14.64	12.63	5.39
Na_2O	0.19	0.48	0.77	0.84	2.73	4.16	8.18
K_2O	–	–	–	–	–	0.17	1.08
Total	100.27	100.34	100.33	100.51	99.00	100.71	100.39
Cation proportions	0 = 4	0 = 6	0 = 6	0 = 6	0 = 8	0 = 8	0 = 8
Si	1.02	1.91	1.95	2.01	2.29	2.39	2.73
Ti	–	0.04	0.02	0.01	–	0.01	–
Al	–	0.11	0.08	0.03	1.70	1.59	1.26
Fe	0.98	0.29	0.31	0.86	0.02	0.02	0.01
Mn	0.02	0.01	0.01	0.03	–	–	–
Mg	0.97	0.78	0.74	0.23	–	–	–
Ca	0.01	0.84	0.84	0.76	0.72	0.61	0.26
Na	–	–	0.06	0.07	0.24	0.36	0.71
K	–	–	–	–	–	0.01	0.06
Total	3.00	3.98	4.01	4.00	4.97	4.99	5.03
Comments	Fo_{50}	Fe-poor intercumulus augite	Fe-poor groundmass augite	Fe-rich interstitial ferroaugite	Bytownite core of cumulate plagioclase	Labradorite core of phenocryst plagioclase	Oligoclase rim of phenocryst plagioclase

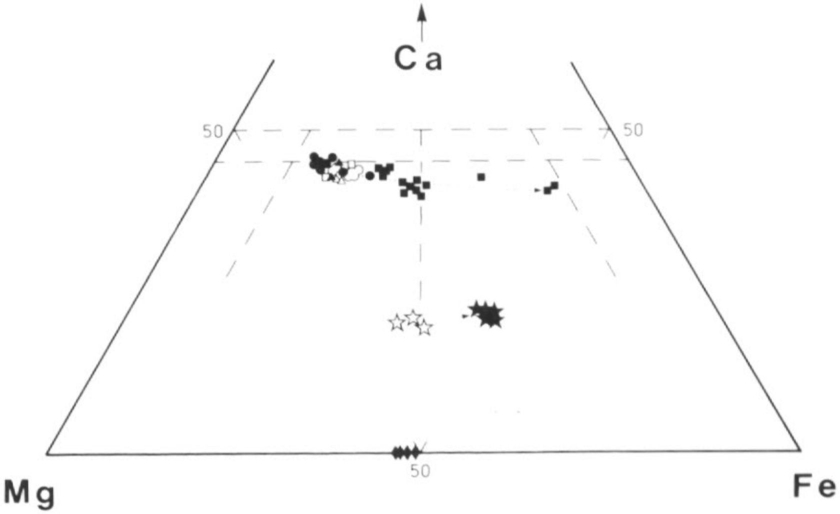

Fig. 9. Triangular variation diagram (cation proportions of Ca, Mg and total Fe as Fe^{2+}) illustrating the composition of selected mafic minerals. Dashed lines represent part of the pyroxene quadrilateral. Solid circles – augite and salite (R.663.1); open circles – augite (R.666.5A); solid triangles – augite (R.665.1); open triangles – augite (R.666.1); open squares – augite (R.664.1); solid squares – augite and ferroaugite (R.664.2B); open stars – richterite rims around augite (R.664.1); solid stars – ferro-richterite rims around ferroaugite (R.664.2B); solid diamonds – olivine (R.665.1).

Pyroxene

Clinopyroxene occurs in all the Danger Islands samples, whereas orthopyroxene is restricted to the gabbroic rocks. Clinopyroxene from six samples has been analysed and representative analyses are given in Table II and plotted in Fig. 9. The gabbroic clinopyroxene is mainly Fe-poor augite and salite. Occasionally it shows weak zoning with higher MgO, CaO, TiO_2 and Al_2O_3 contents in the cores and higher FeO, MnO and SiO_2 contents towards the rims. Mg/(Mg + Fe) values for the gabbroic clinopyroxene show a relatively restricted range (0.65–0.70). More Fe-rich augite and ferroaugite compositions occur in the more acidic rocks of Comb Island. Those in the microdiorite overlap with the field outlined for the gabbroic clinopyroxene (Fig. 9), but are distinguished by having higher Na_2O contents. The clinopyroxene in the syenite is significantly Fe-enriched and exhibits a wide range of composition with Mg(Mg + Fe) values of 0.20–0.62. The content of TiO_2 and Al_2O_3 in clinopyroxene crystals from the suite also show systematic variations. In the basic rocks for example, clinopyroxene typically contains 2.0–4.0 wt% Al_2O_3 and 0.6–1.1 wt% TiO_2, whereas in the syenite it is less Al-rich (0.5–1.2 wt%) and also less Ti-rich (0.2–0.4 wt%). These variations in pyroxene chemistry may reflect changes in temperature, silica activity or coexisting mineral assemblages (Gill, 1981).

Chlorite and serpentine pseudomorphs after orthopyroxene have been observed in several samples (e.g. R.663.3), but no fresh crystals of orthopyroxene remain.

Feldspar

Plagioclase and alkali feldspar have been analysed from six Danger Islands samples (Table II). In the mesocumulate leuco-gabbro the cores of large plagioclase chadacrysts enclosed by pyroxene have compositions in the range An_{84-80}. More commonly, cumulate plagioclase crystals exhibit continuous zoning and have compositions in the range An_{64-40}. Core to rim compositional variations in individual crystals are only minor. FeO contents of plagioclase vary from 0.3 to 0.6 wt%.

Phenocrysts of plagioclase in the porphyritic microdiorite show a marked break in composition from cores (An_{66-54}) to rims (An_{27-25}). In these rocks the groundmass plagioclase is similar in composition to that of the phenocryst rims (An_{30-26}). The alkali-feldspar quartz syenite contains a single perthitic feldspar (patch microcline microperthite). The absence of plagioclase in the Comb Island syenite indicates that this rock crystallized under hypersolvus conditions.

Amphibole

Amphibole in two samples from Comb Island has been analysed. In the porphyritic microdiorite (R.664.1) Fe-rich augite crystals are rimmed by richterite whereas the Fe-rich augite and ferroaugite in the syenite (R.664.2B) are rimmed by ferro-richterite (Leake, 1978) (Fig. 9). Richterite and ferro-richterite are commonly found as late-stage hydrothermal alteration products in syenite (Deer and others, 1974).

GEOCHEMISTRY

Thirteen whole-rock analyses have been performed on rocks from the Danger Islands using a PW1400 X-ray fluorescence spectrometer at Bedford College, University of London. Major elements were determined on lithium tetraborate/lithium carbonate fusion beads and trace element determinations were carried out on pressed powder discs. All calibrations were effected using international and laboratory standards. Mass absorption corrections for trace elements were made by monitoring the Ag- and W-tube lines or by using mass absorption coefficients determined from major element analyses. The analyses are given in Table III, together with published analyses of similar rock types from the Antarctic Peninsula, and plotted in Figs. 10–12.

Major elements

SiO_2 contents in the analysed samples range from 47 to 65%. All the samples plot within the alkaline field on the Na_2O+K_2O versus SiO_2, Ol′–Ne′–Q′ and Cpx–Ol–Opx diagrams of Irvine and Baragar (1971), although the high Al_2O_3 and low TiO_2 contents are more typical of calc-alkaline rocks (Gill, 1981). In general, chemical variation diagrams of the major elements versus SiO_2 show systematic patterns with the greatest scatter occurring in the cumulate rocks. TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO and P_2O_5 all decrease with increasing SiO_2 whereas K_2O increases (Fig. 10a). Na_2O increases from approximately 4% in the gabbro to 6.5% in the microdiorite but then shows a slight decrease in the alkali-feldspar quartz syenite. The rocks show no Fe-enrichment, a feature illustrated by the AFM diagram (Fig. 11). In addition, although FeO* (i.e. total iron expressed as FeO)/MgO ratios are high (2.0–6.0), absolute abundances of both FeO* and MgO are low (Table III).

Trace elements

The relative distribution of a number of trace elements, in addition to several major elements, is summarized on a multi-element mantle-normalized diagram (Fig. 12). The majority of trace elements show a progressive increase in abundance with increasing acidity, and the large-ion lithophile elements (Rb, Ba, La and K) become enriched relative to the high field strength elements.

Table III. Representative whole-rock analyses.

Sample number	*R.666.3*	*R.666.2*	*R.816.2*	*R.818.1*	*R.663.1*	*R.815.2*	*R.817.2*
Locality	*Darwin Island*	*Darwin Island*	*Platter Island*	*Scud Rock*	*Heroine Island*	*Brash Island*	*Earle Island*
Rock type	*Leuco-gabbro*	*Leuco-gabbro*	*Leuco-gabbro*	*Leuco-gabbro*	*Leuco-gabbro-norite*	*Leuco-gabbro*	*Leuco-gabbro*
SiO_2	48.55	48.74	48.79	48.97	49.27	49.41	49.95
TiO_2	0.92	1.04	1.39	1.24	1.09	1.40	1.16
Al_2O_3	21.23	20.85	20.29	20.22	21.95	20.52	18.87
Fe_2O_3	6.70*	7.34*	7.75*	7.92*	6.44*	7.54*	8.14*
FeO	na	na	na	na	na	na	na
MnO	0.11	0.13	0.13	0.14	0.11	0.14	0.14
MgO	3.70	3.73	2.86	4.38	2.88	3.37	4.60
CaO	10.18	9.35	9.19	10.48	10.19	9.68	9.77
Na_2O	4.19	4.50	4.55	3.69	4.18	4.25	4.37
K_2O	0.61	0.73	0.83	0.80	0.68	0.89	0.46
P_2O_5	0.13	0.17	0.26	0.23	0.19	0.26	0.16
Total	96.32	96.58	96.04	98.07	96.98	97.45	97.62
Cr	115	92	49	70	28	50	na
Ni	17	16	7	17	9	11	na
Rb	8	10	14	14	10	15	7
Sr	452	481	506	519	556	493	434
Y	14	15	21	20	18	23	18
Zr	51	54	84	78	70	96	64
Nb	6	8	10	9	9	13	7
Ba	141	177	179	156	165	197	na
La	–	–	6	6	4	11	na
Ce	–	–	–	–	–	–	na

* Total iron expressed as Fe_2O_3.
– Not detected.
na Not analysed.
Analyses for samples TL.567.2 and TL567.9 taken from Saunders and others (1982).

Zr shows a positive correlation with SiO_2 increasing from 50 to 130 ppm in the gabbroic rocks to over 450 ppm in the syenite (Fig. 10b). The cumulate leuco-gabbro contains significantly less Zr than the non-cumulate olivine gabbronorite (e.g. R.665.1), indicating that zircon was not a fractionating phase at this stage. These results compare favourably with the data obtained from a fractionated gabbro-microgranite complex in Adie Inlet, 500 km south of the study area, in central east Graham Land (Saunders and others, 1982).

Ba contents increase with increasing SiO_2 from 130 to 200 ppm in the gabbroic rocks to over 700 ppm in the alkali-feldspar quartz syenite. These high values suggest that alkali feldspar was not an important fractionating phase. In contrast, Sr shows a progressive decrease in abundance with increasing SiO_2. This probably reflects the fractionation of plagioclase feldspar also indicated by the cumulate textures in the leuco-gabbro. Likewise Cr and Ni show a decrease in abundance with increasing SiO_2 attributable to the separation of olivine and pyroxene.

One further feature illustrated by Fig. 12 is the marked enrichment of Nb in the microdiorite and alkali-feldspar quartz syenite. Such levels of Nb are typical of rocks with alkaline affinities (Saunders and Tarney, 1982).

R.817.1 Earle Island Leuco-gabbro	*R.819.1 Darwin Island Leuco-gabbro*	*R.665.1 Dixey Rock Leuco-olivine gabbro-norite*	*R.664.3 Comb Island Micro-diorite*	*R.664.1 Comb Island Micro-diorite*	*R.664.2B Comb Island Alkali-feldspar quartz syenite*	*TL.567.9 Adie Inlet Gabbro*	*TL.567.2 Adie Inlet Micro-granite*
50.29	51.09	52.38	58.03	64.72	50.60	70.40	
1.19	1.14	1.11	0.97	0.94	0.49	0.89	0.30
18.49	21.67	21.02	17.82	17.85	17.91	18.52	15.32
8.47*	5.65*	2.24	3.41	3.39	1.23	7.74*	2.26*
na	na	4.10	2.70	2.65	1.08	na	na
0.14	0.10	0.14	0.14	0.14	0.06	0.14	0.04
5.13	2.79	3.22	1.86	1.79	0.41	6.06	0.32
9.61	9.89	8.78	4.10	3.90	1.37	10.43	0.90
4.54	5.13	4.65	6.38	6.28	5.91	3.69	5.40
0.49	0.49	1.19	2.72	2.91	6.47	0.91	4.99
0.16	0.16	0.20	0.20	0.21	0.14	0.24	0.06
98.51	98.11	99.03	98.33	98.59	99.89	99.31	99.99
39	132	na	17	18	–	103	4
10	9	na	8	8	1	30	–
8	8	21	50	51	88	55	151
395	437	534	303	187	200	586	59
17	18	23	43	41	42	23	36
61	67	130	305	285	454	143	505
7	8	13	29	29	40	7	30
129	140	na	593	590	713	158	432
7	–	na	20	21	18	11	36
–	–	na	21	21	17	28	65

Strontium isotopes

The $^{87}Sr/^{86}Sr$ ratios of seven Danger Islands samples, ranging from cumulate leuco-gabbro and olivine gabbronorite to alkali-feldspar quartz syenite, are listed in Table IV. Excluding sample R.819.1, the remaining samples define an isochron indicating a late Cretaceous age of 89 ± 11 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7040 ± 0.0001 (Fig. 13). Sample R.819.1 has a high initial ratio, assuming it to be of the same age. This sample is mineralogically and geochemically similar to the other leuco-gabbroic rocks but differs in the degree of alteration shown. It is suggested that the higher ratio exhibited by this sample may have resulted from Sr exchange during late-stage hydrothermal activity.

DISCUSSION

The Danger Islands constitute one of the largest areas of basic plutonic rock exposed in the Antarctic Peninsula. Unfortunately, the short duration and limited extent of the landings precludes a conclusive interpretation of the relationship, if any, between the Comb Island rocks and the gabbro of the remaining islands.

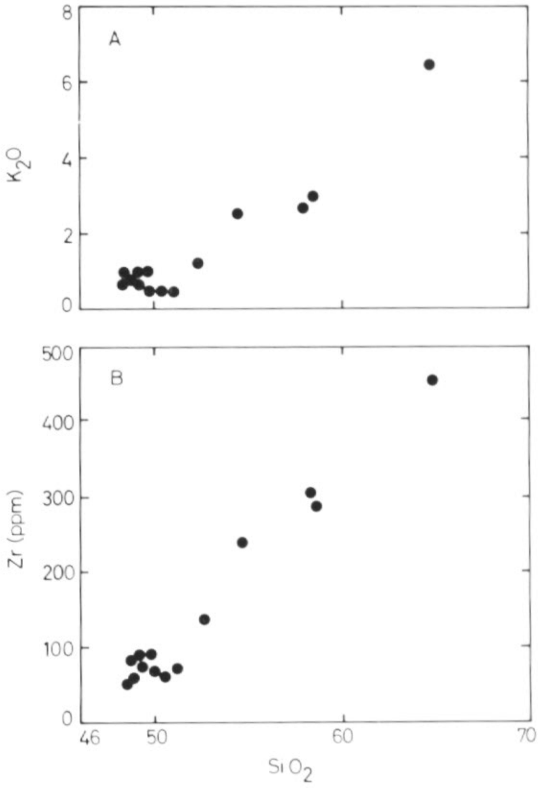

Fig. 10. K_2O and Zr against SiO_2 variation diagrams for Danger Islands samples.

Despite this lack of detailed field control, several features provide indirect evidence for the existence of a genetic relationship between the abundant feldspar-rich gabbros and the less basic Comb Island rocks:

(a) The proximity of the islands to each other and the complete absence of other rock types.
(b) An exposure of porphyritic microdiorite, petrographically similar to that cropping out on Comb Island, occurs at one locality on Beagle Island. This outcrop is situated above gabbro but the contact is not exposed. Aitkenhead and Nelson (1962) suggest that it represents the remains of a sill.
(c) There is a marked overall similarity of mineral assemblages throughout the area and the compositional ranges of individual mineral phases (e.g. pyroxene) in the gabbroic rocks, the porphyritic microdiorite and the syenite show a systematic degree of overlap (Fig. 9).
(d) The coherency of the Rb–Sr whole-rock isochron, obtained from the Danger Islands and including samples from Comb Island, lends further support to a cogenetic relationship.

Porphyritic textures in the microdiorite are interpreted here as indicating a drop in pressure or a change in the cooling rate and the abruptness of this change in the crystallization sequence is shown by the compositional jump from core to rim in the

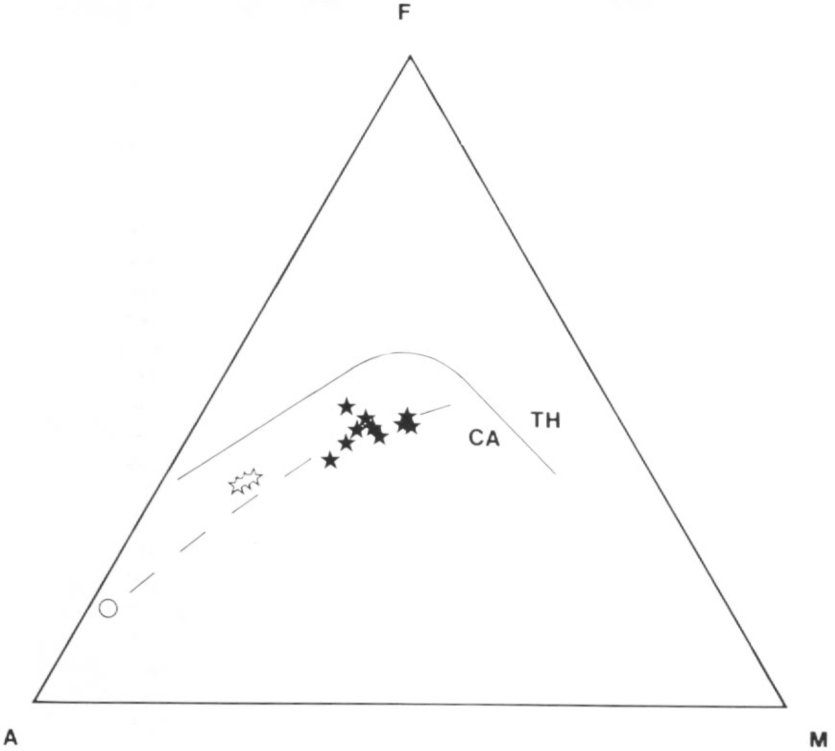

Fig. 11. AFM diagram for the Danger Islands rocks (A, $Na_2O + K_2O$; F, $FeO + 0.9 \times Fe_2O_3$; M, MgO). Solid stars – gabbro; open stars – microdiorite; open circle – alkali-feldspar quartz syenite. The solid line separating tholeiitic (TH) from calc-alkaline (CA) suites is taken from Gill (1981). The dashed line indicates the average trend of calc-alkaline plutonic rocks from the Antarctic Peninsula (Saunders and others, 1982).

plagioclase phenocrysts. It is suggested here that these rocks either form part of a sill or may represent part of a chilled zone at the margin of the main intrusive body. The layering in the Comb Island microdiorite is probably the result of multiple injection similar to that described for the layered minor intrusions of the South Shetland Islands (Smellie, 1979).

The petrography, mineral chemistry and whole-rock chemistry of the Danger Islands gabbroic rocks is similar to published data for basic plutonic rocks occurring throughout the Antarctic Peninsula (Adie, 1955; West, 1974; Saunders and others, 1982; A. B. Moyes, personal communication, and unpublished data). They contain high LIL-element abundances which suggest that they bear the closest comparison with the LIL-element enriched basic calc-alkaline rocks, exposed furthest from the trench, along the east coast of the peninsula (Saunders and others, 1980).

The volumetrically minor microdiorite of Comb and Beagle islands and the syenite of Comb Island, however, have high K_2O, Na_2O, Zr and Nb contents more typical of rocks with alkaline affinities. They are distinct from the calc-alkaline plutonic rocks, with similar SiO_2 levels, which dominate the geology of the Antarctic Peninsula. Their nearest equivalents include the alkali-rich intrusive rocks, with high Zr and

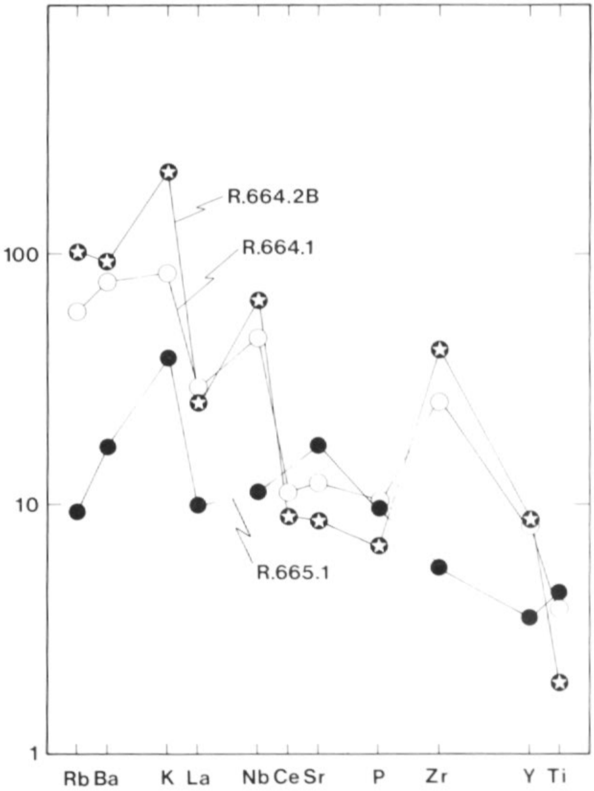

Fig. 12. Multi-element mantle-normalized diagram of representative samples from the Danger Islands. Mantle normalizing values are from Wood and others (1979). R.665.1–olivine gabbronorite; Dixey Rock. R.664.1– porphyritic microdiorite; Comb Island. R.664.2B – alkali-feldspar quartz syenite; Comb Island.

Nb, which occur locally in Adie Inlet. These rocks are considered to have resulted from the differentiation of a gabbro (Marsh, 1968) (Table III).

The incompatible behaviour of Zr in basic rock suites has been commented on by various authors (e.g. Watson and Harrison, 1983) and Zr-rich differentiates occur in both tholeiitic and alkaline complexes (Weaver and others, 1972). Experimental work on alkali-rich rocks indicates that zircon solubility shows a linear dependance upon the agpaitic coefficient and that Zr-enrichment is possible because the feldspar

Table IV. Rb–Sr data.

Sample number	*Rock type*	*Locality*	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
R.665.1	Leuco-olivine gabbronite	Dixey Rock	0.1165	0.70419
R.815.1	Leuco-gabbro	Brash Island	0.0860	0.70410
R.819.1	Altered leuco-gabbro	Darwin Island	0.0497	0.70434
R.664.1	Porphyritic microdiorite	Comb Island	0.5090	0.70471
R.664.2A	Porphyritic microdiorite	Comb Island	0.4049	0.70458
R.664.3	Porphyritic microdiorite	Comb Island	0.4720	0.70459
R.664.2B	Alkali-feldspar quartz syenite	Comb Island	1.2421	0.70559

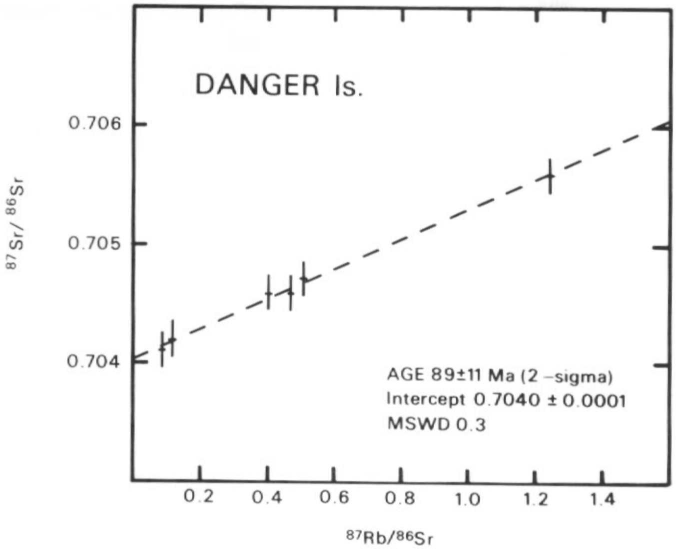

Fig. 13. Rb–Sr whole-rock isochron for six Danger Islands samples.

fractionation that produces these magmas does not drive the melt towards saturation in zircon (Watson, 1979).

However, in the majority of acidic calc-alkaline rocks there is a marked reduction of Zr attributable to the precipitation of zircon crystals. In the Antarctic Peninsula calc-alkaline suite, Saunders and others (1982) showed that Zr saturation was achieved in rocks with approximately 65% SiO_2. Although the silica content of the most acidic sample from the Danger Islands (i.e. the Comb Island alkali-feldspar quartz syenite) does not reach this level, absolute abundances of Zr are high, reaching 450 ppm at 64% SiO_2 compared to a range of 150–400 ppm in calc-alkaline rocks at equivalent SiO_2 contents (Saunders and others, 1982).

Thus, if the less basic rock types of the Danger Islands are related to the gabbro, this provides evidence that differentiation of Antarctic Peninsula gabbroic rocks can produce minor alkali-rich fractions. In this case, the depletion of Sr, P, Ti, Cr and Ni could relate to fractionation of observed mineral phases, chiefly plagioclase, but also including lesser amounts of olivine, pyroxene and apatite. Zircon and K-feldspar do not appear to have been involved in fractionation.

Nb is an incompatible element but it is preferentially incorporated into amphibole and biotite. There is no evidence to suggest the involvement of primary amphibole (except as a late-stage phase) or biotite, in the Danger Islands rocks, whereas the majority of the calc-alkaline plutons of the Antarctic Peninsula show lower Nb contents and widespread evidence for the crystallization of both amphibole and biotite (Adie, 1955; Saunders and others, 1982; A. B. Moyes, unpublished data).

The Rb–Sr isochron (Fig. 13) obtained from the Danger Islands indicates a late Cretaceous age of emplacement. It thus falls into the third pulse of magmatic activity (100–80 Ma) outlined by Rex (1976) and corroborated by Pankhurst (1982) for the plutonic rocks of the Antarctic Peninsula. A similar age of 92 ± 2 Ma has been obtained from the nearby calc-alkaline granodioritic pluton of Lizard Hill at the tip of the Antarctic Peninsula (Pankhurst, 1982) and the gabbro complex in Adie Inlet, with Zr-rich differentiates, gives an age of 83 Ma (Rex, 1976). In addition, the initial

^{87}Sr/^{86}Sr ratio falls within the range (0.7030–0.7050) outlined by Pankhurst (1982) for the Antarctic Peninsula plutons of Late Cretaceous–Tertiary age. These values are characteristic of magmas in active continental margins (Pankhurst, 1982). They indicate derivation from subcontinental mantle slightly enriched in ^{87}Sr, perhaps through the addition of volatiles from the subducted ocean floor (Hawkesworth and others, 1979).

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