THE GEOCHEMISTRY OF ROCKS FROM THE NORDENSKJÖLD COAST AND NORTH-WEST TRINITY PENINSULA, GRAHAM LAND

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ABSTRACT. The analyses of three sandstones from the Trinity Peninsula Series reflect the granitic provenance of these sediments but they are not comparable with previous analyses of the Trinity Peninsula Series. The postulated origin of the banded hornfelses is partly confirmed by two chemical analyses and, although there is considerable chemical similarity to rocks of the Trinity Peninsula Series, other characteristics separate them. The Jurassic intrusions are compositionally close to each other and plot near the earlier suggested variation trends for the Upper Jurassic Volcanic Group; this seems to be additional evidence for an early Mesozoic intrusive phase. Nine Tertiary intrusions are compared with other dykes and lavas from northern Graham Land and the South Shetland Islands; the existence of at least three trends of magmatic activity is suggested and attention is drawn to certain similarities with Tertiary and Quaternary vulcanism of Japan.

DURING the course of work on the geology of the Nordenskjöld Coast (Elliot, 1966) and north-west Trinity Peninsula (Elliot, 1965) a number of rocks have been analysed. Three Trinity Peninsula Series sandstones have been analysed for comparison with previous analyses of sediments of that age, and two banded hornfelses have been analysed for evidence of their original lithology and composition, and for comparison with the Trinity Peninsula Series. Additional evidence for the existence of an early Mesozoic intrusive phase has been obtained from the Upper Jurassic dyke rocks. The Tertiary minor intrusions have been analysed for comparison with other Tertiary and Recent volcanic and hypabyssal rocks from northern Graham Land and the South Shetland Islands, and the co-existence of three rock series: an alkali-basalt series, a tholeiitic series and a calc-alkaline series during the Cainozoic, is postulated.

SEDIMENTS

Trinity Peninsula Series

Three Trinity Peninsula Series sandstones have been analysed for comparison with the arenaceous sediments analysed by Adie (1957). The mineralogy of two of these sandstones (from north-west Trinity Peninsula) has been described in detail in an earlier paper (Elliot, 1965, p. 2, table II). These sediments are immature bimodal feldspathic sandstones in which quartz and feldspar (mainly plagioclase, $Ab_{75}An_{25}$–$Ab_{94}An_{6}$) in the ratio 3 : 2 are the dominant mineral grains, and the matrix forms about half the rock. The mineralogy and maturity of the sandstones, the sedimentary structures and the pebbly shales present in the evenly bedded thick succession comprising mainly sandstones, siltstones and shales suggest a deep-water depositional environment and the re-deposition, in particular by turbidity currents, of the coarser sediments. The third sandstone (D.4807.2) from the Nordenskjöld Coast (Elliot, 1966, p. 7) is also an immature feldspathic sandstone but the effects of regional metamorphism invalidate thin-section analysis.

The three sandstones (Table I, analyses 1, 2 and 3) show comparatively little variation in composition. The slight differences can be attributed to differences in the source area between north-west Trinity Peninsula and the Nordenskjöld Coast, and the unknown relative positions of the sediments in the stratigraphic column. Adie (1957, table II) has analysed four rocks belonging to the Trinity Peninsula Series but none of them is comparable with those given in Table I; of the rock types analysed by Adie, only unmetamorphosed argillaceous sediments, the equivalents of the chiastolite-cordierite-hornfels, have been found either in north-west Trinity Peninsula or on the Nordenskjöld Coast. In marked contrast to all the rocks, except the red quartzite, these sandstones have very little free carbon, but this may only be a function of geographical position, because the carbonaceous rocks are at least 300 miles (483 km.) away.

The composition of greywacke-type sediments, which are the products of incomplete weathering and sorting (Pettijohn, 1957, p. 308), is dependent mainly on the chemical composition of the source area. The postulated provenance of the sediments is predominantly granitic, being composed of acid intrusions, intermediate to acid volcanic rocks and sub-

TABLE I. CHEMICAL ANALYSES OF SEDIMENTS FROM NORTHERN GRAHAM LAND

	1	2	3	4	5	6	7
SiO_2	68·56	68·83	66·16	64·7	70·33	61·43	61·68
TiO_2	0·49	0·53	0·70	0·5	0·57	0·93	0·50
Al_2O_3	14·45	14·71	15·51	14·8	12·74	17·10	16·12
Fe_2O_3	0·78	0·75	1·46	1·5	0·52	1·11	1·16
FeO	2·72	3·07	3·17	3·9	3·51	5·17	4·00
MnO	0·02	0·02	0·04	0·1	0·08	0·06	—
MgO	1·50	1·77	2·02	2·2	1·78	3·17	2·82
CaO	2·33	1·61	3·02	3·1	4·40	2·22	6·17
Na_2O	3·53	4·92	4·41	3·1	3·53	3·07	3·17
K_2O	2·83	1·80	1·61	1·9	0·99	2·55	2·05
H_2O+	1·88	1·97	1·96	2·4	1·06	2·85	1·79
H_2O-	0·10	0·08	0·01	0·7	0·07	0·07	0·03
P_2O_5	0·12	0·13	0·14	0·2	0·17	0·20	—
CO_2	0·62	0·06	Nil	1·3	0·16	0·08	0·35
C	0·02	0·02	0·05	—	—	—	—
TOTAL	99·95	100·27	100·26	101·0	99·91	100·01	99·84

1. D.4405.1 Sandstone from the Trinity Peninsula Series; west of Fidase Peak, north-west Trinity Peninsula (anal. D. H. Elliot).
2. D.4444.1 Sandstone from the Trinity Peninsula Series; west of Mount d'Urville, north-west Trinity Peninsula (anal. D. H. Elliot).
3. D.4807.2 Sandstone from the Trinity Peninsula Series; north-west of Fender Buttress, Nordenskjöld Coast (anal. D. H. Elliot).
4. Average of 23 greywackes (Pettijohn, 1957, table 52).
5. D.4463.3 Banded hornfels (centre of a xenolith); east of Aureole Hills, north-west Trinity Peninsula (anal. D. H. Elliot).
6. D.4465.1 Banded hornfels; south of Aureole Hills, north-west Trinity Peninsula (anal. D. H. Elliot).
7. Average of two analyses (Grout, 1933, table 2, analyses 2 and 3).

ordinate metamorphosed and unmetamorphosed sediments. It is of interest to compare the analyses with that of an acid intrusive rock (D.4862.3; Table II, analysis 1) which shows striking similarities; as might be expected from the provenance, the sediments have slightly more iron and magnesia and less alkalis. Pettijohn (1957, p. 306) has listed the compositions of some greywackes and these show the wide possible range of such sediments. A comparison with Pettijohn's average greywacke (Table I, analysis 4) shows that two of the Trinity Peninsula Series sandstones (D.4405.1, 4444.1) have higher percentages of silica, soda and potash, and lower ones of iron, magnesia and lime; the third sandstone (D.4807.2) is slightly closer in composition. The differences are those to be expected because of the dominantly granitic provenance, and they also indicate that the matrix is probably more quartzo-feldspathic than argillaceous. As with most greywacke-type sediments, ferrous iron exceeds ferric iron and soda exceeds potash.

Banded hornfelses

Two specimens of the banded hornfelses from north-west Trinity Peninsula (Elliot, 1965, p. 15) have been analysed (Table I, analyses 5 and 6) in order to determine whether there are significant differences from or similarities with the Trinity Peninsula Series. One of the rocks (D.4465.1) is a quartz-plagioclase-chlorite-hornfels with a fine alternation of quartzo-feldspathic and ferromagnesian laminae 0·1–0·4 mm. thick. The quartz-plagioclase ($Ab_{68}An_{32}$) bands include a little alkali-feldspar and micaceous minerals, whereas the ferromagnesian bands are composed of penninite, biotite, sericite and muscovite with a little quartz and plagioclase. The other hornfels (D.4463.3), which is a xenolith in tonalite, has more pronounced banding (1·0–6·0 mm. wide) and consists of equal proportions of light and dark bands. The light bands are composed of quartz, plagioclase ($Ab_{59}An_{41}$) and some pyroxene (diopside) and epidote, and the dark bands are formed of chlorite, biotite and some actinolite, sphene and epidote; the mineral segregation is not as pronounced as in the other specimen.

The banded hornfelses are believed to have been derived from an alternating succession of thin laminae of argillaceous and quartzo-feldspathic sediment (Elliot, 1965, p. 16) and thus the two most striking features of the analysis are the reduced state of the iron, though this was probably not altered by thermal metamorphism, and a greater percentage of soda than potash. The reverse is more usual for argillaceous rocks and also for the purer quartzo-feldspathic sediments such as arkoses, though Pettijohn (1957, p. 345) has stated that soda exceeds potash in some shales associated with greywackes. In respect of iron and alkalis, these rocks are similar to the greywacke-type sediments and, although their derivation by metamorphic differentiation from such sediments has been considered, other facts tend to favour the postulated origin. Comparison of the xenolith (D.4463.3) with the other hornfels shows that there is increased silica and decreased alumina, total iron and magnesia; lime, however, is increased and occurs in pyroxene, amphibole, sphene and epidote, as well as in plagioclase. This is believed to be an original compositional difference.

Grout (1933, p. 992–95) has described finely laminated slates having a banded appearance caused by alternations, which may only be a fraction of an inch thick, of dark-weathering clays and light-weathering greywackes. Analyses of a shale and a greywacke which contain more soda than potash and reduced iron have been cited by Grout (1933, table 1, analyses 1 and 2). Thermal metamorphism of these laminated slates by granite does not obliterate the banding until the grain-size is very coarse (Grout, 1933, p. 1001–02). Chemical analyses of the metamorphosed slates include separate analyses of micaceous and sandy laminae (Grout, 1933, table 2, analyses 2 and 3), which also show the reduced state of the iron and more soda than potash. An average of the analyses of the micaceous and sandy laminae (Table I, analysis 7) differs from that of one hornfels (D.4465.1) only in that the amount of lime is much greater; this is caused by the more calcareous composition of the sandy laminae. The average analysis is assumed to show that the chemical analysis of one of the hornfelses (D.4465.1) is compatible with the original rock being an alternation of argillaceous and quartzo-feldspathic sediment. The centre of the xenolith is more siliceous and could also have been derived from alternating sediments but of a more quartz-rich type; there is no sign that the quartz originally formed veins which have lost their identity on metamorphism.

It is clear that the banded hornfelses are similar in some respects to the laminated slates described by Grout, and that the slates are part of a normal geosynclinal succession of shales and greywackes (Pettijohn, 1943). The banding is not always clear-cut in the less metamorphosed hornfelses (D.4465.2) and in that instance it might be attributed to metamorphic segregation of an original siltstone with greywacke-type mineralogy and texture; but the other hornfels has banding which is too regular to have been derived in that way and, therefore, these rocks are more likely to have been an alternation of argillaceous and fine-grained quartzo-feldspathic sediments. The fact that they are similar to the finely laminated slates and greywackes described by Grout (1933) suggests that they might also be part of a geosynclinal succession but there is no conclusive evidence.

There is a close chemical similarity between the banded hornfelses and the Trinity Peninsula Series sandstones; the hornfelses are examples with a higher argillaceous fraction (D.4465.1) and a higher quartzo-feldspathic fraction (D.4463.3) than the sandstones. There is also some possibility of similar depositional environments. There would be a case for placing the banded hornfelses in the Trinity Peninsula Series except for the difficulty of reconciling the structural discontinuity, which is strong evidence for separating the two groups of sediments.

Minor Intrusions

Jurassic dykes

Two porphyritic microgranite dykes from the Nordenskjöld Coast (Elliot, 1966, p. 14) have been analysed, because one (D.4834.1) cuts a gabbro which would otherwise have been assigned to the Andean Intrusive Suite. The other dyke (D.4862.3) is one of a number of porphyritic acid intrusions which cut the Trinity Peninsula Series on the north side of Phoenix Peak. It is a leucocratic rock with phenocrysts (up to 2·0 mm.) of corroded quartz, sericitized plagioclase ($Ab_{86}An_{14}$) and penninite-leucoxene pseudomorphs after biotite in a fine-grained (0·02–0·10 mm.) matrix comprising quartz, alkali-feldspar, a few plagioclase crystals ($Ab_{89}An_{11}$) and a little chlorite and sericite. The dyke (D.4834.1) cutting the gabbro also exhibits the effects of thermal metamorphism. The quartz phenocrysts are more numerous and have been replaced by granoblastic quartz aggregates; the plagioclase phenocrysts are partially recrystallized and the biotite also forms aggregates. The matrix is finer-grained and it contains much muscovite.

These dykes are chemically similar to one another (Table II, analyses 1 and 2), taking into account the numerous quartz phenocrysts which give rise to the higher percentage of silica in one of them (D.4834.1). The larger amount of soda in the other rock (D.4862.3) may be partly accounted for by the more numerous plagioclase phenocrysts. These rocks are plotted on a triangular variation diagram with the co-ordinates (Fe″+Fe‴)—Mg—Alk and Ca—Na—K (Fig. 1). The differentiation trends for the Upper Jurassic Volcanic Group (Adie, 1964, fig. 2) are superimposed on Fig. 1. Both of the new analyses are close to the

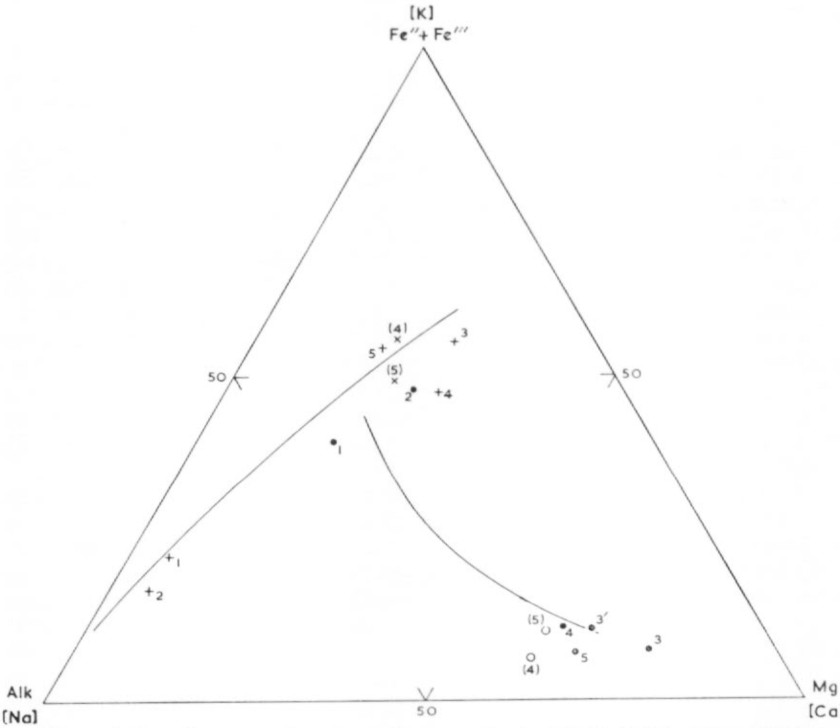

Fig. 1. Triangular variation diagrams plotted on the co-ordinates (Fe″+Fe‴)—Mg—Alk (+ and ×) and Ca—Na—K (● and ○). Variation trends for the Upper Jurassic Volcanic Group (Adie, 1964, fig. 2) have been superimposed.

1 and 2.	Porphyritic microgranite dykes (D.4862.3, 4834.1; Table II).
3 and 4.	Microgabbros (D.4804.3, 4817.2; Table II).
3′.	Microgabbro (D.4804.3; Table III).
5.	Pre-Andean microdiorite (F.110.1; Table II).
(4) and (5).	Pre-Andean microdiorite (Elliot, 1964, table II, analyses F.95.2, 57.2).

TABLE II. CHEMICAL ANALYSES OF DYKES FROM THE NORDENSKJÖLD COAST AND NORTH-WEST TRINITY PENINSULA AND COMPARABLE ANALYSES

	1	2	3	4	5	6	7	8	9	10	11	12	13	
SiO_2	68·50	74·03	46·79	47·99	49·89	48·53	49·21	51·80	51·01	43·71	60·66	55·36	55·38	SiO_2
TiO_2	0·21	0·10	1·06	1·26	1·21	0·82	0·73	1·36	1·26	1·16	1·21	0·63	0·76	TiO_2
Al_2O_3	15·70	14·49	16·42	16·72	19·36	16·66	13·53	14·94	14·84	13·12	13·50	13·71	16·51	Al_2O_3
Fe_2O_3	0·38	0·24	0·94	3·74	3·53	3·08	2·26	2·83	5·37	4·84	2·59	1·54	4·63	Fe_2O_3
FeO	2·26	1·21	8·54	5·70	5·68	6·40	6·82	6·12	2·93	4·39	5·95	6·24	2·99	FeO
MnO	0·01	0·01	0·15	0·13	0·12	0·13	0·14	0·13	0·15	0·16	0·18	0·10	0·10	MnO
MgO	0·82	0·57	5·76	6·87	3·63	7·63	11·58	5·96	3·11	7·43	2·24	7·93	3·89	MgO
CaO	1·99	2·27	10·76	8·48	9·85	7·50	5·15	7·69	10·13	14·88	4·39	7·71	7·34	CaO
Na_2O	4·50	2·46	2·27	3·41	3·87	3·44	3·53	3·04	3·18	2·21	4·30	1·91	2·94	Na_2O
K_2O	3·83	3·83	0·95	1·30	0·90	1·73	0·40	2·10	1·55	0·64	2·58	1·61	1·75	K_2O
H_2O^+	1·40	0·86	2·85	3·18	1·27	3·45	4·77	2·69	1·47	1·49	1·43	2·50	1·75	H_2O^+
H_2O^-	0·07	0·07	0·05	0·42	0·09	0·14	0·58	0·23	1·40	1·07	0·23	0·24	1·17	H_2O^-
P_2O_5	0·05	0·03	0·24	0·24	0·74	0·12	0·14	0·21	0·32	0·24	0·48	0·12	0·36	P_2O_5
CO_2	0·82	0·16	3·08	0·31	0·10	0·75	0·93	1·12	3·09	4·65	0·70	0·18	0·63	CO_2
TOTAL	100·54	100·33	99·86	99·75	100·24	100·38	99·77	100·22	99·81	99·99	100·44	99·78	100·20	TOTAL
ANALYSES LESS TOTAL WATER (Recalculated to 100)														
SiO_2	69·14	74·48	48·26	49·91	50·46	50·14	52·12	53·23	52·62	44·86	61·41	57·05	56·93	SiO_2
TiO_2	0·21	0·10	1·09	1·31	1·22	0·85	0·77	1·40	1·30	1·19	1·23	0·65	0·78	TiO_2
Al_2O_3	15·85	14·58	16·93	17·39	19·58	17·21	14·33	15·35	15·31	13·47	13·67	14·13	16·97	Al_2O_3
Fe_2O_3	0·38	0·24	0·97	3·89	3·57	3·18	2·39	2·91	5·54	4·97	2·62	1·58	4·76	Fe_2O_3
FeO	2·28	1·22	8·81	5·93	5·75	6·61	7·22	6·29	3·02	4·50	6·02	6·43	3·07	FeO
MnO	0·01	0·01	0·15	0·14	0·12	0·13	0·15	0·13	0·15	0·16	0·18	0·10	0·10	MnO
MgO	0·83	0·57	5·94	7·14	3·67	7·88	12·27	6·13	3·21	7·63	2·27	8·17	4·00	MgO
CaO	2·01	2·28	11·10	8·82	9·96	7·75	5·45	7·90	10·45	15·27	4·44	7·95	7·55	CaO
Na_2O	4·54	2·48	2·34	3·55	3·91	3·56	3·74	3·13	3·28	2·27	4·35	1·97	3·02	Na_2O
K_2O	3·87	3·85	0·98	1·35	0·91	1·79	0·42	2·16	1·60	0·66	2·61	1·66	1·80	K_2O
P_2O_5	0·05	0·03	0·25	0·25	0·75	0·12	0·15	0·22	0·33	0·25	0·49	0·12	0·37	P_2O_5
CO_2	0·83	0·16	3·18	0·32	0·10	0·78	0·99	1·15	3·19	4·77	0·71	0·19	0·65	CO_2
NORMS														
Q	23·21	39·23	1·45	—	—	—	—	3·18	11·44	1·83	14·19	9·22	13·44	Q
or	22·88	22·77	5·79	7·96	5·56	10·58	2·51	12·75	9·46	3·90	15·42	9·80	10·56	or
ab	38·39	20·98	19·83	30·05	32·49	30·11	31·63	26·49	27·74	19·20	36·82	16·68	24·63	ab
an	4·34	10·13	32·77	27·52	32·80	25·71	19·75	21·45	22·31	24·62	10·07	24·82	26·69	an
di	—	—	0·41	10·04	8·84	5·70	—	7·35	5·61	15·23	3·53	10·26	2·38	di
hy	5·61	3·31	28·44	5·37	8·27	5·13	31·05	18·78	5·39	14·32	11·08	25·00	9·00	hy
ol	—	—	—	9·61	1·59	14·51	7·04	—		—	—	—	—	ol
mt	0·56	0·35	1·41	5·65	5·10	4·61	3·47	4·21	6·44	7·20	3·80	2·29	6·73	mt
hm	—	—	—	—	—	—	—	—	1·10	—	—	—	—	hm
il	0·39	0·20	2·06	2·49	2·28	1·61	1·46	2·66	2·47	2·26	2·34	1·23	1·52	il
ap	0·13	0·07	0·60	0·60	1·68	0·27	0·37	0·50	0·77	0·60	1·17	0·27	1·01	ap
cc	1·89	0·36	7·24	0·73	0·20	1·77	2·25	2·61	7·26	10·85	1·61	0·43	1·40	cc
C	2·60	2·62	—	—	—	—	0·48	—	—	—	—	—	—	C
CATION PERCENTAGES														
Si^{+4}	32·32	34·82	22·56	23·33	23·56	23·44	24·36	24·88	24·60	20·97	28·71	26·67	26·59	Si^{+4}
Al^{+3}	8·39	7·72	8·96	[illegible]20	10·36	9·11	7·58	8·12	8·10	7·13	7·23	7·48	8·98	Al^{+3}
Fe^{+3}	0·27	0·17	0·68	[illegible]72	2·50	2·22	1·67	2·04	3·87	3·48	1·83	1·11	3·33	Fe^{+3}
Mg^{+2}	0·50	0·34	3·58	[illegible]31	2·21	4·75	7·40	3·70	1·94	4·60	1·37	4·93	2·41	Mg^{+2}
Fe^{+2}	1·77	0·95	6·85	4·61	4·47	5·14	5·61	4·89	2·35	3·50	4·68	5·00	2·39	Fe^{+2}
Na^{+1}	3·37	1·84	1·74	2·63	2·90	2·64	2·77	2·32	2·43	1·68	3·23	1·46	2·24	Na^{+1}
Ca^{+2}	1·44	1·63	7·93	6·30	7·12	5·54	3·90	5·65	7·47	10·91	3·17	5·68	5·40	Ca^{+2}
K^{+1}	3·21	3·20	0·81	1·12	0·76	1·49	0·35	1·79	1·33	0·55	2·17	1·38	1·49	K^{+1}
Ti^{+4}	0·13	0·06	0·65	0·79	0·73	0·51	0·46	0·84	0·78	0·71	0·74	0·39	0·47	Ti^{+4}
Mn^{+2}	0·01	0·01	0·12	0·11	0·09	0·10	0·12	0·10	0·12	0·12	0·14	0·08	0·08	Mn^{+2}
P^{+5}	0·02	0·01	0·11	0·11	0·33	0·05	0·07	0·10	0·14	0·11	0·21	0·05	0·16	P^{+5}
O^{-2}	48·57	49·25	46·01	44·77	44·97	45·01	45·71	45·57	46·87	46·24	46·52	45·77	46·46	O^{-2}
Position $[(\frac{1}{3}Si+K)-(Ca+Mg)]$	+12·04	+12·84	−3·18	−1·71	−0·72	−0·99	−2·83	+0·73	+0·12	−7·97	+7·20	−0·34	+2·54	Position $[(\frac{1}{3}Si+K)-(Ca+Mg)]$
Fe	80·3	76·7	67·8	63·0	75·9	60·8	49·6	65·2	76·2	60·3	82·6	55·3	70·4	Fe
Mg	19·7	23·3	32·2	37·0	24·1	39·2	50·4	34·8	23·8	39·7	17·4	44·7	29·6	Mg
Fe	22·4	17·2	55·1	47·6	54·3	45·4	40·9	47·0	52·2	50·5	49·0	44·0	48·2	Fe
Mg	5·5	5·2	26·2	28·0	17·2	29·2	41·6	25·1	16·3	33·3	10·3	35·5	20·3	Mg
Alk	72·1	77·6	18·7	24·4	28·5	25·4	17·5	27·9	31·5	16·2	40·7	20·5	31·5	Alk
Ca	18·0	24·4	75·7	62·7	66·0	57·3	55·6	57·9	66·5	83·0	37·0	66·7	59·2	Ca
Na	42·0	27·6	16·6	26·2	26·9	27·3	39·5	23·8	21·6	12·8	37·7	17·1	24·5	Na
K	40·0	48·0	7·7	11·1	7·1	15·4	4·9	18·3	11·9	4·2	25·3	16·2	16·3	K

1. D.4862.3 Porphyritic microgranite dyke, near Phoenix Peak, Nordenskjöld Coast.
2. D.4834.1 Porphyritic microgranite dyke, west of Tillberg Peak, Nordenskjöld Coast.
3. D.4804.3 Microgabbro, north-west of Bekker Nunataks, Nordenskjöld Coast.
4. D.4817.2 Microgabbro, south-west of Drygalski Glacier, Nordenskjöld Coast.
5. F.110.1 Pre-Andean microdiorite, north-east island of Three Little Pigs, Argentine Islands (Elliot, 1964).
6. F.26.2 Altered microgabbro, south-east island of The Barchans, Argentine Islands.
7. D.4862.5 Dolerite, near Phoenix Peak, Nordenskjöld Coast.
8. D.4822.6 Dolerite, south-west of Drygalski Glacier, Nordenskjöld Coast.
9. D.4817.5 Porphyritic basaltic dyke, south-west of Drygalski Glacier, Nordenskjöld Coast.
10. D.4816.3 Olivine-basalt dyke, south-west of Fender Buttress, Nordenskjöld Coast.
11. D.4831.2 Hybrid dyke, south of Drygalski Glacier, Nordenskjöld Coast.
12. D.4409.1 Dolerite, Mount Jacquinot, north-west Trinity Peninsula.
13. G.21.8 Porphyritic microdiorite, Keller Peninsula, King George Island (Hawkes, 1961*a*).

Analyses 1–12 by D. H. Elliot.

(Fe″+Fe‴)—Mg—Alk trend but they diverge from the Ca—Na—K trend, although the divergence is no more than that of the rocks from which the general trend has been derived.

The mineralogy places both of the dykes in the Upper Jurassic Volcanic Group and the chemical analyses do not exhibit significant differences compared with those given by Adie (1964, fig. 2). It is therefore concluded that the gabbro into which one of the dykes is intruded is either an earlier Jurassic intrusion or a post-kinematic intrusion associated with the regional deformation of the Trinity Peninsula Series (Elliot, 1966, p. 10).

Tertiary dykes

The majority of the dykes occur on the Nordenskjöld Coast and there are only a few in north-west Trinity Peninsula. The selected dykes have been analysed for comparison with known types from the Argentine Islands, King George Island and James Ross Island. More detailed descriptions of the Nordenskjöld Coast dykes and their field relations have been given already by Elliot (1966, p. 29).

The mineralogy and chemistry of these dykes show that there are affinities to tholeiitic rocks, a calc-alkaline suite and an alkali-basalt series. Insufficient evidence prevents a clear distinction between the first two types, although the chemical and mineralogical compositions of the dykes give a reasonable indication of the respective types. Chemical equivalents for the dykes can be found in calc-alkaline and tholeiitic series in other areas. One striking feature of many of the analyses is their high soda content. All the rocks have been plotted on triangular variation diagrams with the co-ordinates (Fe″+Fe‴)—Mg—Alk and Ca—Na—K (Figs. 1–4).

Microgabbros

The microgabbros from near Drygalski Glacier on the Nordenskjöld Coast (D.4804.3, 4817.2) are equigranular rocks composed mainly of labradorite, hornblende and augite, together with interstitial iron ore and secondary minerals which are particularly marked in one of the dykes (D.4804.3). This is shown in the analyses (Table II, analyses 3 and 4) by their high water contents and, in one instance (D.4804.3), by a high CO_2 content. The analyses, less total water and recalculated to 100 per cent, have some similarities to the pre-Andean microdiorite dykes of the Argentine Islands (Table II, analysis 5; Elliot, 1964, table II). The high lime content of one rock (D.4804.3) is the result of the introduction of lime together with CO_2 to generate calcite; if CO_2 and the corresponding amount of lime to make normative calcite are removed and the analysis is recalculated to 100 per cent, it is closely comparable with another pre-Andean microdiorite dyke from the Argentine Islands (Table III, analyses 1 and 2), except for more magnesia and less soda. Also, the presence of quartz in the norm is no longer remarkable, particularly as some of it may be secondary.

The high water content of the dykes near Drygalski Glacier is due to secondary alteration because the mineralogy is definitely gabbroic, whereas in the Argentine Islands dykes the dioritic mineralogy is due to alteration of the plagioclase to a more sodic composition ($Ab_{53}An_{47}$–$Ab_{60}An_{40}$) and the retention of volatiles to give much interstitial iron ore and green amphibole. This explains the differences in mineralogy of chemically similar dykes.

Adie (1964, p. 542) has suggested that the pre-Andean microdiorite dykes of the Argentine Islands are chemically close to the parental magma of the Upper Jurassic Volcanic Group. The two dykes from the Nordenskjöld Coast plot close to the Argentine Islands dykes on the triangular variation diagram (Fig. 1) on which the trends for the Upper Jurassic Volcanic Group have been superimposed. It is possible that the chemical similarities are fortuitous and the two groups of dykes are not related, but if they are, then either the supposed pre-Andean age of the Argentine Islands dykes is wrong, or the main gabbro intrusion south-west of Drygalski Glacier is older than the Andean Intrusive Suite. If they are related to each other and the Argentine Islands dykes are Jurassic in age, then the main gabbro intrusion may be related to the gabbro near Tillberg Peak (Elliot, 1966, p. 10). Alternatively, the Argentine Islands dykes may be related to the Andean Intrusive Suite, which would suggest a time interval between the intrusion of the main gabbro near Drygalski Glacier and the granodiorites of the Argentine Islands sufficient for the intrusion of a dyke phase. Finally, it is possible

TABLE III. RECALCULATED CHEMICAL ANALYSES OF DYKE ROCKS

	1	2	3	4	5	6
SiO_2	52·03	52·48	56·74	56·93	50·32	49·31
TiO_2	1·17	1·36	1·40	0·78	1·33	1·62
Al_2O_3	18·25	18·39	16·51	16·97	15·11	15·68
Fe_2O_3	1·05	3·89	5·97	4·76	5·57	2·61
FeO	9·50	6·51	3·26	3·07	5·05	8·94
MnO	0·16	0·22	0·16	0·10	0·18	0·17
MgO	6·40	4·31	3·46	4·00	8·56	8·61
CaO	7·59	7·70	6·88	7·55	10·31	8·21
Na_2O	2·52	4·04	3·54	3·02	2·55	3·47
K_2O	1·06	0·71	1·72	1·80	0·74	0·95
P_2O_5	0·27	0·33	0·36	0·37	0·28	0·39
CO_2	—	0·06	—	0·65	—	0·05
TOTAL	100·00	100·00	100·00	100·00	100·00	100·01

1. D.4804.3 Microgabbro, north-west of Bekker Nunataks, Nordenskjöld Coast. Table II, analysis 3; analysis less total water, CO_2 and sufficient lime to form normative calcite (recalculated to 100).
2. F.95.2 Pre-Andean microdiorite, north Uruguay Island, Argentine Islands (Elliot, 1964, table II). Analysis less total water (recalculated to 100).
3. D.4817.5 Porphyritic basaltic dyke, south-east of Drygalski Glacier, Nordenskjöld Coast. Table II, analysis 9; analysis less total water, CO_2 and sufficient lime to form normative calcite (recalculated to 100).
4. G.21.8 Porphyritic microdiorite, Keller Peninsula, King George Island (Hawkes, 1961*a*, p. 20). Analysis less total water (recalculated to 100).
5. D.4816.3 Olivine-basalt dyke, south-west of Fender Buttress, Nordenskjöld Coast. Table II, analysis 10; analysis less total water, CO_2 and sufficient lime to form normative calcite (recalculated to 100).
6. D.3740.1 Olivine-dolerite dyke, Blancmange Hill, James Ross Island (Nelson, 1966, table VIII, analysis 2). Analysis less total water (recalculated to 100).

that as none of the Argentine Islands dykes can be traced from outside the thermal aureole into the contact on The Barchans and the Forge Islands, the dykes may not be pre-Andean in age.

These dykes are plotted on a triangular variation diagram (Fig. 2) on which the trends for the Andean Intrusive Suite have been superimposed (Adie, 1964, fig. 5). The plotted positions diverge more from these trends than from those of the Upper Jurassic Volcanic Group (Fig. 1). This suggests that the dykes are more likely to be Jurassic in age, but until independent evidence is available the problem of their age cannot be solved.

Nordenskjöld Coast dolerites

These dykes, from Pheonix Peak (D.4862.5) and near Drygalski Glacier (D.4822.6), have an unusual mineralogy comprising a few altered plagioclase phenocrysts set in an intergranular matrix of altered labradorite laths ($Ab_{42}An_{58}$), unaltered augite grains, iron ore and interstitial chlorite. The mineralogy has been attributed to the retention of volatiles by the magma from which the dykes crystallized, and the consequent lowering of the temperature of crystallization and modification of the phases present. Three dyke rocks have been analysed, including one of the altered microgabbros (F.26.2) from the Argentine Islands (Elliot, 1964, p. 19; Table II, analyses 6, 7 and 8).

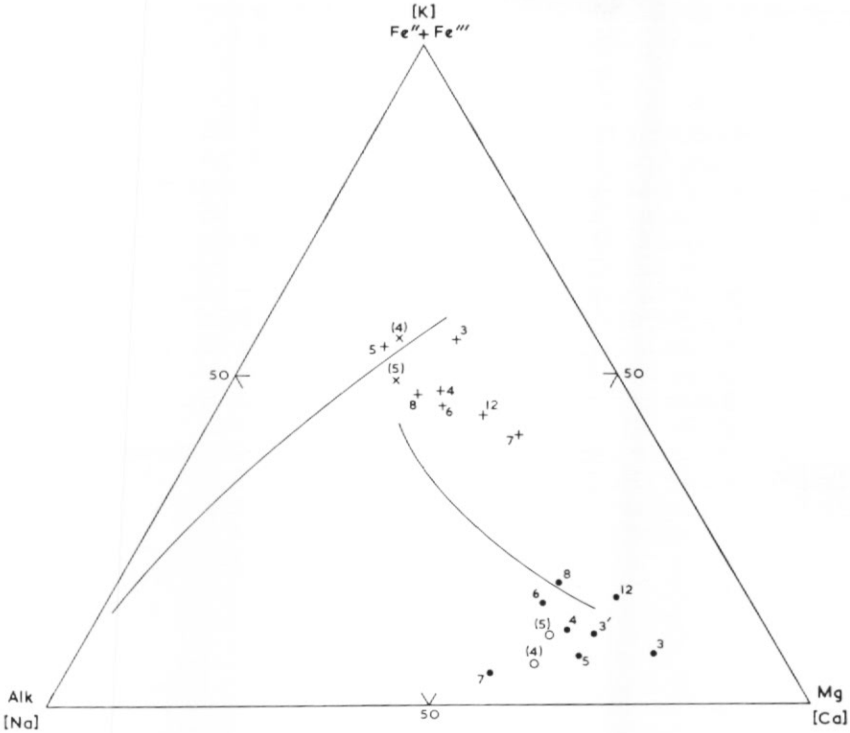

Fig. 2. Triangular variation diagrams plotted on the co-ordinates (Fe″+Fe‴)—Mg—Alk (+ and ×) and Ca—Na—K (● and ○). Variation trends for the Andean Intrusive Suite (Adie, 1964, fig. 5) have been superimposed.

3 and 4.	Microgabbros (D.4804.3, 4817.2; Table II).
3′.	Microgabbro (D.4804.3; Table III).
5.	Pre-Andean microdiorite (F.110.1; Table II).
6.	Altered microgabbro (F.26.2; Table II).
7 and 8.	Dolerites (D.4862.5, 4822.6; Table II).
12.	Dolerite (D.4409.1; Table II).
(4) and (5).	Pre-Andean microdiorites (Elliot, 1964, table II, analyses F.95.2, 57.2).

The mineralogy has similarities with that of spilites but the typical spilite chemistry of high soda and low potash does not occur, although one of the rocks (D.4862.5) is abnormally low in potash. This rock is also low in lime and high in magnesia; the mineralogy includes heavily altered andesine ($Ab_{68}An_{32}$) and a considerable amount of penninite in the matrix, which suggests that lime has been removed and that magnesia has been concentrated in the chlorite though whether or not it was derived from pre-existing magnesium-rich minerals cannot be determined. Normative corundum is present because of the low lime content. The other dykes (D.4822.6, F.26.2), which are mineralogically similar to one another, do not have the striking chemical characteristics of the dyke rock (D.4862.5) described above, though the Argentine Islands dyke has the higher alumina typical of dykes from that area. The higher alumina may be partly accounted for by more numerous plagioclase phenocrysts, and the rock may represent a different stage in the differentiation of the magma from which all these rocks were derived. Although rocks with similar chemical compositions can be found in calc-alkaline suites, the lower alumina is in the range of tholeiitic rocks with the same silica percentage.

These rocks are plotted on a triangular variation diagram (Fig. 2); one of the dykes (D.4862.5) is low in potash and high in magnesia and plots away from the other dykes. The others are close to the general Ca—Na—K trend for the Andean Intrusive Suite but they depart considerably from the general (Fe″+Fe‴)—Mg—Alk trend on the Mg side of the curve. There are insufficient analyses of rocks of this mineralogy for definite trends to be determined. The tholeiitic affinities of these rocks are discussed further on p. 93.

Porphyritic basaltic dyke

The porphyritic basaltic dyke (D.4817.5) south-west of Drygalski Glacier has a few plagioclase phenocrysts ($Ab_{31}An_{69}$) in a matrix of plagioclase laths ($Ab_{48}An_{52}$), unaltered augite grains, iron ore and a very fine-grained indeterminate brown mineral which fills the interstices together with a little quartz and much secondary calcite. Although this dyke has some similarities to the Nordenskjöld Coast dolerites, its chemical composition (Table II, analysis 9) shows significant differences. The high percentage of iron ore in the rock is reflected in the normative haematite and quartz. The large amount of lime and CO_2 has resulted from the introduction of calcite, and the low magnesia content is similar to many of the Argentine Islands dykes (Elliot, 1964, table II). Recalculation of the analysis, less CO_2 and the corresponding amount of lime to form normative calcite, to 100 per cent gives an analysis which is typical of calc-alkaline rocks and can be compared with a porphyritic microdiorite from King George Island (Table III, analyses 3 and 4). On a triangular variation diagram (Fig. 3) this analysis plots close to the porphyritic augite-microdiorites of the Argentine Islands and the dyke from King George Island. The recalculated analysis and the position on the triangular variation diagram suggest that it should be included with those calc-alkaline

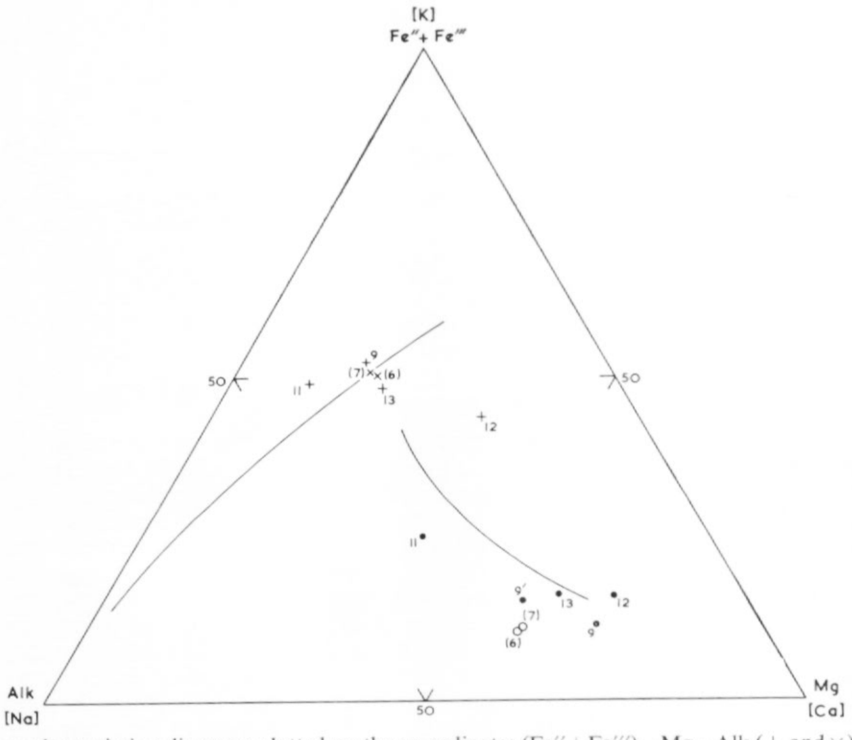

Fig. 3. Triangular variation diagrams plotted on the co-ordinates (Fe''+Fe''')—Mg—Alk (+ and ×) and Ca—Na—K (● and ○). Variation trends for the Andean Intrusive Suite (Adie, 1964, fig. 5) have been superimposed.

9. Porphyritic basaltic dyke (D.4817.5; Table II).
9′. Porphyritic basaltic dyke (D.4817.5; Table III).
11. Hybrid dyke (D.4831.2; Table II).
12. Dolerite (D.4409.1; Table II).
13. Porphyritic microdiorite (G.21.8; Table II).
(6) and (7). Tertiary porphyritic augite-microdiorites (Elliot, 1964, table II, analyses F.15.1, 22.1).

rocks even though the mineralogy is atypical and due to crystallization under different conditions.

Olivine-basalt dyke

This dyke (D.4816.3, west of Drygalski Glacier), which has been correlated with the alkali-basalts of the James Ross Island Volcanic Group, contains olivine pseudomorphs composed of calcite, talc, iddingsite and serpentine, and titanaugite phenocrysts set in a matrix of plagioclase laths ($Ab_{39}An_{61}$), titanaugite, iron ore and interstitial very fine-grained (?) iddingsite and bowlingite, and secondary calcite. Chemically (Table II, analysis 10), as would be expected from the mineralogy, it has a very high percentage of CO_2 and a high lime content. The absence of alteration in the plagioclase laths and the frequent replacement of olivine by calcite suggest that lime has been introduced with the CO_2 to generate calcite. Quartz in the norm is unusual for an alkali-basalt but the low soda content and the high oxidation ratio of the iron, which removes most of the ferrous iron as magnetite, explains its presence.

Recalculation of this analysis to 100 per cent, after removing the CO_2 and lime which form normative calcite, gives an analysis comparable with an olivine-dolerite dyke analysed by Nelson (1966; Table III, analyses 5 and 6). The olivine-basalt dyke (Table II, analysis 10) has been plotted on a triangular variation diagram (Fig. 4) on which the general trends for rocks of the James Ross Island Volcanic Group (Nelson, 1966, fig. 8) have been superimposed; the dyke is on the alkali-deficient side of the (Fe″+Fe‴)—Mg—Alk trend and between the Ca apex and the Ca end of the Ca—Na—K trend, although the recalculated analysis (Table

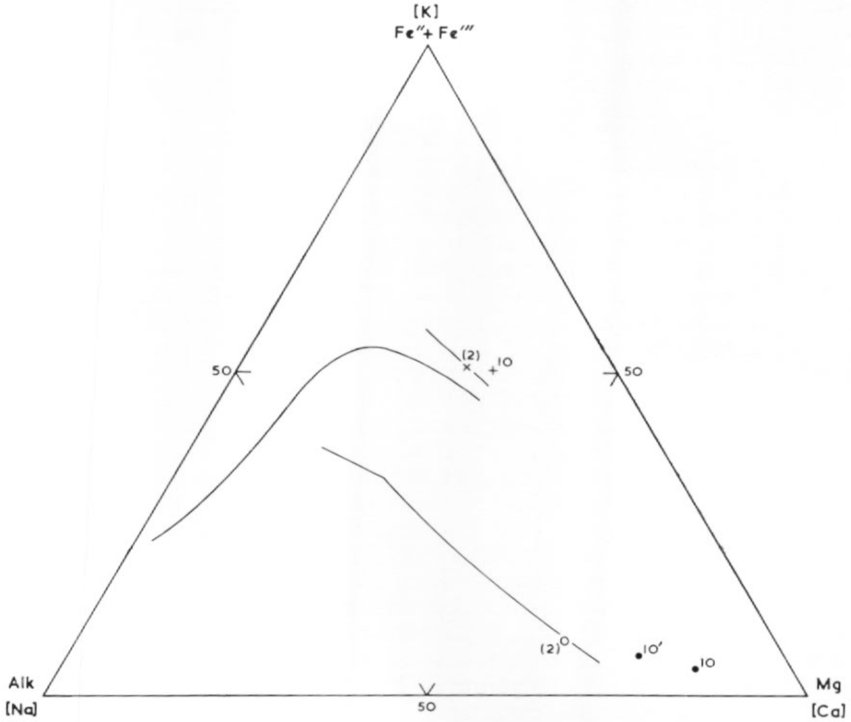

Fig. 4. Triangular variation diagrams plotted on the co-ordinates (Fe″+Fe‴)—Mg—Alk (+ and ×) and Ca—Na—K (● and ○). Variation trends for the James Ross Island Volcanic Group (Nelson, 1966, fig. 8) have been superimposed.

10. Olivine-basalt dyke (D.4816.3; Table II).
10′. Olivine-basalt dyke (D.4816.3; Table III).
(2). Olivine-dolerite dyke (Nelson, 1966, table VIII, analysis 2).

III, analysis 5) plots much closer to the latter trend. Although the chemistry of this dyke is not typical of an alkali-basalt, in that titania and total alkalis are low, the mineralogy is definitely of a rock of that type.

Hybrid dyke

The mineralogy of this dyke (D.4831.2), which crops out south of Drygalski Glacier, is unusual. The phenocrysts are of labradorite, augite, iron ore and rare hornblende, and there are pseudomorphs after orthopyroxene and olivine. The intergranular matrix comprises oligoclase laths, quartz, alkali-feldspar, hornblende, biotite and finely divided iron ore. This dyke is the result of an acid magma mixing with either basic rocks or partially crystallized basic magma. This is confirmed by the chemical analysis (Table II, analysis 11) which is anomalous for a normal rock of the same silica percentage. For such a rock, the percentage of alumina is low and the iron high; the latter is due to the large amount of iron ore in the rock, and the low alumina may be the result of a high percentage of ferromagnesian minerals and acid plagioclase, and alkali-feldspar in the matrix. Plotted on a triangular variation diagram (Fig. 3), this rock is close to the intermediate parts of the trends for the Andean Intrusive Suite.

Mount Jacquinot dolerites

At Mount Jacquinot in north-west Trinity Peninsula there are several basic dykes which cut the Trinity Peninsula Series (Elliot, 1965, p. 2). These dykes, which are 4–5 ft. (1·2–1·5 m.) wide, contain ferromagnesian phenocrysts set in a grey aphanitic matrix; the weathered surface is greyish brown and the phenocrysts are picked out as black laths and rounded crystals. Microscopically, one of the dykes (D.4409.1) has tholeiitic affinities and it is a dolerite. Faintly brown augite and (?) orthopyroxene pseudomorphs form single phenocrysts and aggregates. The augite has $\gamma : c = 44^\circ$ and $2V\gamma = 50^\circ$; much of it has a rim of colourless pyroxene. The orthopyroxene pseudomorphs are composed of a pale green chlorite, flakes and fibres of actinolite and a little calcite, and some of them have narrow clinopyroxene rims. One of the pyroxene aggregates includes basic labradorite ($Ab_{32}An_{68}$). The clinopyroxene rims on the phenocrysts and pseudomorphs are contemporaneous with the groundmass augite. Determination of $2V\gamma$ of this pyroxene was unsatisfactory but it is in the range of 40–45°. The intergranular matrix comprises plagioclase laths ($Ab_{42}An_{58}$), colourless augite, much leucoxene after iron ore, and some interstitial quartz and chlorite.

In some respects this dyke can be compared with the Tertiary porphyritic augite-microdiorites of the Argentine Islands (Elliot, 1964, p. 26) and a microdiorite dyke from King George Island (Hawkes, 1961*a*, p. 19). The porphyritic augite-microdiorites have labradorite phenocrysts in addition to augite and orthopyroxene pseudomorphs, all of which are set in an intergranular matrix of plagioclase ($Ab_{48}An_{52}$–$Ab_{52}An_{48}$), augite, iron ore, and accessory apatite and quartz. Compared with the other dykes, the one from Mount Jacquinot (D.4409.1) does not possess plagioclase phenocrysts, and it has less iron ore but more augite in the groundmass. The differences are exhibited in the chemical analyses (Table II, analyses 12 and 13) by lower percentages of alumina and soda, and higher magnesia in the dolerite. The dolerite and the correlated dykes of the Argentine Islands and King George Island have been plotted on a triangular variation diagram (Fig. 3), on which the general trends for the Andean Intrusive Suite are superimposed. The correlated dykes fall on the ($Fe'' + Fe'''$)—Mg—Alk trend but the Argentine Islands dykes fall on the soda-rich side of the Ca—Na—K trend. The Mount Jacquinot dolerite is close to the Ca—Na—K trend but it departs considerably from the ($Fe'' + Fe'''$)—Mg—Alk trend on the Mg-rich side. When plotted on Fig. 2, it falls in line with the other dolerites from the Nordenskjöld Coast and the altered microgabbro from the Argentine Islands. The comparatively low alumina, high magnesia and the plotted position on the triangular variation diagrams of the dolerite emphasize its tholeiitic affinities, and they are sufficient evidence for separating it from the microdiorites.

The Tertiary intrusions in relation to rocks from other parts of northern Graham Land

The new analyses of the minor intrusions of the Nordenskjöld Coast and Trinity Peninsula extend the usefulness of those of the Argentine Islands dykes. Taking into account other analysed volcanic and hypabyssal rocks from northern Graham Land, it is possible to suggest various trends which Tertiary–Recent intrusion and vulcanicity have followed. There is some difficulty in interpreting some of the analyses because, although the affinities of a clearly related suite of analysed rocks can be determined even though there are members which diverge from the variation trends suggested by the analyses, the affinities of single analyses are not necessarily clear-cut.

The microgabbros from the Nordenskjöld Coast have been compared with the pre-Andean microdiorite dykes of the Argentine Islands (p. 87), but there is some doubt as to the validity of the correlation because one of them (D.4817.2) cuts the main gabbro intrusion south-west of Drygalski Glacier. This has been discussed in greater detail on p. 87-88.

The Nordenskjöld Coast dolerites have tholeiitic affinities (p. 89) despite the high magnesia and low potash of one of the dykes (D.4862.5). The mineralogically similar dyke (F.26.2) from the Argentine Islands has the high alumina which is more typical of a calc-alkaline rock though the more numerous plagioclase phenocrysts may partly explain it and suggests that it might belong to a high-alumina basalt series. Similarly, the Mount Jacquinot dolerite has tholeiitic affinities. Tyrrell (1945, p. 44, table 1b) has described lavas from the west end of King George Island and he has stated that the chemical composition of one of them is definitely tholeiitic; Hawkes (1961*a*, p. 27) has also commented on this analysis and he has suggested that the Fildes Peninsula Group may have crystallized from a tholeiitic magma, whereas other lavas from King George Island are calc-alkaline in character. These lavas cannot be directly correlated with the dykes of Graham Land but they suggest more widespread tholeiitic magma activity, which Hawkes (1961*a*, p. 14) believed may have started in the early Miocene.

The porphyritic basaltic dyke (D.4817.5) has been correlated on chemical grounds with a porphyritic microdiorite from King George Island (Table III, analyses 3 and 4]. The microdiorite (Hawkes, 1961*a*, p. 19) has labradorite, augite and hypersthene phenocrysts in a matrix of acid plagioclase, intergrowths of quartz and alkali-feldspar, and much chlorite and biotite. This mineralogy is repeated in another dyke from Admiralty Bay (Tyrrell, 1945, p. 43, table 1b), in the Tertiary porphyritic augite-microdiorites of the Argentine Islands (Elliot, 1964, p. 26), and in lavas from the Point Hennequin Group of King George Island (Hawkes, 1961*a*, p. 16) and the Osterreith Range of Anvers Island (Hooper, 1962, p. 65). These dykes and lavas appear to be a related group though chemical analyses are necessary for determining their affinities. Hooper (1962, p. 65) has already noted the similarities between the Tertiary volcanic rocks of Anvers Island and the South Shetland Islands.

It is of interest that two of the Argentine Islands dykes (Elliot, 1964, table II, F.2.3 and 8.2) plot on Fig. 5 close to the trends for the Deception Island volcanic rocks (Hawkes, 1961*b*, fig. 15); they are microdiorites which have a trachytic texture composed of andesine laths and intergranular amphibole that may have been derived from pyroxene (Elliot, 1964, p. 24). These dykes show the soda enrichment of the Deception Island rocks but to what extent it may have been caused by secondary alteration is not known and direct correlation is impossible.

There is evidence for four trends in the post-Andean intrusive and extrusive rocks. An alkali-basalt series occurs on the concave side of the arc formed by the Antarctic Peninsula and it has few representatives outside James Ross Island and the area immediately to the north-east. A calc-alkaline trend may be shown by the porphyritic augite-microdiorites of the Argentine Islands and the mineralogically related types. There are a number of rocks with tholeiitic affinities from King George Island, Mount Jacquinot and the Nordenskjöld Coast, and there are the soda-rich rocks of Deception Island which Hawkes (1961*b*, p. 39) believed may have been derived from an original tholeiitic magma because the postulated parental magma is close to that of the porphyritic central magma-type of Mull.

Such an association of alkali, tholeiitic and calc-alkaline rocks has been recorded in Japan by Kuno (1959), who in a later paper (Kuno, 1960) distinguished a high-alumina basalt series as well; as yet there is insufficient evidence to do more than draw attention to this apparent similarity.

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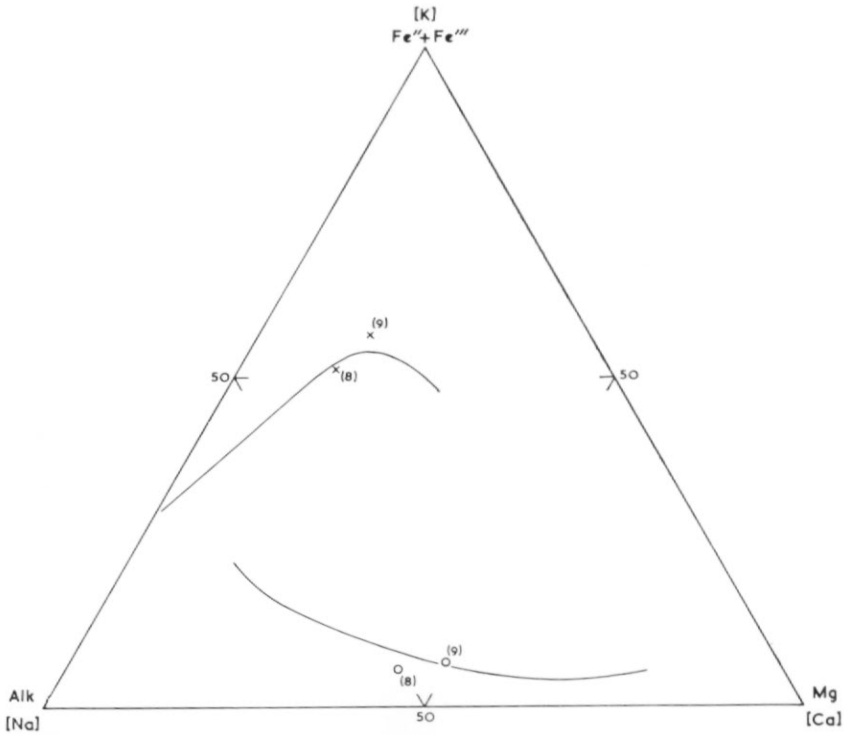

Fig. 5. Triangular variation diagrams plotted on the co-ordinates (Fe''+Fe''')—Mg—Alk (×) and Ca—Na—K (○). Variation trends for the Deception Island volcanic rocks (Hawkes, 1961*b*, fig. 15) have been superimposed.
(8) and (9). Post-Andean microdiorites (Elliot, 1964, table II, analyses F.2.3, 8.2).

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