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Petrochemistry and Geochemistry of Tertiary Volcanic Rocks, Northern Coast of King George Island, West Antarctica

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Abstract: Tertiary volcanic rocks which constitute the Fildes Block along the northern coast of King George Island (South Shetland Islands, West Antarctica) include basalt, basaltic andesite, andesite and dacite effusives (Fildes Peninsula Group, FPG), basaltic and andesitic plugs (Admiralty Bay Group, ABG). Plutonic rocks of the Wegger Peak Group (WPG) in this study were collected from Barton Horst near North Foreland. Most of basic lavas are porphyritic with plagioclase and augite phenocrysts. Rare orthopyroxene is found in andesite and dacite is usually finely crystalline. The component of plugs is much similar to the effusives although it contains less phenocrysts. As shown in majors and traces discrimination plots, all the effusives and intrusives which have higher Al_2O_3 content, are subalkaline rocks following a calc-alkaline trend. The REE abundance increases with increasing SiO_2 content. All chondrite-normalized REE patterns show light rare earth element enrichment and parallel to each other indicating calc-alkaline characteristics and close affinity of the magmas. Comparing with primary mantle composition, the rocks are rich in LIL element and have the same varying patterns as shown by the REE. The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of four samples of FPG and two ABG plugs are about 0.7034 and 0.5128, respectively. All plots of rocks are distributed along the mantle array in $^{143}Nd/^{144}Nd$ vs $^{87}Sr/^{86}Sr$ isotope correlation diagram, near the Prevalent Mantle area and plot together. The average ε_{Nd} value of rocks is +6±, implying these rocks did not undergo any crust contamination and might be derived from the same primary magma source. Almost no changes in $^{87}Sr/^{86}Sr$ ratio has been observed when SiO_2, K_2O, 1/Sr, Rb, Th, Sm of the rocks increased. The distribution of all the rocks on Ce/Yb-Ce and Th/Ta-Th correlation diagrams follows same trend with the slope over zero. It can be concluded that the volcanic rocks of the FPG lavas and the ABG plugs, as well as the WPG granodiorites, are all of calc-alkaline characteristics, being part of the South Shetland magmatic arc. They might have been generated directly by partial melting of upper mantle, being associated with the same simple magma source that resulted from the Mesozoic to Cenozoic volcanism controlled by the subduction of proto-Pacific oceanic crust beneath the Antarctic Plate.

Key words: volcanic rocks, petrochemistry, geochemistry, King George Island, Antarctica

INTRODUCTION

The northern coast of King George Island is largely covered by ice sheet, with only a few small magmatic rock exposures. The samples used in this paper were collected by the second author in 1980/81 along the northern coast of King George Island, between Fildes Peninsula and North Foreland, from onshore and offshore exposures (Figs. 1, 2). The majority of these sites were visited during helicopter flights, the only means of geological work along this dangerous glaciated coast. Systematic studies on petrography, petrochemistry, isotope geochemistry and chronology have been carried out by the Sino-Polish collaborative program recently. This paper is the first publication about the petrochemical features and the geochemical characters of the volcanics in northern coast of

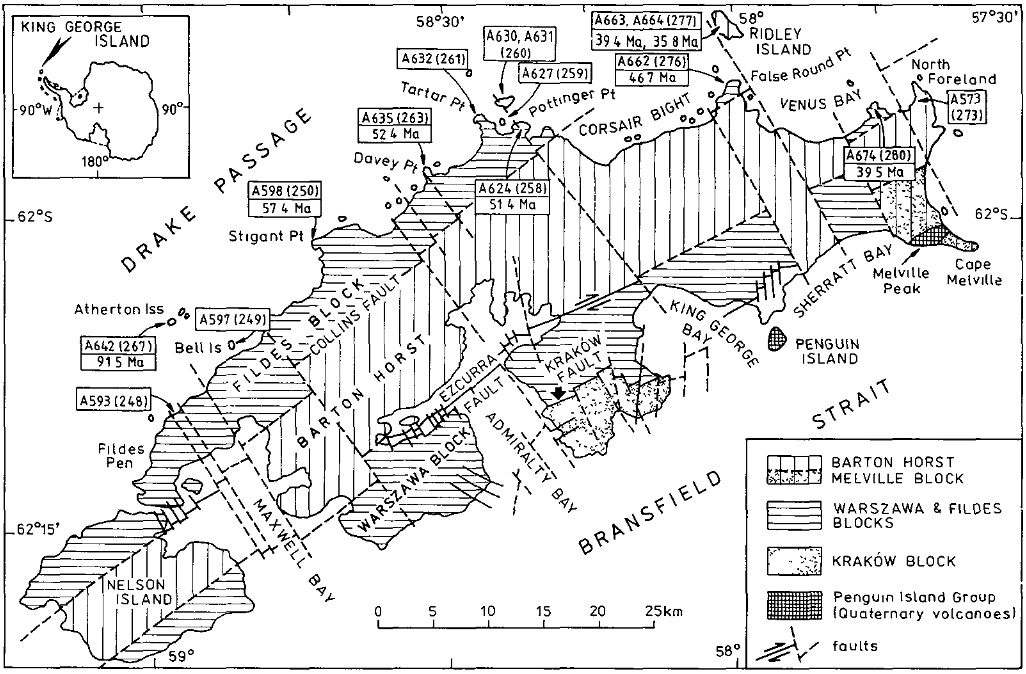

Fig. 1. Location of investigated samples against tectonic structure of King George Island (Birkenmajer, 1993). Numbers of sites and samples, and radiometric dates—as in Table 1.

King George Island.

GEOLOGICAL SETTING

The effusive volcanic rocks and associated hypabyssal and plutonic intrusions of the South Shetland Island arc are related to the subduction of proto-Pacific oceanic crust beneath the Antarctic continental margin during late Mesozoic through late Tertiary (130 to 14 Ma), with renewal of activity since Pleistocene. The magmatism was younging northeastwards along the arc's length (Pankhurst and Smellie, 1983; Smellie *et al.*, 1984; Birkenmajer *et al.*, 1986a).

King George Island lies in the middle of the South Shetland Islands arc. It consists mainly of Late Cretaceous through Oligocene terrestrial basaltic and andesitic lavas and associated pyroclastic rocks and plant-bearing volcaniclastic deposits, moreover of small-size andesitic and basaltic hypabyssal plugs, and moderate-size granodioritic through gabbroic plutons. Eocene through Miocene terrestrial glacial and fossiliferous glaciomarine deposits and associated volcanics occur only along the southeast coast of the island.

The ages of these rocks have been determined mainly on numerous K-Ar, subordinately $^{40}Ar/^{39}Ar$ and Rb-Sr dating of magmatic rocks, whenever possible supplemented by palaeontological dating (see, e.g., Grikurov *et al.*, 1970; Birkenmajer and Narebski, 1981; Birkenmajer *et al.*, 1983a, b, 1985, 1986a-c, 1988, 1990; Pankhurst and Smellie, 1983; Smellie *et al.*, 1984; Soliani *et al.*, 1988; Kawashita and Soliani, 1988; Zheng *et al.*, 1988, 1991; Birkenmajer, 1989a, b; Cao, 1989, 1990, 1992; Shen, 1989; Zhu *et al.*, 1992; Li *et al.*, 1992).

King George Island consists of several tectonic blocks bounded lengthwise by the NE-SW-trending strike-slip faults (Fig. 1). The axial upthrust Barton Horst is bounded in the south by the downthrown Warszawa Block and the Krakow Block, and in the north by the downthrown Fildes Block. These blocks are traversed by a younger system of strike-slip faults trending NW-SE (Birkenmajer, 1983, 1989b). The northern coast of King George Island, between Fildes Peninsula in the west and North Foreland in the east (Fig. 2) exposes the eastern

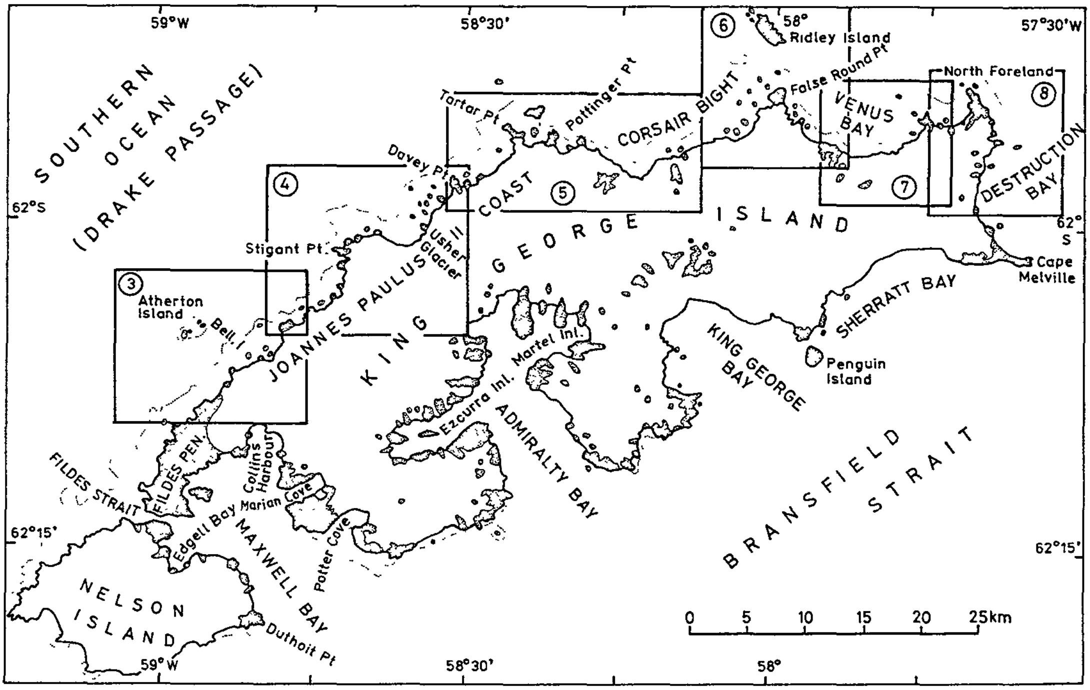

Fig. 2. Location of Figs 3-8 in King George Island. Ice-free areas stippled

parts of the Fildes Block and the Barton Horst (Fig. 1). The Fildes Block, between Fildes Peninsula and Pottinger Point (Figs 3-5), and at Venus Bay (Figs 6, 7), consists mainly of basaltic to andesitic effusives belonging to the Fildes Peninsula Group (FPG), cut by infrequent hypabyssal basaltic and andesitic plugs and dykes belonging to the Admiralty Bay Group (ABG). The Barton Horst at Corsair Bight, and between Venus Bay and North Foreland (Figs 2, 5-8), is built mainly of altered Early Tertiary volcanics (Martel Inlet Group) intruded by moderate-size diorite and granodiorite plutons of the Wegger Peak Group (WPG).

NEW RADIOMETRIC DATING

New radiometric dating ($^{40}Ar/^{39}Ar$ and K-Ar) was performed in the Institute of Geology, Chinese Academy of Sciences (Hu *et al.*, 1995a, b) on samples of andesitic lavas from 4 sites (FPG), and of basaltic plugs from 2 sites (ABG), collected by Birkenmajer in 1980/81 (Table 1; Figs 1-8).

The andesite lavas of the Fildes Peninsula Group (Table 1) ranged in $^{40}Ar/^{39}Ar$ age between 57.4 ± 0.7 Ma and 41.9 ± 1.8 Ma. These lavas are thus of Late Paleocene to Middle/Late Eocene ages, a result conformable with previous radiometric dating of volcanic rocks at Fildes Peninsula (see Smellie *et al.*, 1984; Birkenmajer, 1989a).

Two basaltic andesite plugs attributed to the Admiralty Bay Group were K-Ar dated at 91.5 ± 2.3 Ma (?Late Cretaceous, K-Ar dilute date) and 54.2 ± 1.1 Ma (Early Eocene, laser $^{40}Ar/^{39}Ar$ isochron age).

PETROGRAPHIC FEATURES

Petrographic characteristics of the samples (Fig. 9) were studied with microscope and the composition of major rock-forming minerals was determined with microprobe by the first author. Most of basic to intermediate lavas are porphyritic with plagioclase phenocryst content of 10% to 30%, however a few samples (such as A631) contain almost no phenocrysts. The plagioclase phenocrysts in basalt (e.g., A593) show normal zoning with bytownite core (An > 85%) and labradorite rim (An = 69% ±). Labradorite-andesine occurs in basaltic andesite (e.g. A624) and andesine was only found in an andesitic sample (A674). Basaltic andesite

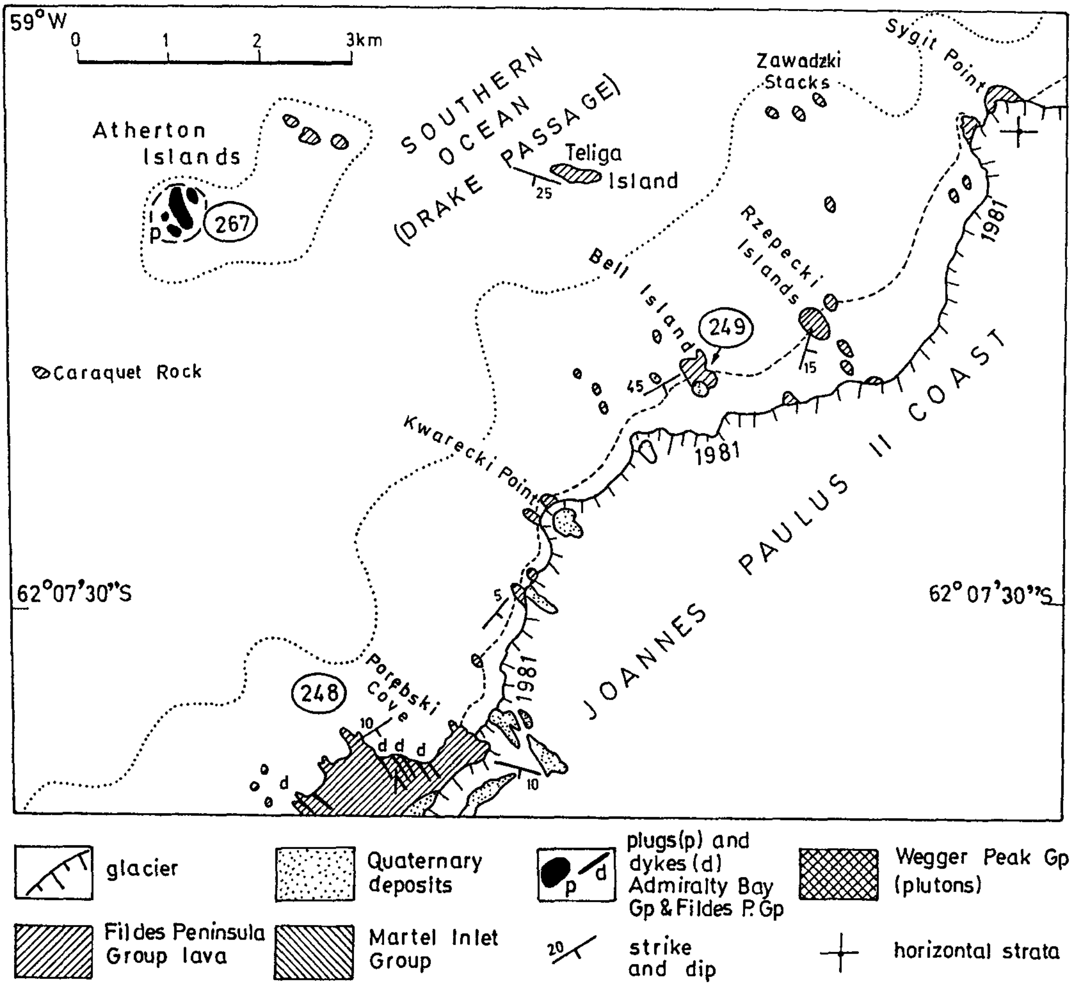

Fig. 3. Geological map of the area between Atherton Islands and northern coast of King George Island (after Birkenmajer, 1966). Location given in Fig. 1. Numbers denote sampling sites (see Table 1). Geological explanations refer to Figs 3-8

and andesite contain more clinopyroxene (augite) phenocrysts, while only a few orthopyroxene minerals are present in andesite (A674). The matrix of lava is composed predominantly of long lath-shaped plagioclase microlites ranging in composition from labradorite (A593) to andesine (A674), less frequent anhedral pyroxene grains and some opaque iron minerals, often showing intergranular texture. The altered dacitic lava is finely crystalline (A597, A598) with individual andesine phenocrysts and andesine microlites as well as a little brown volcanic glass (< 5%) occurring in groundmass.

Petrographic character of the basaltic to andesitic rocks of the ABG plugs is much similar to that of the lavas. The rocks are usually oligophyric or microcrystalline (A630). Normal zoning is developed in plagioclase phenocrysts with bytownitic composition in the center and labradorite (A635) or andesine (A642) outside it. The matrix exhibits pilotaxitic or intergranular texture, composed predominantly of long lath-shaped plagioclase (A635) or andesine (A642) microlites, pyroxene grains, and some opaque iron minerals.

The granodiorite consists mainly of labradorite or andesine (50%), orthoclase (20%), quartz (10%), amphibole (5%-10%), clinopyroxene (<3%), and

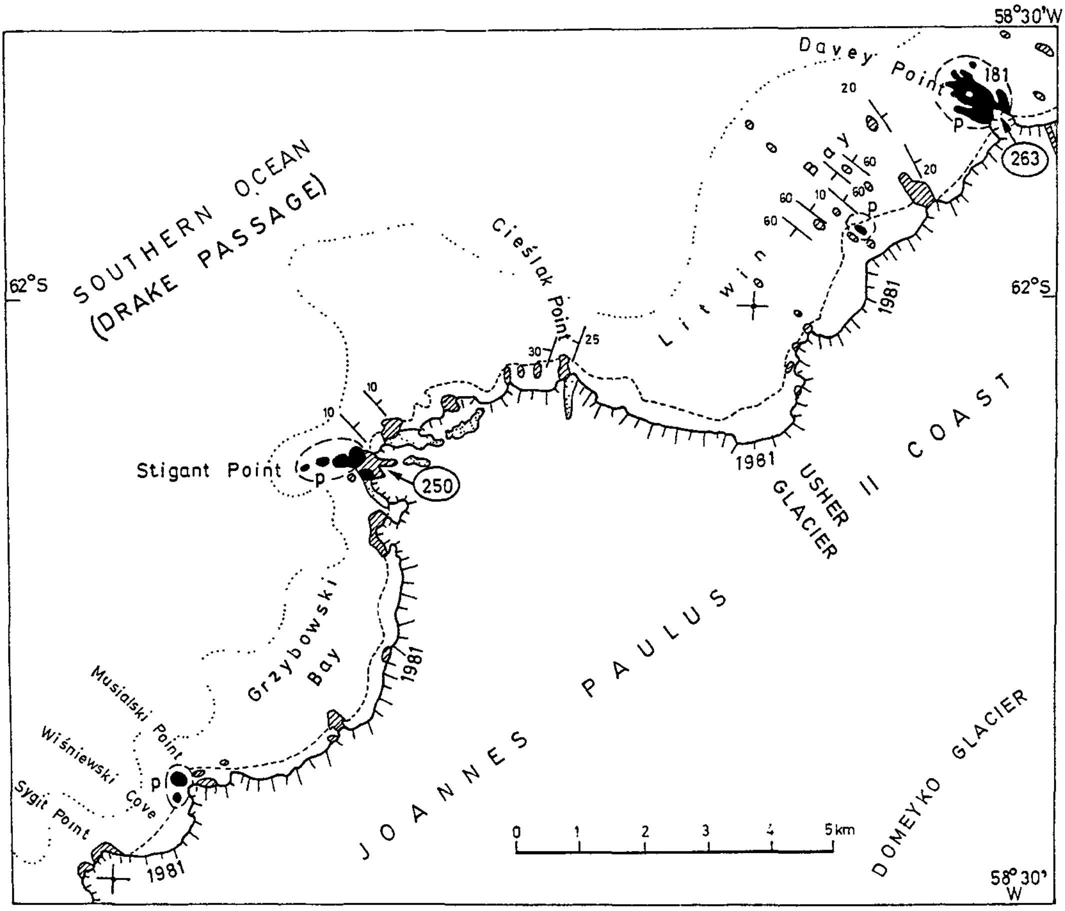

Fig. 4. Geological map of the area between Sygit Point and Davey Point, northern coast of King George Island (after Birkenmajer, 1996). Location given in Fig. 2. Numbers denote sampling sites (see Table 1). For explanation of geological symbols - see Fig. 3.

fine iron grains (<3%), sometimes with trace content of biotite, it shows a holocrystalline granitic texture. It should be pointed out, however, that the A573 granodiorite collected from North Foreland and consists of plagioclase (more than 30%), orthopyroxene (5%) and some clinopyroxene, with about 3% olivine phenocrysts (Fo=81%). The plagioclase phenocrysts range in composition from labradorite in the corn to andesine outwards, and the matrix includes oligoclase, pyroxene, anhedral quartz, and iron grains. The origin and significance of the forsterite , a foreign xenocryst associated with quartz, found in this granodiorite should be studied in detail.

PETROCHEMICAL CHARACTERISTICS

Major oxides of rocks were analyzed with XRF in Institute of Geology, Chinese Academy of Sciences (CAS) (Table 2). Trace and rare earth element contents, except for Nb, Y, V, were determined by INAA in the Application Division of the Institute of High Energy Physics, CAS (Table 3). Some samples contain higher water and volatile matter content due to chlorite and calcite alteration, therefore recalculated dry composition has been used in petrochemical study.

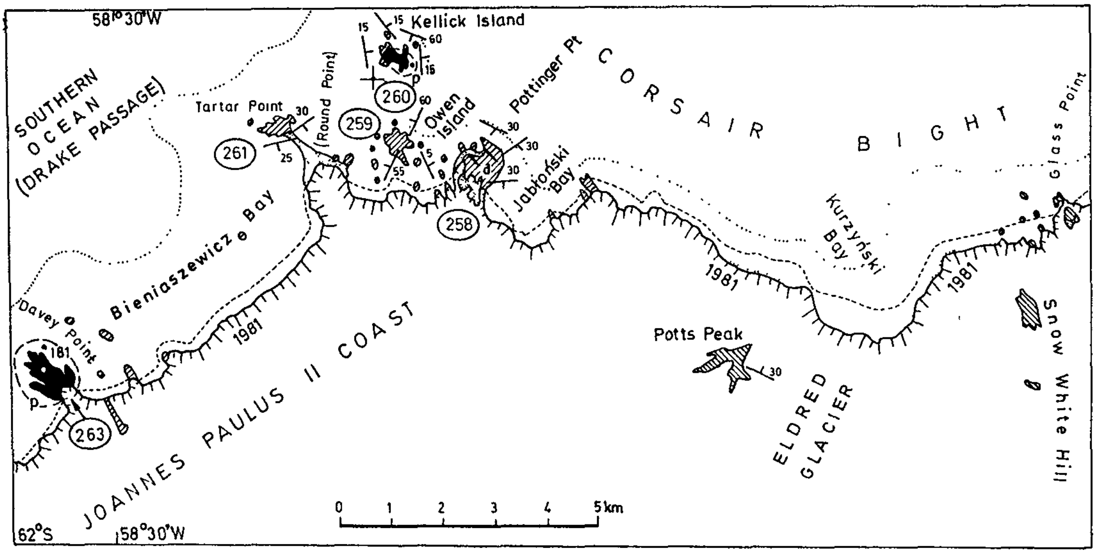

Fig. 5. Geological map between Davey Point and Glass Point, northern coast of King George Island (after Birkenmajer, 1996). Location given in Fig. 2. Numbers denote sampling sites (see Table 1). For explanation of geological symbols—see Fig. 3.

Table 1. List of igneous rock samples used for petrological and geochemical studies

Site No	Sample No	Rock	Unit	Age (Ma)
248 Porebski Cove, Fildes Pen.	A-593	basalt lava	FPG	-
267 Atherton Isl.	A-642	basalt plug	ABG	91.5 ± 2.3*
249 Bell Island	A-597	dacite lava	FPG	—
250 Stigant Pt	A-598	dacite lava	FPG	57.4 ± 0.7
263 Davey Pt	A-635	basalt plug	ABG	52.4 ± 1
261 Tartar Pt	A-632	andesite lava	FPG	—
259 Owen Island	A-627	andesite lava	FPG	—
260 Kellick Island	A-630	basalt plug	ABG	—
	A-631	andesite lava	FPG	—
258 Pottinger Pt	A-624	andesite lava	FPG	51.5 ± 3
276 False Round Pt	A-662	andesite lava	FPG	46.7 ± 0.97
277 Ridley Island	A-663	granodiorite	WPG	39.4 ± 1.2*
	A-664	granodiorite	WPG	35.8 ± 1.1*
280 Czeslaw Point, Brimstone Pk	A-674	andesite lava	FPG	41.9 ± 1.8
237 North Foreland	A-573	diorite	WPG	-

Note: for radiometric dating, King George Island, northern coast radiometric dating by Hu *et al.*, 1995a, b; Ridley Island dates from Birkenmajer *et al.*, 1986a.

*: K-Ar age and the others: $^{40}Ar/^{39}Ar$ ages.

ABG - Admiralty Bay Group; FPG - Fildes Peninsula Group; WPG - Wegger Peak Group. For location of sites and samples see Figs 2-8

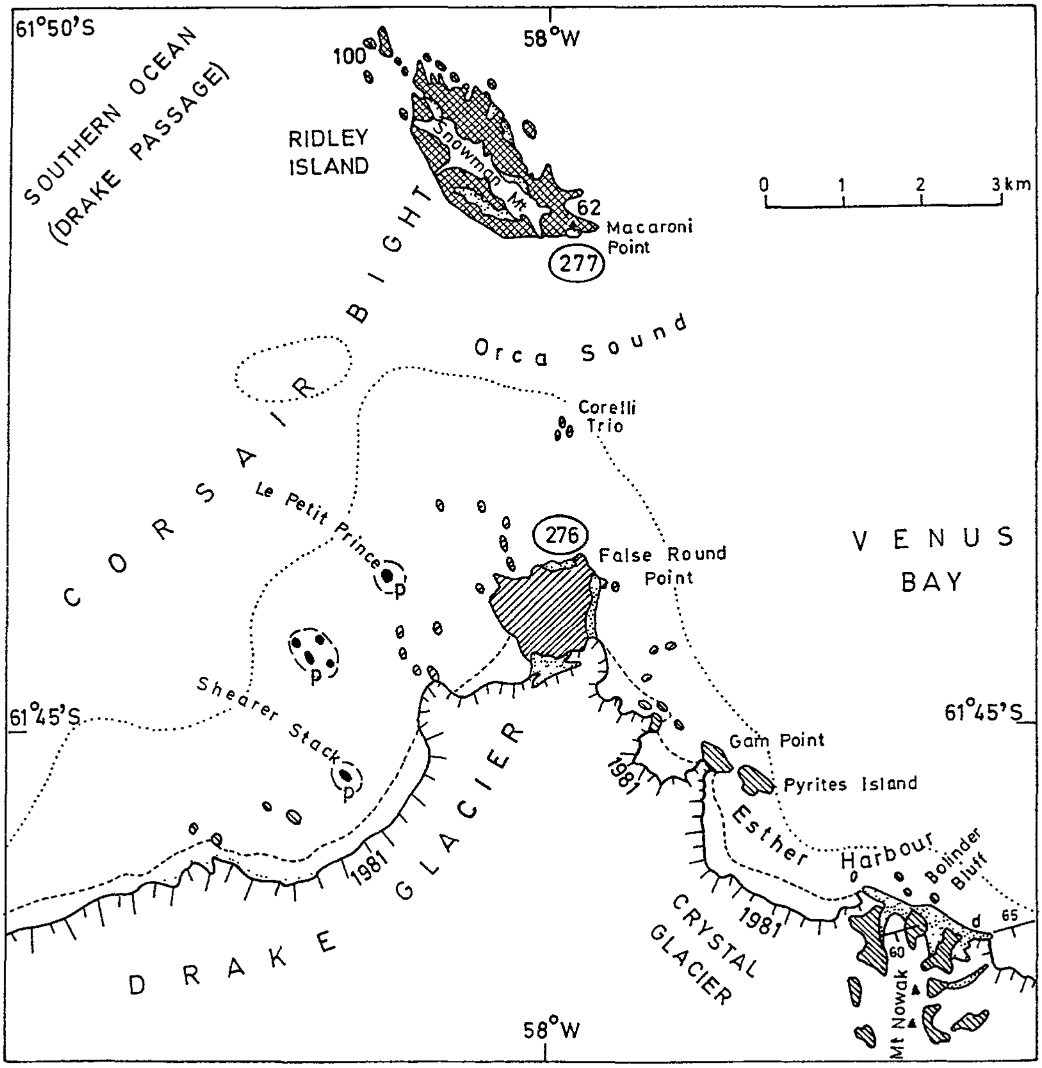

Fig. 6. Geological map of Ridley Island and the vicinity of False Round Point, northern coast of King George Island (after Birkenmajer, 1996). Location given in Fig. 2. Numbers denote sampling sites (see Table 1). For explanation of geological symbols—see Fig. 3.

Rock Series

Based on the composition of rocks (Table 2) and the Silicon-alkali chemical classification of igneous rocks (Cox *et al.*, 1979), the FPG lavas vary from basalt to dacite, ABG plugs include basaltic andesite and andesite, and the rock of WPG is basically granodiorite. All samples contain higher alumina content (Al_2O_3>17%), only the dacite has lower Al_2O_3content, which is, however, up to 16% also (Table 2). The contents of MgO, FeO and CaO are obviously decreasing and Na_2O, K_2O, and P_2O_5 increasing with increasing SiO_2, showing the evolution from basic to acid magma and the chemical affinity of different rocks.

All of studied rocks are subalkaline on the basis of SiO_2 and (Na_2O+K_2O) correlation (Irvine & Barager, 1971). On the discrimination plots of FAM (Fig. 2, Irvine and Barager, 1971) and Ti-Zr-Sr triangle diagram (Pearce and Cann, 1973), these

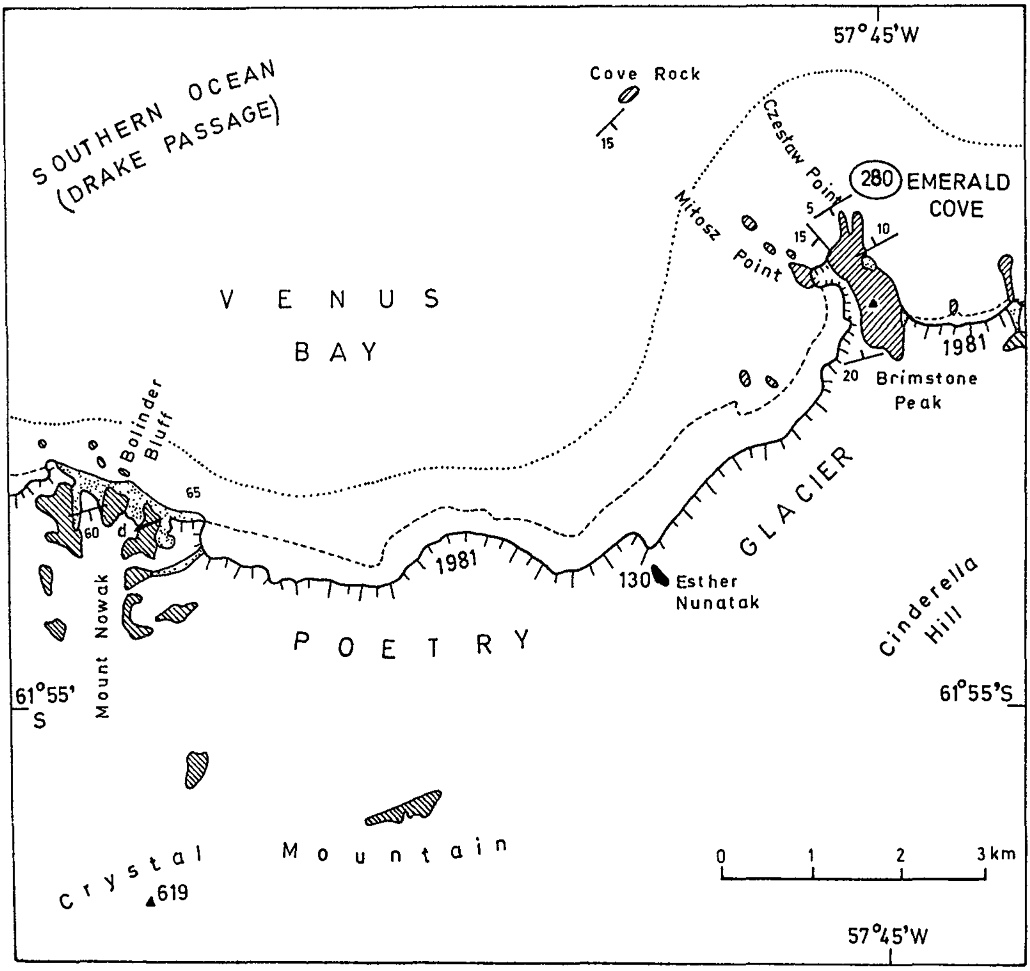

Fig. 7. Geological map of Venus Bay, northern coast of King George Island (after Birkenmajer, 1996). Location given in Fig. 2. Numbers denote sampling sites (see Table 1). For explanation of geological symbols—see Fig. 3.

rocks belong to calc-alkaline association. Furthermore, Trace element discrimination suggests that they are the calc-alkaline members formed in a volcanic arc environment (Fig. 10, Wood, 1980).

Rare Earth Element

The REE contents of 9 FPG samples vary greatly and increase along with silicon content increases. The lowest content, 35.96 ppm, was found in the A593 basalt, and the highest content of 124.52 ppm has been determined in A597 dacite. A630 basaltic andesite of ABG contains higher alkali and higher REE content, however, the REE contents of another two andesites are higher than that of FPG lavas, which are increasing with increasing silicon. The REE contents of the WPG intrusives are usually higher than the lava's (Table 3). The REE content of above rocks is compatible to that of the Cenozoic volcanic rocks in Fildes Peninsula and southern part of King George Island and the late Mesozoic volcanics of Livingston Island (Zheng *et al.*, 1991; Li *et al.*, 1992; Birkenmajer *et al.*, 1991; Zheng *et al.*, 1995a), which is at the same level of calc-alkaline rocks.

From the REE chondrite-normalized distribution patterns (Sun, 1982) (Fig. 11) and Table 3, it can be seen that the light REE of all samples was slightly enriched, obviously distinguishable from the flat or LREE depleted patterns of tholeiiete. Although the

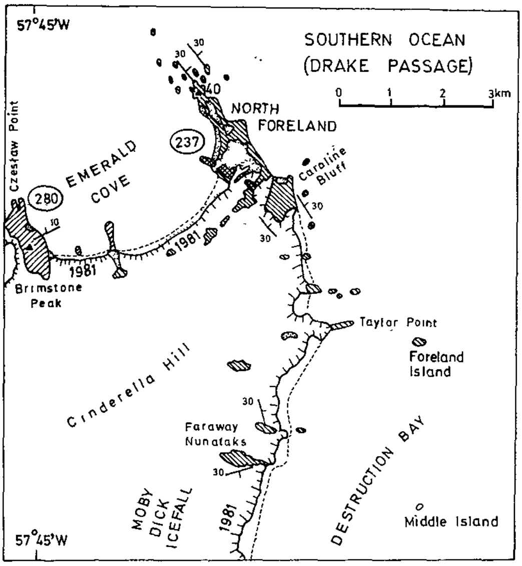

Fig. 8. Geological map of North Foreland and vicinity (after Birkenmajer, 1996). Location given in Fig. 2. Numbers denote sampling sites (see Table 1). For explanation of geological symbols—see Fig. 3.

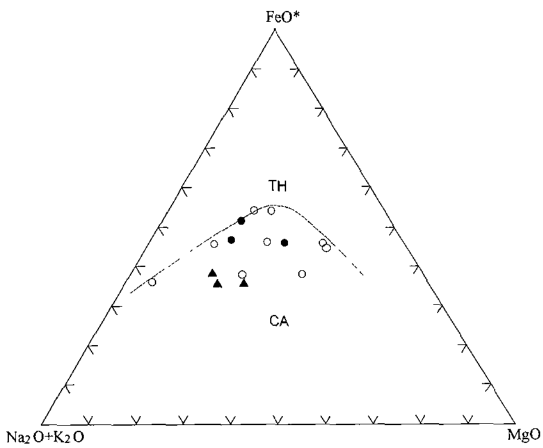

Fig. 9. F(FeO*) - A(Na_2O+K_2O) - M(MgO) diagram. The boundary between tholeiitic (TH) and calc-alkaline (CA) series is after Irvine and Barager (1971). Circle (○): lava of FPG; solid circle (●): rock of ABG; solid triangle (▲): intrusives of WPG

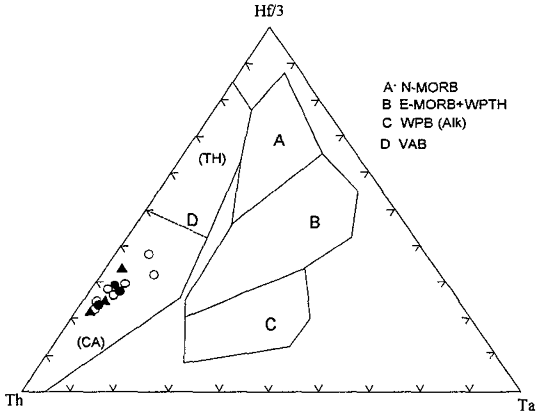

Fig. 10. Hf - Th - Ta triangle diagram to determine tectonic settings (after Wood, 1980). N-MORB: Normal Middle Ocean Ridge Basalt; E-MORB+WPTH: Enriched-Middle Ocean Ridge Basalt+Within Plate THoleiite; WPB (Alk): Within Plate Basalt (Alkaline); VAB: Volcanic Arc Basalt including THoleiitic and Calc-Alkaline. Symbols are the same as in Fig. 9.

FPG basalt has the lowest REE content and WPG granodiorite has the highest, they do not show any Eu anomaly. The very weak negative anomaly of Eu was found only in the basaltic andesite and andesite of FPG (Fig. 11). Besides the FPG basalt which shows lower $(Ce/Yb)_{CN}$ ratio, either lavas and intrusives display similar $(Ce/Yb)_{CN}$ ratio and the chondrite-normalized distribution patterns almost parallel to each other, reflecting the affinities of different rocks and the evolutionary trend of magma controlled by fractional crystallization (Fig. 11). The Eu anomaly is usually considered as the reflection of plagioclase fraction in magma generation process, however, there is basically no Eu anomaly in basalt or granodiorite, suggesting that plagioclase did not play an important role during magma evolution

Trace Element

Discussion on the trace element characteristics of rocks is based on the MORB (Pearce, 1983), and the spider diagrams are shown in Fig.12. It can be seen that, on the one hand, all rock are rich in LIL element, such as Rb, Ba and Th, and slightly enriched in mediate incompatible element Zr ($D<0.2$) on the level of MORB. On another hand, the distribution curves of rocks presented show the same shape, increasing from the FPG basalt to the WPG granodiorite, indicating the inherent genera-

Table 2. Chemical composition of the igneous rocks from the northern coast of King George Island

No.	1	2	3	4	5	6	7	8
Sam.N.	A631	A593	A627	A632	A662	A624	A674	A597
Loc.	Kellick Island	Porebski Cove	Owen Island	Tartar Pen.	False R. Point	Pottinger Point	Czeslaw Point	Bell Island
Occ.	lava	lava	lava	lava	lava	lava	lava	lava
Group	FPG	FPG	FPG	FPG	FPG	FPG	FPG	FPG
SiO_2	48.86	48.97	49.5	50.95	52.71	53.79	56.84	60.31
TiO_2	1.22	0.7	0.42	0.9	0.69	0.76	0.65	1.04
Al_2O_3	15.33	17.92	17.37	18.11	16.78	17.72	17.67	15.76
Fe_2O_3	5.2	5.56	2.08	3.84	3.67	2.74	4.31	4.88
FeO	4.73	3.49	4.38	3.82	4.42	5.05	1.43	2.61
MnO	0.22	0.14	0.15	0.15	0.13	0.13	0.11	0.12
MgO	3.77	6.68	5.67	2.31	5.65	3.9	3.44	2.17
CaO	7.04	10.88	6.66	9.74	9.21	6.12	6.33	5.04
Na_2O	2.78	2.92	4.14	3.07	2.52	2.89	3.82	4.3
K_2O	1.59	0.33	0.32	0.72	0.41	1.88	1.73	1.73
$P2O^5$	0.22	0.08	0.07	0.15	0.1	0.13	0.14	0.18
H_2O	4.67	1.31	5.46	2.93	2.59	3.42	2.69	1.56
Loi	4.46	0.92	3.71	3.47	1.36	1.66	0.92	0.49
total	100.09	99.9	99.93	100.16	100.24	100.19	100.08	100.19

No.	9	10	11	12	13	14	15
Sam.N.	A598	A630	A635	A642	A573	A664	A663
Loc.	Stigant Point	Kellick Island	Davey Point	Atherton Island	North Foreland	Ridley Island	Ridley Island
Occ.	lava	plug	plug	plug	intrusive	intrusive	intrusive
Group	FPG	ABG	ABG	ABG	WPG	WPG	WPG
SiO_2	64.16	49.82	53.84	57.2	58.29	58.7	59.48
TiO_2	0.8	1.21	0.73	1.55	0.69	0.87	0.71
Al_2O_3	16.24	14.77	17.67	15.82	17.4	17.69	16.88
Fe_2O_3	2.79	7.17	3.79	3.27	2.45	3.12	3.65
FeO	1.52	3.27	4.27	5.07	3.65	2.69	2.67
MnO	0.14	0.16	0.15	0.18	0.08	0.12	0.12
MgO	0.49	3.01	4.49	2.93	3.89	3.03	2.8
CaO	3.33	6.88	8.48	5.81	6.36	5.5	4.93
Na_2O	4.47	5.13	3.45	4.68	4.45	4.33	4.23
K_2O	2.17	0.85	0.89	1.49	1.8	2.38	2.57
P_2O_5	0.19	0.22	0.12	0.35	0.14	0.12	0.15
H_2O	2.04	3.37	1.83	1.27	0.76	1.19	1.26
Loi	1.57	4.28	0.44	0.39	0.25	0.37	0.5
total	99.91	100.14	100.15	100.01	100.21	100.11	99.95

tion relationship of different rocks. It is worth considering that the depletion degree of Nb was increasing and the positive anomaly of Sr decreasing with the increase of the silica content in rocks, the transitional metal element Ti becoming greatly depleted (Fig. 12) and Cr, Ni strongly depleted (Table 3), this implies that the ferromagnesian minerals and the plagioclase crystallized from melt at same time.

The above petrochemical features as shown by major and trace element studies prove that the Tertiary volcanic and intrusive rocks exposed along the northern coast of King George Island are much compatible with the Mesozoic to Cenozoic volcanic

Table 3. Trace element contents of the igneous rocks from the northern coast of King George Island (ppm)

No.	1	2	3	4	5	6	7	8
Sam.N.	A631	A593	A627	A632	A662	A624	A674	A597
Cr	11.2	91	105	20.4	208	34.4	26.8	80.4
Ni	77.3	79.4	63.9	72	73.9	68.1	42.6	67
Co	26.6	37.4	30.7	22.3	30.1	23.1	13.5	15.6
Sc	31.1	35.4	22.9	29	30.7	24.4	11.9	24.6
V*	393	280	199	287	248	279	190	228
Zn	8.15	8.49	6.79	7.51	7.82	7.17	27.5	56.5
Rb	46.3	37	9.07	6.3	13.8	42	23.9	37.5
Cs	4.45	0.381	3.92	1.8	3.32	2.31	0.623	0.737
Ba	213	186	95	227	302	329	347	396
Sr	382	461	775	576	473	507	518	445
Ta	0.305	0.096	0.64	0.158	0.214	0.13	0.184	0.254
Nb*	0	0	22	19	11	14	24	7
Hf	5.26	1.68	1.51	2.77	2.94	3.97	3.64	5.68
Zr	130	82	66.3	214	182	110	121	119
Y*	12	8	12	13	9	18	16	16
Th	4.35	0.824	1	2.32	2.19	3.75	4.06	4.69
U	1.65	0.454	0.571	0.701	0.698	1.23	1.27	1.57
La	28.9	6.03	6.55	15.7	11.9	17	18.1	24
Ce	49.8	12.6	14.2	34.3	23.7	36.6	38	51.4
Nd	23.8	8.6	8.49	19.9	14.4	20.7	18.4	29.2
Sm	6.01	2.4	2.06	4.96	3.7	4.54	4.15	6.33
Eu	1.89	0.872	0.83	1.59	1.14	1.12	1.22	1.88
Gd	5.95	2.61	1.99	4.62	3.69	4.37	3.96	6.1
Tb	0.954	0.46	0.347	0.712	0.643	0.719	0.654	0.985
Ho	1.21	0.585	0.412	0.815	0.891	0.885	0.802	1.21
Tm	0.492	0.231	0.15	0.316	0.328	0.316	0.292	0.441
Yb	3.04	1.37	0.876	1.86	1.97	1.84	1.67	2.6
Lu	0.451	0.2	0.125	0.267	0.273	0.256	0.232	0.372
No.	9	10	11	12	13	14	15	
Sam.N.	A598	A630	A635	A642	A573	A664	A663	
Cr	4.11	46.2	118	113	87	34.6	235	
Ni	43.2	75.2	71.2	68.5	107	61.2	62.4	
Co	4.18	24.2	29.5	15.1	18.9	16.8	18.8	
Sc	13.7	31.3	26.9	24.6	16.9	18.2	18.7	
V*	92	392	253	147	180	143	148	
Zn	25.2	8.12	7.56	55.4	26.8	27	44.1	
Rb	30.3	22.7	32.3	33.5	35	58.8	56.9	
Cs	1.05	1.64	2.58	1.16	1.21	1.63	1.18	
Ba	408	449	32	432	384	448	502	
Sr	260	503	725	455	501	532	494	
Ta	0.353	0.356	0.208	0.323	0.243	0.319	0.329	
Nb*	0	0	0	0	0	18	0	
Hf	3.12	5.11	3.9	5.7	4.43	9.26	6.53	
Zr	114	181	73.6	158	210	222	223	
Y*	21	18	12	18	17	18	25	
Th	1.88	4.14	3.98	4.44	4.27	5.77	7.46	
U	0.803	1.42	1.45	1.43	1.65	1.3	1.39	
La	13.5	22.6	16.8	27.9	17.1	23.8	31.1	
Ce	30.1	45.8	35.3	61.6	34	50.9	62.1	
Nd	16.7	27.6	18.9	32.2	18.2	26.4	30	
Sm	4.17	6.33	4.75	7.77	4.27	5.72	6.12	
Eu	1.5	1.67	1.4	2.5	1.39	1.62	1.63	
Gd	4.46	6.17	4.26	7.2	4.46	4.98	5.51	
Tb	0.743	1.09	0.672	1.15	0.757	0.816	0.894	
Ho	0.964	1.34	0.818	1.34	0.957	1.02	1.12	
Tm	0.392	0.486	0.303	0.496	0.355	0.399	0.432	
Yb	2.44	2.86	1.79	2.91	2.12	2.44	2.57	
Lu	0.347	0.386	0.249	0.408	0.291	0.349	0.373	

Analysed with INAA in the Application Division of Institute of High Energy Physics, CAS the element with * analysed with XRF in Institute of Geology, CAS

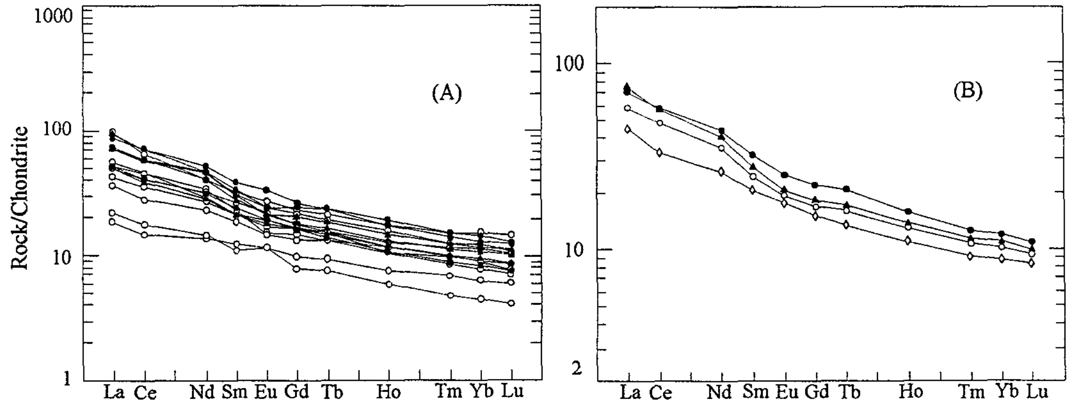

Fig. 11. Chondrite-normalized REE patterns of all samples (A) and average value (B). Rhombus (◇): average of FPG basalts; circle (○): average of FPG andesites, other symboles are the same as Fig. 9.

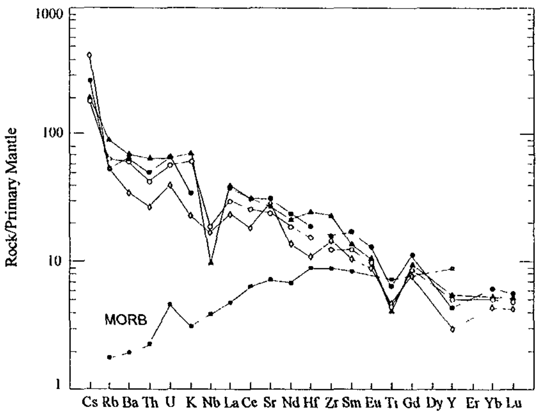

Fig. 12. Trace element spider diagram. Symbols are the same as in Fig. 11.

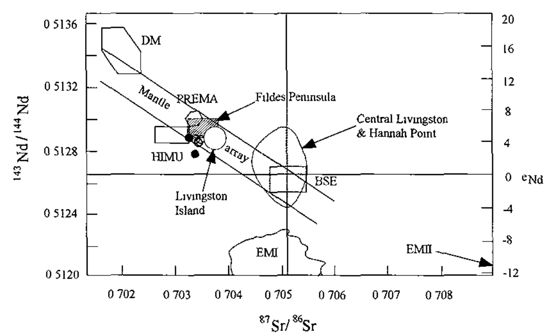

Fig. 13. $^{143}Nd/^{144}Nd$ - $^{87}Sr/^{86}Sr$ isotope correlation diagram. DM, depleted mantle; BES, bulk silicate Earth; EMI and EMII, enriched mantle; HIMU, mamtle with high U/Pb ration; PREMA, frequently observed PREvalent MAntle composition. Symbols are the same as in Fig. 9.

rocks of this island (Birkenmajer *et al.*, 1991; Zheng *et al.*, 1991; Li *et al.*, 1992) and also other islands of the South Shetland Islands (Smellie *et al.*, 1984; Zheng *et al.*, 1995a), all belonging to the South Shetland calc-alkaline magma arc formed during the subducting process of proto-Pacific ocean crust beneath Antarctic continent.

GEOCHEMISTRY AND MAGMA GENERATION DISCUSSION

Sr, Nd, Pb Isotope Composition

The Sr, Nd, Pb isotope composition of 6 fresh samples selected after petrochemical study (Table 4) were determined in the Isotope Division of Institute of Geology, CAS.

The isotope composition of these samples, both lavas and plugs, is almost the same: the $^{87}Sr/^{86}Sr$ ratios range from 0.7033 to 0.7035, $^{143}Nd/^{144}Nd$ ratio between 0.51278 and 0.51288 (Table 4), similar as in other Cenozoic volcanic rocks from Fildes Peninsula (Jin *et al.*, 1991; Li *et al.*, 1992), from the southern part of King George Island (Barbieri *et al.*, 1989; Birkenmajer *et al.*, 1991), and from the Mesozoic volcanic rocks in the eastern part of Livingston Island (Zheng *et al.*, 1995b). It differs from those of contaminated volcanic rocks of central Livingston and Hannah Point (Fig. 13). All results plot together on the $^{143}Nd/^{144}Nd$ vs $^{87}Sr/^{86}Sr$ isotope correlation diagram, within or nearby the

Table 4. Isotopic composition of the igneous rocks from the northern coast of King George Island

No.	1	2	3	4	5	6
Sam.N.	A662	A624	A674	A597	A635	A642
Rb(ppm)	8.10	34.57	28.98	35.67	27.77	32.35
Sr(ppm)	472.302	499.060	723.096	476.058	696.971	554.504
$^{87}Rb/^{86}Sr$	0.04951	0.70335	0.11569	0.21626	0.11501	0.16836
$(^{87}Rb/^{86}Sr)i$	0.703494	0.703347	0.703360	0.703364	0.703331	0.703386
$(^{87}Rb/^{86}Sr)p$	0.703557±23	0.703603±15	0.703508±22	0.703641±14	0.703478±23	0.703601±18
Sm(ppm)	4.117	4.973	5.004	6.151	5.044	9.401
Nd(ppm)	17.368	22.976	24.868	28.3	22.688	39.348
$^{147}Sm/^{144}Nd$	0.143379	0.130894	0.121701	0.131449	0.134417	0.144502
$^{143}Nd/^{144}Nd$	0.512862±10	0.512879±10	0.512875±8	0.512851±10	0.512868±10	0.512775±9
ε_{Nd}	+6.6	+7.0	+6.9	+6.4	+6.7	+4.9
$^{206}Pb/^{204}Pb$		18.570	18.671	18.653	18.533	18.648
		±0.005	±0.005	±0.005	±0.004	±0.003
$^{207}Pb/^{204}Pb$		15.608	15.707	15.676	15.606	15.693
		±0.013	±0.013	±0.018	±0.006	±0.011
$^{208}Pb/^{204}Pb$		38.567	38.941	38.613	38.686	38.960
		±0.021	±0.037	±0.032	±0.016	±0.027

Determined by Isotope Division of Institute of Geology, CAS

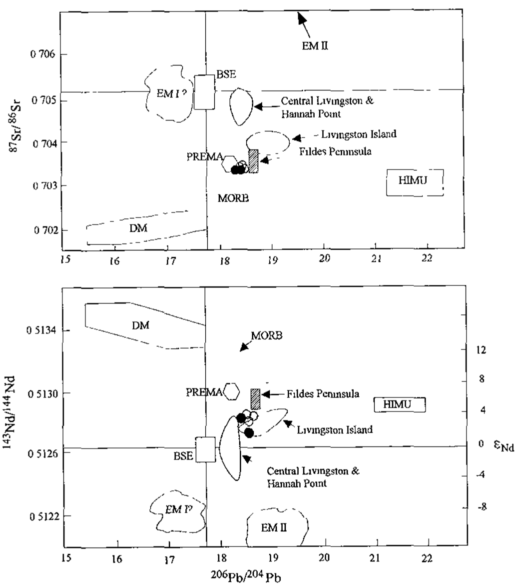

Fig. 14. $^{87}Sr/^{86}Sr$ - $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ - $^{206}Pb/^{204}Pb$ isotope correlation diagram. MORB, mid-ocean ridge basalt; others are the same as in Fig. 13.

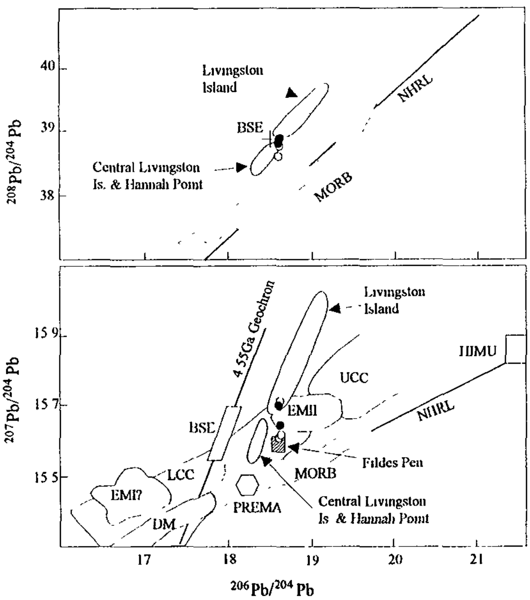

Fig. 15. $^{207}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ isotope correlation diagram. Symboles are the same as in Fig. 13.

Mantle array as defined by many MORB and OIB basalts, and near the frequently observed Prevalent Mantle (PREMA) composition (Fig. 13). It demonstrates that isotope composition of our rocks is close to that of their primary magma source. On the $^{87}Sr/^{86}Sr$ against $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ against $^{206}Pb/^{204}Pb$ correlation diagram (Fig. 14), the above primary igneous source feature is also well displayed. The plots of the rocks of the northern coast

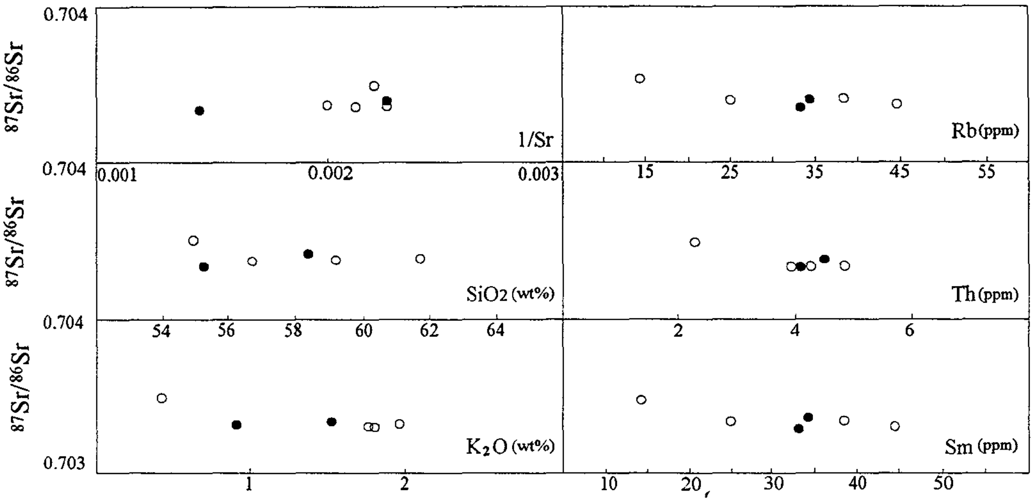

Fig. 16. $^{87}Sr/^{86}Sr$ vs 1/Sr, SiO_2, K_2O, Rb, Th, Sm correlation diagrams. Symboles are the same as in Fig. 9.

of King George Island, together with those of Fildes Peninsula (Jin *et al.*, 1991) and Livingston Island (Zheng *et al.*, 1995b), construct a negative correlation line nearly parallel to the 4.55 Ga geochron of the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ covariation diagram (Fig. 15), showing the magma evolutionary trend from PREMA to enriched mantle (EMII) composition. On the $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ correlation diagram (Fig. 15), the projections of all rocks also show a positive relation with similar slope to NHRL. However, the Pb isotope composition is closer to the BSE value (Allegre *et al.*, 1988). Therefore, it seems that all our volcanic rocks are enriched in radiogenic Pb isotopes with the same $^{206}Pb/^{204}Pb$ background.

Igneous Source Character Determination

The chemical composition of igneous rocks, may be subjected to changs by subsequent geological and petrogenetic processes on their journey from the source region where the melt was being extracted from the mantle to their site of emplacement, during or after solidification. Therefore, Sr, Nd and Pb isotope ratios of magma are frequently used to identify reservoirs and particular petrological processes. Sr isotopic ratios of igneous rocks of northern coast in Livingston Island vary between 0.7033 to 0.7035 (Table 3) and follow the "Mantle array" (Fig. 13), that are equal to, even lower than, the value of uncontaminated basalt (0.704 ± 0.002), suggesting that the magma was derived directly from upper mantle andwas otcotaminated by crustal material. The ε_{Nd} values of recent volcanic rocks are different, depending on their different tectonic settings: the value, ε_{Nd}=+12 is the representative of modern upper mantle and the mean of continental crust is about -15; they are complementing each other (Depaolo, 1981, 1988). The mantle-derived, uncontaminated magma has the ε_{Nd} value equal to, or above, zero and the value $\varepsilon_{Nd} < 0$ is considered to be an indicator of crust contamination. The average ε_{Nd} of the rocks from the northern coast of King George Island is +6±, implying that their magma was extracted directly from the upper mantle. Both the Sr and Nd isotopes also prove that the effusive and intrusive rocks of the northern coast of King George Island were derived directly from upper mantle.

Using $^{87}Sr/^{86}Sr$ vs 1/Sr correlation diagram, Brigueu *et al.* (1979) discussed the isotope differentiation during magma evolving process. The $^{87}Sr/^{86}Sr$ ratios will express a near-horizontally linear relation with 1/Sr ratios when no foreign material entered, because of too small influence on Sr isotopic composition caused by crystal differentiation and partial melting. Once the crust materials mixed with primary magma, the $^{87}Sr/^{86}Sr$ ratios of rocks will obviously increase and a positive linear relation between the $^{87}Sr/^{86}Sr$ ratios and Si, Rb, Ba, K, or Sr will prevail. Fig 16 shows the relationship

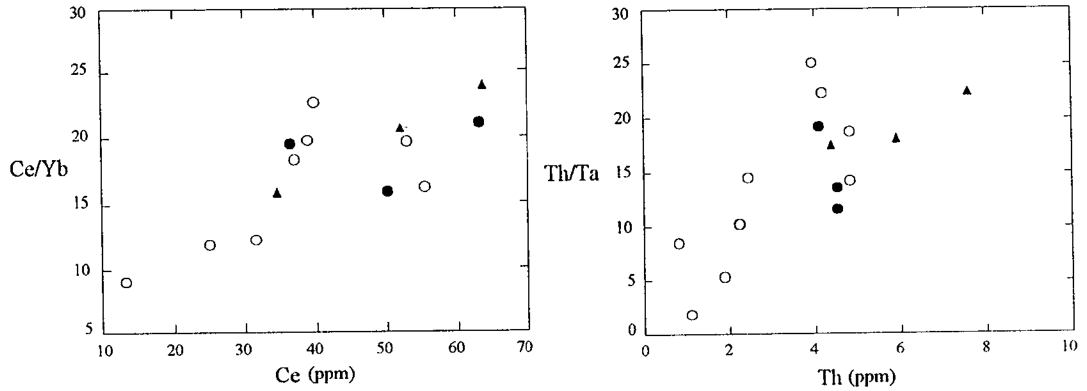

Fig. 17. Ce/Yb - Ce and Th/Ta-Th diagrams. Symboles are the same as in Fig. 9.

of 1/Sr, SiO_2, K_2O, Rb, Th and Sm to $^{87}Sr/^{86}Sr$ ratio. It can be clearly seen that the 87Sr/86Sr ratios of rocks keep unchanged and construct horizontal correlation lines with all reference elements, improving magma almost uncontaminated (Fig. 16).

Magma Generation Process

The magma generation process of the rocks in northern coast of King George Island have been discussed by using the H/M vs H bivariate diagram (Fig.17) proposed by Treuil *et al.*, (1975). Here, H is a highly incompatible element, such as Th, Ta, La, Ce with bulk partition coefficient less than 0.1, M is mediate incompatible (D=0.2-0.5), such as Zr, Hf, Yb, Sm. On these bivariate plots, the slope of correlation line defined by fractional crystallization nearly equals to zero and that by equilibrate partial melting is over zero. The different slopes indicate different magma sources (Saunders *et al.*, 1988).On the Th/Ta-Th and Ce/Yb-Ce correlation diagrams (Fig. 17), all plots of FPG, ABG, and WPG are distributed along the same trend, and the slopes of the distribution line are higher than zero, suggesting that the rocks of differet lithostratigrapic units from different locations were derived from same magma sources by partial melting of mantle material (Fig. 17), with fractional crystallization.

CONCLUSION

The magmatic processer in the South Shetland Island arc continued from Late Mesozoic to Cenozoic time with the igneous rocks becomig younger and younger northeastwards. They represent high-Al basalt, basaltic andesite, andesite and dacide (rhyolite) association belonging to the calc-alkaline magmatic arc. The volcanic activity in Byers Peninsula and Cape Shirreff, Livingston Island started in Early Cretaceous, (Smellie *et al.*, 1984; 1995; Zheng *et al.*, 1995a,b), and continued during Late Cretaceous and Tertiary in King George Island (Fildes Peninsula - Zheng *et al.*, 1991; Li *et al.*, 1992; southern part of the islad - Birkenmajer *et al.*, 1991). The volcanic rocks studied in this paper are closely comparable with those from other parts of King George Island both in petrography and in petrochemistry. The trace element and isotope geochemistry studies proved that the rocks of the northern coast of this island all have the same isotopic composition as mantle materials indicating that there was no crust component contamination. The FPG lavas and the ABG plugs, as well as the WPG granodiorites are all of calc-alkaline characteristics. They might be directly generated by partial melting of upper mantle, deriving from the same simple magma source during the Late Mesozoic to Cenozoic subduction of proto-Pacific oceanic crust beneath Antarctic continent.

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