Korean Journal of Polar Research
Vol. 7, No. 1/2, pp. 35-45, December 1996

Mesozoic-Cenozoic Volcanism on Livingston Island, South Shetland Islands, Antarctica: Geochemical Evidences for Multiple Magma Generation Processes

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Abstract: Meso-Cenozoic volcanic rocks widely distributed on Livingston Island are part of the South Shetland magmatic arc. Early to Late Cretaceous volcanism is particularly well represented, but the magmatism also includes Early Tertiary plutonic tonalite and Quaternary volcanic rocks.

Eight representative lava and dolerite, as well as tonalite samples were analyzed for Sr, Nd, Pb isotope study. The isotope composition and other geochemical characteristics of rocks, such as the relationship of $^{87}Sr/^{86}Sr$ vs 1/Sr, Rb, K and SiO_2, combining with the published and new petrographical and petrochemical data, indicate that the magmatic rocks of different locations in Livingston Island should be from different magma sources with distinguishable isotope features. Therefore multiple magma generation processes of the volcanism in Livingston Island have been suggested.

The Late Cretaceous volcanic rocks from Byers Peninsula and Cape Shirreff, the dolerite at Siddons Point, and the Tertiary tonalite at Barnard Point are all characteristic of relatively low $^{87}Sr/^{86}Sr$ ratios ($\leq$0.7040) and positive ε_{Nd}, showing syngenetic mantle-derived magma features. By contrast, rocks from the central Livingston Island and Hannah Point have significantly higher $^{87}Sr/^{86}Sr$ ratios ($\geqq$ 0.7050), implying a possible contamination process. All of the rocks analyzed are distributed within the mantle array in Sr-Nd isotopic space, but data for the low-Sr ratio group cluster close to primitive mantle values, whereas the high-Sr ratio group did not. The primitive compositions of the Quaternary olivine basalt suggests the direct derivation from a deep-level, primary magma.

Studies on the La/Sm-La and Ce/Yb-Ce pairs of incompatible elements further suggest that the formation of above rocks was due to different magma resources by different partial melting degrees. The primary magma of the volcanic rocks from Byers Peninsula, Cape Shirreff, and Siddons Point would be generated by partial melting of upper mantle material in a deeper magma chamber and was directly erupted onto surface. Conversely, the rocks in central Livingston and Hannah Point might be undergone contamination process when the derived magma had to stay in a shallow chamber. The possible crustal source ("contamination") could be the Early Triassic Miers Bluff Formation, the basement of Livingston Island, which is a sequence of continental-derived metasedimentary rocks deposited in a submarine fan environment. The Pleistocene to Recent volcanism is closely related to the extension of Bransfield Strait and the primary magma was directly derived from the upper mantle by partial melting.

Key words: Sr, Nd, Pb isotope, volcanic rock, multiple magma generation processes, Livingston Island, Antarctica

INTRODUCTION

The volcanic strata, including effusive, subvolcanic and intrusive rocks, outcropping on Livingston Island is an important part of the South Shetland magmatic arc. Previous researches on geology, petrology and geochronology show that these rocks were basically belong to the calc-alkaline series and might be formed by different magma processes. Based on the new data yielded during the collaborative research carried out by Chinese, Spanish and British geologists, this paper is tried to bring to light the relatively complex magma generation processes.

AGE AND DISTRIBUTION OF THE VOLCANIC ROCKS

Meso-Cenozoic volcanic rocks are widely distributed on Livingston Island where the majority are of late Mesozoic. Thick agglomerates and coarse breccias of volcanic conduct phase cumulated on the northwest end of Byers Peninsula, at the western part of Livingston Island. Basaltic andesitic lavas and corresponding pyroclastic rocks occurred mostly on the eastern part of peninsula, and doleritic and dacitic intrusives scattered throughout the whole peninsula (Smellie *et al.*, 1984). Published K-Ar isotopic ages provide that the rocks are younging from 120 Ma or more in the northwest part eastwards with the youngest one of about 70 Ma (Pankhurst *et al.*, 1979; Smellie *et al.*, 1984).

Porphyritic basaltic lava and some pyroclastic rocks outcropped at Cape Shirreff, where the olivine basalt has a K-Ar age of 90.2±5.6 Ma (Smellie *et al.*,1996, in press*). The interlayered basaltic andesitic lava and pyroclastic beds at Hannah Point were formed by three volcanic activities (Zheng *et al.*, 1994), where the K-Ar ages are from 87.9±2.6 Ma (the middle of the stratigraphic section) to 67.5±2.5 Ma (the top of the section). Basaltic dikes intrude into the middle section (Smellie *et al.*,1996, in press) suggesting the volcanic activities lasted from Middle Cretaceous to Early Tertiary. Eastwards, all the effusive rocks on the central Livingston Island are deformed and metamorphosed: the igneous structure of rocks was still remained but most of the original minerals has been substituted by secondary ones. The K-Ar ages of the lava are limited within 35.0 Ma-44 Ma (Smellie *et al.*,1996, in press), showing the affect of a thermal event caused by late intrusions. However, two new $^{40}Ar/^{39}Ar$ ages (unpublished data) prove that these rocks are also caused by Cretaceous volcanism, coherent with the regional stratigraphic and petrographic relation.

The occurrences of doleritic sill and plugs are usually later than lavas of the same generation. The ages of the dolerite in Byers peninsula range from 109 Ma to 89 Ma (Pankhurst *et al.*, 1979; Smellie *et al.*,1984) and the dolerite at Siddons Point was formed in Late Cretaceous (73±2.3 Ma, Smellie *et al.*,1996, in press). Intermediate-acid intrusive rocks were developed in Early Tertiary, for example, the ages of the tonalite at Barnard Point are 46±1 M and 40±1 Ma (Dalziel *et al.*,1973; Del Valle *et al.*,1974; Smellie *et al.*,1984), and the tonalitic stocks near False Bay are 41.4±1.3 Ma (K-Ar whole rock) and 43.3±2.8 Ma (amphibole, K-Ar age) (Smellie *et al.*,1996, in press).

Cenozoic volcanic rocks including very fresh, undeformed olivine basaltic lava, doleritic stocks and layered pyroclastic strata are distributed in the northeast part of island, nearly in NE-SW direction. Isotopic age dating indicates that they were the products of Pleistocene to Recent volcanism (< 1 Ma, Smellie *et al.*, 1984; 1996, in press).

PETROCHEMICAL EVOLUTION

Published and new petrochemical data suggest that the Cretaceous igneous rocks in Livingston Island include olivine basalt (dolerite), basalt, basaltic andesite, andesite, as well as few dacite, and the main component of Tertiary intrusives is tonalite. These rocks belong basically to a calc-alkaline series related to arc magmatism, however, they show some characters of low-K tholeiite including Al-enrichment, low Rb/Sr and Ba/Sr, and high K/Rb ratios (Adie,1972; Baker, 1972; Weaver *et al.*, 1982; Smellie *et al.*, 1984, 1996, in press; Zheng Xiangshen *et al.*, 1995a). The K_2O content of most rocks is almost typical of the calc-alkaline rocks. They are light rare earth-enriched and Eu-anomalies are weakly positive in basic lavas and no or only slightly negative in basaltic andesite and andesite. The enrichment of Rb, Ba, Th and deple-

Table 1. Some major element (wt%) and trace element (ppm) contents of the volcanic rocks from Livingston Island

Sam.N.	Loc.	SiO_2	Al_2O_3	K_2O	Rb	Sr	La	Ce	Sm	Yb
45D	1	57.49	17.29	1.29	42	428	13.5	29	4.2	2.7
80A	1	55.87	17.04	1.07	28	453	10	22	3.5	2.2
105E	1	47.22	16.96	0.3	13	305	6.1	16	2.6	1.6
262	1	53.13	16.04	0.49	10	771	10.4	25	3.9	2.2
43	1	53.84	17.09	0.32	10	245	11.2	27	3.7	2.3
44	1	54.05	15.25	1.01	22	214	16.9	38	4.7	2.8
433*	2	54.43	15.09	0.64	3	283	11.9	29	4.7	3.2
407	2	51.76	15.92	1.59	34	434	11.4	28	4.4	3.1
434	2	52.6	16.51	0.62	15	498	7.1	15	2.8	2.0
419C*	2	51.72	15.82	0.65	10	467	7.1	16	2.8	2.1
258A	3	59.75	18.04	1.29	38	575	11.8	27	3.5	2
258B	3	58.32	18.46	1.09	35	597	11.9	29	4	2.5
278	4	50.42	17.86	0.5	11	622	6.9	17	2.5	1.3
281*	4	47.67	18.38	0.24	2	570	3.8	9	1.5	0.8
325C3	5	48.55	18.12	0.31	6	483	11.6	28	3.9	1.9
307S*	5	48.44	18.09	0.48	4	492	7.9	19	3.0	1.8
378A*	5	45.84	17.55	0.74	13	521	9.3	22	3.7	2
260	6	47.4	16.16	0.46	10	536	7.8	19	2.4	1.3
230	6	46.64	16.21	0.34	7	418	4.6	10	1.8	1.2
228*	6	49.51	17.32	0.51	5	568	6	13	2.1	1.5

Note:The sample with * and the rare earth elements were analyzed in Activation Lab. LTD, Canada, other data are from Smellie *et al.* (1996, in press). Loc. (location): 1. central Livingston, 2. Hannah Point, 3. Tonalite in central Livingston, 4. Siddons Point dolerite, 5. Cape Shirreff, 6. Quaternary olivine basalt of Inott Point Formation

tion in Cr and Ni vary synchronously with the SiO_2 content of rocks, conherent with the differentiation and evolution from basic to acid magma. Smellie *et al.* (1984) pointed out the rhyolitic ignimbrites of Byers Peninsula being more evolved in terms of oxides and element contents. Zheng *et al.* (1995a) believe the Tertiary tonalite in eastern Livingston Island was the late product of magma evolution.

However, the chemical compositions of rocks are distinguishable from each locations. The basalt and basaltic andesite from central Livingston Island and Hannah Point are similar in petrochemistry, they should be the products of same volcanism. Although the rocks of Cape Shirreff occurred at almost the same time as those at Hannah Point, they contain more Al_2O_3 (> 17.5%, Table 1) and olivine in mineral assemblage. These features are obviously different from that of central Livingston Island and Hannah Point rocks, but much more similar to that of Byers Peninsula lava and Siddons Point dolerite (Table 1). The Quaternary olivine basalt is distinguishable to the Mesozoic rocks by higher M value (M=100 Mg/(Mg+Fe^{2+})) and olivine content, either the olivine in rock or the ol norms (9.93-21.29%) (Zheng *et al.*, 1995a).

Sr, Nd, Pb ISOTOPE COMPOSITION

On the basis of petrochemical study, eight samples were selected for Sr, Nd and Pb isotope composition analysis in order to approach the magma generating features. The analyzed results were carried out in the Isotope Lab. of the Institute of Geology, CAS and listed in Table 2, combining with some published Sr data of Byers Peninsula volcanic rocks.

Sr and Nd isotope composition

The plots of the Sr and Nd isotope composition of Livingston Island are dispersed with a negative correlation on the $^{143}Nd/^{144}Nd$ vs $^{87}Sr/^{86}Sr$ isotope correlation diagram (Fig.1), following the Mantle array, which was defined by many MORB and OIB basalts and evolving from frequently observed PREvalent MAntle (PREMA) composition to Bulk Silicate Earth (BSE) value (Zindler and Hart,

Table 2. Sr, Nd, Pb isotope composition of the volcanic rocks from Livingston Island

Sam.N.	Rb	Sr	$^{87}Rb/^{86}Sr$	$(^{87}Sr/^{86}Sr)p$	Age (Ma)	$(^{87}Sr/^{86}Sr)_i$	εSr
105E	115.56	305.2	1.0932	0.705120±19	35.0±3.9	0.70450	0.60
262	27.7	748.7	0.1068	0.704916±21	39.8±1.6	0.70486	5.66
407	1.82	433.4	0.0121	0.704545±18	87.9±2.6	0.70453	1.79
434	8.97	517.6	0.0501	0.705285±30	67.5±2.5	0.70524	11.51
258A	9.7	553.8	0.0506	0.704088±21	41.4±1.3	0.70406	-5.64
278	7.58	611.6	0.0358	0.703930±14	73.0±2.3	0.70391	-7.77
325C3	4.71	476.8	0.0285	0.704004±16	90.2±5.6	0.70397	-6.18
260	7.18	539.5	0.0389	0.704135±18	<1	0.70413	-5.17
P862(2)*	23	334		0.70450	125	0.70414	
P845(4)*	18	462		0.70435	110	0.70422	
P848(5)*	22	457		0.70386	110	0.70364	
P850(1)*	2	559		0.70410	90	0.70409	
P725(1)*	31	411		0.70465	100	0.70435	
P864(2)*	5	366		0.70429	100	0.70424	
P864a(1)*	10	402		0.70431	75	0.70423	

Table 2. cc ıtinued

Sam.N.	Sm	Nd	Sm/Nd	$(^{143}Nd/^{144}Nd)_p$	$^{147}Sm/^{144}Nd$	$(^{143}Nd/^{144}Nd)_p$	ε_{Nd}
105E	2.711	10.390	0.260	0.512486±45	0.15781	0.512445±45	-2.767
262	4.396	17.176	0.256	0.512880±13	0.15479	0.512840±13	4.935
407	4.730	18.516	0.255	0.512712±10	0.15449	0.512622±10	1.923
434	2.792	16.009	0.174	0.512625±7	0.10549	0.512577±7	0.561
258A	3.741	16.035	0.233	0.512784±10	0.14111	0.512747±10	3.132
278	2.805	11.393	0.246	0.512874±10	0.14893	0.512835±10	4.848
325C3	3.862	15.675	0.246	0.512824±22	0.14901	0.512736±22	4.177
260	2.614	11.654	0.224	0.512836±13	0.13568	0.512835±13	3.870

Sam.N.	$^{204}Pb\%$	$^{206}Pb\%$	$^{207}Pb\%$	$^{208}Pb\%$	$^{206/204}Pb$	$^{207/204}Pb$	$^{208/204}Pb$
105E	1.3528	25.0975	21.1313	52.4184	18.55	15.62	38.75
262	1.3527	25.0742	21.1072	52.4659	18.54	15.60	38.79
407	1.3632	25.0585	21.1247	52.4537	18.38	15.50	38.48
434	1.3648	25.0726	21.1653	52.3972	18.37	15.51	38.39
258A	1.3365	25.0782	21.1081	52.4772	18.76	15.79	39.27
278	1.3158	25.1907	21.1646	52.3289	19.14	16.08	39.77
325C3	1.3455	25.0836	21.1149	52.456	18.64	15.69	38.99
260	1.3398	25.148	21.112	52.4003	18.77	15.78	39.11

Note: Samples with* are after Smellie *et al.* (1984) and the number in brackets represents the number of samples analyzed. The ages are from Smellie *et al.* (1996, in press); Rb, Sr, Nd, Sm were determined together with isotopes (ppm).

1986). However, the eight results could be obviously divided into two groups. The isotopic ratios of the Cape Shirreff olivine basalt, Siddons Point dolerite and the tonalite in central Livingston Island are almost coincident within analysis limit, that is, the $^{87}Sr/^{86}Sr$ ratios are about 0.704 and $^{143}Nd/^{144}Nd$ vary within 0.51274 to 0.51284 (Table 2). The Quaternary olivine basalt of Inott Point Formation has the same Sr, Nd isotope ratio as above mentioned samples, suggesting that they all have the isotope composition of primary mantle. By contrast, two samples from Hannah Point and another

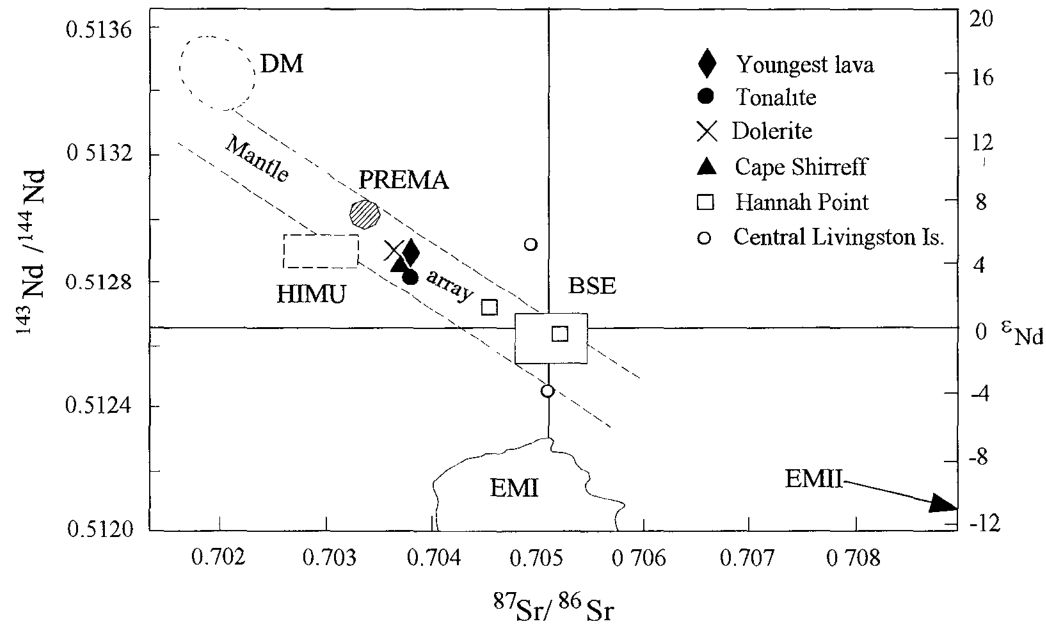

Fig. 1. ^{143}Nd/^{144}Nd-^{87}Sr/^{86}Sr isotope correlation diagram. DM, depleted mantle; BES, bulk silicate Earth; EMI and EMII, enriched mantle; HIMU, mantle with high U/Pb ration; PREMA, frequently observed PREvalent MAtle composition. (after Zindler and Hart, 1986)

two of central Livingston Island are with higher 87Sr/86Sr ratio, near 0.705, and greatly varied ^{143}Nd/^{144}Nd ratios (Table 2, Fig. 1). It can be seen that ^{87}Sr/^{86}Sr ratios of the igneous rocks from Byers Peninsula vary from 0.7036 to 0.7044, (Table 2), and the average value is 0.70413, same as those of the first group.

Pb isotope composition

There are also some differences in Pb isotope composition between above the two groups of the igneous rocks differentiated with Sr and Nd isotope (Table 2). All plots on ^{207}Pb/^{204}Pb vs ^{206}Pb/^{204}Pb correlation diagram (Fig.2) construct a negative relation line nearly parallel to the 4.55 Ga geochron. Furthermore, the rocks from Hannah Point and central Livingston Island have lower ^{207}Pb/^{204}Pb ratio comparing with those of another group. Comparing with the northern hemisphere reference line (NHRL) the slope of this relation line is little bit higher, suggesting a evolving trend from PREMA to Enriched Mantle II (EMII) composition. On the ^{208}Pb/^{204}Pb vs ^{206}Pb/^{204}Pb correlation diagram (Fig. 2), the plots of rocks also show a positive relation with similar slope to NHRL.

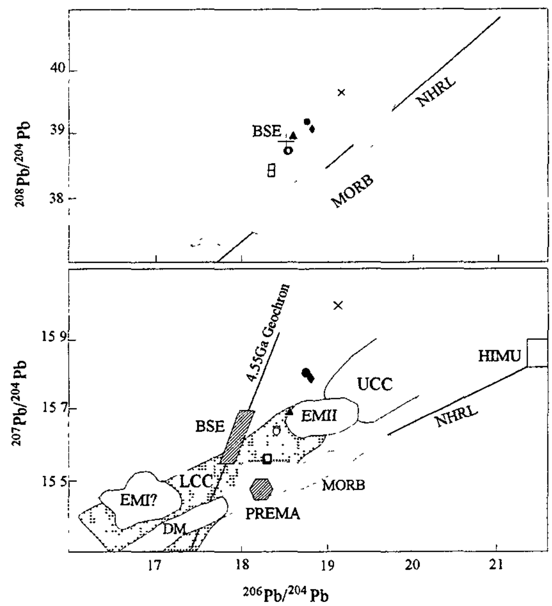

Fig 2. ^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb-^{206}Pb/^{204}Pb isotope correlation diagram. Symbols are the same as in Fig. 1

However, the Pb isotope composition is generally higher than MORB and near the BSE value

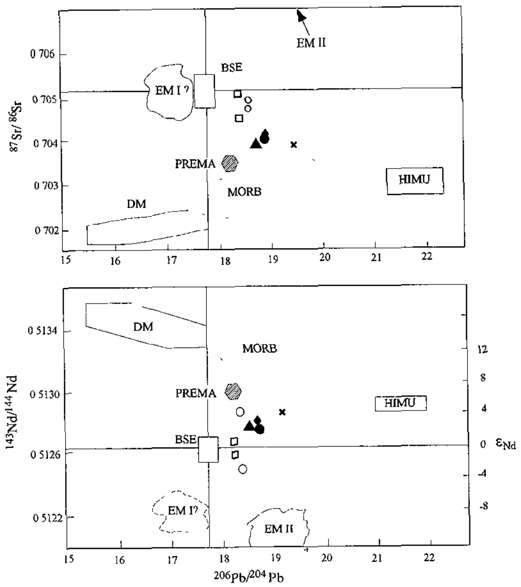

Fig. 3. $^{87}Sr/^{86}Sr$-$^{206}Pb/^{204}Pb$(A) and $^{143}Nd/^{144}Nd$-$^{206}Pb/^{204}Pb$(B) isotope correlation diagram. MORB, mid-ocean ridge basalt; others are the same as in Fig. 1.

(Allegre *et al.*, 1988), within them the rocks from Hannah Point and central Livingston Island might contain more isotope Pb. These features mean that the all volcanic rocks are enriched in radiogenic Pb isotopes on the same $^{206}Pb/^{204}Pb$ background.

Relationship between Sr-Pb and Nd-Pb isotope composition

The characteristics of magma sources defined by Sr, Nd, Pb isotope are clearly seen on the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ vs $^{206}Pb/^{204}Pb$ isotope correlation diagrams (Fig.3). The plots of the Cape Shirreff basalt, Siddons Point dolerite and the tonalite from central Livingston Island are cumulated together showing homogeneous feature. Also, the olivine basalt of Inott Point Formation has the isotopic composition similar to primary mantle's. Whereas the isotopes of the lavas from Hannah Point and central Livingston Island are inclined to BSE suggesting the contamination of crustal material.

DISCUSSION ON MAGMA GENERATION PROCESS

1. The chemical composition of igneous rocks, in general, has changed by subsequent geological and petrogenetic processes in their journey from the source region where melt extracted from mantle to their site of emplacement, during or after solidification, so only parts of the petrogenetic information can be yielded from petrochemical study. Therefore, isotope ratios of magma, such as Sr, Nd and Pb isotopes are frequently used to identify the reservoirs and particular petrological processes. This is because the mass difference between any pair of radiogenic isotopes used in geochemistry is so small that they can hardly be fractionated by crystal-liquid equilibrium fractionation and the ratios remain unchanged during petrogenetic processes. Based on the petrographical characteristics and the different features of major and trace elements the authors already proposed a new suggestion on the magma generation of the volcanic rocks from Cape Shirreff, Hannah Point and the Quaternary olivine basalt (Zheng *et al.*, 1995 a, b). However, following questions should be answered clearly: Are the igneous rocks outcropped in different locations from the same magma source? Are they directly derived from mantle materials and is there any crustal material entering the mantle-derived melts?

Most of Sr isotopic ratios of the igneous rocks in Livingston Island vary between 0.7039 to 0.7049 (Table 2), and follow the "Mantle array" (Fig.1), they are equivalent all to the value of uncontaminated basalt (0.704±0.002). However, the ratios of the rocks from Byers Peninsula, Cape Shirreff, Siddons Point and the Tertiary tonalite are equal to, even lower than, the value of uncontaminated basalt and obviously lower than those ratios of the rocks in Hannah Point and central Livingston Island. This means that the isotopic features of the sources would be different, and the magma with higher $^{87}Sr/^{86}Sr$ ratio should have been mixed, more or less, with outside Sr. Furthermore, the ε_{Nd} values of recent volcanic rocks are different corresponding to their different tectonic settings: the value, $\varepsilon_{Nd}=+12$, is the represent of modern upper mantle and the mean of continental crust is about −15, they are complement each other (Depaolo, 1981, 1988). The mantle derived and uncontaminated magma has the ε_{Nd} value equal to or over zero and the value, $\varepsilon_{Nd} < 0$ is explained as an indicator of crust contamination. The average ε_{Nd} of the rocks at

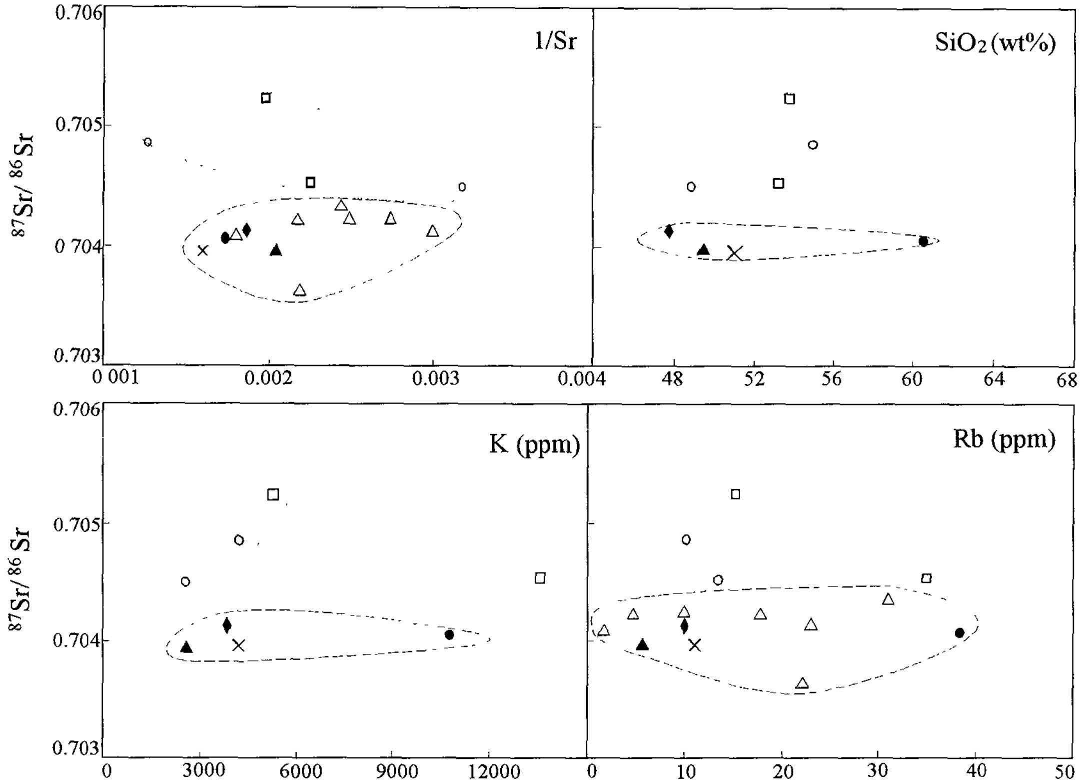

Fig. 4. $^{87}Sr/^{86}Sr$-1/Sr, $^{87}Sr/^{86}Sr$-SiO_2, $^{87}Sr/^{86}Sr$-K, $^{87}Sr/^{86}Sr$-Rb correlation diagrams. Triangle (Δ): volcanic rocks from Byers Peninsula, other symbols are the same as in Fig. 1.

Cape Shirreff, Siddons Point and the Tertiary tonalite is 4±, implying the magma of them is extracted directly from upper mantle. By contrast, the ε_{Nd} values of the rocks from Hannah Point and central Livingston Island are near zero and with one negative, showing the magma was contaminated by crust material during petrogenetic process. Both Sr and Nd isotopes prove that the Quaternary olivine basalt of Inott Point Formation was 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 evolution process. The $^{87}Sr/^{86}Sr$ ratios will express a near-horizontally linear relation with 1/Sr ratios when no foreign material enter, because of too small influence on Sr isotopic composition caused by crystal differentiation and partial melting. Once the crust materials entered into the 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 4 shows the relationship of 1/Sr, SiO_2, Rb or K to $^{87}Sr/^{86}Sr$ ratio. It can be clearly seen that the ratios of the rocks from Byers Peninsula, Cape Shirreff, Siddons Point and the Tertiary tonalite, as well as the olivine basalt of Inott Point Formation keep unchangeable and construct horizontal correlation lines with reference elements, proving that the magma was almost uncontaminated. Comparatively, the higher $^{87}Sr/^{86}Sr$ ratios of the rocks in Hannah Point and central Livingston Island show basically positive relationship to references, except 1/Sr, declaring the contamination by crust clearly (Fig. 4).

2. Trace elements are very effective in discussing the source characteristics and petrogenetic process. The ratio of a pair of highly incompatible elements whose bulk partition coefficients are very similar will not vary in the course of fractional crystallization and vary little during partial melting. Thus the

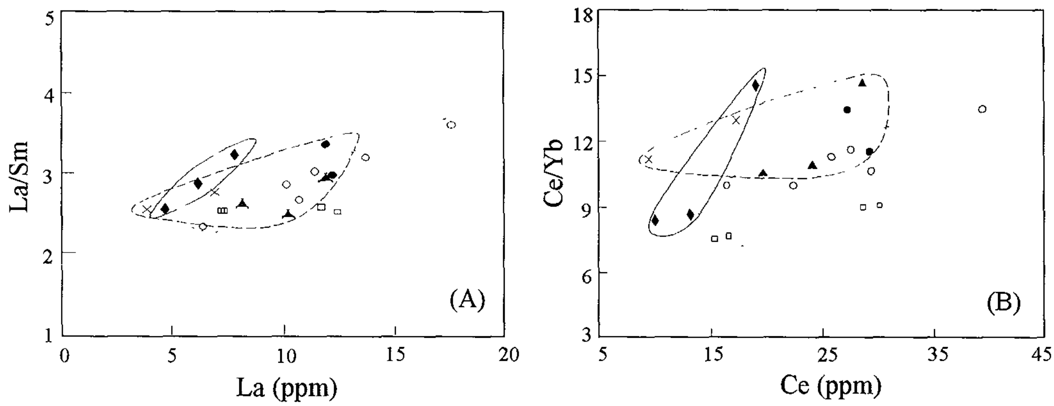

Fig. 5. La/Sm-La (A) and Ce/Yb-Ce (B) bivariate diagrams. Symbols are the same as in Fig. 1.

slope of a correlation line on a bivariate plot of two such highly incompatible elements gives the ratio of the concentration of the elements in the source (Sun and McDonough, 1989), and any variation in the ratio reflects heterogeneity in the source caused by magma mixing or contamination (Bougault *et al.*,1980).

The generation characteristics of the volcanic rocks in Livingston Island have been discussed by using the H/M vs H bivariate diagram (Fig. 5) proposed by Trenil *et al.* (1975). Here the H is a highly incompatible element, such as Th, Ta, La, Ce with bulk partition coefficient less than 0.1, the M is a mediate incompatible (D=0.2-0.5) element, 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 our La/Sm-La and Ce/Yb-Ce correlation diagrams (Fig. 5), the slope of Byers Peninsula and Cape Shirreff (also together with dolerite and tonalite), the slope of Hannah Point and central Livingston Island, and the slope of Quaternary Inott Point Formation are distinguishable and all higher than zero suggesting the rocks from different locations resulted from separated magma sources and by different partial melting degrees (Fig. 5).

3. Above mentioned differences in igneous source character and magma generation processes are controlled by the tectonic settings of the volcanic rocks. Systematically petrographical study (Zheng *et al.*, 1995b) showed that the olivine basalt of Cape Shirreff, the dolerite at Siddons Point and Quaternary olivine basalt are with porphyritic texture, same as the basic lava of Byers Peninsula (Smellie *et al.*, 1984). The occurrence of olivine phenocryst and a lot of plagioclase phenocrysts with high calcite core (An > 80%) in rocks indicated that the primary magma should be a more basic one and had a long stopover in the deeper magma chamber before its eruption. The An content decreasing from the center toward margin of the plagioclase phenocrysts forming a normal zoning proves no foreign material entered melt during phenocryst growing. Therefore, combining with petrochemical and geochemical information, it can be conclude that the volcanic rocks from above locations were directly resulted from a mantle-derived magma, which was staying and evolving in a deeper reservoirs for a longer time. Besides forsterite crystals, some olivine xenocrysts with the composition of Fo content up to 90% are found in Quaternary olivine basalt (Zheng *et al.*, 1995b). This suggests that the magma is the product of a less differentiated magma coming directly from a deep magma chamber. Comparatively, the lavas from Hannah Point and central Livingston Island are finely crystalline with sporadophyric texture mainly and contain only a few small labradorite and andesine phenocrysts, without olivine, exhibiting rapidly rising and crystallizing process of the magma from a shallower chamber (Zheng *et al.*, 1995b).

South Shetland Islands is a magmatic arc related to the gradually subducting of Pacific Plate underneath Antarctic Plate since Mesozoic. The islands is basically covered by the volcanic rocks formed in or later than Late Cretaceous. The only stratigraphic unit considered as the late Paleozoic to early Mesozoic basement is located on the Hurd Peninsula, the southeastern part of the Livingston Island. The strongly deformed, turbiditic sandstone, mudstone and lenticular conglomerate are stratigraphically named as Miers Bluff Formation (MBF, Smellie *et al.*, 1995), their thickness above sea level is more than 3000 m, with no unconformity inside (Arche *et al.*, 1992a,b; Pallás *et al.*, 1992; Smellie *et al.*, 1995) and is covered by late Mesozoic volcanic sequences. Isotopic age of 210Ma (Pankhurst, 1983; Herve, 1992) for the shales of the MBF provided a minimum age for metamorphism, and the age of the zircons in sandstone gave a maximum age of sedimentation, about 322Ma (Loske *et al.*, 1988). Smellie *et al.* (1995) believe that the depositional environment of the lower member of MBF comprised an upper midfan suprafan lobes and lobe-fringe or interchannel sedimentation, and the upper member consisted of a lower min-fan setting with thin channel sequences, whereas the volcanic detritus in the clastic rocks of Cretaceous volcanic units, which unconformably overlie the MBF, was probably produced mainly during phreatomagmatic eruptions, as a result of interaction of magma and groundwater. Smellie *et al.* (1995) further suggested that the MBF palaeotopography might have been more subdued or obscured by Late Cretaceous volcanic rocks. Therefore, the crust in the Hurd Peninsula region, where local basement outcropped, may be thicker than the other areas of Livingston Island when late Mesozoic volcanism occurred. The volcanic rocks of Hannah Point and central Livingston Island just erupted through the thicker crust, so the magma generation process of Mesozoic volcanism there should be greatly affected by Paleozoic basement sequence.

The process of proto-Pacific oceanic crust subducting beneath Antarctic Plate caused the partial melting of upper mantle and the mantle-derived basaltic magma extraction under studied region. When magma rose from deep reservoir and erupted through the structural weak zone of crust on the surface directly, crustal material could not be easily fused, so magma would not be greatly contaminated by continental crust and the produced volcanic rocks are basically of source characters. It is during this generation process when the rocks of Byers Peninsula and Cape Shirreff occurred. However, the magma derived from deep magma chamber might be resisted by the thicker crust in central Livingston Island area and had built a small shallow reservoir, where crust material was melted and primary magma was contaminated, resulting in the different isotope composition of the volcanic rocks from Hannah Point and central Livingston Island. Pleistocene to Recent volcanic rocks of the Inott Point Formation, with primary magma characteristics, might be erupted under essentially dry, subaerial conditions and the youngest volcanism is related to the extension during arc-splitting and formation of the Bransfield Strait marginal basin (Smellie *et al.*,1984, 1995).

SUMMARY AND CONCLUSIONS

1. The isotopic composition of the volcanic rocks at Cape Shirreff, the dolerite at Siddons Point and the tonalite from central Livingston Island are of homogeneous characteristics: $^{87}Sr/^{86}Sr$ ratios are around 0.704, $^{143}Nd/^{144}Nd$ ratios range from 0.51274 to 0.51284 and average ε_{Nd} value about +4±. The mean $^{87}Sr/^{86}Sr$ ratio of Byers Peninsula is 0.70413. The Sr and Nd isotope composition of the Quaternary olivine basalt of the Inott Point Formation is completely commensurate with above rocks and they all have the isotopes of mantle-derived magma indicating the primary magma was derived directly from upper mantle. The rocks from Hannah Point and central Livingston Island show higher $^{87}Sr/^{86}Sr$ ratios (near 0.705), lower and variable $^{143}Nd/^{144}Nd$ ratios, and ε_{Nd} value near 0 or negative, implying the crust contamination occurred during magma generation and evolution. On the similar $^{206}Pb/^{204}Pb$ ratio background, all rocks show Pb isotope enrichment, especially the volcanic rocks from Hannah Point and central Livingston Island contain more isogenetic lead.

2. The correlation diagrams of 1/Sr, SiO_2, Rb or K against $^{87}Sr/^{86}Sr$ ratio show that the ratios of the rocks from Byers Peninsula, Cape Shirreff, Siddons Point and the Tertiary tonalite, as well as the olivine basalt of the Inott Point Formation fit a horizontal lines correlated with reference elements,

proving that the magma was uncontaminated by crust. The higher $^{87}Sr/^{86}Sr$ ratios of the rocks from Hannah Point and central Livingston Island exhibit essentially a positive relationship to references, indicating the contamination by continental crust.

3. Discussion on the magma source and petrogenetic processes by incompatible element pairs of La/Sm-La and Ce/Yb-Ce further stated clearly that the rocks from different locations resulted from three separated magma sources and by different partial melting degrees.

4. The igneous rocks of Livingston Island are a part of the South Shetland Islands magmatic arc. The rocks outcropped on Byers Peninsula and Cape Shirreff represent a mantle-derived magma, which was formed in a deeper magma reservoir by partial melting of the upper mantle and erupted onto surface directly through a zone of structural weakness. Paleozoic basement played an important role in the generation and evolution of the volcanic rocks of central Livingston Island and Hannah Point. The magma derived from deep magma chamber might be stopped in a small, shallow chamber and contaminated by the crust materials. The primary magma of the youngest, Pleistocene to Recent volcanic rocks was from upper mantle extraction and the volcanism is responding to the tectonic extension during late Cenozoic in Antarctic Peninsula region

ACKNOWLEDGEMENTS

This work is a part of the Chinese/Spanish collaborative research on Antarctic geology, supported by CICYT of Spain (ANT-1270/91), and by National Science & Technology Committee of China (85-03-04) and CAS (KJ85-08-03). Financial support is also provided by NSFC (49172092). Dr. Zheng gratefully thank the DGICIT of Spanish government for the opportunity working with Spanish geologist in Spain (SAB92-0390)

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