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# Geochemical Comparisons on the Volcanic Rocks in the Antarctic Peninsula, the South Shetland Islands and southern South America

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Abstract : Jurassic to recent magmatic activities throughout the Antarctic Peninsula, the South Shetland Islands and southern South America have changed over time in their chemical natures, but the fractionation trends, as a whole, show the intermediate between the tholeiitic and calc-alkaline trends. Different chemical natures of volcanic rocks on the regions are thought to be due to the different environments where volcanic magmas generate. High aluminium contents in Tertiary volcanic rocks on the South Shetland Islands and southern South America represent the contribution of crustal materials. The LIL/HFS elements ratios are relatively high and almost constant in Jurassic to Tertiary volcanic rocks, but become lower in Quaternary ones. The high LIL/HFS elements ratios are characteristic features caused by concentration of the LIL elements due to dehydration processes with the subduction slab and by fractionation of mineral phases containing the HFS elements from the magma. Enrichment of HFS elements and depletion of LIL elements in Quaternary volcanic rocks indicate that the Quaternary volcanic magma was generated from the depleted mantle. Quaternary volcanic rocks, which formed at marginal basin floor due to back-arc spreading, have affinities of alkaline rock and MORBs (mid-oceanic ridge basalts).

Key words : tholeiitic, calc-alkaline, alkaline, depleted mantle, back-arc spreading

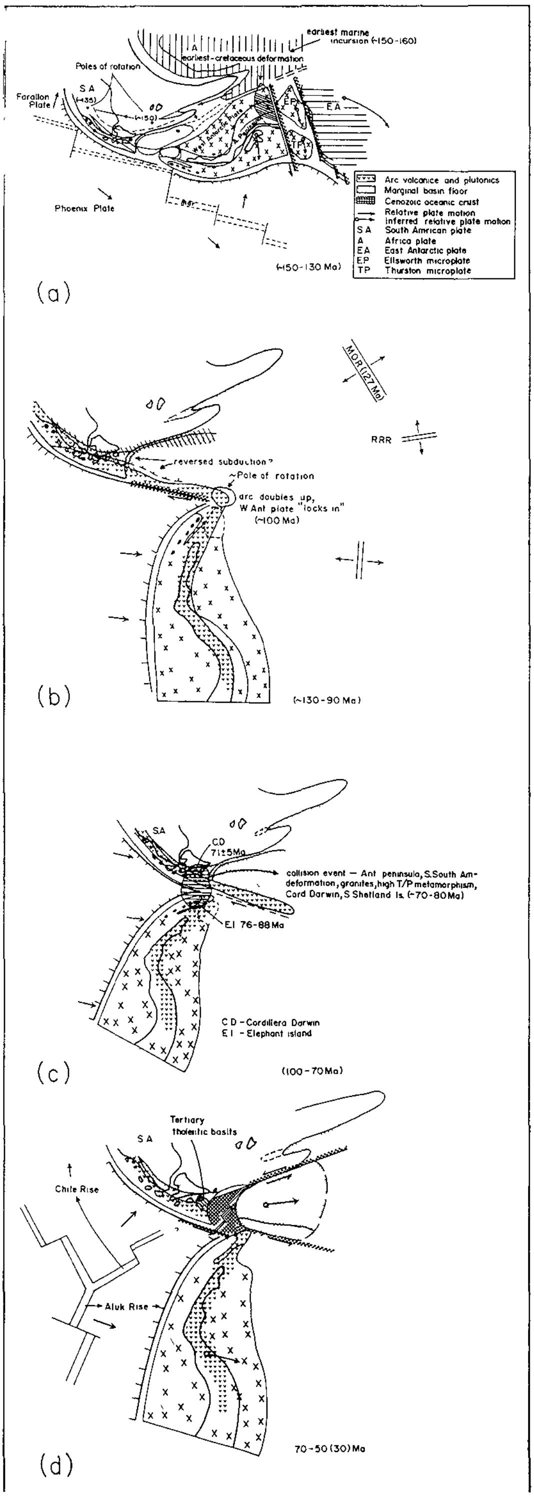
## Introduction

Since the 1970's, volcanic magmatism throughout South America to the Antarctic Peninsula has been studied, especially focusing on the chemical evolution of magma with time and place. From the previous studies, it has been recognized that Jurassic to late Tertiary igneous activities on the regions are similar in their chemical characteristics (Ewart and Le Maitre, 1980; Saunders et al., 1980), but Quaternary ones are quite different (Weaver et al., 1979).

The chemical evolution of volcanic magma on the regions considered has a close relationship to the tectonic movement around the Antarctic Peninsula region (de Wit, 1977;Dalziel, 1983). Therefore, it is necessary to compare the chemical natures of the magma under the different tectonic situations and times. Here, considering three tectonic provinces (the Antarctic Peninsula, the South Shetland Islands and southern South America) and three geochronological times (Jurassic to Cretaceous, Tertiary and Quaternary), the geochemical data on the volcanic rocks are compared to interpret their differences in magma generation.

## Tectonic Setting and Igneous Activity

The similarity in Mesozoic geology between the Antarctic Peninsula and South America indicates the possibility that they had situated along the same tectonic line before the separation of southwestern Gondwanaland (de Wit, 1977 ; Dalziel, 1983) (Fig. 1). The igneous activity around the Antarctic Peninsula, including the South Shetland Islands, can be correlated with the South American Cordillera Orogeny due to the subduction of Farallon/Phoenix plate until late Mesozoic (Larsen and Pitman, 1972). However, igneous activity in Tertiary correlates



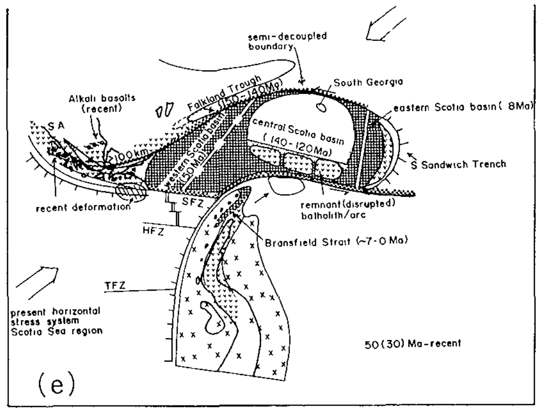




Fig. 1(a—e). Diagrammatic plate tectonic evolution of SW Gondwanaland and the Scotia Sea region (after de Wit, 1977).

with the tectonic movement accompanying the formation of Drake Passage and Scotia Sea.

In the late Tertiary to Quaternary, Bransfield Strait has begun to open due to back-arc spreading. The South Shetland Islands form a Jurassic—Quaternary magmatic island arc on the sialic basement (Smellie et al., 1984) (Fig. 2). Forming of the South Shetland Islands arc began during the latest Jurassic or earliest Cretaceous from the southwestern part of the archipelago. The igneous activity migrated northeasterly and continued in most areas until late Tertiary. The entire arc-forming period, between late Jurassic and late Tertiary times, was characterized by emplacement and eruption of magmas of the intermediate between island-arc tholeiite and calc-alkaline types (Tarney and Saunders, 1979; Smellie et al., 1984). However, Quaternary volcanic rocks show alkaline affinities which corresponds to the switch from compressional to intra-plate tensional tectonics.

## Geochemical Comparisons

The source of data on the volcanic rocks from the regions considered are listed in Table 1. The data of ten major elements (Si, Ti, Al, Fe, Mg, Mn, Ca, Na, K, P) and five minor elements (Rb, Sr, Ba, Y, Zr) for each rock is cited from the sources. For the consideration of the geo-

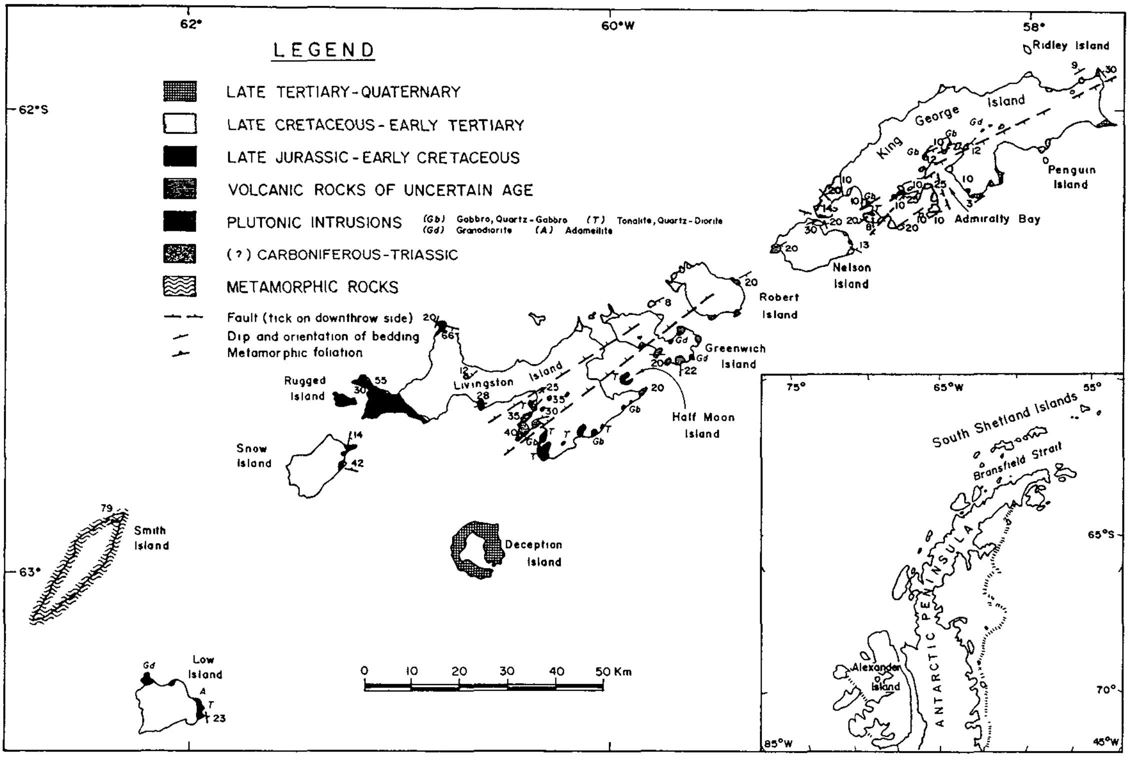



Fig. 2. Geological map of the South Shetland Islands and their location (after Smellie et al., 1984).

Table 1. Data sources and elements.

| Authors | Data No. |
|---|---|
| Baker et al.(1975) | 23 |
| Lopez–Escobar et al.(1977) | 10 |
| Laudon (1982) | 9 |
| Weaver (1982) | 22 |
| Hamer (1983) | 12 |
| Park et al.(1988) | 12 |
| Jwa and Park (unpub. data) | 12 |
| Elements | |
| Major elements : Si, Ti, Al, Fe, Mg, Mn, Ca, Na, K, P | |
| Minor elements : Rb, Sr, Ba, Y, Zr | |

Table 2. Groups of the volcanic rocks.

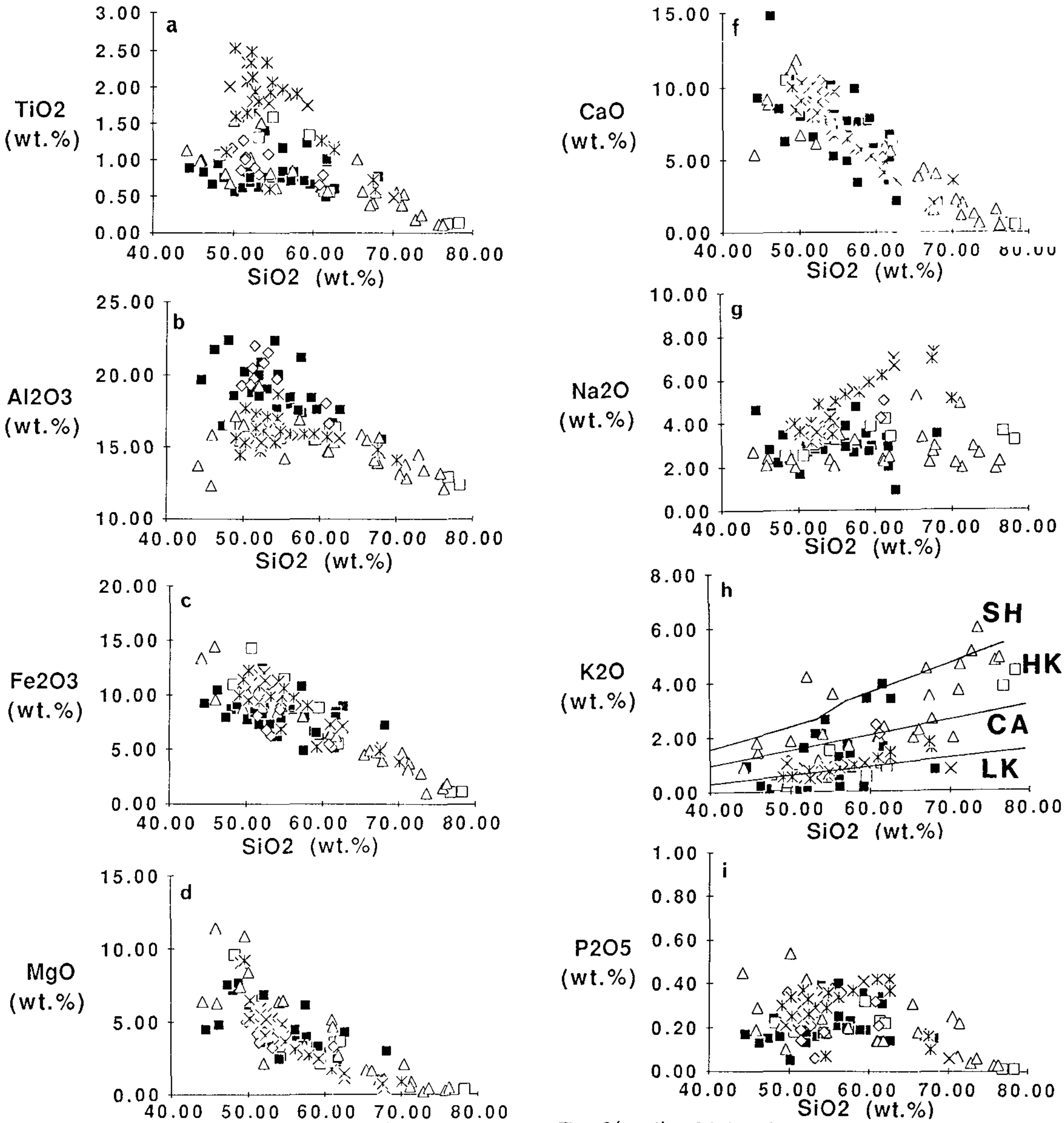
| | |
|---|---|
| Group 1 | Jurassic to Cretaceous volcanic rocks in the Antarctic Peninsula |
| Group 2 | Jurassic to Cretaceous volcanic rocks in the South Shetland Islands (Livingston Is.) |
| Group 3 | Tertiary volcanic rocks in the South Shetland Islands (King George Is.) |
| Group 4 | Tertiary volcanic rocks in southern South America |
| Group 5 | Quaternary volcanic rocks in the South Shetland Islands (Deception Is.) |

chemical differences with place and time, the volcanic rocks on the regions examined are divided into five groups in Table 2.

Figures 3 and 4 show the variation diagrams of the contents of major element oxides and minor elements versus $SiO_2$ content. Geochemical characteristics of the volcanic rocks in each group are briefly explained to compare with each other in the following.

Group 1 : Jurassic to Cretaceous volcanics in the Antarctic Peninsula

The content of $Al_2O_3$ is relatively low and the variation trend consists of both increasing and decreasing patterns (Fig. 3b). These two patterns are also recognized in CaO and Zr contents (Fig. 3f and Fig. 4e). Tarney and Saunders (1979) reported that Zr content of the Mesozoic volcanic rocks in the Antarctic



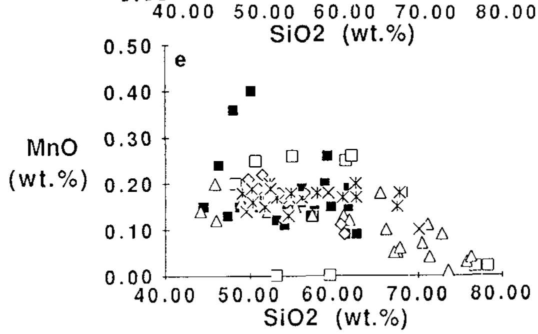
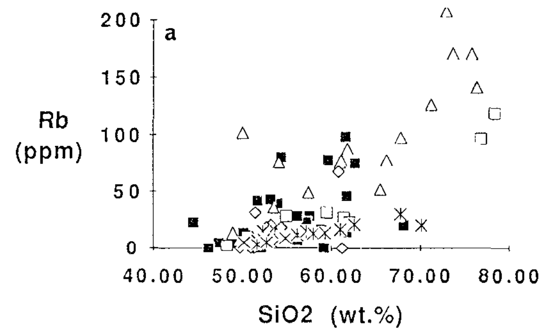
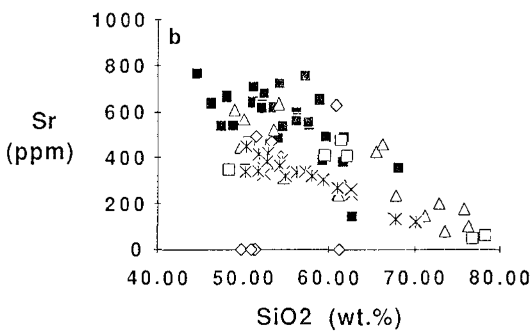
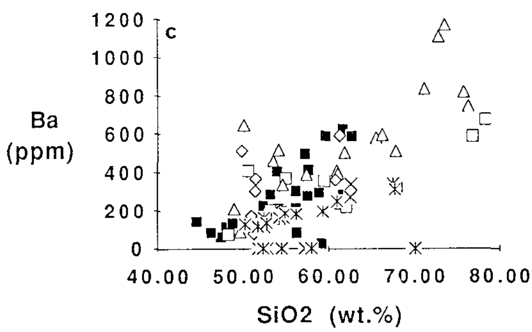
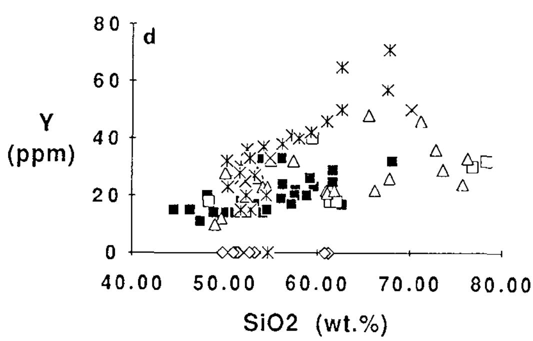




Fig. 3(a–i). Major element oxides vs. $SiO_2$ content variation diagrams. $Fe_2O_3$ means total iron as $Fe_2O_3$. The boundaries in Fig. 3–h are from Percellio and Taylor (1976).
Symbols : △, Group 1 (Jurassic to Cretaceous volcanics in the Antarctic Peninsula) ; □, Group 2 (Jurassic to Cretaceous volcanics in the South Shetland Islands) ; ■, Group 3 (Tertiary volcanics in the South Shetland Islands) ; ◇, Group 4 (Tertiary volcanics in southern South America) ; *, Group 5 (Quaternary volcanics in Deception Island).



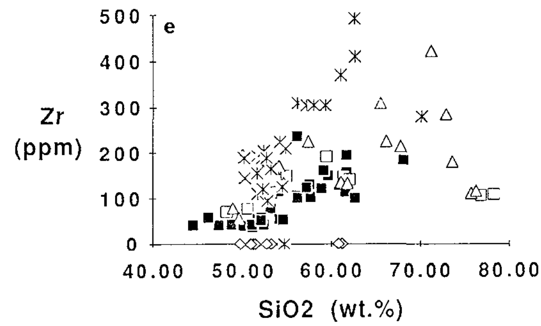




Fig. 4(a−e). Minor elements vs. $SiO_2$ content variation diagram. Symbols are the same as Fig. 3.

Peninsula increases to 60−65% of $SiO_2$ content and then decreases. The contents of $K_2O$, Rb, Sr and Ba (Fig. 3h and Fig. 4a, 4b, and 4c) are relatively high. In addition, the content of Zr is high, though it is lower than that of Quaternary volcanics in Deception Island (Group 5).

Group 2 : Jurassic to Cretaceous volcanics in the South Shetland Islands

The content of $TiO_2$ is slightly high but that of $Al_2O_3$ is low (Fig. 3a and 3b). The chemical compositions of this group are fairly similar to the Antarctic Peninsula group (Group 1) except $K_2O$ and Rb, whose contents are lower.

Group 3 : Tertiary volcanics in the South Shetland Islands

This group has higher contents of Rb, Sr and Ba, comparing with other groups (Fig. 4a, 4b, and 4c). Different from the Jurassic to Cretaceous Antarctic Peninsula group (Group 1), $Al_2O_3$ content is higher (Fig. 3b) but Y and Zr contents are lower (Fig. 4d, and 4e). This Tertiary South Shetland Island group has lower contents of $TiO_2$ and $Fe_2O_3$ (total iron as $Fe_2O_3$) than the Jurassic to Cretaceous South Shetland Islands group (Group 2) (Fig. 3a, and 3c), but exhibit higher contents of $Al_2O_3$and Sr (Fig. 3b and Fig. 4b).

Group 4 : Tertiary volcanics in southern South America

The high contents of $Al_2O_3$ and CaO are characteristic features in this group (Fig. 3b, and 3f). For the limited compositions of $SiO_2$ contents (49−62%), the entire variation patterns of this group are generally similar to the Tertiary South Shetland Islands group (Group 3).

Group 5 : Quaternary volcanics in Deception Island

Compared with other groups, this group has higher contents of $TiO_2$, $Fe_2O_3$ $Na_2O$, Y and Zr (Fig. 3a, 3c, and 3g and Fig. 4d, and 4e), whereas lower contents of $Al_2O_3$ $K_2O$, Rb, Sr and Ba (Fig. 3b and 3h and Fig. 4a, 4b and 4c). The most prominent features in this group are that they possess the highest contents of $TiO_2$, $Na_2O$, Y and Zr, and the lowest contents of Rb, Sr and Ba.

For certain elements such as $Al_2O_3$, $K_2O$, Rb, Ba, Y and Zr, their chemical variations with three steps of time (Jurassic to Cretaceous, Tertiary and Quaternary) can be summarized as in Table 3. The content of $Al_2O_3$ increases till Tertiary and then decreases. The contents of Y and Zr continuously increase. The contents of $K_2O$, Rb, Sr and Ba are nearly constant till Tertiary but begin to decrease after Tertiary. The regional and geochronological similarities in the geochemistry are recognized between the Jurassic to Cretaceous Antarctic Peninsula and South Shetland Islands, and between Tertiary South Shetland Islands and southern South America, respectively.

Table 3. Chemical variations with time for 8 elements.

| Elements | Jurassic | Tertiary | Quateranary |
|---|---|---|---|
| Ti, Y, Zr | ---- (constant) ---> | ---- (increase) ----> | |
| Al | ---- (increase) ----> | --- (decrease) ----> | |
| K, Rb, Ba | ---- (constant) ----> | --- (decrease) ----> | |
| Sr | ---- (constant) ----> | --- (decrease) ----> | |

## Discussion

In magmatic arc regions, the geochemical characteristics of the volcanic rocks generally represent the chemical nature and genetic environment of volcanic magma. In the above section, it could be recognized that the chemical compositions of the volcanic rocks on the regions considered have changed with time, indicating that the chemical natures of the upper mantle and consequent volcanic magma have changed with time.

As shown in Table 3, the contents of high field strength (HFS) elements such as Ti, Y and Zr increase with time, whereas the contents of large ionic-radius lithophile (LIL) elements such as K, Rb and Ba sequentially decrease. Consequently, it can be said that the LIL/HFS elements ratios are relatively high and almost constant in Jurassic to Tertiary volcanic rocks, but become lower in Quaternary volcanic ones. On the one hand, high LIL/HFS elements ratios is fundamentally characteristic of subduction zone magmas (Tarney and Saunders, 1979). The LIL elements become mobile from the source of calc-alkaline magmas during dehydration of subduction slab, but the HFS elements are retained in the source due to the fractionation of mineral phases containing the elements. The fact that the Jurassic to Tertiary volcanic rocks have relatively high LIL/HFS elements ratios indicates that the igneous activities throughout the regions considered are mainly correlated with subduction processes.

On the other hand, enrichment of HFS elements and depletion of LIL elements (that is, low LIL/HFS elements ratio) in the Quaternary volcanic rocks indicate that the magma was generated from the source (possibly mantle) depleted in LIL elements, and the igneous activity has no relationship with subduction processes and calc-alkaline magmatism. The low content of Sr and its drastic decreasing pattern in the Quaternary group (Fig. 4b) means that this element also depleted in the source over Quaternary time. Since the HFS elements are generally incompatible in the tholeiitic and alkaline basalt suites, the low LIL/HFS ratios on Quaternary may show the tholeiitic and/or alkaline characteristics. Considering that the Quaternary volcanic rocks erupted along the spreading axis in Bransfield Strait, the Quaternary magmatism is thought to be quite different from the Jurassic to Tertiary magmatisms.

On the basis of the genetic discrimination methods, the environment of the volcanic magma erupted on the regions examined is considered. From the $K_2O$ vs. $SiO_2$ variation diagram (Fig. 3h), it is understood that there exist some differences. The boundaries in Figure. 3h are from Percellio and Taylor (1976). Except for the

Quaternary Deception Island group, four Jurassic to Tertiary groups are plotted in similar fields, from low-K to high-K through calc-alkaline. In general K content in volcanic rock on subduction zone is closely related to the depth of magma generation (Tatsumi, 1986). Since the high content of potassium reflects the deep condition of magma generation, the volcanic magma, whose K content is high, can be interpreted to be generated in a deeper part below the surface. The deeper part is possibly the lower crust or upper mantle below the deep crust. Further, the high contents of $Al_2O_3$ in the Tertiary South Shetland Islands and southern South America groups (Fig. 3b) may be due to the contribution of crustal materials.

Figure 5 shows the variation diagram of alkali ($Na_2O+K_2O$) content. The boundaries are from Kuno (1966), indicating fields of olivine tholeiitic basalt (OTB), high alumina basalt (HAB) and alkali olivine basalt (AOB), respectively. Below 60 % of $SiO_2$, all of the groups are plotted in entire fields, whereas above 60 %, they are mainly plotted in the fields of OTB and HAB except for the Quaternary Deception Island group, whose plotted fields are restricted within HAB and AOB. The high alkali content in the Quaternary group is due to the high content of $Na_2O$. The area Q enclosed by a broken line indicates the total area of Quaternary volcanic rocks on Deception, Penguin and Bridgeman Islands (Weaver et al., 1979). This area is in harmony with the distribution of alkali contents of the Quaternary group in this study.

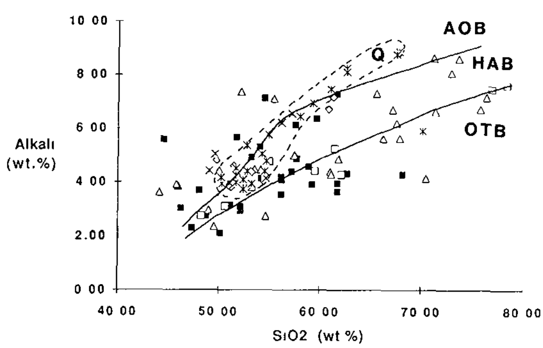



Fig. 5. Alkali ($Na_2O+K_2O$) vs. $SiO^2$ content variation diagram. Symbols are the same as Fig. 3. The boundaries are from Kuno (1966). OTB, olivine tholeiitic basalt ; HAB, high alumina basalt ; AOB, alkali olivine basalt. The area Q enclosed by broken line indicates the total area of Quaternary volcanic rocks in Deception, Penguin and Bridgeman Islands (Weaver et al., 1979).

The ratio of Fe/Mg is shown in the form of $Fe_2O_3/MgO$ (Fig. 6). The Fe/Mg ratio in the Quaternary group is relatively higher than the other groups, indicating that the magma of the Quaternary group has possibly experienced more advanced fractionation.

So-called AFM (alkali−total iron-MgO) diagram (Fig. 7) shows that the volcanic rocks in the regions examined are plotted in the intermediate field between the average tholeiite (TH) and average calc-alkaline (CA) trends.

Figure 8 shows the variation diagram of Zr vs. Rb. The boundary of mid-oceanic ridge basalt (MORB) and island-arc tholeiite (IATH) is the extrapolation of Tatsumi (1986). The Quaternary group enters into the field of MORB, whereas the other four groups into IATH. Though the Quaternary group has an intermediate character between tholeiite and calc-alkaline (Fig. 7), it has another characteristic, that being MORB and high alkalinity (Fig. 5 and Fig. 8).

Combining these geochemical characteristics and tectonic situations, it can be said that the Jurassic to Tertiary groups erupted when sub-

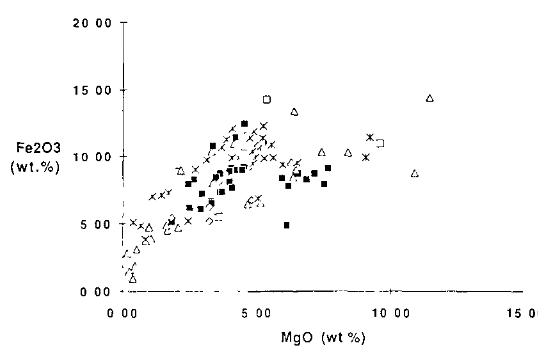



Fig. 6. $Fe_2O_3$ vs. MgO variation diagram. Symbols are the same as Fig. 3.

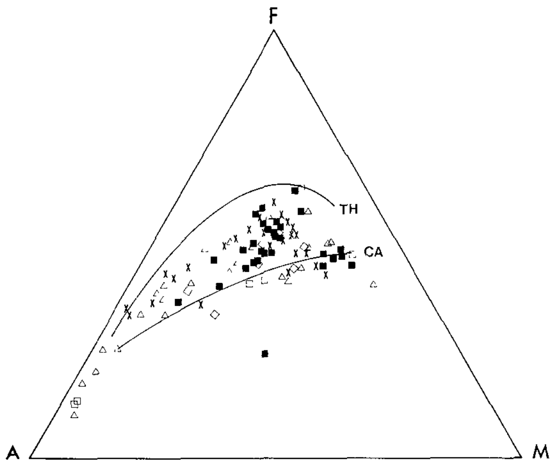



Fig. 7. AFM (alkali—total iron—MgO) diagram. Symbols are the same as Fig. 3. CA, average clac-alkaline trend ; TH, average tholeiitic trend.

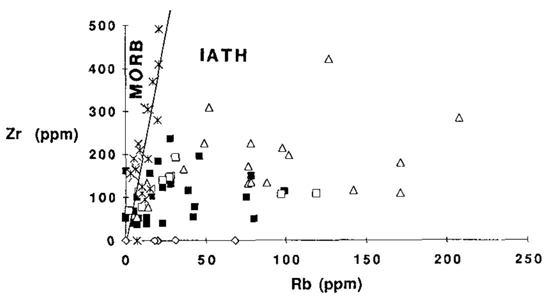



Fig. 8. Zr vs. Rb variation diagram. Symbols are the sams as Fig. 3. The boundary of MORB (mid—oceanic ridge basalt) and IATH (island—arc tholeiite) is the extrapolation of Tatsumi (1986).

duction prevailed, and the Quaternary group erupted during back-arc spreading. Both groups are quite different in the nature of their volcanic magmas.

## Conclusions

(1) Jurassic to recent magmatic activities throughout the Antarctic Peninsula, the South Shetland Islands and southern South America have been changed over time in their chemical natures, but the fractionation trends, as a whole, show the intermediate between the tholeiitic and calc-alkaline trends.

(2) High aluminium contents in Tertiary volcanic rocks on the South Shetland Islands and southern South America represent the contribution of crustal materials.

(3) The LIL/HFS elements ratios are relatively high and almost constant in Jurassic to Tertiary volcanic rocks, but become lower in Quaternary ones.

(4) Enrichment of HFS elements and depletion of LIL elements in Quaternary volcanic rocks indicate that the Quaternary volcanic magma was generated from the depleted mantle.

(5) Quaternary volcanic rocks, which formed at the marginal basin floor due to back-arc spreading, have affinities of alkaline rock and MORBs (mid-oceanic ridge basalts).

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