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# TRACE ELEMENT CHARACTERISTICS OF METAMORPHIC AND PLUTONIC ROCKS FROM THE BELGICA MOUNTAINS, EAST ANTARCTICA

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***Abstract:*** Metamorphic and plutonic rocks from the Belgica Mountains, East Antarctica, have been geochemically examined to evaluate original rock types and petrogenesis. Trace element compositions on 16 samples from the Belgica Mountains and 4 samples from the Yamato Mountains were determined with an X-ray fluorescence spectrometer.

High concentrations of Ba, Rb and Sr with very low levels of Nb, P and Y were found on granitic gneisses. The chemical feature is considered to represent the result of *in situ* partial melting. Basic and intermediate metamorphic rocks show variable compositions. Some of the rocks have slight enrichment of LIL elements with distinct Nb depletion. The chemical characteristics indicate that the rocks were generated probably under subduction environment. Syenitic rocks from the Belgica Mountains and gneisses from the Yamato Mountains are extremely enriched in Ba, Rb, Sr and Zr. Enriched source must be considered for the generation of the syenitic magma.

## 1. Introduction

The Belgica Mountains in the East Queen Maud Land, East Antarctica, consist dominantly of metamorphic rocks and lesser amounts of plutonic rocks. Similarly, other areas of the East Queen Maud Land are mostly composed of high-grade metamorphic rocks. A number of petrological studies have been made on those metamorphic rocks (*e.g.* ASAMI *et al.*, 1986; HIROI *et al.*, 1987), and tectonic models derived from examinations of metamorphism were presented (HIROI and SHIRAISHI, 1986). However, discussions on protoliths of metamorphosed rocks or on tectonic models derived from the examination of the protoliths are limited, because of the difficulty in obtaining original rock types of the high-grade metamorphic rocks by a petrographic approach. KANISAWA *et al.* (1987) presented major and trace element data of six metabasites collected from around Syowa Station, East Queen Maud Land, and briefly discussed a possible tectonic setting for the rocks. Geochemical approaches to metamorphic rocks are particularly important in order to classify rock types and to evaluate petrogenesis. Some of the elements, such as LIL (large ion lithophile) elements (*e.g.* Na, K and Rb), are susceptible to the latter alteration or metamorphism (ROLLINSON and WINDLEY, 1980), and major element data alone may not be sufficient to identify protoliths. It has been indicated that some trace elements, such as high field strength elements (Ti, Nb, P, Zr, etc.), are relatively immobile during a metamorphism (WINCHESTER and FLOYD, 1977). In this paper, the trace element analysis of samples from the Belgica Mountains was carried out to estimate original rock types and evaluate tectonic setting of the area.

## 2. Geological Setting

The Belgica Mountains are located at about 500 km southwest of Syowa Station, and lie about midway between the Yamato Mountains and the Sør Rondane Mountains. Metamorphic and plutonic rocks crop out in the Belgica Mountains. The metamorphic rocks are termed Belgica Group (KOJIMA *et al.*, 1981). The Belgica Group consists of the following rock types: (1) granitic gneiss, (2) marble and skarn, (3) amphibolite, (4) hornblende-biotite banded gneiss, (5) augen gneiss, (6) clinopyroxene gneiss, (7) garnet-biotite gneiss. The meta-basic rock, syenite, granodiorite-diorite, and pink granite intrude the Belgica Group (KOJIMA *et al.*, 1981).

The granitic gneiss is mainly exposed in the southwest massif of the mountains, and the hornblende-biotite banded gneiss occupies most of the southeast and northwest massifs (Fig. 1). Thin continuous beds of amphibolite and marble occur in those rocks. The regional structure indicated by foldings of those beds was formed by two generations of folding event. The type of folds is gentle to open. Banding structure is pronounced in the region. Large scale compositional bandings would be primary sedimentary in origin, but most of the banding structure would be produced by latter tectono-thermal event.

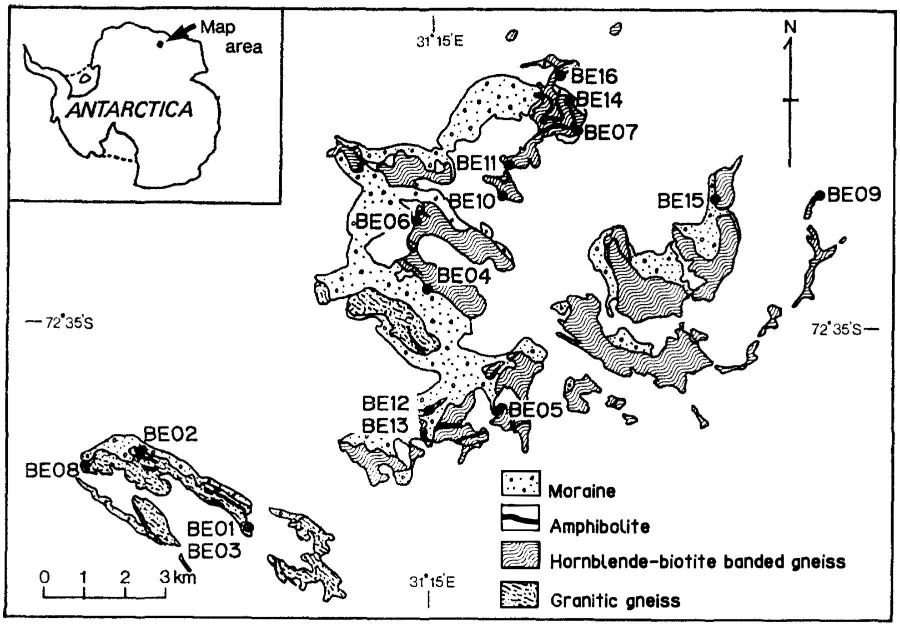


*Fig. 1. Geological map of the Belgica Mountains showing sample localities. Gological map after KOJIMA et al. (1982).*

Representative 16 samples of various rock types collected from this area (Fig. 1) have been examined, and additional four samples from the Yamato Mountains were analyzed for the purpose of comparison. Brief petrographic descriptions of the samples from the Belgica Mountains are given in KOJIMA *et al.* (1982).

## 3. Analytical Method

Trace element contents of the samples were determined with an X-ray fluorescence spectrometer following the method of NORRISH and CHAPPELL (1977). Details of the analytical procedure are found in OGASAWARA (1987). Major element data of 16 samples from the Belgica Mountains presented by KOJIMA *et al.* (1982) and those of four samples from the Yamato Mountains reported by SHIRAISHI (1986) are used for a matrix correction of the trace element analysis. Trace element data together with major element data from the above reference are presented in Table 1.

## 4. Geochemical Results

Geochemical results are plotted on the variation diagrams to demonstrate distinct geochemical features between the rock types (Fig. 2). Primodial mantle normalized patterns (Figs. 3 and 5) are also presented to facilitate an examination of the data. Although granitic rocks would not have a direct genetic link to the primordial mantle, a relative concentration level between elements may be easily manifested by the patterns.

### *4.1. Granitic gneiss*

Two samples (BE01 and BE02) of the granitic gneiss collected from the southwestern massif were analyzed (Table 1 and Fig. 1). Most of the elements show identical concentrations in the two samples, except for a small difference in $Na_2O$. The rocks are characterized by high $SiO_2$ (around 74 wt %), and very low levels of $Fe_2O_3$, FeO, MnO, and MgO. The $K_2O$ content is moderately high (Fig. 2B). The Ba and Sr contents are also high (Figs. 2D and E), but Y and Nb are extremely depleted. Niobium is less than the detection limit of the analysis. The relatively large depletion of Y is clearly shown in the primordial mantle normalized pattern (Fig. 3A). Although a depletion of Y is commonly found in tonalite-trondhjemite from the continental region (*e.g.* ARTH, 1979), high $K_2O$ granitoids generally do not show such Y depletion (*e.g.* WHITE and CHAPPELL, 1983).

The field observation indicated that the granitic gneiss has migmatitic and agmatitic structures, and also contains heterogeneous inclusions of amphibolite of various sizes (KOJIMA *et al.*, 1982). Those features imply that the granitic gneiss had been partially melted. However, the presence of continuous beds of marble and amphibolite interlayerd within the granitic gneiss body does not imply any partial melting of large extent which might destroy such original structure. Yttrium can be depleted by a separation of amphibole or garnet from the granitic melt during either partial melting or crystal fractionation processes (ARTH and BARKER, 1976). If a small degree of *in situ* partial melting (anatexis) took place during the high grade metamorphism and separating an amphibole-rich residue from the original source rocks, Y could be preferentially accommodated into the amphibole-rich residue, and depleting Y in the granitic gneiss. The granitic gneiss was formed from a melt component and residual crystals which were not separated from the source rocks. This model also explains high Ba and Sr contents in the granitic gneiss, as mineral/melt Kd's of amphibole for those elements are low (HANSON, 1978). ASAMI *et al.* (1986) estimated metamorphic condition of the Belgica Mountains based on the mineral assemblage and gave the temperature of 680–700°C and total fluid pressures around 5 kb. Under those temperature and pressure, the gneisses which are composed largely of quartz, alkali feldspar and plagioclase can be partially melted (WINKLER, 1979), though the amount of melt produced strongly depends on composition of the original rock. Under the metamorphism of *P-T* condition indicated above, basic rocks and carbonate rocks in the Belgica Mountains were changed to amphibolite facies metamorphic rocks, and slightly acidic source rocks would be

*Table 1. Chemical compositions of metamorphic and plutonic*

| Sample<br>Rock type | BE01<br>Grgn | BE02<br>Grgn | BE03<br>Amph | BE04<br>Amph | BE05<br>Amph | BE06<br>Amph | BE07<br>Hogn | BE08<br>Hogn | BE09<br>Hogn | BE10<br>Bign |
|---|---|---|---|---|---|---|---|---|---|---|
| (wt%) | | | | | | | | | | |
| $SiO_2$ | 73.85 | 74.05 | 43.86 | 47.23 | 48.63 | 49.19 | 55.76 | 50.69 | 57.34 | 72.42 |
| $TiO_2$ | 0.10 | 0.06 | 0.95 | 2.36 | 2.11 | 3.65 | 2.27 | 1.06 | 0.68 | 0.41 |
| $Al_2O_3$ | 13.99 | 14.93 | 14.92 | 10.21 | 12.65 | 14.66 | 14.27 | 18.58 | 14.43 | 11.48 |
| $Fe_2O_3$ | 0.61 | 0.62 | 4.72 | 3.87 | 2.84 | 4.97 | 2.82 | 3.55 | 6.60 | 3.09 |
| FeO | 0.71 | 0.63 | 9.18 | 7.77 | 9.90 | 8.53 | 7.02 | 4.71 | 4.91 | 2.25 |
| MnO | — | — | 0.23 | 0.22 | 0.26 | 0.20 | 0.14 | 0.16 | 0.23 | 0.06 |
| MgO | — | 0.21 | 6.73 | 10.56 | 6.20 | 3.76 | 3.43 | 5.53 | 2.59 | 0.80 |
| CaO | 1.86 | 1.66 | 14.43 | 12.34 | 11.89 | 7.12 | 6.51 | 7.41 | 5.97 | 3.18 |
| $Na_2O$ | 2.75 | 4.27 | 1.10 | 1.43 | 2.25 | 2.13 | 2.70 | 5.85 | 3.66 | 3.26 |
| $K_2O$ | 4.11 | 4.10 | 1.20 | 1.23 | 1.00 | 1.82 | 1.85 | 1.76 | 1.74 | 0.83 |
| $P_2O_5$ | 0.03 | 0.04 | 0.12 | 0.18 | 0.16 | 1.22 | 0.86 | 0.23 | 0.34 | 0.10 |
| $H_2O$ (+) | 0.77 | 0.14 | 0.73 | 0.93 | 0.64 | 1.20 | 1.07 | 0.86 | 0.91 | 0.68 |
| $H_2O$ (−) | 0.32 | 0.22 | 0.23 | 0.37 | 0.27 | 0.58 | 0.33 | 0.28 | 0.24 | 0.24 |
| Total | 99.10 | 100.93 | 98.40 | 98.70 | 98.80 | 99.03 | 99.03 | 100.67 | 99.64 | 98.80 |
| (ppm) | | | | | | | | | | |
| Ba | 1307. | 1488. | 120. | 48.1 | 82.3 | 541. | 576. | 289. | 641. | 326. |
| Rb | 105. | 131. | 14.3 | 40.8 | 15.9 | 55.1 | 58.2 | 82.8 | 42.1 | 26.2 |
| Sr | 610. | 569. | 862. | 316. | 328. | 763. | 645. | 776. | 386. | 218. |
| Y | 1.7 | 1. | 8.8 | 21.0 | 47.6 | 49.9 | 50.9 | 19.0 | 19.8 | 22.4 |
| Zr | 81.8 | 97.4 | 14.9 | 126. | 121. | 472. | 369. | 65.2 | 64.0 | 57.7 |
| Nb | — | — | — | 19.1 | 5.3 | 45.4 | 35.0 | 3.6 | 2.0 | 2.1 |
| V | 15.9 | 8.9 | 593. | 324. | 404. | 79.4 | 136. | 158. | 253. | 5.6 |
| Ni | 7.2 | 6.2 | 45.6 | 141. | 65.5 | 18.3 | 26.0 | 122. | 10.3 | 10.8 |
| Cu | 1.1 | 25.0 | 18.6 | 8.5 | 10.6 | 26.6 | 10.7 | 88.6 | 79.4 | 37.0 |
| Zn | 13.9 | 10.6 | 141. | 202. | 225. | 202. | 153. | 99.2 | 183. | 49.2 |

Major element data are taken from KOJIMA *et al.* (1982).
—: the value is less than the lower limit of detection.
n.d.: not determined.
Original Sample Number
BE01; A79122004, BE02; K79122014, BE03; A79122002, BE04; K79121517, BE05; A79121902, BE06; K79121521, BE07; N79122602, BE08; K79122001, BE09; N79123101, BE10; A79122401,

partially melted. The *P-T* condition during the metamorphism would not be sufficient to separate the melt effectively from the source rocks, and amphibole rich residue and the granitic gneiss which contains unmelted residual crystals and a melt component were produced.

The source rock of the granitic gneiss must have been more basic as the amphibole-rich residue was separated from it. From the field observation, amphibole-rich inclusions do not exceed more than one-third of the volume in the outcrop. If the source rock has changed to one part of amphibole-rich residue (assuming its $SiO_2$ content is around 45 wt% from the chemistry of typical amphibole) and two parts of granitic gneiss ($SiO_2$; 74 wt%), the $SiO_2$ content of the source rock is still around 64 wt%. This indicates that the original rocks had intermediate to slightly acidic composition. As the granitic gneiss is peraluminous, the source rock had a peraluminous character too. This

*rocks from the Belgica and Yamato Mountains, East Antarctica.*

| Sample<br>Rock type | BE11<br>Cpgn | BE12<br>Gr | BE13<br>Di | BE14<br>Sy | BE15<br>Sy | BE16<br>Cbgn | YA01<br>Grgn | YA02<br>Cbgn | YA03<br>Chgn | YA04<br>Chgn |
|---|---|---|---|---|---|---|---|---|---|---|
| (wt%) | | | | | | | | | | |
| $SiO_2$ | 63.44 | 73.14 | 53.04 | 57.70 | 55.54 | 55.55 | 66.10 | 46.03 | 47.37 | 49.74 |
| $TiO_2$ | 0.91 | 0.17 | 1.85 | 1.29 | 1.94 | 1.52 | 0.54 | 1.16 | 1.39 | 2.11 |
| $Al_2O_3$ | 10.82 | 14.24 | 14.07 | 13.35 | 15.53 | 11.84 | 15.80 | 5.77 | 12.50 | 13.82 |
| $Fe_2O_3$ | 1.26 | 0.23 | 2.84 | 2.07 | 1.97 | 0.94 | 1.14 | 1.86 | 1.60 | 2.45 |
| FeO | 5.17 | 1.67 | 5.76 | 3.84 | 5.62 | 5.86 | 1.19 | 7.59 | 7.45 | 6.82 |
| MnO | 0.21 | 0.02 | 0.13 | 0.12 | 0.12 | 0.14 | 0.04 | 0.21 | 0.17 | 0.14 |
| MgO | 3.19 | 0.24 | 6.83 | 5.95 | 2.37 | 6.57 | 1.04 | 18.33 | 9.29 | 6.30 |
| CaO | 12.23 | 1.24 | 7.29 | 4.95 | 4.04 | 5.82 | 2.42 | 10.01 | 7.99 | 7.12 |
| $Na_2O$ | 2.49 | 4.59 | 2.15 | 1.43 | 1.55 | 0.58 | 4.33 | 0.46 | 1.94 | 3.09 |
| $K_2O$ | 0.22 | 4.45 | 2.09 | 6.41 | 7.10 | 7.37 | 5.41 | 4.08 | 6.49 | 5.37 |
| $P_2O_5$ | 0.22 | 0.04 | 0.70 | 0.74 | 1.34 | 1.75 | 0.24 | 1.68 | 1.21 | 0.88 |
| $H_2O$ (+) | 0.43 | 0.46 | 1.38 | 0.79 | 0.98 | 0.84 | 0.73 | 1.17 | 1.03 | 1.16 |
| $H_2O$ (−) | 0.25 | 0.41 | 0.46 | 0.50 | 0.42 | 0.30 | 0.23 | 0.21 | 0.27 | 0.20 |
| Total | 100.84 | 100.90 | 98.59 | 99.14 | 98.52 | 99.08 | 99.92 | 98.56 | 98.70 | 99.20 |
| (ppm) | | | | | | | | | | |
| Ba | 140. | 265. | 1734. | 1776. | 3758. | 3969. | 1445. | 1262. | 3888. | 1703. |
| Rb | 5.2 | 386. | 87.6 | 282. | 193. | 291. | 109. | 324. | 311. | 249. |
| Sr | 246. | 84.4 | 1361. | 961. | 2070. | 1654. | 501. | 259. | 1058. | 795. |
| Y | 41.3 | 54.4 | 29.1 | 20.5 | 39.3 | 39.2 | 11.2 | 32.4 | 25.2 | 25.6 |
| Zr | 193. | 271. | 246. | 524. | 419. | 188. | 328. | 663. | 385. | 417. |
| Nb | 12.8 | 40.7 | 25.0 | 27.0 | 64.6 | 16.1 | 8.4 | 18.0 | 11.3 | 53.0 |
| V | 102. | — | 132. | 108. | 75.9 | 113. | 37.2 | 87.1 | 212. | 120. |
| Ni | 41.6 | 7.9 | 63.1 | 131. | 12.7 | 113. | 8.4 | 393. | 60.9 | 107. |
| Cu | 1.4 | n.d. | 17.1 | 2.5 | 13.0 | 4.9 | n.d. | n.d. | 1.2 | n.d. |
| Zn | 116. | 55.5 | 111. | 94.9 | 131.1 | 170. | 58.3 | 247. | 160. | 182. |

BE11; K79121610, BE12; K79121914, BE13; K79121913, BE14; K79122607, BE15; N79122607, BE16; K79122601, YA01; 74121709, YA02; A79112910, YA03; 74121604, YA04; K79112911-1. Rock type (Grgn; granitic gneiss, Amph; amphibolite, Hogn; hornblende-biotite gneiss, Bign; biotite gneiss, Cpgn; clinopyroxene gneiss, Gr; pink granite, Di; diorite, Sy; syenite, Cbgn; clinopyroxene-biotite gneiss, Chgn; clinopyroxene-hornblende gneiss).

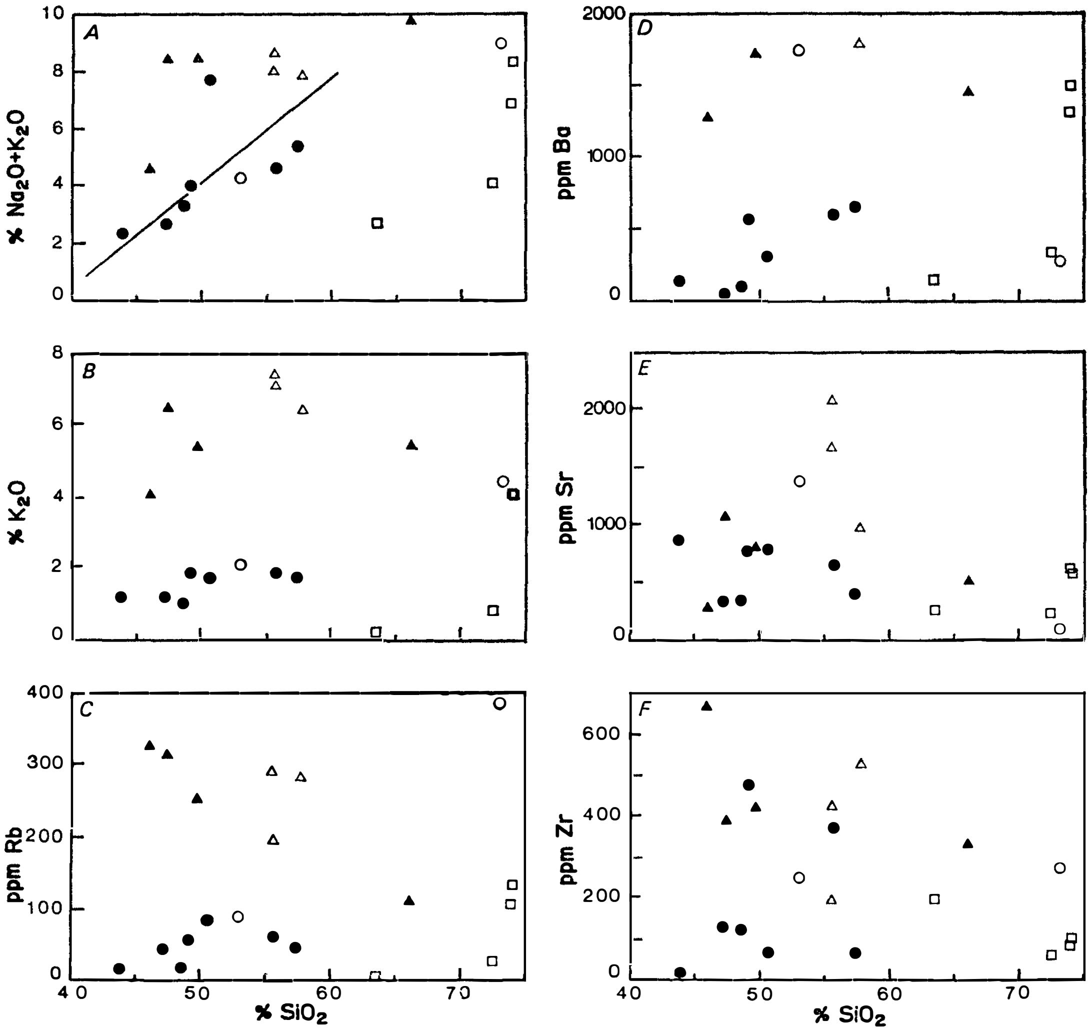


*Fig. 2. Selected vatiation diagrams for metamorphic and plutonic rocks from the Belgica Mountains and Yamato Mountains. A line in the diagram A indicates the boundary between alkalic and subalkalic rocks after* MACDONALD *and* KATSURA *(1964).*
*□ : Granitic gneiss, biotite gneiss and clinopyroxene gneiss. ● : Amphilbolite and hornblende-biotite gneiss. △: Syenite and clinopyroxene-biotite gneiss of syenitic composition. ○ : Diorite and pink granite. ▲: Metamorphic rocks from the Yamato Mountains.*

peraluminous nature and possible chemical composition estimated are compatible with the source rock to be a clastic sedimentary rock.

Granitic gneiss (YA01) from the Yamato Mountains also has a similar normalized pattern (Fig. 3A) to that from the Belgica Mountains, indicating that the same petrogenetic model could be applied. However, lower $SiO_2$ content and smaller Y depletion of YA01 than the samples from the Belgica Mountains may imply that the amount of separating amphibole-rich residue is smaller for YA01.

## 4.2. *Mafic metamorphic rocks*

Geochemistry of the amphibolite and hornblende-biotite banded gneiss, excluding a sample (BE09) of the hornblende-biotite gneiss, is described in this section. Based on

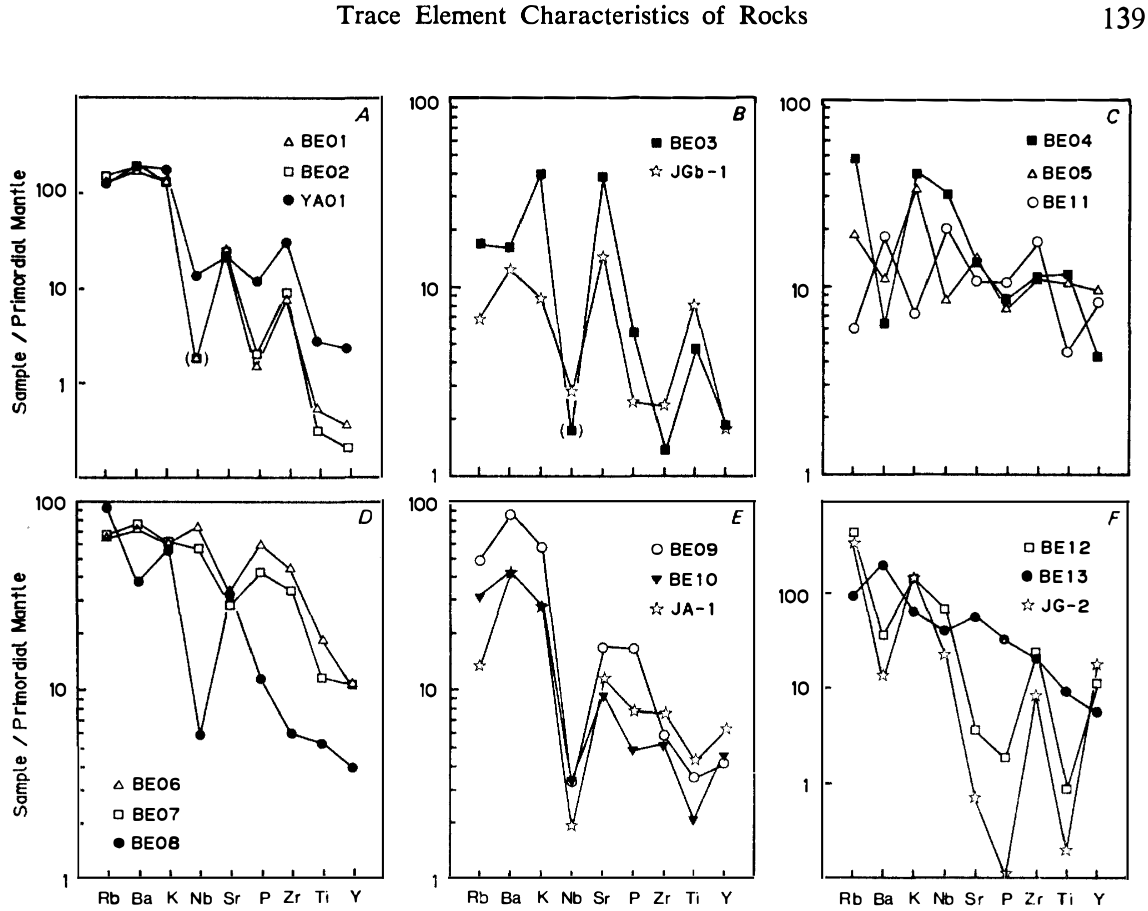


*Fig. 3. Primordial mantle normalized patterns of metamorphic and igneous rocks from the Belgica and Yamato Mountains. Abundances of incompatible elements are normalized using primordial mantle abundance of* WOOD *et al. (1981). Nb values in the bracket in the diagrams are derived from the lower limit of detection of analysis.*

the $SiO_2$ content (Table 1), one sample is classified as an ultrabasic rock, and four samples fall in the field of basic rock. Another sample has $SiO_2$ of 55.7 wt%. Total alkali contents of the mafic metamorphic rocks vary from 2.30 to 4.55 wt%, except for BE08 (7.61 wt%). Although alkali elements are susceptible to remobilization by alteration or metamorphism, an initial comparison of the mafic metamorphic rocks with fresh modern volcanic rocks on the $Na_2O+K_2O$ versus $SiO_2$ diagram (Fig. 2A) indicates that five samples of the mafic metamorphic rocks are plotted in the field of tholeiite defined by MACDONALD and KATSURA (1964).

Sample BE03, amphibolite from the southwest massif, has extremely low $SiO_2$ content (43.86 wt%). The rock is characterized by high CaO (14.43 wt%), Sr (862 ppm) and V (593 ppm). Primodial mantle normalized pattern of the rock (Fig. 3B) indicates relative depletions of Nb, Zr, and Y. Similar chemical feature is typically found in gabbroic rocks (*e.g.* JGb-1 from the Abukuma Mountains, Fig. 3B), and is considered to be a result of the presence of cumulative plagioclase, mafic minerals, and oxide minerals in the gabbro (OGASAWARA, 1987). High CaO and Sr values are derived by cumulative plagioclase, and high V, Zn and Ti contents are due to cumulative mafic and oxide minerals. Therefore, the gabbro which contains cumulate minerals is likely to be a protolith for the amphibolite.

Two amphibolites (BE04 and BE05) have high MgO contents. Slight enrichment of LIL element is shown in Fig. 3C. The patterns indicate a Ba depletion relative to Rb and K, and it may imply a result of selective elemental mobility by the alteration or metamorphism.

An amphibolite (BE06) and hornblende-biotite gneiss (BE07) from the northwest massif have high Zr content and Zr/Y ratio. Figure 4 shows that those are plotted in the field of within plate basalt of PEARCE and NORRY (1979) or in the field of continental arc basalt of PEARCE (1983). High Zr content of the rocks indicates that those could be derived from Zr-enriched source, probably similar to the enriched sub-continental mantle (PEARCE, 1983). Primordial mantle normalized pattern (Fig. 3D) indicates LIL-enriched character with a small Sr depletion which may be a result of plagioclase fractionation.

A sample of hornblende-biotite gneiss (BE08) from the western end of the southwest massif (Fig. 1) has high total alkali, due to high $Na_2O$ content. In fact, normative nepherine is indicated from CIPW norm of this sample. Primordial mantle normalized pattern of this sample (Fig. 3D) shows LIL enrichment with strong Nb depletion. The depletion of Nb may imply a subduction mechanism for the generation of the protolith of the rocks, as it is typically found in island arc volcanics, including alkaline basalts (NAKAMURA *et al.*, 1985).

The geochemical features of the mafic metamorphic rocks studied are significantly different from those of the Lützow-Holm Complex which is characterized by MORB-like nature (KANISAWA *et al.*, 1987).

Trace element data of three mafic metamorphic rocks from the Yamato Mountains are also presented for comparison (Table 1). Samples are clinopyroxene-biotite gneiss (YA02) and clinopyroxene-hornblende gneisses (YA03 and YA04). They have high $K_2O$ and Rb contents (Figs. 2B and C), and are plotted in the field of alkali basalt of MACDONALD and KATSURA (1964). They also have high Ba and Zr contents (Figs. 2D

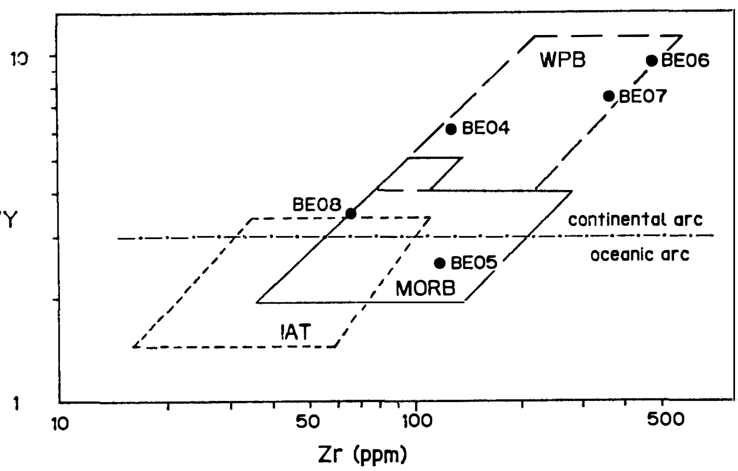


*Fig. 4. Zr/Y versus Zr diagram for discrimination of basalt types of PEARCE and NORRY (1979) and showing the position of the oceanic-continental arc discrimination for basalts already identified as having volcanic arc character (PEARCE, 1983). IAT: island arc tholeiite, MORB: mid-ocean ridge basalt, WPB: within plate basalt.*

and F). The high Zr values support alkaline characteristics of the rocks. Primordial mantle normalized patterns (Fig. 5A) indicate LIL-enriched profile with relative depletion of Sr and Nb. Although the $SiO_2$ content of the mafic metamorphic rocks is much lower than the syenitic rock, levels of the LIL elements are comparable to those of syenitic rocks (SHIRAISHI *et al.*, 1983), as discussed in section 4.5. The basic metamorphic rocks of the Yamato Mountains could have been derived from an extremely enriched source.

### 4.3. *Other metamorphic rocks*

Hornblende-biotite gneiss (BE09) was collected from the northern end of the southeast massif (Fig. 1). The $SiO_2$ content of the gneiss is 57.34 wt%. Most of the chemistry has a similarity to the typical andesitic rock. Figure 3E shows LIL-enriched pattern with large Nb and Ti depletions, indicating a geochemical similarity to that of island arc andesite (one example, andesite of the Hakone volcano from the GSJ standard rock, is shown in Fig. 3E). It is considered that the rock could have been derived from the andesitic rock.

Biotite gneiss (BE10) was collected from the northwest massif (Fig. 1). The $SiO_2$ content of the biotite gneiss is 72.42 wt%. The rock is metaaluminous as mol. $Al_2O_3/CaO + Na_2O + K_2O$ ratio is 0.953, suggesting the rock was not derived from a clastic sedimentary rock. Primordial mantle normalized pattern (Fig. 3E) indicates that BE10 has geochemical characteristics similar to BE09 and typical andesites. This pattern and major element chemistry may imply that protolith of the biotite gneiss is a rhyolitic rock which was derived from the andesitic magma by the fractional crystallization.

Clinopyroxene gneiss (BE11) occurs in the central part of the northwest massif within the hornblende-biotite banded gneiss and is several to ten meters thick. It is characterized by high CaO and extremely low $K_2O$ and Rb (Figs. 2B and C). Ba and Sr are relatively low (Figs. 2D and E). Low concentration of alkali elements may imply leaching of alkali elements from the rocks during the metamorphism. Another possibility to explain such chemical characteristics is that the protolith of the clinopyroxene gneiss is a calc-silicate rock.

### 4.4. *Pink granite and diorite*

Pink granite (BE12) occurs as a small dyke in the Belgica Mountains. It is a metaaluminous rock with high total alkali content. As shown in Fig. 3F, the Rb, K, Zr, and Y contents are relatively high. Those geochemical characteristics is similar to those of A-type granitoids (COLLINS *et al.*, 1982). A normalized pattern of the pink granite has many similarities to that of JG-2 (Fig. 3F) which has been considered to have A-type characteristics (OGASAWARA, 1987).

Diorite (BE13) collected from the central part of the Belgica Mountains contains high Ba and Sr. Figure 3F shows a smooth primordial mantle normalized pattern with LIL elements enrichment, suggesting that the diorite could have been derived from the LIL-enriched basic magma without much crystal fractionation.

### 4.5. *Syenitic rocks*

Small dykes of syenite intrude the hornblende-biotite gneiss and amphibolite. Two

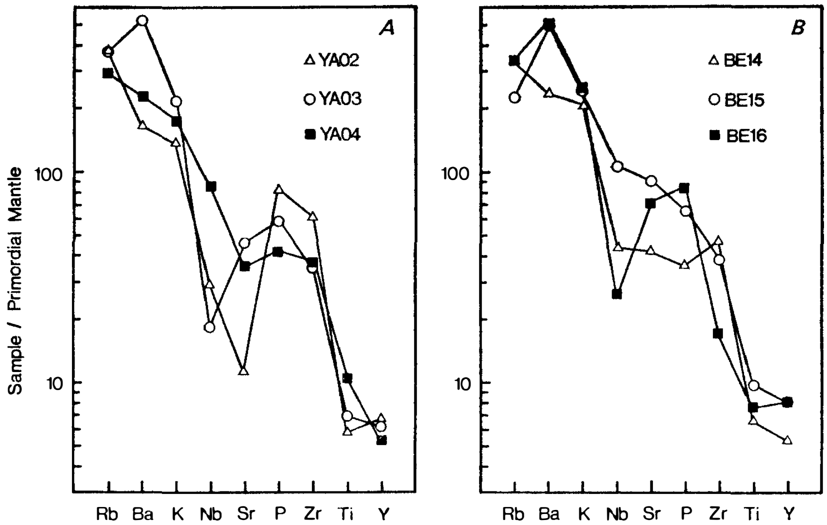


*Fig. 5. Primodial mantle normalized pattern for the syenitic rocks from the Belgica Mountains and basic metamorphic rocks from the Yamato Mountains. Normalizing values are the same as those in Fig. 3.*

samples of the syenite (BE14 and BE15) are examined here. A sample of clinopyroxene-biotite gneiss (BE16) from the north of Mt. Bastin also has a syenitic composition (Table 1), though it occurs as a concordant body within the hornblende-biotite gneiss.

The $SiO_2$ content of the syenitic rocks ranges from 55.54 to 57.70 wt%. The range of the $SiO_2$ is similar to that of syenitic rocks from the Yamato Mountains (SHIRAISHI *et al.*, 1983). The syenitic rocks are characterized by extremely high $K_2O$ content (Fig. 2B), ranging from 6.41 to 7.37 wt%. Results of trace element analysis exhibit extremely high concentrations of Ba, Rb, Sr and Zr. Similar high concentrations of Rb, Sr and Zr are also found in the syenitic rocks from the Yamato Mountains (SHIRAISHI *et al.*, 1983; SHIRAISHI and KANAYA, 1983). Difference in Zr content is found between the syenite and the clinopyroxene-biotite gneiss (BE16), as Zr of syenite is about twice that of clinopyroxene-biotite gneiss. The difference may imply different magma source between those. Primordial mantle normalized patterns (Fig. 5B) show extreme enrichment of LIL elements. Nb is depleted relative to the other elements in the clinopyroxene-biotite gneiss, but only small Nb depletion is found in the syenites. Concentrations of the LIL elements and Zr of the syenitic rocks are much higher than those of ordinary alkaline rocks (WOOD *et al.*, 1981; NAKAMURA *et al.*, 1985). Such extremely enriched character of the syenite could imply that the syenitic magma has been generated from enriched source by the small degree of melting. Similar enriched source may be considered for the source of the LIL-enriched mafic metamorphics in the Yamato Mountains.

## 5. Tectonic Implications

As discussed in the previous sections, protoliths of the Belgica Group could have comprised the following: (1) clastic sedimentary rocks, (2) gabbro, (3) basaltic rocks, (4) andesitic-rhyolitic rocks, (5) carbonate rocks. The presence of clastic sedimentary rocks in the Belgica Group implies that the depositional environment of the group was not distant from the continental margin. Nb-depleted basic and intermediate rocks also suggest that the Belgica Group was deposited possibly in the active continental margin or back arc basin. SHIBATA *et al.* (1986) presented high initial $^{87}Sr/^{86}Sr$ ratios of the samples from the Yamato Mountains and suggested older protolith of the Yamato Complex than that of the Lützow-Holm Complex. The interpretation implies the presence of older continental crust under the Yamato Complex. Though no Sr isotopic data are available at this stage from the Belgica Mountains, a provenance for the clastic sediments of the Belgica Group may contain older continental crust. Geochemical data presented for the mafic metamorphic rocks indicated that those from the Yamato Mountains are alkaline and significantly enriched in incompatible elements. However, those from the Belgica Mountains show limited enrichments of incompatible elements. The difference of the chemistry of the mafic rocks between the two mountains could indicate development of the crust under slightly different tectonic setting.

Incompatible element-enriched magma indicated by the syenitic rocks could be attributed to the small degree of partial melting of source materials as well as the presence of enriched source. Enriched magma could be derived from mantle plume or could be generated from the sub-continental lithosphere (PEARCE, 1983). As the active continental margin or marginal basin is considered for the depositional environment for the Belgica Group, the sub-continental lithosphere is the most likely source for the enriched magma.

The pink granite which has similar geochemical characteristics to A-type granite, could be generated by a small degree of partial melting of crustal rocks which may be enriched in incompatible elements. The diorite could be derived from the slightly LIL elements-enriched basic magma.

## 6. Summary

Results of analysis on ten trace elements together with previously published major element data indicated geochemical characteristics of the various metamorphic and igneous rocks from the Belgica Mountains. The granitic gneisses show high concentrations of LIL elements and low levels of Nb, P and Y. The features are interpreted to be a result of *in situ* partial melting of originally clastic sediments during metamorphism. Geochemical characteristics of the mafic metamorphic rocks from the area are variable between the samples. Protolith of the amphibolite (BE03) is suggested to be a gabbroic rock which has formed from melt and cumulate crystals. The other amphibolites show slight enrichment of LIL elements with moderate level or high content of Zr. Hornblende-biotite gneisses include an andesitic rock which was possibly generated under subduction environment. Biotite gneiss also has a chemical similarity to the island arc rhyolite. Those chemical characteristics suggest an active continental margin or back arc basin environment for the deposition of the Belgica Group. Syenitic rocks have extremely high concentrations of Ba, Rb, Sr and Zr. Syenitic magma could be generated from source enriched in those elements.

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