Polar Geosci., 14, 119–138, 2001

Geochemical characteristics of two types of early Paleozoic granitoids from the Sør Rondane Mountains, East Antarctica

Zilong Li[1]*, Yoshiaki Tainosho[2], Kazuyuki Shiraishi[3], Masaaki Owada[4] and Jun-ichi Kimura[5]

[1]*Graduate School of Science and Technology, Kobe University, Nada, Kobe 657-8501*
[2]*Faculty of Human Development, Kobe University, Nada, Kobe 657-8507*
[3]*National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*
[4]*Department of Earth Sciences, University of Yamaguchi, Yamaguchi 753-8512*
[5]*Department of Geology, Shimane University, Nishikawatsu 1060, Matsue 690-8504*

Abstract: Early Paleozoic granitoids of the Sør Rondane Mountains, which occur as stocks, batholiths or sheets and intrude into late Proterozoic high- to intermediate-grade metamorphic rocks, represent prominent Pan-African to post Pan-African intermediate-acidic magmatic events. They are mainly composed of granite and syenite and are enriched in alkalis. Based on geochemical features, there are two types of early Paleozoic granitoids: (1) volcanic-arc type (including Dufek and Lunckeryggen) granitoid, and (2) within-plate type (including Austkampane, Pingvinane, Vikinghøgda and Rogerstoppane) granitoid.

The volcanic-arc type granitoid has higher Mg#, Sr, and Sr/Ba, Sr/Y, La/Sm, La/Yb and LREE/HREE ratios, lower A/CNK and Ga/Al ratios, and ΣREE with no or positive Eu anomalies. On the other hand, the within-plate type granitoid has relatively higher A/CNK and Ga/Al ratios, and ΣREE, lower Mg#, Sr, and Sr/Ba, Sr/Y, La/Sm, La/Yb and LREE/HREE ratios with moderate to strong negative Eu anomalies. Geochemical characteristics as well as isotopic data of two types of early Paleozoic granitoids indicate two possibilities of their petrogenesis. One is that the volcanic-arc type granitoid may have been derived from deeper parental magma source by process of fractional crystallization with or without assimilation and/or mixing, subsequently, successive fractional crystallization from the same magma source (should be altered components) after assimilation by crustal materials during ascending, to produce the within-plate type granitoid; the other is that they are derived from different source materials and have different processes. The volcanic-arc type granitoid may be derived from partial melting of the Nils Larsen tonalite with minor mixing with, for example, host gneisses, while the within-plate type granitoid is formed by assimilation of crustal materials of host metamorphic rocks by the melt and then fractional crystallization.

key words: early Paleozoic volcanic-arc type and within-plate type granitoids, trace and rare earth elements, petrogenesis, Sør Rondane Mountains, East Antarctica

* Corresponding author: Tainosho's Lab., Division of Earth and Environmental Sciences, Faculty of Human Development, Kobe University, Nada, Kobe 657-8507 (Fax: +81-078-803-7761; E-mail: 974d931n@kobe-u.ac.jp).

1. Introduction

In recent years, plutonic rocks from the Sør Rondane Mountains, East Antarctica have been studied because the late-Proterozoic to early-Paleozoic igneous activity in that area is very important, as one part of the Pan-African to post Pan-African events (Sakiyama *et al.*, 1988; Takahashi *et al.*, 1990). The older and younger intrusive rocks are widely distributed in the Sør Rondane Mountains (Sakiyama *et al.*, 1988; Shiraishi *et al.*, 1997) and they are dated at *ca.* 950 Ma and 500-530 Ma respectively by the whole-rock Rb-Sr isochronal method (Takahashi *et al.*, 1990; Tainosho *et al.*, 1992). Whole-rock Rb-Sr and Sm-Nd, and biotite K-Ar geochronological studies (Table 1) indicate that younger plutonism in the Sør Rondane Mountains occurred at 500–530 Ma.

To date, some geochemical studies of older (late Proterozoic) and younger (early Paleozoic) plutonic rocks have been carried out (*e.g.* Sakiyama *et al.*, 1988; Tainosho *et al.*, 1992, 1993). The older plutonic rock is called the Nils Larsen tonalite, having high CaO, MgO, Ni and Cr, and low alkali, Ba and Rb, and belongs to the M-type granite (Tainosho *et al.*, 1992). On the other hand, the younger plutonic rocks can firstly be divided into the concordant (Austkampane, Pingvinane, Rogerstoppane and Vikinghøgda granitoids) and discordant granites (Dufek and Lunckeryggen granitoids except for Mefjell granitoid) based on the field relationships as well as the Lunckeryggen syenite, which is intruded by the Lunckeryggen granitoid (Sakiyama *et al.*, 1988). Subsequently, two types of the volcanic-arc (Dufek, Lunckeryggen and Mefjell granitoids) and within-plate type granitoids (Austkampane, Pingvinane, Rogerstoppane and Vikinghøgda granitoids) were subdivided judged from different geochemistry and isotopic data between them (Tainosho *et al.*, 1992; Arakawa *et al.*, 1994). The two types of granitoids have nearly same ages (Table 1); however, they display different field occurrence, mineral composition, geochemical characteristics and isotopic data. Moreover, the Mefjell plutonic rocks are separated from the volcanic-arc type granitoid in this study, and will be not introduced here because they consist of syenite with granite and have different chemical composition of minerals (Li *et al.*, 2001) and geochemical characteristics compared with the Dufek and Lunckeryggen granitoids, which are volcanic-arc type granitoids. Further studies of two types of granitoids may provide better understanding of their petrogenesis and of Pan-African crustal evolution (Sakiyama *et al.*, 1988). In this paper, we exhibit the two types of granitoids (volcanic-arc type and within-plate type granitoids), which have clearly different geochemical characteristics, particular trace and rare earth elements, and discuss their petrogenesis.

2. Regional geology, field occurrences and petrography

The Sør Rondane Mountains (22°E to 28°E, 71.5°S to 72.5°S) in Queen Maud Land, East Antarctica (Fig. 1), mainly consist of Proterozoic intermediate- to high-grade metamorphic rocks (1000–1100 Ma) and various plutonic rocks with minor mafic dykes (~500 Ma) (Kojima and Shiraishi, 1986; Ishizuka and Kojima, 1987; Sakiyama *et al.*, 1988; Takahashi *et al.*, 1990; Shiraishi *et al.*, 1991; Shiraishi and Kagami, 1992; Asami *et al.*, 1992; Grew *et al.*, 1992; Osanai *et al.*, 1992, 1996; Tainosho *et al.*, 1992, 1993; Arakawa *et al.*, 1994; Ikeda and Shiraishi, 1998). This region can be divided into two

Table 1. Summary of geological, mineralogical, geochronological and initial Sr ratio characteristics of two types of granitoids.

	Plutons	Related faults	Host rocks	Mineralogical assemblages	Age (Ma)	Sri
Volcanic-arc type granitoid	Dufek	SZ (inferred)	intermediate-grade gneiss	Kfs+Pl+Qtz±Hbl+Bt±Flt	528±31[a]	0.70372±0.00029
	Lunckeryggen	SZ (inferred)	intermediate to high-grade gneiss	Kfs+Pl+Qtz+Hbl+Bt±Flt	525±31[a, b]	0.70504±0.00025
Within-plate type granitoid	Austkampane	SRS	granulite facies gneiss[1]	Kfs+Pl+Qtz±Hbl+Bt±Grt+Ms	-	-
	Pingvinane	SRS	high-grade gneiss	Kfs+Pl+Qtz+Hbl+Cpx+Bt	510[a], 500[c]	0.70345-0.70680
	Rogerstoppane	SRS	high-grade gneiss	Kfs+Pl+Qtz±Hbl+Bt±Grt+Ms	-	0.7302[a]
	Vikinghøgda	SRS	high-grade gneiss	Kfs+Pl+Qtz+Bt±Ms	525[a]	0.7067-0.7184

Note: SZ: Suture zone; MSZ: Main suture zone; SRS: Sør Rondane shear zone; Symbols for minerals are after Kretz (1983); [1]: Sappirine-bearing gneiss; [a]: Rb-Sr whole-rock isotopic data (Tainosho *et al.*, 1992; Takahashi *et al.*, 1990; Arakawa *et al.*, 1994); [b]: 519±98 Ma of the Dufek granitoid (whole-rock); Sm-Nd isotopic data, Arakawa *et al.*, 1994); [c]: K-Ar biotite isotopic analysis (Takigami *et al.*, 1991).

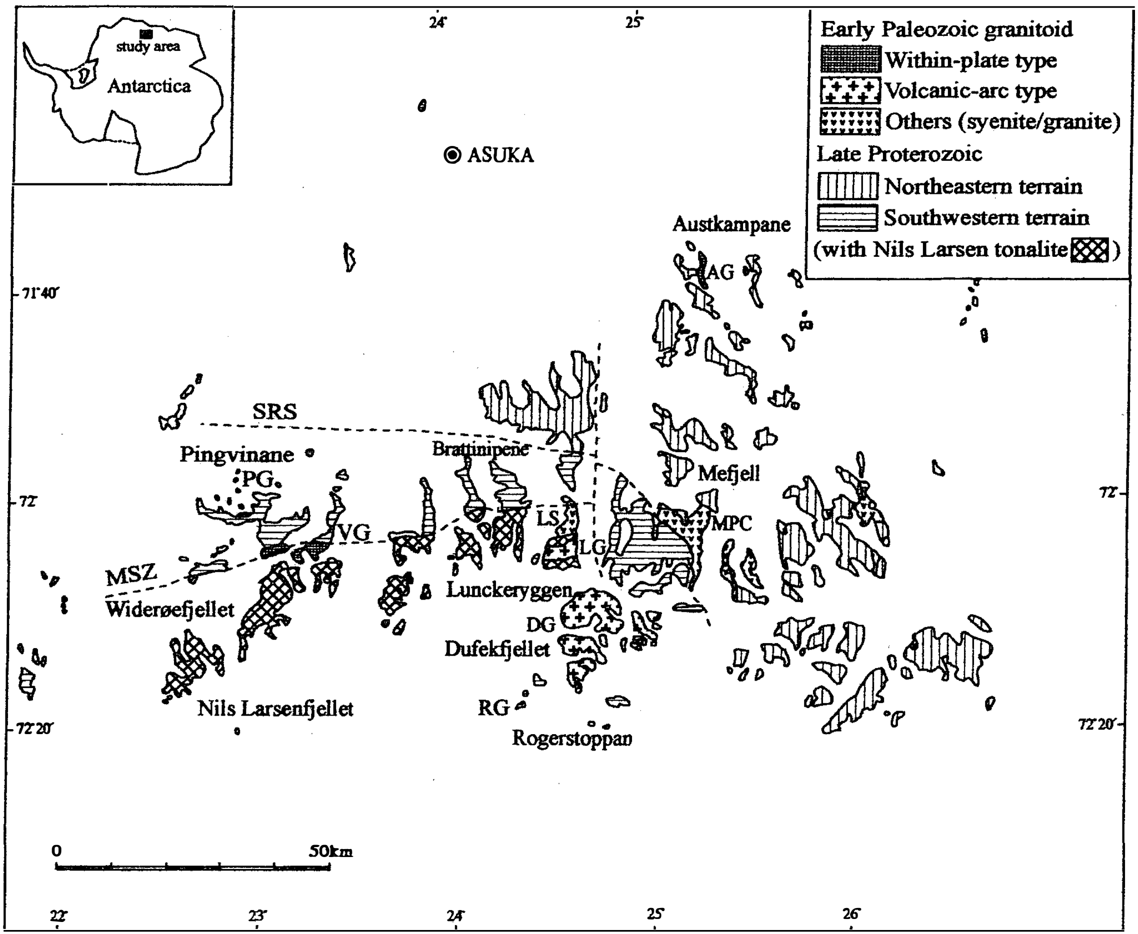

Fig. 1. Simplified geological map of the Sør Rondane Mountains (modified from Shiraishi et al., 1997). AG: Austkampane granitoid; PG: Pingvinane granitoid; VG: Vikinghøgda granitoid; RG: Rogerstoppane granitoid; DG: Dufek granitoid; LG: Lunckeryggen granitoid; MPC: Mefjell plutonic complex; MSZ: Main Shear Zone; SRS: Sør Rondane Suture Zone.

terrains on the basis of the metamorphic conditions: amphibolite to granulite facies northeastern and amphibolite to greenschist facies southwestern terrains. The boundary between the two terrains is a large shear zone (Sør Rondane Suture Zone). Moreover, the southwestern terrain is cut by the Main Shear Zone (Osanai *et al.*, 1996). The metamorphic *P-T* conditions of the granulite facies rocks are 750–850°C and 7–8 kbar for non-mylonitized gneisses and 530–630°C and 5–5.5 kbar for mylonitized gneisses (Shiraishi and Kojima, 1987; Asami and Shiraishi, 1987; Osanai *et al.*, 1988; Asami *et al.*, 1992). The plutonic rocks can be divided into the late Proterozoic Nils Larsen tonalite and early Paleozoic plutonic rocks (Takahashi *et al.*, 1990; Tainosho *et al.*, 1992, 1993). The Nils Larsen tonalite is exposed in the southern part of the Sør Rondane Mountains, and was affected by regional mylonitization with relatively low-grade metamorphic condition (Kojima and Shiraishi, 1986). This tonalite is medium- to coarse-grained biotite-hornblende tonalite, and is mainly composed of plagioclase, quartz, hornblende and biotite with accessory apatite, zircon and opaque minerals. Hornblende and biotite show a preferred orientation.

The early Paleozoic plutonic rocks widely distributed in the Sør Rondane Mountains, such as Dufek, Lunckeryggen, Austkampane, Pingvinane, Rogerstoppane and Vikinghøgda granitoids, Mefjell plutonic complex and Lunckeryggen syenite. The field relationship displays that the Lunckeryggen syenite intruded into the Nils Larsen tonalite and was intruded by the Lunckeryggen granitoid in the Lunckeryggen area (Sakiyama *et al.*, 1988). The Mefjell plutonic rocks are mainly composed of syenite with granite, charnockite, tonalite and diorite, and concordantly intruded into basement of metamorphic rocks.

Two types of early Paleozoic granitoids (concordant and discordant granitoids) can be subdivided on the basis of their field relations with the surrounding metamorphic rocks. Dufek and Lunckeryggen granitoids discordantly intrude into the metamorphic rocks. They show massive, no gneissosity, occurring as batholiths. Austkampane, Pingvinane, Rogerstoppane and Vikinghøgda granitoids concordantly intrude the metamorphic rocks and have gneissosity and schistosity. Most of them are small in size and mainly occurs as sheet or dyke. These granitoids can be divided into two type granitoids based on geochemical characteristics using Rb *vs.* (Y+Nb) and Nb *vs.* Y diagrams by Pearce *et al.* (1984): one is the volcanic-arc type granitoid and the other is the within-plate type granitoid (Tainosho *et al.*, 1992). The discordant and concordant granites are corresponding to the volcanic-arc type (Dufek and Lunckeryggen granitoids) and within-plate type (Austkampane, Pingvinane, Rogerstoppane and Vikinghøgda granitoids) granitoids, respectively. The field occurrence and petrography of each pluton from two type granitoids described below is after Tainosho *et al.* (1992) and Osanai *et al.* (1996).

The Dufek granitoid is exposed in an area of approximately 10×10 km^2 in and around the Dufekfellet. This granitoid is one of large pluton in the Sør Rondane Mountains and located in south of SRS (Fig. 1). It clearly cuts gneissosity of the gneisses. It includes many xenoliths of tonalite in the north and huge blocks of gneisses in the south. The granitoid is massive and unfoliated, and is composed mainly of medium-grained biotite granite with fine-grained biotite granite. Medium-grained biotite granodiorite occurs in border part of the Dufek granitoid body. The medium-grained biotite granite consists of plagioclase, K-feldspar, quartz and biotite with accessory sphene, apatite, zircon, muscovite and opaque minerals (Table 1). Among these mineral crystals, plagioclase and hornblende crystallized firstly and plagioclase has normal zonal structure.

The Lunckeryggen granitoid is exposed in an area of 6×6 km^2 in the southern part of Lunckeryggen in the central part of the mountains. This granitoid has discordant contact with the gneisses and has not gneissosity with massive texture. It intrudes into the Nils Larsen tonalite and quartz syenite of the Lunckeryggen syenite, and has angular xenoliths of these rocks. It is composed of coarse-grained biotite granite to hornblende-biotite granite stock and many dikes of fine-grained biotite granite. The coarse-grained granite is generally homogeneous and massive. It is composed of quartz, K-feldspar, plagioclase and biotite with or without hornblende. Accessory minerals are sphene, apatite, zircon and magnetite with or without fluorite. The fine-grained granite does not contain hornblende. Among these mineral crystals, plagioclase and hornblende firstly crystallized.

The Austkampane granitoid is exposed in an area 1×3 km^2 in the eastern part of Austkampane. This granitoid has concordant contact with the host gneisses and has gneissosity. Mafic minerals of the granite show a parallel arrangement defining a foliation. It consists of quartz, plagioclase, K-feldspar, hornblende and biotite with minor zircon, apatite, sphene and ilmenite. Plagioclase and hornblende are idiomorphic and firstly crystallized judged from texture. Many small granitic dikes and sheets intrude into the metamorphic rocks; they are mostly fine- to medium-grained muscovite-bearing granite, containing garnet in places.

The Pingvinane granitoid occurring as stock intrudes into gneisses and includes a xenolith of the host gneisses. This granitoid concordantly contacts with the host gneisses. It displays weak schistosity in contact part, however, central part of this granitoid is massive. Equigranular coarse-grained biotite hornblende granite is composed of K-feldspar, quartz, plagioclase, hornblende and biotite with or without clinopyroxene, with accessory sphene, apatite, zircon and opaque minerals. Plagioclase and hornblende crystallized earlier.

The Rogerstoppane granitoid occurs at the southern end of Rogerstoppane and separates by ice-river with the Dufek granitoid. It has strongly bedded gneissosity with banding mafic mineral concentration. Its structure is parallel with gneissosity of the gneisses, and this granitoid consists mainly of plagioclase, quartz, K-feldspar, biotite and hornblende with accessory allanite, epidote, zircon, apatite and opaque minerals with or without garnet.

The Vikinghøgda granitoid concordantly intrudes into biotite gneisses and is small in size. This granitoid has gneissose structure and includes many xenoliths of gneisses. It is mainly composed of quartz, plagioclase, K-feldspar, biotite and muscovite with accessory sphene, apatite, zircon and opaque oxides.

3. Mineral composition

Chemical analyses of minerals were obtained by JEOL-8900M electron probe microanalyzer at the Venture Business Laboratory at Kobe University using an accelerating potential of 15 kV and a probe current of 12 nA.

Mineral compositions of the two types of granitoids show that Mg/(Mg+Fe) ratios of mafic minerals of the within-plate type granitoid are very low (0.02–0.40 in biotite), while those of the volcanic-arc type granitoid have intermediate Mg/(Mg+Fe) ratios (0.47–0.68 in biotite and hornblende). Anorthite contents of plagioclase in the within-plate type granitoid are low (5–15 mol%), while those of the volcanic-arc type granitoid are higher (about 33 mol% in core and 18 mol% at rim in zonal crystals). Fluorine in biotite from the volcanic-arc type granitoid (1.50–2.30 wt%) is much higher than that (0.01–0.80 wt%) from the within-plate type granitoid (Li, unpub.). These reflect different chemical characteristics of minerals between the two types of granitoids.

4. Geochemistry

4.1. Analytical methods

Analyzed samples of two types of granitoids were collected from the central part of

Table 2. Representative major, trace and rare earth elements of two types of granitoids.

	volcanic-arc type granitoid					within-plate type granitoid											
Plutons	Lunckeryggen		Dufek			Austkampane					Pingvinane			Vikinghøgda		Rogerstoppane	
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
(wt%)																	
SiO_2	72.14	77.13	73.32	71.90	73.47	74.18	73.62	74.10	68.10	66.94	65.48	68.23	67.13	77.15	79.38	72.61	73.31
TiO_2	0.44	0.12	0.22	0.42	0.19	0.18	0.13	0.10	0.36	0.25	0.62	0.58	0.35	0.08	0.09	0.17	0.09
Al_2O_3	13.67	12.74	14.90	14.30	13.34	14.92	13.09	13.73	13.90	13.10	17.19	14.24	14.20	12.15	11.18	13.47	13.87
Fe_2O_3(T)	2.63	1.75	1.74	3.48	1.69	1.16	1.97	0.80	2.09	2.76	3.65	5.14	5.17	1.05	1.90	2.43	1.85
MnO	0.03	0.01	0.02	0.03	0.01	0.02	0.03	0.01	0.04	0.04	0.04	0.05	0.09	0.02	0.01	0.04	0.03
MgO	0.91	0.20	0.36	0.66	0.20	0.32	0.17	0.13	0.84	1.12	1.18	0.28	2.01	0.11	0.15	0.28	0.18
CaO	2.10	1.05	1.63	1.88	1.05	1.13	1.39	1.27	4.41	4.83	3.48	1.88	2.34	0.45	0.73	1.19	1.13
Na_2O	3.96	3.85	4.60	4.12	3.79	3.76	3.37	3.14	2.38	2.29	5.17	3.41	3.57	3.72	3.60	4.30	5.09
K_2O	3.45	4.59	3.69	4.31	4.99	5.04	5.09	5.93	7.01	6.45	2.40	5.91	4.00	4.67	3.21	3.83	3.59
P_2O_5	0.20	0.11	0.07	0.17	0.02	0.09	0.02	0.05	0.09	0.08	0.58	0.12	0.09	0.00	0.00	0.03	0.01
Total	99.53	101.55	100.55	101.27	98.75	100.80	98.88	99.26	99.22	97.86	99.79	99.84	98.95	99.40	100.20	98.35	99.15
C.I.P.W. norms																	
q	30.75	34.52	28.45	26.66	30.31	30.13	31.98	30.62	20.32	21.27	18.68	22.23	23.57	36.73	44.28	30.56	27.79
or	20.48	26.71	21.69	25.15	29.86	29.55	30.42	35.31	41.75	38.95	14.21	34.98	23.89	27.76	18.93	23.01	21.40
ab	33.67	32.08	38.71	34.43	32.48	31.56	28.84	26.77	20.30	19.80	43.84	28.90	30.53	31.67	30.40	37.00	43.44
an	9.15	3.86	7.59	7.70	4.71	4.98	5.62	5.90	6.59	6.56	13.50	6.10	11.02	2.25	3.61	5.80	4.43
di	0.00	0.14	0.00	0.00	0.00	0.00	0.69	0.00	4.55	6.15	0.00	0.49	0.00	0.00	0.00	0.00	0.75
wo	0.00	0.08	0.00	0.00	0.00	0.00	0.37	0.00	2.44	3.30	0.00	0.26	0.00	0.00	0.00	0.00	0.40
en	0.00	0.07	0.00	0.00	0.00	0.00	0.32	0.00	2.11	2.85	0.00	0.23	0.00	0.00	0.00	0.00	0.35
hy	2.28	0.42	0.89	1.62	0.50	0.79	0.11	0.33	0.00	0.00	2.95	0.47	5.06	0.28	0.37	0.71	0.11
en	2.28	0.42	0.89	1.62	0.50	0.79	0.11	0.33	0.00	0.00	2.95	0.47	5.06	0.28	0.37	0.71	0.11
il	0.06	0.02	0.04	0.06	0.02	0.04	0.06	0.02	0.09	0.09	0.09	0.11	0.19	0.04	0.17	0.09	0.06
hm	2.64	1.72	1.73	3.44	1.71	1.15	1.99	0.81	2.11	2.82	3.66	5.15	5.22	1.06	0.33	2.47	1.87
tn	0.00	0.26	0.00	0.29	0.31	0.00	0.24	0.08	0.78	0.51	0.00	1.29	0.08	0.00	0.00	0.00	0.14
ru	0.41	0.00	0.20	0.26	0.06	0.16	0.00	0.05	0.00	0.00	0.58	0.00	0.22	0.06	0.00	0.13	0.00
ap	0.47	0.25	0.16	0.39	0.05	0.21	0.05	0.12	0.21	0.19	1.35	0.28	0.21	0.00	0.00	0.07	0.02
D.I.	84.91	93.31	88.85	86.24	92.65	91.25	91.24	92.69	82.37	80.02	76.73	86.12	77.99	96.16	93.61	90.57	92.62

Note: Sample No.1: B90011902A; 2: B90012003B; 3: B90012305A; 4: B90012305B; 5: B90012309A; 6: B90011107B; 7: B90011107D; 8: B90011206B; 9: B90011206A-1; 10: B90011206A-2; 11: B90011305B; 12: B90011305D; 13: B90011405B; 14: B90011702; 15: B90011703A; 16: B90012310A; 17: B90012310C; D.I.=q+ab+or; Fe_2O_3(T): as total of Fe_2O_3. Mg# =100*(MgO/40.30)/(MgO/40.30+Fe_2O_3(T)*0.9/71.85); Chondrite normalized REE data after Taylor and McLennan (1985).

Table 2. Continued.

	volcanic-arc type granitoid				within-plate type granitoid												
Plutons	Lunckeryggen		Dufek		Austkampane						Pingvinane			Vikinghøgda		Rogerstoppane	
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
(ppm)																	
Ba	865	300	1315	1390	260	530	215	2217	852	762	344	2226	1635	302	128	554	4221
Rb	155	225	97	120	145	170	349	238	270	245	118	131	102	117	90	123	80
Sr	617	227	971	884	283	128	75	126	554	510	181	291	277	55	34	64	45
Nb	7.6	10.0	8.4	20.0	-	3.8	41.4	11.4	13.9	8.9	29.2	25.0	19.4	8.1	49.6	59.9	64.4
Y	9.5	25.0	7.8	27.0	10.4	16.7	136.3	24.7	50.4	36.3	145.7	57.2	25.9	66.7	57.0	91.6	121.5
Ga	21	18	22	18	18	19	27	20	17	16	28	28	20	19	24	28	26
Th	30.8	-	12.5	-	-	11.4	129.9	56.5	10.5	17.9	53.9	11.9	3.3	9.4	9.5	14.5	11.9
Hf	10.7	6.1	3.2	6.1	5.5	3.3	9.1	3.9	2.2	1.2	5.4	18.6	7.6	5.1	15.5	8.9	6.8
Ta	0.5	0.3	0.7	0.7	1.5	0.3	1.3	1.1	1.6	1.2	1.6	1.5	0.9	1.0	2.9	4.1	2.7
La	96.4	59.5	46.2	113.8	93.3	26.3	99.4	31.4	39.9	33.1	234.7	114.8	34.8	47.8	30.1	21.3	15.3
Ce	91.6	66.9	74.9	77.8	132.9	47.0	146.4	61.3	92.4	75.2	464.4	238.1	62.8	99.7	56.2	58.1	40.1
Pr	7.8	4.6	6.6	14.9	14.5	4.4	19.5	5.9	10.4	8.1	50.3	26.2	6.3	9.6	5.9	5.3	4.8
Nd	28.0	11.2	26.9	46.3	41.7	18.8	91.5	26.0	49.8	38.3	229.7	127.2	29.7	42.3	25.7	27.5	26.4
Sm	4.1	1.2	4.0	5.9	5.1	4.4	21.9	5.8	11.4	8.4	54.2	24.9	6.1	10.4	6.0	8.9	10.5
Eu	0.9	0.3	0.9	5.4	0.8	0.8	1.0	0.8	1.0	0.9	1.9	3.5	2.6	0.2	0.2	0.8	1.0
Gd	2.6	1.1	2.4	3.9	4.0	3.5	18.2	4.1	9.1	6.7	40.8	16.4	5.0	9.5	5.3	9.1	12.7
Tb	0.4	0.1	0.3	0.4	0.4	0.6	3.0	0.6	1.5	1.1	6.1	2.3	0.8	1.8	1.1	1.9	2.7
Dy	1.4	0.5	1.1	1.9	2.0	2.5	14.5	3.1	7.4	5.3	24.9	9.4	3.6	9.4	7.0	10.8	16.0
Ho	0.3	0.1	0.2	0.3	0.3	0.5	3.1	0.7	1.6	1.1	4.6	1.8	0.8	2.1	1.9	2.8	3.9
Er	0.7	0.3	0.6	0.8	0.9	1.4	8.7	2.4	4.4	3.2	10.4	4.8	2.3	6.2	6.9	9.3	12.1
Tm	0.1	0.0	0.1	0.1	0.2	0.2	1.4	0.4	0.7	0.5	1.4	0.7	0.3	1.0	1.3	1.6	1.9
Yb	0.6	0.4	0.5	0.9	1.1	1.2	7.3	2.9	3.5	2.7	5.8	3.7	2.1	5.6	9.2	10.2	11.4
Lu	0.1	0.1	0.1	0.1	0.2	0.2	1.1	0.5	0.5	0.4	0.8	0.6	0.3	0.8	1.7	1.6	1.8
K_2O/Na_2O	0.9	1.2	0.8	1.0	1.3	1.3	1.5	1.9	2.9	2.8	0.5	1.7	1.1	1.3	0.9	0.9	0.7
A/CNKmol	0.97	0.96	1.03	0.96	0.99	1.09	0.96	0.99	0.71	0.67	0.99	0.92	0.98	1.01	1.04	1.01	0.97
Ga/Al	2.90	2.67	2.79	2.38	2.55	2.41	3.90	2.75	2.31	2.31	3.08	3.71	2.66	2.95	4.06	3.93	3.54
Mg#	40.7	18.5	29.1	27.3	19.0	35.3	14.6	24.4	44.3	44.6	39.0	9.7	43.5	17.2	13.5	18.6	16.2
Sr/Ba	0.71	0.76	0.74	0.64	1.09	0.24	0.35	0.06	0.65	0.67	0.53	0.13	0.17	0.18	0.27	0.12	0.01
Rb/Sr	0.25	0.99	0.10	0.14	0.51	1.33	4.67	1.89	0.49	0.48	0.65	0.45	0.37	2.14	2.62	1.92	1.78
K/Rb	0.02	0.02	0.04	0.04	0.03	0.03	0.01	0.02	0.03	0.03	0.02	0.05	0.04	0.04	0.04	0.03	0.04
Sr/Y	64.93	80.78	124.54	101.96	27.16	7.64	0.55	5.11	10.99	14.04	1.24	5.08	10.68	0.82	0.60	0.70	0.37
La/Sm	23.51	48.36	11.55	19.29	18.21	5.98	4.54	5.41	3.50	3.94	4.33	4.61	5.70	4.60	5.02	2.39	1.46
La/Yb	160.67	160.76	92.40	133.88	83.26	21.92	13.62	10.83	11.40	12.26	40.47	31.03	16.57	8.54	3.27	2.09	1.34
Ce/Y	9.64	2.68	9.60	2.88	12.75	2.81	1.07	2.48	1.83	2.07	3.19	4.16	2.42	1.49	0.99	0.63	0.33
ΣREE (ppm)	244.50	148.95	172.60	281.14	307.71	128.50	573.30	170.60	284.00	221.30	1275.70	631.60	183.40	313.10	215.50	260.80	282.10
Y/ΣREE	0.04	0.17	0.05	0.10	0.03	0.13	0.24	0.14	0.18	0.16	0.11	0.09	0.14	0.21	0.26	0.35	0.43
LREE/HREE	36.76	1129.02	29.92	1427.34	707.42	9.99	6.61	8.87	7.10	7.77	10.90	13.38	9.19	5.76	3.60	2.56	1.55
Eu/Eu^*_N	0.79	0.75	0.82	3.22	0.54	0.60	0.15	0.48	0.29	0.36	0.12	0.50	1.40	0.06	0.11	0.27	0.26
$(La/Yb)_N$	108.57	108.63	62.44	90.47	56.26	14.81	9.20	7.32	7.70	8.28	27.34	20.97	11.20	5.77	2.21	1.41	0.91

the Sør Rondane Mountains. Major and trace elements were analyzed by XRF (Rigaku 3270E) at Kobe University using the analytical methods of Miyake *et al.* (1996) and Yamamoto and Morishita (1997). Rare earth elements were determined by ICP-MS at Chemex Labs Ltd., Canada, and Shimane University using the methods of Kimura *et al.* (1995) and Roser *et al.* (2000). Representative major, trace and rare earth elements of the two types of granitoids are listed in Table 2.

4.2. Major elements

Both the volcanic-arc type and within-plate type granitoids have a range of silica content (64.25 to 79.38 wt% in SiO_2) and high K_2O+Na_2O (6.80–11.40 wt%). They fall in the field of alkaline rocks (Fig. 2) in the diagram of Cox *et al.* (1979). In the SiO_2-A/CNK diagram (Fig. 3), the volcanic-arc type granitoid has lower A/CNK ratios and most of them are plotted in metaluminous field although some of them are plotted in the field of peraluminous. The within-plate type granitoid has much higher values of these ratios and falls in both metaluminous and peraluminous fields although the Pingvinane granitoid falls in the metaluminous field. In the Harker diagram, the within-plate type granitoid has much higher FeO_t (Fig. 4a) than that in the volcanic-arc type granitoid.

4.3. Trace elements

The volcanic-arc type granitoid has higher Sr and F (Fig. 4b), and Sr/Ba ratio, and lower Rb/Sr ratios (Fig. 5c) than those of the within-plate type granitoid. Individual granitic bodies such as the Austkampane and Rogerstoppane granitoids from the within-plate type granitoid clearly show crystallization differentiation of feldspars (Fig. 5b). The

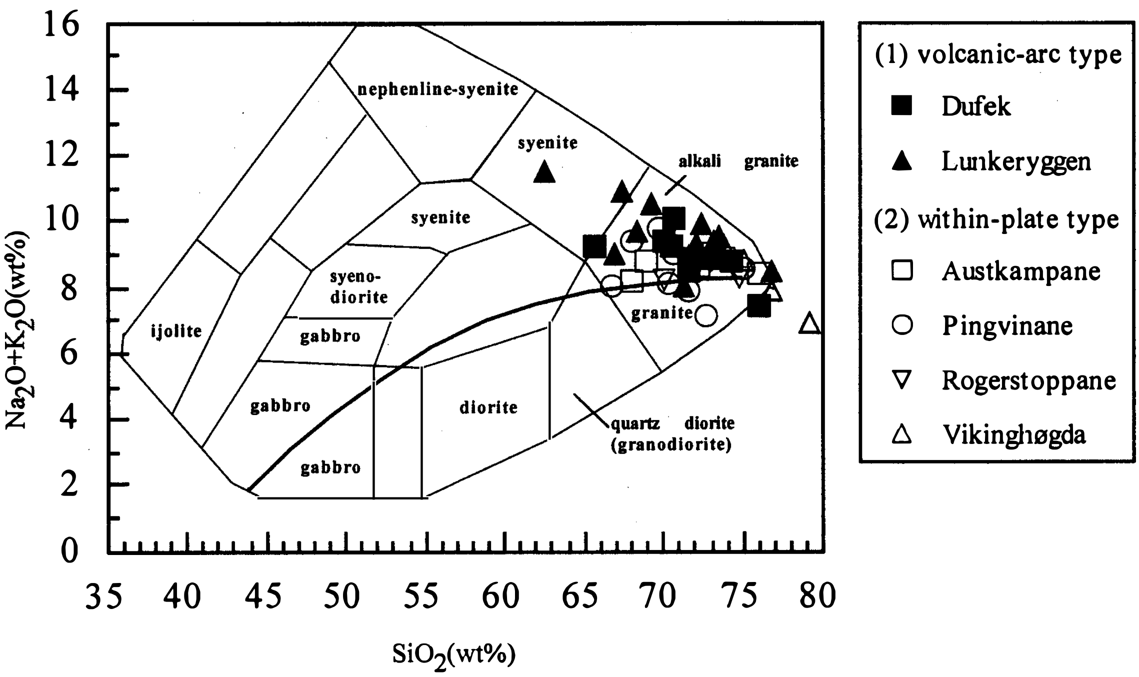

Fig. 2. Chemical classification diagram of Cox et al. (1979) for two types of granitoid samples. The closed and open symbols show the volcanic-arc type and within-plate type granitoids respectively.

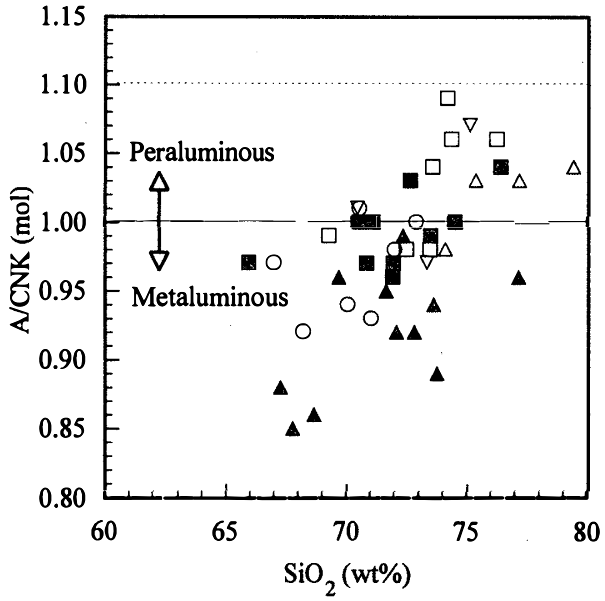

Fig. 3. SiO_2-A/CNK plots of two types of granitoid samples. Peraluminous and metalumineous scheme is after Shand (1947). Symbols as in Fig. 2.

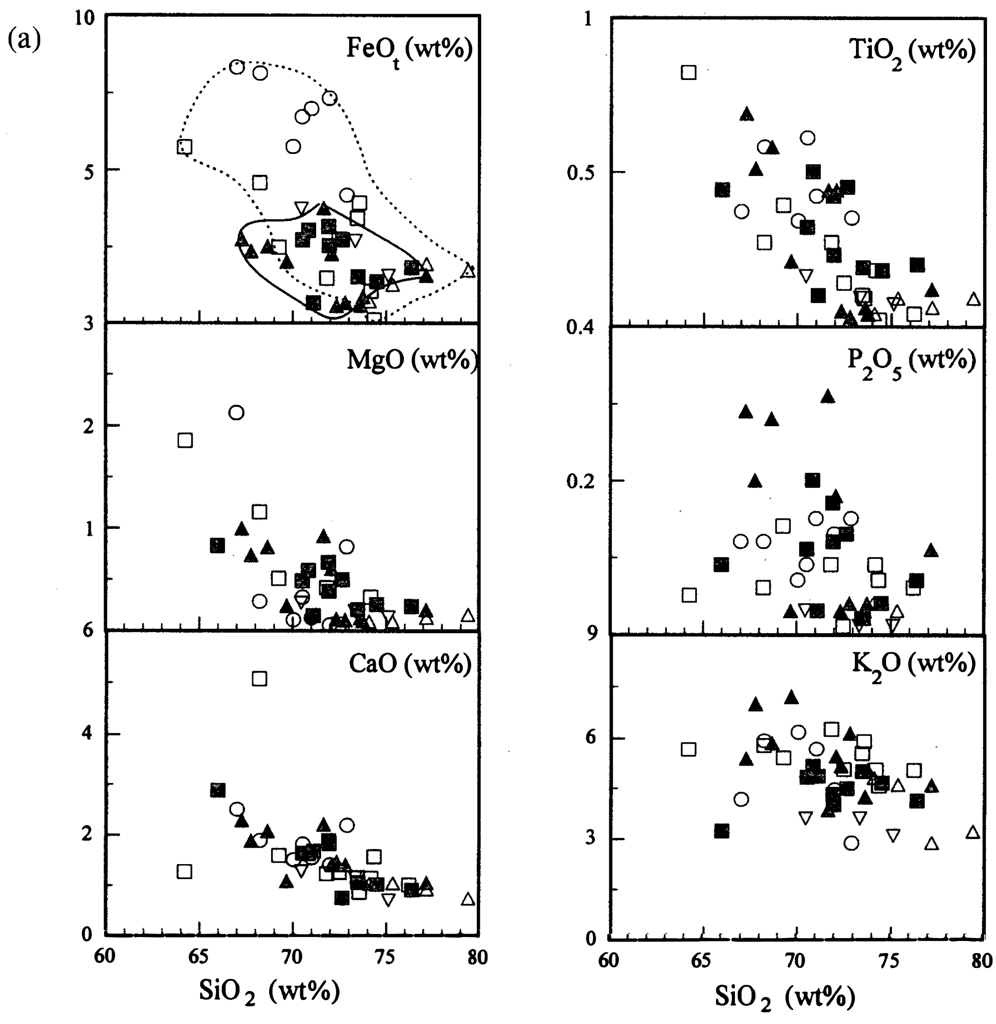

Fig. 4. Harker diagram of (a) SiO_2 vs. major elements, and (b) SiO_2 vs. trace elements for two types of granitoid samples. Symbols as in Fig. 2.

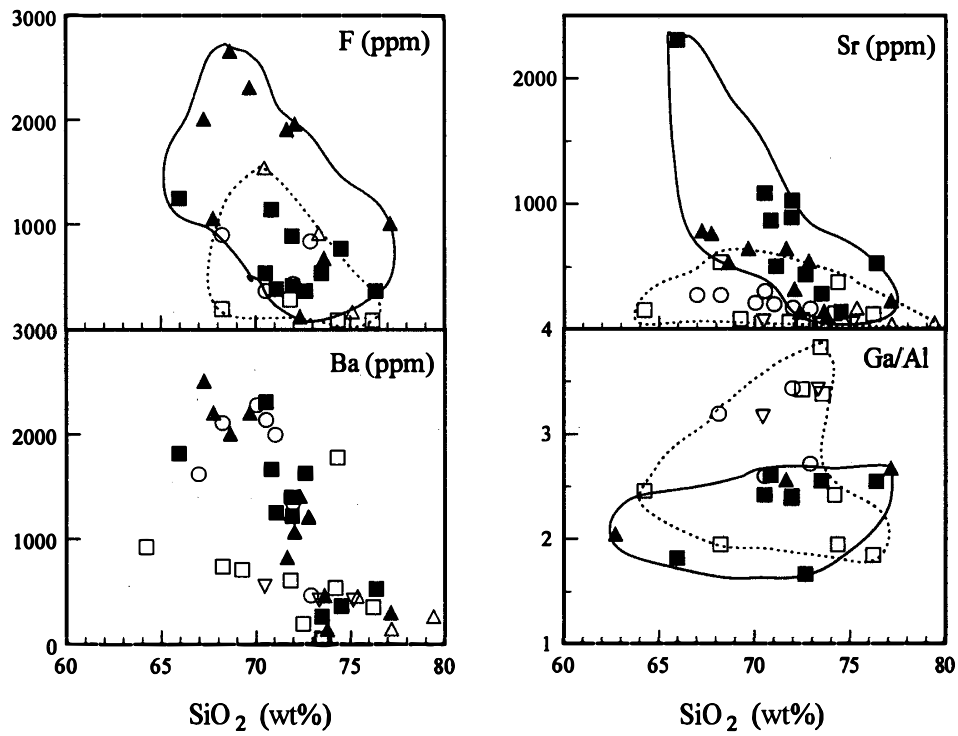

Fig. 4 (continued).

volcanic-arc type granitoid has a trend of extensive crystallization differentiation of feldspar in the Sr *vs.* Ba diagram. The within-plate type granitoid is higher in Ga/Al and Rb/Sr ratios, and lower in Sr/Ba ratio compared to those in the volcanic-arc type granitoid (Fig. 4b, 5c, Table 2). The majority of samples from the Austkampane, Pingvinane, Rogerstoppane and Vikinghøgda granitoids are plotted in the field of within-plate type granite, while those from the Dufek and Lunckeryggen granitoids are of volcanic-arc and/or collisional type granite in the Y *vs.* Nb and Rb *vs.* (Y+Nb) discriminative diagrams (Fig. 6) as defined by Pearce *et al.* (1984). Ocean ridge normalized spiderdiagrams (Fig. 7) show that the two types of granitoids differ Nb, Y and Zr depletion although they have the same Nb depletion. Furthermore, the within-plate type granitoid has different in Nb and Zr anomalies compared with those of typical within-plate granite as reported in Pearce *et al.* (1984).

4.4. Rare earth elements

The within-plate type granitoid has remarkable high ΣREE (264.3–696.9 ppm), Y (54.3–76.3 ppm), Nb (19.1–28.9 ppm) and HREE concentrations, and moderate to strong negative Eu anomalies (Fig. 8). REE patterns of the Austkampane and Pingvinane granitoids are weakly fractionated with La/Yb ratios, while the Vikinghøgda and Rogerstoppane granitoids show almost flat MREE and HREE patterns and strongly negative Eu anomalies. The volcanic-arc type granitoid has low ΣREE (172.60–184.35 ppm), Y (7.8–9.5 ppm) and HREE. It has higher LREE/HREE ratios and lacks Eu anomalies or positive Eu anomaly (one sample from the Dufek granitoid).

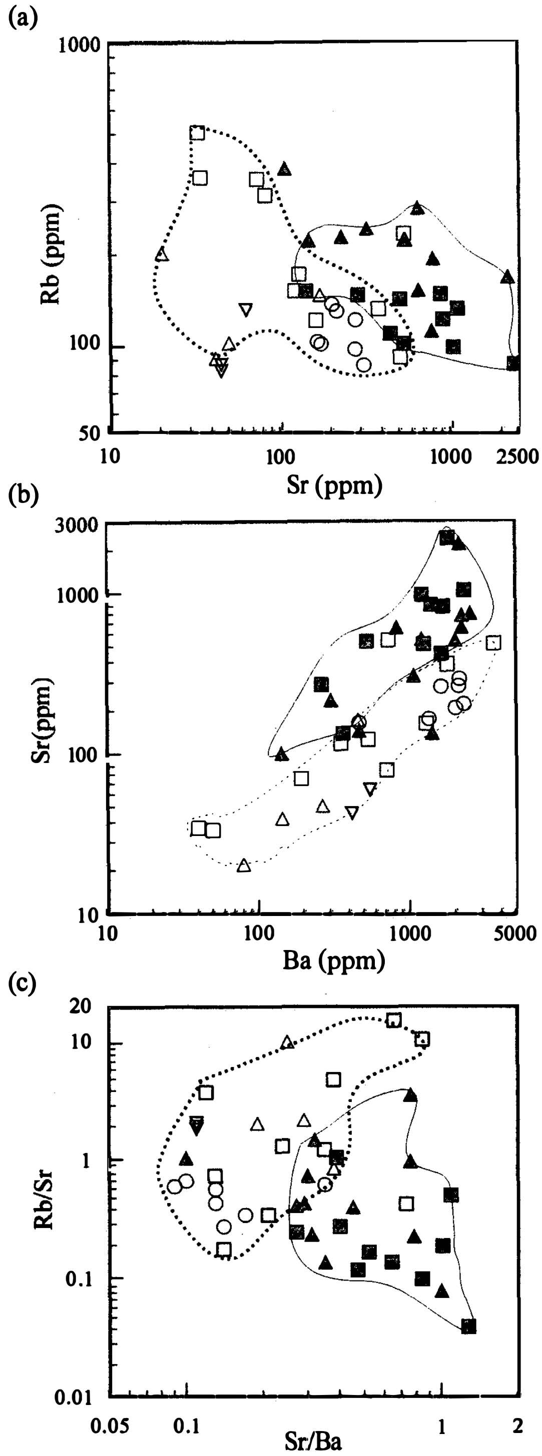

Fig. 5. *(a) Rb vs. Sr, (b) Sr vs. Ba, and (c) Sr/Ba vs. Rb/Sr diagrams for two types of granitoids. Symbols as in Fig. 2.*

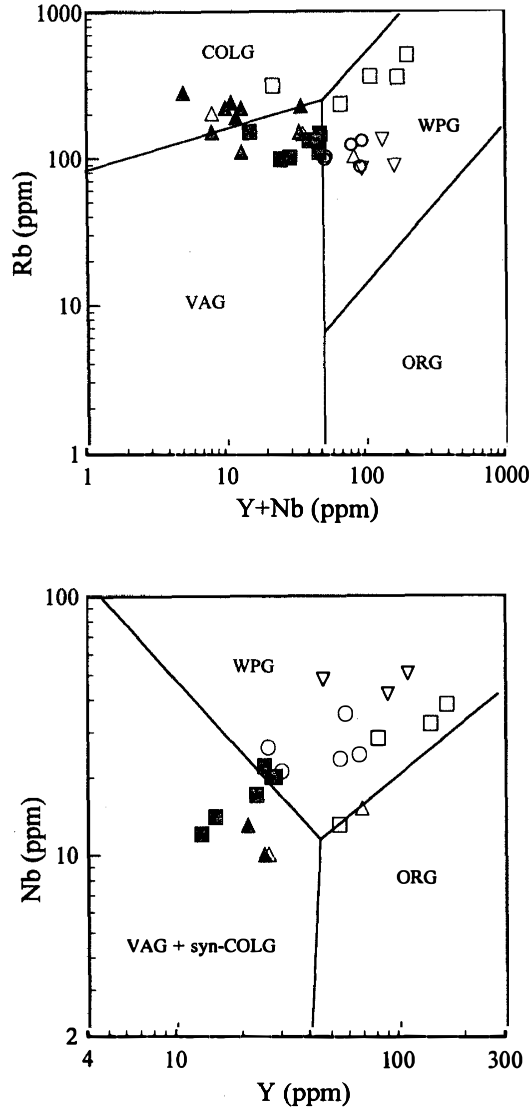

Fig. 6. *Y vs. Nb and Rb vs. (Y+Nb) plots of two types of granitoid samples. Granite fields are after Pearce et al. (1984): WPG=Within-plate granite, ORG=Ocean-Ridge granite, VAG=Volcanic-Arc granite, syn-COLG=syn-Collisional granite. Symbols as in Fig. 2.*

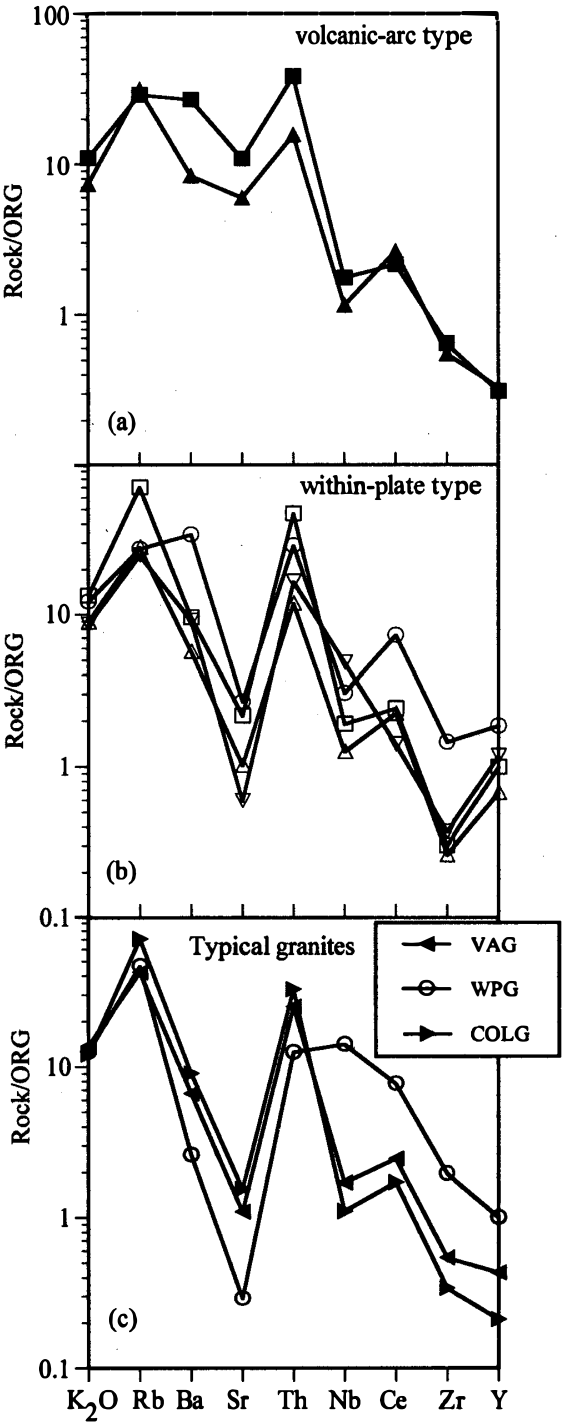

Fig. 7. Ocean-ridge granite (ORG) normalized (Pearce et al., 1984) geochemical patterns of two types of granitoid samples. (a) Volcanic-arc type granitoid, (b) Within-plate type granitoid, and (c) Typical granites and their patterns are after Pearce et al. (1984). WPG: within-plate granite, VAG: volcanic-arc granite and COLG: collisional granite; syn-COLG: syn-collisional granite. Symbols as in Fig. 2.

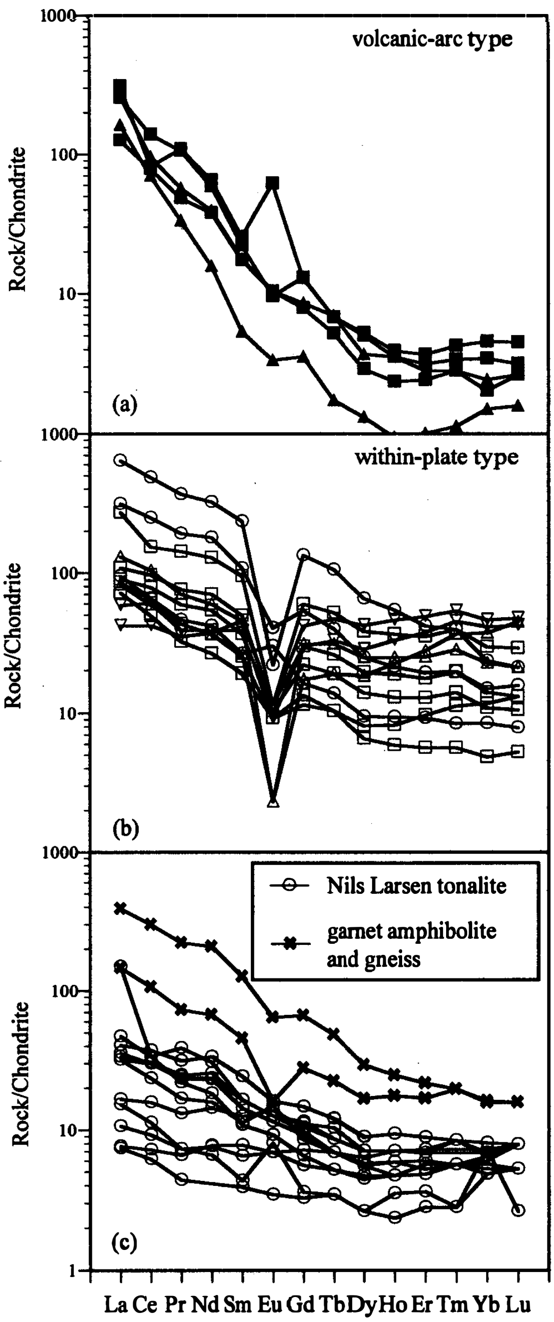

Fig. 8. Chondrite normalized REE patterns of two types of granitoids. Normalized values after Taylor and McLennan (1985). The REE data of the Nils Larsen tonalite are from Ikeda and Shiraishi (1998), and those from the metamorphic rocks are unpublished (not shown). Symbols of (a) and (b) diagrams as in Fig. 2.

5. Discussion

5.1. Geochemical comparison

As mentioned above, the two types of granitoids show clearly different geochemical characteristics. The volcanic-arc type granitoid has higher Sr and Sr/Ba, Sr/Y, La/Sm and La/Yb ratios with lower Y and Nb contents and A/CNK, Ga/Al and Rb/Sr ratios, compared with those from the within-plate type granitoid. Furthermore, the volcanic-arc type rocks have low ΣREE, large LREE/HREE ratios and none or positive Eu anomalies. The lack of Eu-anomalies indicates that plagioclase was not a significant residual phase and the positive Eu anomaly can be dominated by plagioclase cumulate. On the other hand, the within-plate type granitoid has high ΣREE, low LREE/HREE ratios, and negative Eu anomalies. Negative Eu-anomalies can be explained by crystal differentiation of plagioclase from melt although the plagioclase depleting part of the melt or partial melt of plagioclase-poor source possibly affects negative Eu anomalies. The reason for decreasing LREE/HREE ratios in the within-plate type granitoid can be explained by differentiation crystallization of enriched REE accessory minerals such as allanite and monazite. Depletion Nb anomalies in both of the within-plate type and volcanic-arc type granitoids can be explained by assuming that they have affinity with subduction-related materials. All of the volcanic-arc type granitoids are plotted within the field of adakite or Archean high-Al tonalite-trondhjemite-granodiorite (TTG) whereas most of the within-plate type granitoids fell in island-arc andesite-dacite-rhyolite (ADR) field in the Sr/Y-Y diagram (Fig. 9a). In the La/Sm-La diagram (Fig. 9b), the volcanic-arc type granitoid shows that La/Sm ratios have positive correlation with La content whereas the within-plate type granitoid does horizontal trend. According to the La/Yb-Yb plot (Fig. 9c), the two types of granitoids fall in different fields because the volcanic-arc type granitoid has high La/Yb ratios (19 to 160) and low Yb (0.3 to 1.0 ppm), while the within-plate type granitoid has low La/Yb ratios (3 to 40) and high Yb (1.0 to 11.3 ppm).

5.2. Possible petrogenesis of two type granitoids

The geochemical and isotopic features indicate two possibilities of their petrogenesis. One is two types of granitoids are derived from same magma source and are produced by different magma process and condition, such as different degrees of fractional crystallization and/or partial melting as well as assimilation. The other is that two type granitoids may have been derived from different sources and had different petrogenetic processes.

5.2.1. First possibility of petrogenesis

It is proposed that the volcanic-arc type granitoid is probably derived from deeper parental magma source by process of fractional crystallization with or without assimilation or mixing, subsequently, successive fractional crystallization from the same magma source (should be altered components) accompanied with intense assimilation during ascending, to produce the within-plate type granitoid.

Magma processes that reflect of equilibrium partial melting or fractional crystallization, are identified by Allègre and Minster (1978). They argued that two trends of partial melting and fractional crystallization based on magmatophile elements (M elements) and hypermagmatophile elements (H elements). The bulk partition coefficients

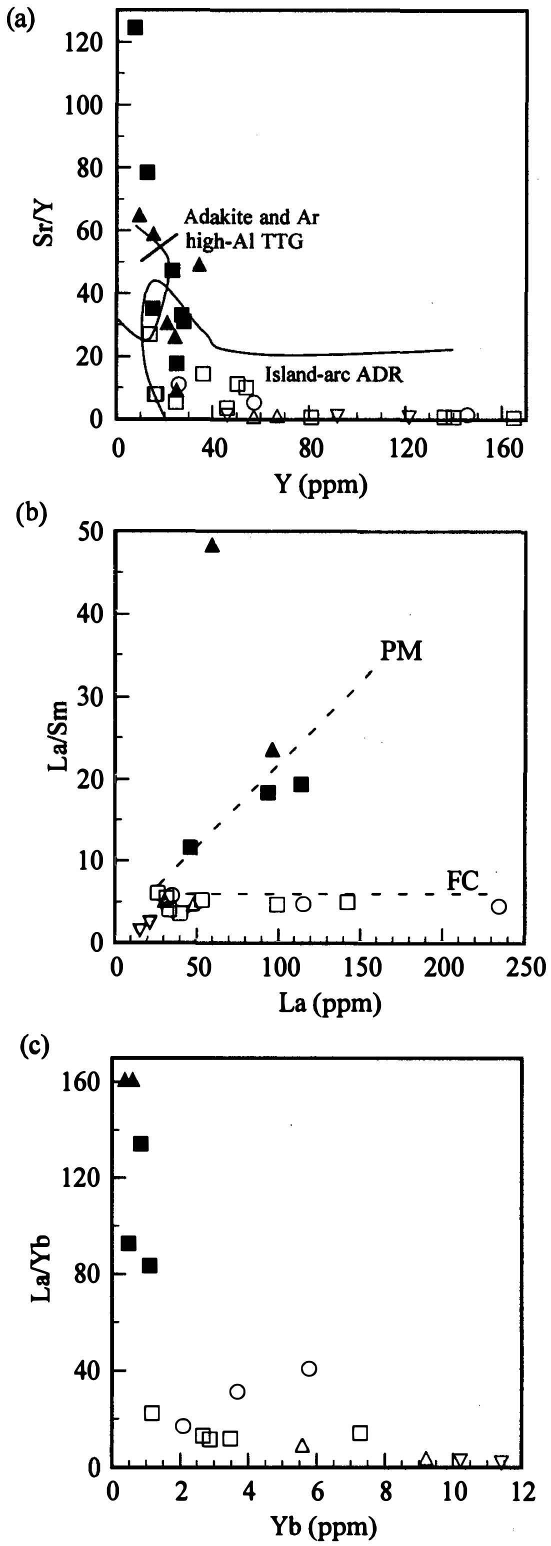

Fig. 9. (a) Sr/Y vs. Y (Defant and Drummond, 1990; Defant et al., 1991). Island-arc ADR: island-arc andesite-dacite-rhyolite. Adakite and Ar high-Al TTG: adakite and Archean high-Al tonalite-trondhjemite-granodiorite. (b) La/Sm vs. La. PM: partial melting, and FC: fractional crystallization. (c) La/Yb vs. Yb diagram for two types of granitoid samples. Symbols as in Fig. 2.

(D) of M elements are negligible against 1, whereas those of H elements can be neglected against values as low as 0.2–0.5. Typical H elements are Ta, Th, La or Ce, and M elements comprise the heavy REE, Zr or Hf. Simplified equations during fractional crystallization following the Rayleigh law (Neumann *et al.*, 1954) are: $C_L^M = C_{0,\ L}^M/f$, $C_L^H = C_{0,\ L}^H/f$ and $C_L^H/C_L^M = C_{0,\ L}^H/C_{0,\ L}^M =$ constant, where C_L is concentration of element and f is fraction of residual magma. In a C_L^H/C_L^M *vs.* C_L^M diagram the points plot along a horizontal line. For the case of equilibrium partial melting: $C_L^M = C_{0,\ S}^M/(D_0^M + F)$, $C_L^H = C_{0,\ S}^H/F$ and in the C_L^H/C_L^M *vs.* C_L^M diagram the points will plot along a straight line of slope $D_0^M/C_{0,\ S}^M$, where F is degree of partial melting and D_0 is initial bulk distribution coefficient. Here concentrations of La and Sm are as for C_L^H and C_L^M respectively and La/Sm *vs.* La diagram can be shown trends, which belong to products of fractional crystallization or partial melting. The within-plate type granitoid shows a fractional crystallization trend along a relatively horizontal line whereas the volcanic-arc type granitoid seems to display a partial melting trend along a relatively steep slope (Fig. 9b). Moreover, in Ce/Yb *vs.* Ce diagram, there are similar results compared with those from La/Sm *vs.* La diagram. This feature indicates that fractional crystallization is an important process during formation of the within-plate type granitoid. Increasing degrees of negative Eu anomalies in the chondrite-normalized REE diagram (Fig. 8b) from coarse to intermediate granite to fine-grained granite and granitic pegmatite, which was found from the Austkampane granitoid (being within-plate type granitoid), can be explained by increasing fractional crystallization of plagioclase. Arakawa *et al.* (1994) argued that parental mafic (to intermediate) magma assimilated (or mixing) by crustal rocks resulted in formation of the within-plate type granitoid and the volcanic-arc type granitoid is produced by crystal fractionation of parental magma without large amounts of crustal assimilation. We should add this argument that process of fractional crystallization also is an important role during formation of the within-plate type granitoid.

Two types of granitoids have similar chemical features in major elements though they display some variation. Chemical characteristics result in major elemental affinity between them and becomes more peralumineous with increasing SiO_2 from the volcanic-arc type to within-plate type granitoids (Fig. 3). Iron-enriched in bulk composition in the within-plate type granitoid can be explained by assimilation (or mixing) with crustal rocks or by enrichment in late stage of granitic formation. From trace elements, crystal fractionation with some individual granitoids is evidenced by decrease together between Ba and Sr, and negative correlation between Rb and Sr (Fig. 5). This reflects that there is differentiation trend of feldspars in both two types, and the volcanic-arc type and within-plate type granitoids have more crystallization tendency of plagioclase and K-feldspar, respectively. The within-plate type granitoid has much higher HFS elements, such as Ga, Y, Nb, MREE and HREE, and low LREE/HREE ratios, than those from the volcanic-arc type granitoid. These features indicate such as successive crystallization of heavy minerals of zircon, garnet or sphene.

Mineral chemistry, such as fluorine in biotite and hornblende, and zonal composition of plagioclase and anorthite content of plagioclase, can be explained by two stages of magma processes. Biotite and hornblende with higher fluorine in the volcanic-arc type granitoid, crystallized under much higher temperature and lower water fugacity than those from the within-plate type granitoid. Crystallization of mafic and accessory minerals with high F content, caused residual melt with a relatively lower concentration of fluorine and this is as a case of formation of the within-plate type granitoid. During fractional crystallization process and ascending, magma components become much felsic, decreasing Mg# both in bulk and mafic minerals as well as anorthite content in plagioclase, and having transition from clearly zoned structure (33–10 mole% in anorthite content from the volcanic-arc type granitoid) to weak or none (almost albite component in the within-plate type granitoid) in plagioclase crystal. These features are corresponding to this assumption that successive process of fractional crystallization to produce the two types of granitoids.

Initial $^{87}Sr/^{86}Sr$ ratios from the volcanic-arc type granitoid display low values and concentrated in narrow ranges of 0.7037–0.7050 (Table 1), which may suggest a similar source and magma evolution for the Dufek and Lunckeryggen granitoids. There are a suitable argument by assuming that in principle granite containing higher Mg# and low initial $^{87}Sr/^{86}Sr$ ratios was fractionated earlier and relatively lower Mg# in bulk and mafic minerals in later stage. The volcanic-arc type granitoid has higher Mg# in bulk chemistry and mafic minerals and lower initial $^{87}Sr/^{86}Sr$ ratios can be explained this type granitoid crystallized in early stage and the within-plate type granitoid, which has relatively lower Mg# in bulk chemistry and mafic minerals with higher initial $^{87}Sr/^{86}Sr$ ratios (two groups of 0.7067 and 0.7184, Arakawa *et al.*, 1994), may did in later stage. So that we proposed that a successive fractional crystallization process is as an important mechanism to produce two types of granitoids although they have different degree of assimilation or mixing.

5.2.2. Second possibility of petrogenesis

A possibility above explained that they suffered crystallization process with different degree of assimilation or mixing from same magma source. However, it is not denied this fact that they may be derived from different magma source and had different petrogenetic processes due to some different aspects. For example, the two types of granitoids show two trends in the Harker diagram (Fig. 4a, b) and have different trace and rare earth elements (Fig. 5, 7, 8) as well as isotopic data (Arakawa *et al.*, 1994).

Although the differentiation by fractional crystallization of parental magma was suggested by Arakawa *et al.* (1994), in the La/Sm-La diagram (Fig. 7b) of magma process identification by Allègre and Minster (1978), the volcanic-arc type granitoid shows a partial melting trend along a relatively steep slope, Normalized REE patterns show that the volcanic-arc type granitoid has higher LREE/HREE ratios than those from the Nils Larsen tonalite, and some samples of the Nils Larsen tonalite with lack of Eu anomalies display similar REE patterns with those from the volcanic-arc type granitoid. This evidence argues that partial melting of the Nils Larsen tonalite can produce the volcanic-arc type granitoid, which has relatively higher LREE/HREE ratios with no Eu anomalies. Although initial $^{87}Sr/^{86}Sr$ ratios from the volcanic-arc type granitoid are slightly higher (0.7037 and 0.7050) than that from the Nils Larsen tonalite (0.7024), these ratios show low values and are concentrated in narrow ranges, which may suggest a similar source and magma evolution for the Dufek and Lunckeryggen granitoids with similar ages. A narrow range of εNd values (−1.48 to +0.62) and model ages (900–1000 Ma) (Arakawa *et al.*, 1994) can further support the hypothesis that the volcanic-arc type granitoid has affinity with the Nils Larsen tonalite. The presence of xenoliths of the Nils

Larsen tonalite in the Lunckeryggen and Dufek granitoids provides evidence of petrogenetic affinity during partial melting. It is possible to assume that partial melting of the mantle source results in the formation of the first phase of the Nils Larsen tonalite, and partial melting of the Nils Larsen tonalite with minor mixing with such as host gneisses, produces a second phase of the volcanic-arc type granitoid. The within-plate type granitoid has enriched in HFS elements, higher MREE and HREE, and low LREE/HREE ratios with negative Eu anomalies, and this seems affinity with those from such as host gneisses (Fig. 8). Tainosho *et al.* (1992) argued that local difference in the degree of mixing with gneisses explains the different initial $^{87}Sr/^{86}Sr$ ratios (two groups of 0.7067 and 0.7184) in the Vikinghøgda granitoid. The wide variation of initial Sr values (Table 1) precludes the derivation of their parental magma from an isotopic unique source (Arakawa *et al.*, 1994). So we suggest that the within-plate type granitoid has affinity with such as the host gneisses and may be derived from assimilation of host gneisses by melts and then fractional crystallization.

In summary of petrogenesis, based on geochemical signatures and isotopic data from two types of granitoids in the Sør Rondane Mountains, it is proposed that two possibilities of their petrogenesis so far. One is that the volcanic-arc type granitoid is probably derived from deeper parental magma source by process of fractional crystallization with or without assimilation, subsequently, successive fractional crystallization from the same magma source (should be altered components) accompanied with assimilation during ascending, to produce the within-plate type granitoid. The other is that they may be derived from different magma source and had different petrogenetic processes.

Acknowledgments

We express our sincere thanks to the geologists who participated in JARE-26, -28, -30 and -31 for their kind permission to use their samples. The authors thank Dr. K. Morioka (Kobe Univ.) for XRF analytical support.

References

Allègre, C.J. and Minster, J.F. (1978): Quantitative models of trace element behavior in magma processes. Earth Planet. Sci. Lett., **38,** 1–25.

Arakawa, Y., Takahashi, Y. and Tainosho, Y. (1994): Nd and Sr isotopic characteristics of the plutonic rocks in the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **7**, 49–59.

Asami, M. and Shiraishi, K. (1987): Kyanite from the western part of the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 150–168.

Asami, M., Osanai, Y., Shiraishi, K. and Makimoto, H. (1992): Metamorphic evolution of the Sør Rondane Mountains, East Antarctica. Recent Progress in Antarctic Earth Science, ed. by Y. Yoshida *et al.* Tokyo, Terra. Sci. Publ., 7–15.

Cox, K.G., Bell, J.D. and Pankhurst, R.J. (1979): The Interpretation of Igneous Rocks. London, Allen and Unwin, 450 p.

Defant, M.J. and Drummond, M.S. (1990): Derivation of some modern arc magma by melting of young subducted lithosphere. Nature, **347**, 662–665.

Defant, M.J., Richerson, P.M., De Bore, J.Z., Stewart, R.H., Maury, R.C., Bellon, H., Drummond, M.S., Feigenson, M.D. and Jackson, T.E. (1991): Dacite gneiss via both slab melting and differentiation: Petrogenesis of La Yeguada volcanic complex, Panama. J. Petrol., **32**, 1101–1142.

Grew, E.S., Manton, W.I., Asami, M. and Makimoto, H. (1992): Reconnaissance geochronologic data on Proterozoic polymetamorphic rocks of the eastern Sør Rondane Mountains, East Antarctica. Recent Progress in Antarctic Earth Science, ed. by Y. Yoshida *et al.* Tokyo, Terra. Sci. Publ., 45–54.

Ikeda, Y. and Shiraishi, K. (1998): Petrogenesis of the tonalite from the Sør Rondane Mountains, East Antarctica. Polar Geosci., **11**, 143–153.

Ishizuka, T. and Kojima, H. (1987): A preliminary report on the geology of the central part of the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 113–128.

Kimura J.-I., Takaku, Y. and Yoshida, T. (1995): Igneous rock analysis using ICP-MS with internal standardization, isobaric ion overlap correction, and standard addition methods. Sci. Rep. Fukushima Univ., **56**, 1–12.

Kojima, S. and Shiraishi, K. (1986): Note on the geology of the western part of the Sør Rondane Mountains, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 116–131.

Kretz, R. (1983): Symbols for rock-forming minerals. Am. Mineral., **68**, 277–279.

Li, Z.L., Tainosho, Y. and Owada, M. (2001): Petrography and characteristics of mineral composition of syenitic rocks from the Mefjell granitoid complex in the Sør Rondane Mountains, East Antarctica. Mem. Grad. School Sci. & Technol., Kobe Univ., **19-A**, 33–44.

Miyake, Y., Tsugane, T., Kanai, T. and Ikemoto, M. (1996): X-ray fluorescence analysis of major elements in silicate rocks -preparation of glass bead pellets of a high ratio of sample to flux and the accuracy of the rapid analysis. J. Fac. Sci., Shinshu Univ., **31**, 105–117 (in Japanese with English abstract).

Neumann, H., Mead, J. and Vitaliano, C. J. (1954): Trace element variation during fractional crystallization as calculated from the distribution law. Geochim. Cosmochim. Acta, **6**, 90–99.

Osanai, Y., Takahashi, Y. and Sakiyama, T. (1988): High-grade metamorphic rocks from the central part of the Sør Rondane Mountains, East Antarctica (abstract). Proc. NIPR Symp. Antarct. Geosci., **2**, 170.

Osanai, Y., Shiraishi, K., Takahashi, Y., Ishizuka, H., Tainosho, Y., Tsuchiya, N., Sakiyama, T. and Kodama, S. (1992): Geochemical characteristics of metamorphic rocks from the central Sør Rondane Mountains, East Antarctica. Recent Progress in Antarctic Earth Science, ed. by Y. Yoshida *et al.* Tokyo, Terra Sci. Publ., 17–27.

Osanai, Y., Shiraishi, K., Takahashi, Y., Ishizuka, H., Moriwaki, K., Tainosho, Y., Tsuchiya, N., Sakiyama, T., Toyoshima, T., Owada, M. and Kojima, H. (1996): Explanatory text of geological map of Brattnipene, Sør Rondane Mountains, Antactica. Antarctic Geological Map Series, Sheet 34, Brattnipene. Tokyo Natl Inst. Polar Res., 29 p.

Pearce, J.A., Harris, N.B.W. and Tindle, A.G. (1984): Trace element discrimination diagram for the tectonic interpretation of granitic rocks. J. Petrol., **25**, 956–983.

Roser B.P., Kimura J.-I. and Hisatomi, K. (2000): Whole-rock elemental abundances in sandstones and mudrocks from the Tanabe Group, Kii Peninsula, Japan. Sci. Rep. Shimane Univ., **19**, 101–112.

Sakiyama, T., Takahashi, Y. and Osanai, Y. (1988): Geological and petrological characters of the plutonic rocks in the Lunckeryggen-Brattnipene region, Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **2**, 80–95.

Shand, S.J. (1947): Eruptive Rocks. Their Genesis, Composition, Classification, and their Relation to Ore-Deposits, 3rd ed. New York, J. Wiley, 488 p.

Shiraishi, K. and Kagami, H. (1992): Sm-Nd and Rb-Sr ages of metamorphic rocks from the Sør Rondane Mountains, East Antarctica. Recent Progress in Antarctic Earth Science, ed. by Y. Yoshida *et al.* Tokyo, Terra. Sci. Publ., 29–35.

Shiraishi, K. and Kojima, S. (1987): Basic and intermediate gneisses from the western part of the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 129–149.

Shiraishi, K., Asami, M., Ishizuka, H., Kojima, S., Osanai, Y., Sakiyama, T., Takahashi, Y., Yamazaki, M. and Yoshikura, S. (1991): Geology and metamorphism of the Sør Rondane Mountains, East Antarctica. Geological Evolution of Antarctica, ed. by M.R.A. Thomson *et al.* Cambridge,

Cambridge Univ. Press, 77–82.

Shiraishi, K., Osanai, Y., Ishizuka, H. and Asami, M. (1997): Antarctic Geological Map Series, Sheet 35, Sør Rondane Mountains. Tokyo, Natl Inst. Polar Res.

Tainosho, Y., Takahashi, Y., Arakawa, Y., Osanai, Y., Tsuchiya, N., Sakiyama, T. and Owada, M. (1992): Petrochemical character and Rb-Sr isotopic investigation of the granitic rocks from the Sør Rondane Mountains, East Antarctica. Recent Progress in Antarctic Earth Science, ed. by Y. Yoshida *et al.* Tokyo, Terra Sci. Publ., 45–54.

Tainosho, Y., Takahashi, Y., Maekawa, H., Osanai, Y. and Tsuchiya, N. (1993): Preliminary petrological studies of the granitic rocks in the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **6**, 83–102.

Takahashi, Y., Arakawa, Y., Sakiyama, T., Osanai, Y. and Makimoto, H. (1990): Rb-Sr and K-Ar whole rock ages of the plutonic bodies from the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **4**, 1–8.

Takigami, Y., Funaki, M. and Tokieda, K. (1991): ^{40}Ar-^{39}Ar ages and paleomagnetic studies of igneous and metamorphic rocks from the Sør Rondane Mountains, East Antarctica. Abstracts: Sixth International Symposium on Antarctic Earth Sciences. Tokyo, Natl Inst. Polar Res., 570–575.

Taylor, S.R. and McLennan, S.M. (1985): The Continental Crust: Its Composition and Evolution. Oxford, Blackwell, 312 p.

Yamamoto, K. and Morishita, T. (1997): Preparation of standard composites for the trace element analysis by X-ray fluorescence. J. Geol. Soc. Jpn., **103**, 1037–1045 (in Japanese with English abstract).

(Received April 5, 2001; Revised manuscript accepted May 22, 2001)