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GEOCHEMISTRY OF POST-OROGENIC MAFIC DIKE ROCKS FROM THE EASTERN QUEEN MAUD LAND, EAST ANTARCTICA

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Abstract: Two types of mafic dike rocks intruded the late Proterozoic metamorphic terrains of eastern Queen Maud Land: thermally metamorphosed rocks and unmetamorphosed rocks. The former is metamorphosed by *ca.* 500 Ma granite intrusions, whereas the latter is Jurassic in age. The metadike rocks are continental tholeiites, although the geochemical character is variable from place to place. In particular, the rocks from the Sør Rondane Mountains are transitional between quartz tholeiite and alkaline basalt. By analogy with other areas, the suggested tectonic environment for intrusion is an initial continental rift system. Unmetamorphosed dike rocks are similar in composition to Jurassic tholeiitic dike rocks from western Queen Maud Land. A Jurassic basalt-dolerite suite may widely occur under the continental ice of eastern Queen Maud Land.

1. Introduction

Mafic dike rocks of various compositions and ages intrude Precambrian metamorphic terrains of East Antarctica (SHERATON *et al.*, 1980; SHERATON and ENGLAND, 1980; SHERATON and BLACK, 1981; FURNES *et al.*, 1982; SHERATON, 1983; KAISER and WAND, 1985; COLLERSON and SHERATON, 1986; KANISAWA *et al.*, 1987). The dike rocks are useful stratigraphic markers and their chemical compositions provide the information about not only the nature of source material but the tectonic environment at the time of their emplacement.

The mafic dikes of eastern Queen Maud Land (Fig. 1) are divided into the following four types on the basis of their mode of occurrence: I) concordant layers which are metamorphosed under the same conditions as the surrounding high-grade gneisses, II) discordant dikes which are metamorphosed under the same high-grade conditions, III) thermally metamorphosed discordant dikes with chilled margins in places and IV) unmetamorphosed discordant dikes. I and II are considered to have been emplaced before or during regional metamorphism, whereas III and IV clearly intruded after the regional metamorphism. The ages of regional metamorphism in eastern Queen Maud Land are not well defined by available isotopic data, which suggest a late Proterozoic age for the last regional metamorphic event.

The aim of this study is to describe the geochemical characteristics of mafic dike rocks emplaced after the regional metamorphism in eastern Queen Maud Land (Types III and IV), and to consider how the mafic dikes are related to the tectonic environment.

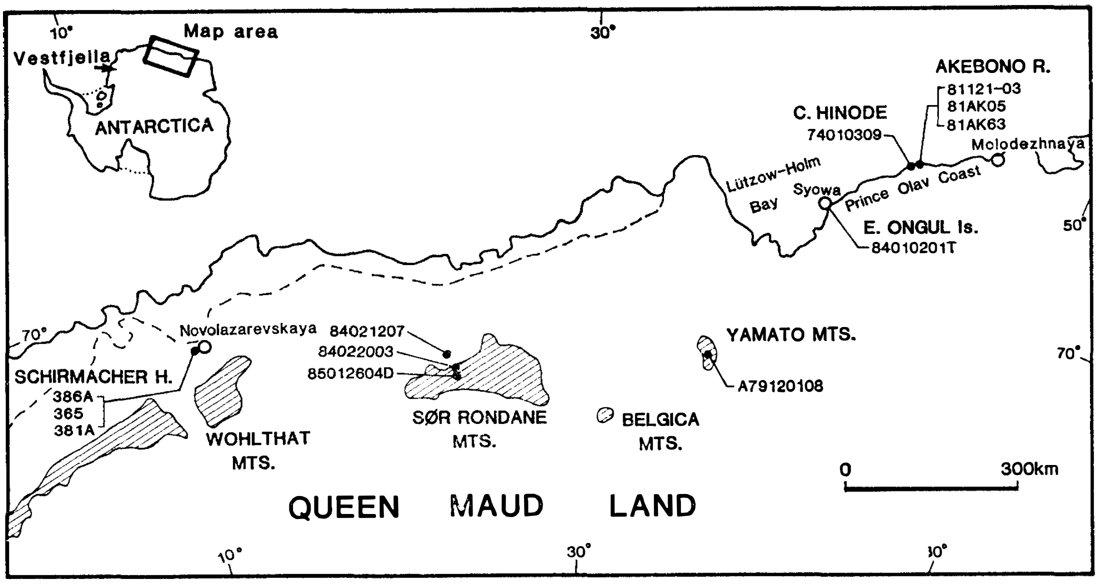

Fig. 1. Sample localities of post-orogenic mafic dikes in the eastern Queen Maud Land.

2. Brief Geology of Eastern Queen Maud Land

Eastern Queen Maud Land, which includes a sizable part of the East Antarctic Precambrian shield (Fig. 1) is composed of several Precambrian metamorphic complexes whose tectonic relationships are not well established (*e.g.* RAVICH and KAMENEV, 1975). Two contrasting high-grade metamorphic terrains of late Proterozoic age have been recognized around Syowa Station: Lützow-Holm Complex in the east and Yamato-Belgica Complex in the west (HIROI *et al.*, 1984; SHIRAISHI *et al.*, 1987). Rb-Sr isochron dating studies suggest that the regional metamorphism and the subsequent thermal event throughout the two complexes occurred around 700 Ma and 500 Ma ago, respectively (SHIBATA *et al.*, 1985, 1986). The Lützow-Holm Complex is characterized by medium-pressure type prograde metamorphism increasing in grade southwestward from upper amphibolite-facies on the Prince Olav Coast to granulite-facies on the Lützow-Holm Bay region, whereas the Yamato-Belgica Complex is characterized by the low-pressure type metamorphism and by extensive granite and syenite plutonism in the Yamato and Belgica Mountains. The Lützow-Holm Complex is also characterized by the low initial $^{87}Sr/^{86}Sr$ ratios (0.705–0.706) and by the ubiquitous ultramafic rocks in the metasedimentary sequences especially in the western part of the Complex. HIROI *et al.* (1986b) considered that the ultramafic rocks had originated from various parts of layered gabbro which were tectonically fractured and emplaced in the metasedimentary rocks. This contrast in metamorphic pressures between the two complexes and the occurrence of ultramafic rocks in the Lützow-Holm Complex have been proposed as evidence for continent-continent collision type tectonics (HIROI *et al.*, 1984; HIROI *et al.*, 1986b; SHIRAISHI *et al.*, 1987).

The Sør Rondane Mountains are largely underlain by high-grade metamorphic rocks in various compositions, and plutonic rocks comprising granitic, syenitic, dioritic and tonalitic compositions (VAN AUTENBOER, 1969; VAN AUTENBOER and LOY, 1972;

SHIRAISHI *et al.*, 1988). A distinct mylonite zone at least 10 km in width trends E-W in the southwestern part of the mountains. The regional metamorphism is of the medium-pressure type and reaches the granulite-facies in grade (ASAMI and SHIRAISHI, 1987; SHIRAISHI *et al.*, 1988). Intense deformation and plutonism resulted in extensive mylonitization and retrogression. PASTEELS and MICHOT (1970) inferred the climax age of the "catazonal" (presumably upper amphibolite- to granulite-facies) metamorphism to be 650 to 600 Ma.

The Schirmacher Hills are largely underlain by granulite-facies metamorphic rocks of pelitic, basic and calcareous compositions. These rocks were re-metamorphosed by an amphibolite-facies event associated with pegmatite intrusion (GREW and MANTON, 1983; GREW, 1983). The granulite-facies metamorphism is inferred to be about 1500 Ma, and the amphibolite-facies one to be 630 Ma based on U-Th-Pb ages of minerals from a gneiss and a pegmatite (GREW and MANTON, 1983). K-Ar ages (460–490 Ma) on migmatites reported by RAVICH and SOLOV'EV (1969) could be cooling ages related to the 630 Ma event (E. S. GREW, pers. commun.) or suggest a later thermal event.

Thus, there seems to be a common feature that the ages of the high-grade regional metamorphism throughout eastern Queen Maud Land are almost equivalent to be late Proterozoic although their tectonic relationships are obscured. However, it is also evident that the latest Proterozoic to early Paleozoic granite activity, which may correspond to the Pan-African event, is widespread and that the activity caused the thermal metamorphism for the preexisting rocks.

3. Description of Samples

3.1. *Localities*

Twelve post-regional metamorphism mafic dike rocks from a wide area in eastern Queen Maud Land were selected for chemical analyses (Fig. 1): five from the Lützow-Holm Complex, one from the Yamato-Belgica Complex, three from the Sør Rondane Mountains and three from the Schirmacher Hills. These samples are divided into two groups; an unmetamorphosed group and a metamorphosed group, which correspond to the types IV and III, respectively.

3.2. *Mode of occurrence and petrography*

3.2.1. Lützow-Holm Complex

Type III mafic dikes were emplaced after the main regional metamorphic event in the amphibolite-facies rocks at Akebono Rock and Cape Hinode on the Prince Olav Coast (HIROI *et al.*, 1986a). The dikes from Akebono Rock (sp. 81121-03, 81AK05, 81AK63) are dark brownish gray to dark green and very fine- to fine-grained massive rocks. These dikes, a few tens to several tens of centimeters in width, sharply cut the surrounding gneisses, but no distinct chilled margins were found. The degree of metamorphism of the dikes varies with the distance from the Paleozoic pink gneissose granite, but in the dikes ophitic to sub-ophitic textures and igneous minerals are generally preserved. Relict igneous clino- and ortho-pyroxenes are surrounded by greenish hornblende. Plagioclase laths show normal zoning (An 40–48 at core and An 31–41 at rim). Opaque minerals are ilmenite and pyrite. A mafic dike rock from Cape

Hinode (sp. 74010309), described as amphibolite by YANAI and ISHIKAWA (1978), intruded a distinctive tonalitic gneiss referred to as anorthositic gneiss by YANAI and ISHIKAWA (1978). The dike rock shows a decussate texture defined by pale green hornblende and yellowish brown biotite with fine-grained albite. However, igneous plagioclase laths with corroded rims are well preserved. Therefore, it may be a thermally metamorphosed basalt-dolerite dike.

Pebbles and boulders of basaltic rocks have been reported from the morainic debris in ice-free areas of the Lützow-Holm Bay region and the Prince Olav Coast. As none of the basaltic rocks have been found in outcrop, the mode of occurrence is not known (*e.g.* ISHIKAWA *et al.*, 1976). It is believed that these basaltic rocks originated from under the ice sheet. The basalts are aphyric to porphyritic in texture. Since they have not been metamorphosed, they belong to type IV mafic dike. Sp. 84010201T was collected from the morainic debris on East Ongul Island. It shows a typical ophitic texture and consists of plagioclase, clinopyroxene and needles of ilmenite with minor amounts of secondary carbonate and chlorite.

3.2.2. Yamato-Belgica Complex

Slightly metamorphosed mafic dikes a few tens of centimeters wide are exposed in the central part of the Yamato Mountains (YANAI *et al.*, 1982). They show a clean-cut relationship with the surrounded amphibolite-facies gneisses, but no distinct chilled margins are observed. Igneous textures are well preserved in sp. A79120108 despite recrystallization of Ti-rich biotite (up to 5.14 wt% TiO_2) in randomly orientated flakes. This rock has a fine-grained equigranular texture with porphyritic pyroxenes. Relict igneous minerals are porphyritic clinopyroxene ($Mg_{36}Fe_{17}Ca_{47}$), porphyritic orthopyroxene ($Mg_{49}Fe_{50}Ca_1$), plagioclase (An35–46 at core and An25–33 at rim) and ilmenite.

3.2.3. Sør Rondane Mountains

Metamorphosed mafic dike rocks (metadolerites) have been found at about 20 localities in the Sør Rondane Mountains (SHIRAISHI *et al.*, 1988). The metadolerite dikes uniformly strike NNW-SSE with nearly vertical or moderate westerly dips. Moreover, the metadolerites are especially abundant in the western part of the Sør Rondane Mountains. They can generally be traced for a few hundred meters, the maximum possible because of the limited size of outcrops. However, two dikes over a few kilometers long are observed in an airphotograph of Walnumfjellet. The metadolerite dikes generally range in width from a few tens of centimeters to a few meters (maximum 6 m). The dike rock is in sharp contact with the host gneisses and distinct chilled margins are commonly present. The dikes also intrude Paleozoic granite, but are cut in places by the youngest veins of Paleozoic granite and pegmatite.

Sp. 85012604C was collected from the core of a dike 6 m wide. Sp. 84022003 is a narrow dike 30 cm wide. These rocks show a sub-ophitic dolerite texture and are composed essentially of igneous pyroxenes and plagioclase, and of metamorphic biotite with or without hornblende. Quartz occurs in many rocks as minute interstitial grains and ocelli surrounded by biotite and carbonate. In one dike, orthopyroxene is overgrown by clinopyroxene that shows sector zoning. In other rocks, either clino- or orthopyroxene is present. Clinopyroxene ($Mg_{47}Fe_{13}Ca_{40}$) is characteristically rich in TiO_2 (up to 2.6%) and Al_2O_3 (up to 3.9%) (in sp. 85012604C). Ilmenite is a dominant opaque mineral and accessory minerals are apatite, magnetite and sulfide minerals.

Sp. 84021207 occurs in contact with one of the youngest granite dikes and is partly brecciated by the granitic veins. It is a fine-grained nematoblastic hornblende-biotite schist. Schistosity which is parallel to the trend of the granite intrusion is more intense at the margin than at the interior. It suggests that the deformation of the dike is related to the granite intrusion. Constituent minerals are metamorphic biotite, hornblende, plagioclase, quartz, sphene, apatite and opaque minerals. Igneous plagioclase occurs in places but no pyroxene was preserved.

3.2.4. Schirmacher Hills

Mafic dikes were emplaced before and after the amphibolite-facies event in the Schirmacher Hills (GREW and MANTON, 1983). Sp. 381A is a fresh unmetamorphosed dolerite, whereas sp. 365 and 386A are from the older metamorphosed mafic dikes. The metamorphosed dike rocks have a very fine- to fine-grained granoblastic matrix composed of metamorphic biotite, hornblende, albitic plagioclase, sphene and ore minerals. Porphyritic plagioclase is well preserved in places. Biotite and hornblende make decussate clots in sp. 386A. Thus, these textures characterize the hornfels origin of these rocks, although the rocks are not in direct contact with any plutonic rocks (E.S. GREW, pers. commun.). Sp. 386A contains ovoid- or veinlet-like aggregates of quartz which seems to be xenocryst or secondary in origin.

The unmetamorphosed dike rock (Sp. 381A) is a typical dolerite which consists of olivine, clinopyroxene, plagioclase and ore minerals.

3.3. *Age of mafic dikes*

No isotopic data are available for the mafic dike rocks from the Prince Olav Coast. Field relation indicates that they intruded between the 700 Ma metamorphic event and the 500 Ma thermal event associated with granite and pegmatite.

In the Yamato Mountains, a new K-Ar whole-rock age of 477±24 Ma (Table 1) is greater than the 360 to 400 Ma ages obtained on the amphibolite-facies gneiss and syenites that are intruded by the mafic dike (YANAI *et al.*, 1982). However, it is compatible with a Rb-Sr mineral isochron age (493.3±4.5 Ma) and K-Ar ages on biotite (469±14 and 483±15 Ma) of the surrounding gneisses (SHIBATA *et al.*, 1985).

KOJIMA and SHIRAISHI (1986) and TAKIGAMI *et al.* (1987) reported K-Ar and Ar-Ar whole-rock ages for the metadolerites from the Sør Rondane Mountains. A dolerite from Nunatak "1550", which was collected from the same dike as sp. 84022003, yields 440–450 Ma by the K-Ar and Ar-Ar methods, whereas sp. 85012604D (same dike as to 85012604C) yields 536±27 Ma by the K-Ar method. The cause of this discrepancy

Table 1. K-Ar whole-rock ages of mafic dike rocks from eastern Queen Maud Land.

Sample No.	Locality	^{40}Ar (scc/g 10^{-5})	^{40}Ar (%)	K (%)	Age (Ma)
A79120108	Massif C	3.90	97.9	1.86	477.1±23.9
84010201T*	Ongul Is.	0.488	80.0	0.89	138.1± 6.9

* boulder from moraine.

Decay constants are after STEIGER and JÄGER (1977).

Analyst: Teledyne Isotope.

Table 2. Major elements and CIPW norms of mafic dike rocks from eastern Queen Maud Land.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	54.78	54.34	55.41	43.58	54.12	58.78	51.60	51.83	50.89	54.12	50.25	49.20
TiO_2	1.68	1.63	1.59	2.03	1.53	0.96	1.51	3.50	3.22	2.52	4.45	0.89
Al_2O_3	15.21	15.30	15.72	12.67	14.65	14.70	12.83	13.94	13.71	14.14	12.18	15.02
Fe_2O_3	3.35	3.13	3.18	3.67	1.29	1.73	2.40	3.80	2.57	2.24	3.37	4.51
FeO	7.65	7.33	6.82	7.79	7.19	4.92	5.54	7.12	8.95	6.67	11.17	6.36
MnO	0.14	0.13	0.14	0.18	0.14	0.10	0.12	0.15	0.15	0.13	0.20	0.16
MgO	4.77	4.99	5.23	14.73	5.63	7.06	8.67	4.12	5.24	5.12	4.36	8.69
CaO	7.94	7.81	7.78	8.40	6.98	5.11	6.78	6.43	6.92	6.20	8.37	10.20
Na_2O	3.14	3.45	3.26	2.17	3.60	2.12	2.78	2.90	3.02	3.43	2.77	2.63
K_2O	0.12	0.06	0.06	2.02	2.38	3.07	4.11	2.47	2.00	2.46	1.09	0.72
H_2O (+)	1.05	1.49	0.96	1.40	1.07	1.64	1.61	0.96	0.77	1.21	1.13	2.55
(−)	0.13	0.08	0.08	0.16	0.19	0.05	0.04	0.12	0.17	0.17	0.61	0.25
P_2O_5	0.10	0.07	0.07	0.39	0.36	0.38	0.83	1.32	1.15	0.92	0.51	0.13
Total	100.06	99.81	100.30	99.19	99.13	100.62	98.82	98.66	98.76	99.33	100.46	101.31
mg	44	46	49	70	55	66	66	41	45	51	35	59
					C.I.P.W. norm							
Q	10.74	8.86	10.69	—	0.59	11.76	—	8.49	3.97	5.39	6.52	—
or	0.71	0.35	0.35	11.94	14.07	18.14	24.29	14.60	11.82	14.54	6.44	4.26
ab	26.57	29.19	27.59	8.88	30.46	17.94	23.52	24.54	25.55	29.02	23.44	22.25
an	27.05	26.08	28.08	18.86	16.79	21.53	10.39	17.72	17.95	15.92	17.58	27.05
ne	—	—	—	5.14	—	—	—	—	—	—	—	—
di wo	4.88	5.10	4.20	8.46	6.47	0.56	7.44	2.32	3.70	3.69	8.61	9.48
di en	2.70	2.91	2.52	6.24	3.64	0.38	5.32	1.51	2.08	2.30	4.24	6.61
di fs	1.99	1.97	1.46	1.40	2.56	0.13	1.46	0.65	1.48	1.17	4.20	2.07
hy en	9.18	9.52	10.51	—	10.28	17.20	4.50	8.75	10.97	10.46	6.62	11.03
hy fs	6.77	6.45	6.07	—	7.31	6.07	1.23	3.78	7.80	5.31	6.55	3.45
ol fo	—	—	—	21.34	—	—	8.25	—	—	—	—	2.81
ol fa	—	—	—	5.29	—	—	2.49	—	—	—	—	0.97
mt	4.86	4.54	4.61	5.32	1.87	2.51	3.48	5.51	3.73	3.25	4.89	6.54
il	3.19	3.10	3.02	3.86	2.91	1.82	2.87	6.65	6.12	4.79	8.45	1.69
ap	0.23	0.16	0.16	0.90	0.83	0.88	1.92	3.06	2.66	2.13	1.18	0.30
Analyst	K	K	K	K	J	K	K	K	K	J	K	K

Analyst: K. KANISAWA & ISHIKAWA; J. Japan Chemical Analysis Center.

Thermally metamorphosed rocks

1. 810121-03, Loc. Akebono Rock, Prince Olav Coast
2. 81AK05, Loc. Akebono Rock, Prince Olav Coast
3. 81AK63, Loc. Akebono Rock, Prince Olav Coast
4. 74010309, Loc. Cape Hinode, Prince Olav Coast
5. A79120108, Loc. Massif C, Yamato Mountains
6. 386A, Loc. Schirmacher Hills
7. 365, Loc. Schirmacher Hills
8. 84021207, Loc. Vesthaugen, Sør Rondane Mountains
9. 84022003, Loc. Nunatak "1550", Sør Rondane Mountains
10. 85012604C, Loc. Walnumfjellet, Sør Rondane Mountains

Unmetamorphosed rocks

11. 84010201T, Loc. East Ongul Island, Lützow-Holm Bay
12. 381A, Loc. Schirmacher Hills

between the two age groups is not clear. The last thermal event in both the Sør Rondane and Yamato Mountains is dated at about 500 Ma, which is consistent with the previously reported U-Pb data for younger granites (520±20 Ma) (PASTEELS and MICHOT, 1970). Therefore, the metadolerite intruded probably in the latest Proterozoic to early Paleozoic, that is, roughly coeval with those of the Lützow-Holm Complex.

GREW and MANTON (1983) suggested the metamorphosed mafic dikes from the Schirmacher Hills are late Precambrian in age, while the unmetamorphosed mafic dikes are late Precambrian or Phanerozoic in age. KAISER and WAND (1985) reported K-Ar ages of basalt-dolerites from the Schirmacher Hills. The fresh unmetamorphosed rocks show bimodal ages of 154–163 Ma and 290–302 Ma. Petrographical differences between

Table 3. Trace elements in parts per million.

	1	2	3	4	5	6	7	8	9	10	11	12
Be	<0.5	<0.5	<0.5	<0.5	1.0	3.0	3.5	1.5	0.5	1.0	1.5	<0.5
V	165	146	148	173	136	111	139	135	145	125	391	264
Cr	155	158	123	721	155	419	474	55	155	119	89	375
Co	38	36	36	58	29	39	39	29	33	29	42	55
Ni	84	110	108	323	47	219	167	30	69	73	51	186
Cu	31	45	44	42	9	20	46	<1	12	10	352	70
Zn	115	98	103	73	126	96	99	174	150	132	147	75
Rb	4	3	3	11	87	83	78	70	25	61	46	9
Sr	485	425	442	548	568	975	1580	1235	1045	891	432	366
Y	17	15	12	22	43	37	46	59	44	49	64	20
Zr	80	70	70	190	230	235	375	350	315	290	350	89
Nb	<5	<5	<5	19	20	11	26	28	21	20	28	<5
Mo	<1	<1	<1	<1	2	<1	<1	<1	<1	<1	<1	<1
Ag	0.5	0.5	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Cd	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.5	1.5	2.0	1.5	2.0
Ba	90	40	80	140	980	2340	6250	2100	1620	1260	480	420
W	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Pb	4	<2	<2	2	24	24	20	12	8	14	<2	<2
Bi	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Th	<1	<1	<1	1	5	17	15	3	2	9	4	2
U	<1	1	1	1	2	3	3	4	1	4	1	1
La	2	1	1	18	34	61	117	65	55	53	37	13
Ce	9	6	6	40	66	110	206	149	125	122	77	25
Pr	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Nd	<5	<5	<5	19	32	38	93	91	76	80	56	9
Sm	3.2	2.5	2.5	3.8	4.9	7.4	16.0	15.0	12.0	12.0	13.0	3.2
Eu	1.3	1.2	1.2	1.5	1.8	1.8	3.3	4.6	3.9	3.2	3.2	1.1
Gd	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
Tb	0.5	0.4	0.4	0.6	0.6	0.6	0.9	1.6	1.1	0.9	1.7	0.3
Dy	1	1	1	1	1	2	6	10	9	7	10	<1
Ho	<2	<2	<2	<2	<2	<1	<1	<1	<2	<2	<1	<1
Er	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Tm	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Yb	1.3	0.9	0.9	1.4	1.4	1.3	1.6	2.3	1.9	2.0	3.2	1.3
Lu	0.2	0.2	0.2	0.2	0.3	0.2	0.3	0.5	0.4	0.4	0.7	0.2

Analyst: Chemex Laboratory Inc.

the two age groups of the unmetamorphosed dike rocks are not given by KAISER and WAND (1985). Although age determination of sp. 381A has not been performed, it is probable of Jurassic because of the petrographic similarity with those from Vestfjella (FURNES *et al.*, 1987). The unmetamorphosed basaltic rock from East Ongul Island yields Jurassic age of 138 ± 7 Ma (Table 1), which is close to the ages of the Ferrar dolerites and related dikes in western Queen Maud Land and in other parts of East Gondwanaland (*e.g.* MCDOUGALL, 1963).

4. Geochemistry

4.1. *Analytical method*

Major and trace element analyses, as well as the CIPW norm of twelve mafic dike rocks are presented in Tables 2 and 3. Major element abundances were determined by X-ray fluorescence spectrometry (XRF) in combination with flame photometry (FP) (Na, K) and ordinary wet chemical analyses method (WCM) (FeO, Fe_2O_3, H_2O) except for sp. 81AK63, A79120108 and 85012604C which were analyzed by FP (Na, K) and WCM (other elements). Trace elements were analyzed by combination of XRF (Nb, Y, Zr), atomic absorption spectrometry (Ag, Rb), instrumental neutron activation analyses (U, Th, REE) and inductively coupled plasma spectrometry (other elements).

4.2. *Metamorphosed rocks*

Most of samples are quartz and hyperthene normative basaltic and andesitic rocks. Major element abundances characterize relatively high contents of K_2O (2.00 to 4.11 wt%) except for the rocks from Akebono Rock. The rocks from the Sør Rondane Mountains are rich in TiO_2 (up to 3.50 wt%) and P_2O_5 (up to 1.32 wt%). A rock from the Schirmacher Hills (Sp. 386A) is the richest in SiO_2 (58.78 wt%) but shows high mg-value (mg$=100\times$Mg/(Mg+Fe)) and high Ni and Cr contents. These results

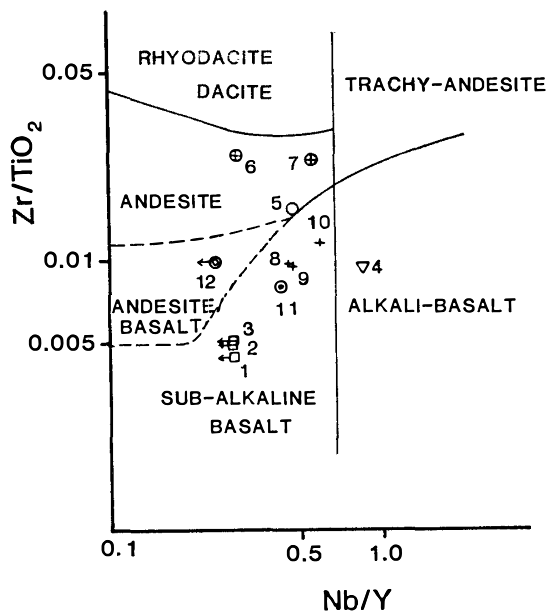

Fig. 2. Zr/TiO_2 vs. Nb/Y plot for post-orogenic mafic dike rocks from eastern Queen Maud Land. Nos. 1, 2, 3 and 12 show the maximum Nb/Y ratios because of the detection limits of Nb abundance. Square: Akebono Rock, triangle: Cape Hinode, circle: Yamato Mountains, circle with cross: Schirmacher Hills, cross: Sør Rondane Mountains, circle with dot and double circle: unmetamorphosed rocks from East Ongul Island and Schirmacher Hills, respectively. Numbers as in Table 2.

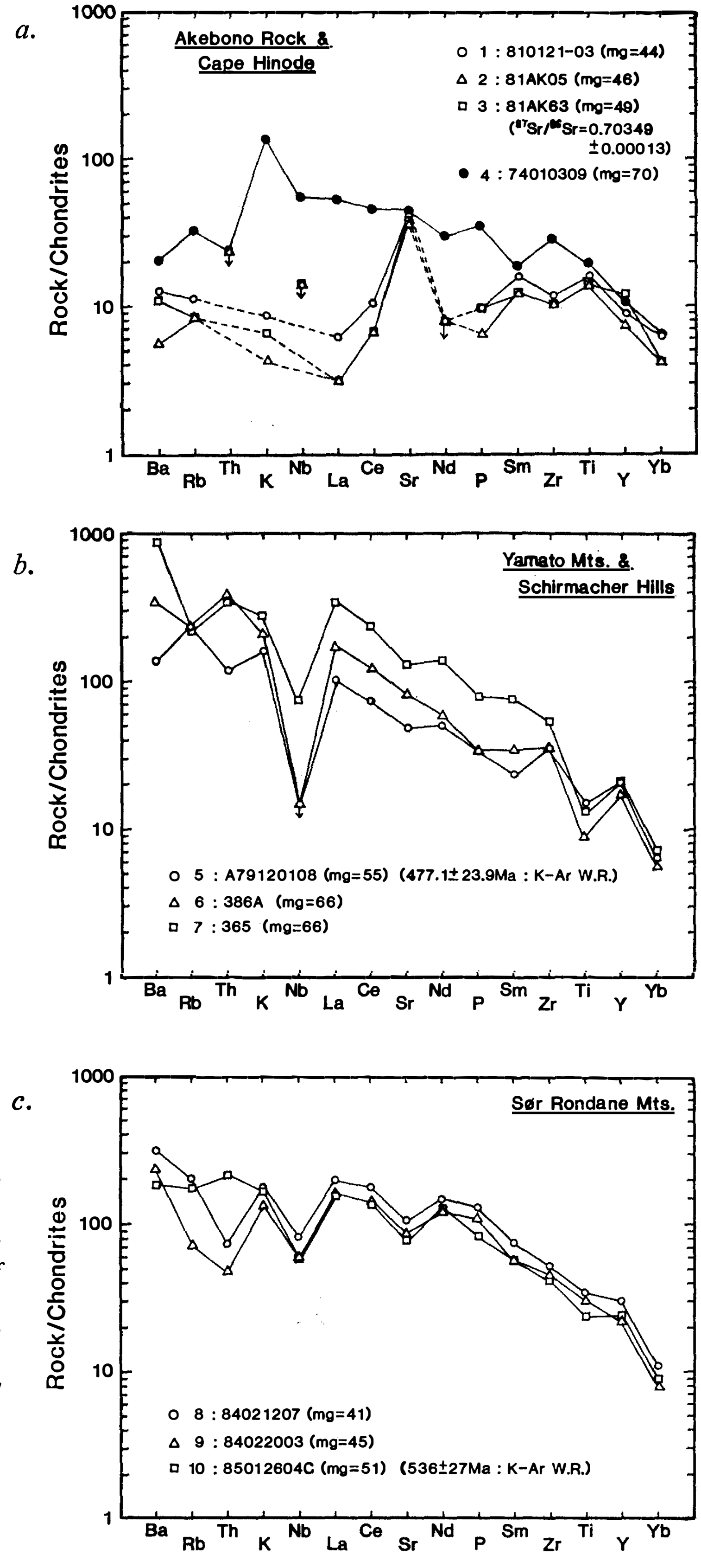

Fig. 3. Spidergrams of thermally metamorphosed mafic dike rocks. Symbols with an arrow indicate the maximum value because of the detection limits.
a. Akebono Rock and Cape Hinode.
b. Yamato Mountains and Schirmacher Hills.
c. Sør Rondane Mountains.

suggest that the ovoid- or veinlet-like quartz aggregates are of secondary origin, possibly related to introduction of silica at the time of the dikes were metamorphosed.

Because the samples are metamorphosed, the WINCHESTER and FLOYD's (1977) chemical classification was applied. On the discrimination diagrams such as SiO_2 vs. Zr/TiO_2 (not shown), SiO_2 vs. Nb/Y (not shown) and Zr/TiO_2 vs. Nb/Y (Fig. 2) in which relatively immobile elements are considered, most of the rocks plot in the sub-alkaline basalt to andesite fields. A rock from Cape Hinode (sp. 74010309), which shows the highest mg-value in the analyzed samples, plots in the alkali-basalt field. Spidergrams (approach of THOMPSON *et al.*, 1983) of each sample are shown in Fig. 3. Negative Nb anomalies are present in all samples except for sp. 74010309 from Cape Hinode. No pattern emerges for the highly incompatible elements in the lefthand side of the diagram (Ba, Rb, Th, K). There is a contrast between the patterns for Akebono Rock and Cape Hinode in the Lützow-Holm Complex and those for other regions. Those of Akebono Rocks show relatively low element abundances with a strong positive Sr anomaly.

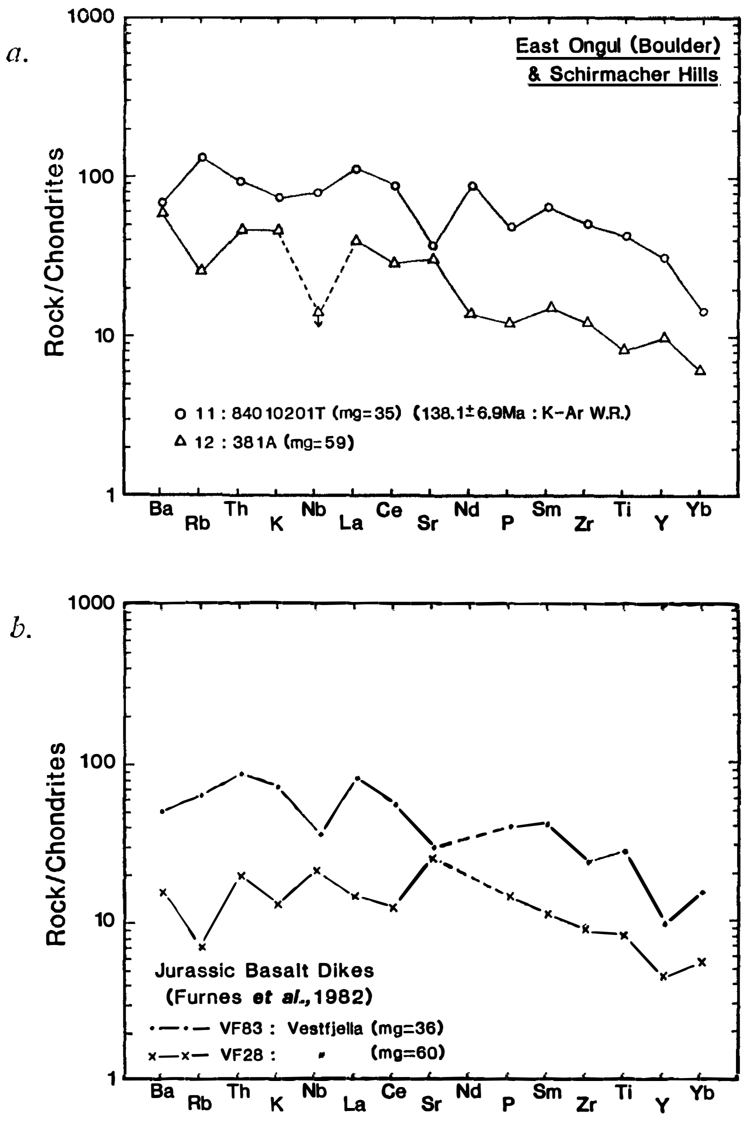

Fig. 4. a. Spidergrams of unmetamorphosed mafic dike rocks from East Ongul Island (boulder) and Schirmacher Hills. A symbol with an arrow as in Fig. 3.
b. Spidergrams of Jurassic basalt dike rocks from Vestjella, western Queen Maud Land (FURNES et al., 1982).

Compared with the rocks from Akebono Rock, a rock from Cape Hinode shows a relatively smooth curve from La to Yb with a positive K anomaly and depletion from Ba to Th. On the other hand, trends for the metamorphosed mafic dike rocks from the Yamato Mountains, Sør Rondane Mountains and Schirmacher Hills are roughly parallel in elements from La to Yb with negative anomalies for Nb, Sr, P and Ti. In addition, the rocks from the Yamato Mountains and Schirmacher Hills have similar characters in both major and trace elements.

4.3. Unmetamorphosed rocks

Two unmetamorphosed Jurassic mafic dikes are typically tholeiitic on the all discrimination diagrams by IRVINE and BARAGAR (1971) and MIYASHIRO (1975) as well as WINCHESTER and FLOYD (1977) (Fig. 2). Quartz and hypersthene normative sp. 84010201T is rich in TiO_2 and poor in Ni and Cr relative to olivine normative sp. 381A. Although sample locations are different, spidergrams (Fig. 4a) show a general tendency toward increasing incompatible elements with decreasing mg-values, consistent with predicted fractionation patterns.

5. Discussion

5.1. Metamorphosed rocks

5.1.1. Chemical changes during the thermal metamorphism

Modification of chemical composition by metamorphism has been discussed by many authors (*e.g.* WEAVER and TARNEY, 1981; SHERATON, 1984). In the present sutdy, compositions of the three dike rocks from the Sør Rondane Mountains including the throughly recrystallized rock presumed to have been a dolorite (sp. 84021207) were compared to assess the effects of metamorphism. Sp. 84021207 and sp. 84022003 which are slightly recrystallized dolerites differ only slightly from sp. 84021207. The result suggests that the main chemical modification, if happened, might have occurred during a lower grade metamorphism (Fig. 3c). WEAVER and TARNEY (1981) concluded that the mobility of trace elements depends more on the availability of a fluid phase than on the grade of metamorphism. The chemical compositions of the metamorphosed mafic dike rocks could have thus been modified at the time of the beginning of thermal metamorphism, especially for large-ion lithophiles (LIL). The granite intrusions, which are heat sources of the thermal metamorphism, might also be associated with a fluid phase enriched in LIL. This modification would explain the scattering contents of the highly incompatible elements (Ba to K). In the discussion that follows, abundances of highly incompatible elements in the metamorphosed rocks will not be considered.

5.1.2. Geochemical characteristics in relation to the tectonic environments

Many attempts have been made to apply the chemical compositions of mafic igneous rocks to discriminate among tectonic environments. The post-orogenic metamorphosed mafic dike rocks from eastern Queen Maud Land clearly intruded into a continental environment. On a Ti-Zr-Y diagram (PEARCE and CANN, 1973) most of metamorphosed mafic dike rocks plot in the within-plate basalt field as expected. However, dike rocks from the Yamato Mountains and Schirmacher Hills are more like calc-alkali basalts, although their Al_2O_3 content (12.83–14.70 wt%) is lower than that

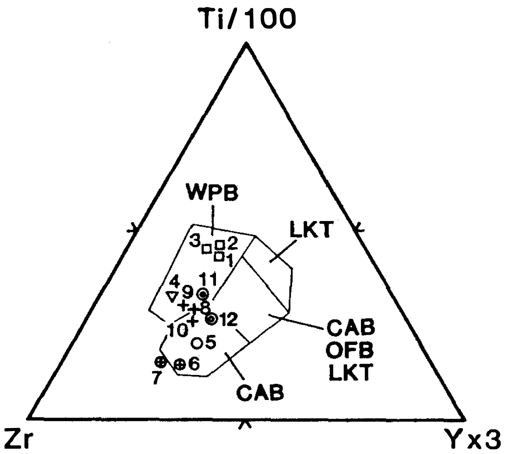

Fig. 5. Ti-Zr-Y plot. WPB: within-plate basalt, LKT: low-potassium tholeiite, CAB: calc-alkali basalt, OFB: ocean floor basalt. Symbols and numbers as Fig. 2.

of typical calc-alkali basalts (Fig. 5). On the FeO-MgO-Al_2O_3 diagram (PEARCE *et al.*, 1977), the rocks from Akebono Rock and the Sør Rondane Mountains plot mostly in the continental basalt field, whereas those from the Yamato Mountains and Schirmacher Hills are plotted in the ocean ridge and floor basalt field. In the Sør Rondane Mountains, the mafic dike rocks are characterized by high TiO_2, high P_2O_5, low MgO and enrichment of the light rare earth elements (LREE) relative to the heavy rare earth elements (HREE). The Ce content tends to increase with decreasing mg-value, which WINCHESTER and FLOYD (1977) reported for alkaline rocks. Moreover, clinopyroxene in the Sør Rondane dikes is titaniferous augite which is characteristic of typical alkali basalt series. The dike rocks are therefore considered to be transitional between quartz tholeiite and alkali basalt.

Late Proterozoic high TiO_2, high P_2O_5 and low MgO metadolerite dikes with enrichment in LREE have been reported from the Hudson Highlands, North America (RATCLIFFE, 1987). Late Proterozoic metabasites having very high contents of TiO_2, P_2O_5, Zr, Y and LREE have been also reported from Vermont, North America (COISH *et al.*, 1985). As explained by these authors, such chemistry may result from a small degree of partial melting during the early stages of continental rifting. By analogy, late Proterozoic to early Paleozoic dolerite in the Sør Rondane Mountains could also have been emplaced at the initial stages of a continental rift system. If this were the case, the metamorphosed mafic dike rocks in the Sør Rondane Mountains might be a precursor either of the late Paleozoic to Mesozoic continental splitting when Africa, India and Antarctica drifted apart, or of the latest Proterozoic to early Paleozoic continental splitting that ended in failure. Furthermore, the bimodal association of granitic and basaltic magmatism in the early stages of continental separation is observed in both the late Proterozoic North American craton and the Tertiary rift zones (GOLDBERG *et al.*, 1986). The extensive *ca.* 500 Ma granite intrusions in eastern Queen Maud Land should be examined in the light of such a bimodal association with basic magmatism.

In contrast, the rocks from the Yamato Mountains and Schirmacher Hills are rather calc-alkaline on the Ti-Zr-Y plot and are characterized by higher mg-value and lower TiO_2 abundances relative to the rocks with similar SiO_2 contents from the Sør Rondane Mountains. However, they show strong enrichment of LREE relative to HREE (*La*/*Yb*

=24.3–73.1) and strong negative Nb and Ti and weak negative Sr and P anomalies. Although the tectonic environment cannot be specified, such geochemical tendency is similar to the early Proterozoic high-Mg quartz tholeiitic dikes of the Vestfold Hills and Enderby Land in East Antarctica (SHERATON and BLACK, 1981; COLLERSON and SHERATON, 1986).

Strong Sr positive anomalies in the rocks from Akebono Rock are difficult to explain (Fig. 3a). Sr might be a mobile element during the later thermal event. However, relatively low $^{87}Sr/^{86}Sr$ ratios of the rocks (0.70386 ± 0.00011: mean of three samples, HIROI *et al.*, 1986a) exclude the possibility of the assimilation or addition of partial melt from the pre-existing crustal material. One possible interpretation is that the rocks were derived from Sr-enriched source such as a plagioclase-rich cumulate.

5.2. *Unmetamorphosed rocks*

Incompatible element abundances of tholeiitic basalt-dolerite dike rocks from East Ongul Island and Schirmacher Hills are compared with the Jurassic basalt dike rocks having similar mg-values from Vestfjella in western Queen Maud Land (Fig. 1; FURNES *et al.*, 1982). Figures 4a and 4b are coherent between these regions although some discrepancy is found especially between the higher mg-value rocks. Differences between the two regions may be due to either 1) mantle heterogenity of the source region, 2) influences of crust contamination or 3) mixing of magma. Enrichment of Rb and K relative to Sr, P (and Nb) of sp. 84010201T suggests crustal contamination (NORRY and FITTON, 1983) but it is not possible to identify with confidence the main cause at present.

Mesozoic (mostly Jurassic) basaltic rocks have been reported from many portions of the Gondwanaland such as Antarctica, South Africa, South America and Tasmania, and are considered to be as proponents of continental splitting (*e.g.* COMPSTON *et al.*, 1968). In Antarctica, however, they have been found in the limited areas of the Transantarctic Mountains and western Queen Maud Land. Our results imply that Jurassic tholeiitic magmatism extends 1500 km eastward in Queen Maud Land. This is consistent with the occurrence of Mesozoic tholeiitic basalts from Sri Lanka which was once situated in contact with eastern Queen Maud Land (COORAY, 1978; ELLIS and ABEYSINGHE, 1987).

6. Conclusion

1) In eastern Queen Maud Land, post-orogenic mafic dike rocks are divided into two groups: a thermally metamorphosed one and an unmetamorphosed one. Dikes of the first group were metamorphosed by *ca.* 500 Ma granite intrusions, whereas the unmetamorphosed dikes may be Jurassic in age.

2) Geochemical characteristics of the metamorphosed dike rocks vary from place to place. The rocks are continental tholeiites that may have been chemically modified by thermal metamorphism. However, the metamorphosed mafic dikes (metadolerite) from the Sør Rondane Mountains are probably transitional between quartz tholeiite and alkaline basalt. By analogy with the metadike rocks with similar geochemical characteristics in eastern North America, the tectonic environment during intrusion of the Sør Rondane dikes could have been an initial continental rift system.

3) Geochemical characteristics of unmetamorphosed mafic dike rocks are similar to those from western Queen Maud Land. It is highly probable that the Jurassic basalt-dolerite suites occur under the ice in eastern Queen Maud Land.

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