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GEOCHEMICAL CHARACTERISTICS OF METAMORPHOSED HIGH K/Na DYKES IN EASTERN QUEEN MAUD LAND, ANTARCTICA: ULTRAPOTASSIC IGNEOUS ACTIVITY LINKED TO PAN-AFRICAN OROGENY

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Abstract: Major and trace element abundances and mineralogy of exceptionally potassium-rich metamorphosed dyke rocks are described from Cambrian metamorphic terrains of eastern Queen Maud Land. They are characterized by extremely high K_2O, P_2O_5, Rb, Ba, Sr, Zr, and light rare earth elements. Although the dyke rocks have been metamorphosed to amphibolite facies grade, the geochemical characteristics collectively indicate that their precursors were ultrapotassic mafic igneous rocks of minette or lamproite affinity. The dykes are interpreted as a manifestation of post orogenic ultrapotassic igneous activity linked to the Pan-African orogeny.

1. Introduction

Ultrapotassic mafic and ultramafic igneous rocks, namely lamproite, minette, leucitite, etc. (GUPTA and YAGI, 1980; ROCK, 1984; FOLEY *et al.*, 1987; BERGMAN, 1987) occur in a diversity of continental tectonic settings such as continental rift zones, active orogenic zones, and in stable continental areas (FOLEY *et al.*, 1987; MITCHELL and BERGMAN, 1991). They are distinguished by their peculiar mineralogy and petrography, and more importantly by unusual geochemical features such as high K/Na ratio, and extreme enrichment in both incompatible (K, Rb, Ba, Th, etc.) and compatible (Ni, Cr, etc.) elements. Their geochemical characteristics indicate that they are formed from mantle derived magmas. Genetic models involving source enrichment processes (metasomatism) have been suggested (*cf.* ARIMA and EDGAR, 1983a, b; MITCHELL and BERGMAN, 1991) and the ultrapotassic rocks would provide important clues to understand sub-continental mantle processes (*cf.* MCKENZIE, 1989; GIBSON *et al.*, 1993).

During geological mapping by Japanese Antarctic Research Expedition (JARE) programs (JARE-20, -21, and -25), exceptionally potassium-rich mafic metamorphosed dykes have been found at Innhovde, Lützow-Holm Complex (LHC) and in the Yamato Mountains, Yamato-Belgica Complex (YBC), eastern Queen Maud Land (Fig. 1). The dykes are metamorphosed ultrapotassic rocks of potassium-rich minette or lamproite affinity. In this paper we describe geochemical and miner-

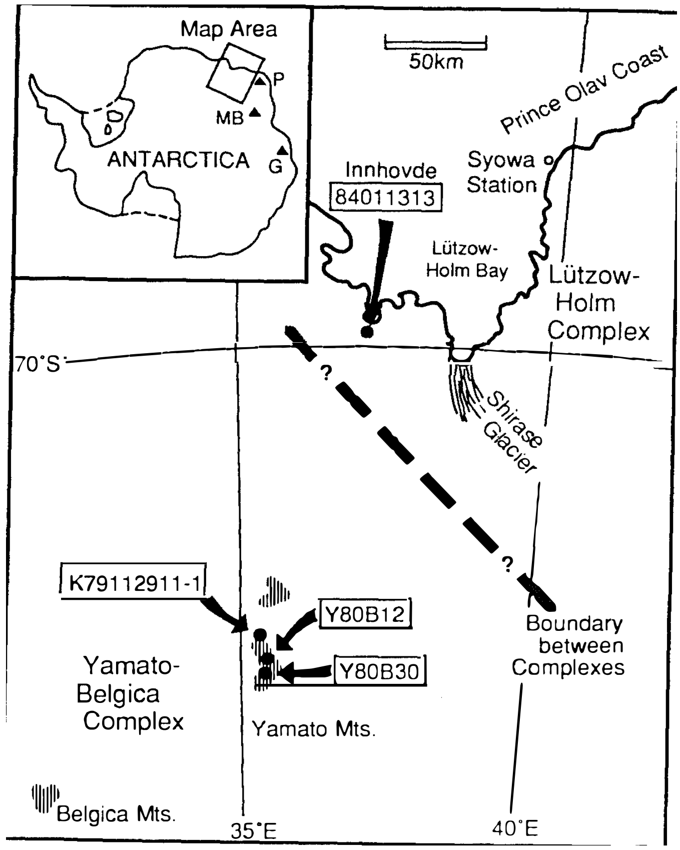

Fig. 1. Sample localities of metamorphosed ultrapotassic mafic dykes in eastern Queen Maud Land. Lamproite localities known in East Antarctica are also given after SHERATON *and* CUNDARI *(1980) and* SHERATON *and* ENGLAND *(1980). P = Priestley Peak ; MB = Mount Bayliss ; G = Gaussberg.*

alogical characteristics of the dykes and discuss tectonic significances of their occurrences.

2. Geological Setting

The LHC and YBC are located between 30° and 45°E in East Antarctica (Fig. 1) and have been studied in extensive geological and petrological investigations by JARE. Details of geology and petrology of the area are given by SHIRAISHI *et al.* (1987), ASAMI *et al.* (1986), MOTOYOSHI *et al.* (1989), and HIROI *et al.* (1991). The LHC is dominantly composed of amphibolite to granulite facies metamorphic rocks including pelitic, quartzo-feldspathic, basic, calcareous and ultramafic compositions. A clockwise *P-T-t* path is well constrained for the complex (HIROI *et al.*, 1983, 1991; MOTOYOSHI *et al.*, 1985, 1989). The YBC consists of metamorphic rocks and widespread granite and syenite intrusions. Metamorphic rocks are mainly amphibolite facies quartzo-feldspathic and intermediate compositions. Low-pressure type granulite facies rocks locally occur but their relations to the amphibolite facies rocks are uncertain. Recent geochronological study (U-Pb zircon SHRIMP age) of the area indicates that high-grade metamorphism and intense deformation occurred between 521-553 Ma in the LHC and between 500-600 Ma in the YBC, being coeval with the Pan-African orogeny (SHIRAISHI *et al.*, 1992, 1994).

Mafic dykes with various ages and compositions have been reported from eastern Queen Maud Land (SHIRAISHI *et al.*, 1988). They are subdivided, based on their mode of field occurrence and petrographical features, into four distinct types: concordant layers deformed and metamorphosed under the same conditions as the surrounding gneisses (Type I), discordant dikes thermally metamorphosed to the same grade as the host gneisses (Type II), discordant dikes undeformed and slightly metamorphosed (Type III), and unmetamorphosed discordant dykes (Type IV). Types I and II are interpreted to be pre- and syn-metamorphic dykes respectively, whereas Types III and IV were intruded after regional metamorphism (SHIRAISHI, *et al.*, 1988). SHIRAISHI *et al.* (1988) described various compositions from Type III dykes ranging from continental tholeiite to alkali basalt. They suggested that the dyke activity was a manifestation of an initial stage of continental rift system at about 500 Ma.

The dykes studied in this paper belong to Type II. The dyke at Innhovde (sample 84011313) and the dykes in the Yamato Mountains (samples Y80B12 and Y80B30 from Massif B, and K79112911-1 from Massif C) cut sharply surrounding host gneisses of amphibolite or granulite grade. The dykes are a few tens of centimeters to a few meters wide and consist of medium to fine-grained texturally homogeneous rocks. They exhibit weak foliation defined by aligned biotite flakes. In all cases, the foliation of the dyke is discordant to that of the surrounding gneisses but parallel to the dyke contact. The dikes studied are undeformed, except for the dike in Innhovde which was locally deformed along the shear zone. Field occurrences indicate that the Type II dykes in the Yamato Mountains were intruded prior to the last stage of pegmatite emplacement which was associated with widespread granite and syenite intrusions in the area.

The dyke from Innhovde (sample 84011313) yields a K-Ar whole rock age of 434±21.7 Ma (Table 1) which is younger that the U-Pb zircon SHRIMP age of 550±12 Ma obtained for a garnet-hornblende gneiss (sample 84011106) from Innhovde (SHIRAISHI *et al.*, 1992). No isotope data are available for the ultrapotassic metamorphosed dykes from the Yamato Mountains, but for a Type III dyke rock (sample A79120108) collected from Massif C, Yamato Mountains, a K-Ar whole rock age of 477±27 Ma was reported (SHIRAISHI *et al.*, 1988). As pointed out by

Table 1. K-Ar whole rock age of the metamorphosed dyke from Innhovde, East Queen Maud Land.

Sample No.	^{40}Ar	^{40}Ar(%) (scc/g 10^{-5})	K (%)	Age (Ma)
84011313	11.7	99.2	6.14	434.6±21.7

Decay constants are after STEIGER and JÄGER (1977).
Analyst: Teledyne Isotope Co.

SHIRAISHI *et al.* (1988, 1992), the Type II dykes studied are interpreted to have been intruded at the waning stage of regional metamorphism of the Cambrian age.

3. Petrography and Mineralogy

All of the rocks studied exhibit a well recrystallized grano-lepidoblastic texture and no apparently igneous texture is preserved. The rocks from the YBC consist dominantly of biotite and alkali-feldspar together with subordinate amounts of plagioclase, clinopyroxene and amphibole, and a trace amount of quartz. Apatite, zircon and monazite are ubiquitous accessary phases, and in sample Y80B12 sphene is an additional accessary mineral. It is noteworthy that iron oxide phases rarely occur in the dykes. A rock from the LHC (sample 84011313) has similar mineral paragenesis to the YBC rocks, apart from a lack of amphibole.

Extensive search has been done by an electron microprobe to identify relict minerals and/or chemical zoning of minerals which were potentially inherited from igneous precursor, but all of the silicates show nearly homogeneous chemistry and no exotic igneous mineral (*ex.* priderite) or mineral composition (*ex.* potassium richterite) diagnostic of ultrapotassic igneous rocks was encountered. Clinopyroxenes in the dykes are salite in composition and characterized by low Al_2O_3 and TiO_2 (Table

Table 2. Representative microprobe analyses of clinopyroxene and hornblende in metamorphosed dykes.

Sample No. Mineral	84011313 Clinopyroxene	Y80B12	Y80B30	Y80B12 Hornblende	Y80B30
SiO_2	52.02	53.24	52.74	51.26	50.26
TiO_2	0.00	0.00	0.15	0.00	0.60
Al_2O_3	1.06	0.48	0.74	2.78	4.18
Cr_2O_3	0.00	0.00	0.02	0.82	0.00
FeO*	9.43	7.79	8.22	10.51	11.03
MnO	0.43	0.54	0.51	0.00	0.29
MgO	12.75	13.51	13.35	16.29	16.48
CaO	21.86	23.35	22.47	11.83	12.07
Na_2O	1.09	0.80	0.88	1.19	1.35
K_2O	0.00	0.00	0.02	0.33	0.48
Total	98.64	99.71	99.10	95.01	96.74
	O=6			O=23	
Si	1.980	1.994	1.988	7.581	7.344
Ti	0.000	0.000	0.004	0.000	0.066
Al	0.047	0.021	0.033	0.484	0.720
Cr	0.000	0.000	0.001	0.096	0.000
Fe	0.300	0.244	0.259	1.300	1.348
Mn	0.014	0.017	0.016	0.000	0.036
Mg	0.723	0.754	0.750	3.592	3.590
Ca	0.891	0.937	0.907	1.875	1.890
Na	0.080	0.058	0.064	0.341	0.382
K	0.000	0.000	0.001	0.062	0.089
Total	4.037	4.025	4.024	15.331	15.466

* Total iron reported as FeO or Fe^{2+}.

Table 3. Representative microprobe analyses of biotite in metamorphosed dykes.

Sample No.	84011313	Y80B12	Y80B30
SiO_2	35.38	38.68	37.93
TiO_2	5.08	3.42	3.46
Al_2O_3	12.76	12.93	12.77
Cr_2O_3	0.00	0.00	0.03
FeO*	17.07	14.12	15.22
MnO	0.00	0.00	0.19
MgO	13.30	15.76	15.80
CaO	0.00	0.00	0.06
Na_2O	0.85	0.41	0.16
K_2O	8.81	9.77	9.33
BaO	1.30	—	—
Total	94.54	95.09	94.95
O = 22			
Si	5.501	5.777	5.704
Ti	0.594	0.384	0.391
Al	2.338	2.223	2.263
Cr	0.000	0.000	0.004
Fe	2.219	1.764	1.914
Mn	0.000	0.000	0.024
Mg	3.083	3.509	3.542
Ca	0.000	0.000	0.010
Na	0.256	0.119	0.047
K	1.747	1.862	1 .790
Ba	0.079	—	—
Total	15.818	15.637	15.689

* Total iron reported as FeO or Fe^{2+}.

2). They exhibit no significant chemical zoning. Amphiboles are tremolitic hornblende which are chemically homogeneous and poor in Al_2O_3 and TiO_2 (Table 2). As listed in Table 3, biotite in the dykes is characterized by relatively high TiO_2 (up to 5 wt%). Comparing to metamorphic biotite compositions (GUIDOTTI, 1984), biotite in sample 84011313 contains exceptionally high BaO (1.3 wt%). High BaO is one of the characteristic features of trioctahedral mica in minette, lamproite and its affinity (MITCHELL and BERGMAN, 1991; ROCK, 1991).

Alkali-feldspar is homogeneous and contains a small amount of BaO (up to 1.7 wt%) and negligible CaO (less than 0.1 wt%) and Fe_2O_3 (less than 0.1 wt%). Its composition ranges from $Ab_{24}Or_{73}Cn_3$ to $Ab_{13}Or_{84}Cn_3$. Plagioclase is also homogeneous and its composition ranges from $An_{24}Ab_{75}Or_1$ to $An_{20}Ab_{80}Or_1$.

4. Geochemistry

Major elements were analyzed by X-ray fluorescence spectrometry (XRF) in combination with flame photometry (for Na and K) and wet chemical analysis method (for FeO, Fe_2O_3, and H_2O) at the Japan Chemical Analysis Center. Abundances of Y, Zr, and Nb were determined by XRF and those of U, Th and rare

Table 4. Major elements abundances (wt%) of metamorphosed dykes from Innhovde and Yamato Mountains.

Sample No. Locality	84011313 Innhovde	Y80B12 Yamato Mt.	Y80B30 Yamato Mt.	K79112911-1 Yamato Mt.	Minette Navajo[1]	Ave. Lamp.[2]	Gaussberg[3]
SiO_2	54.79	53.93	49.99	49.74	54.03	52.1	51.4
TiO_2	1.35	1.73	1.89	2.11	1.39	2.9	3.5
Al_2O_3	11.89	12.71	11.02	13.82	11.32	8.9	10.0
Fe_2O_3	1.54	1.32	2.49	2.45	—	—	2.5
FeO	5.46	5.38	5.79	6.82	5.94*	6.2*	3.8
MnO	0.11	0.11	0.13	0.14	0.10	0.09	0.09
MgO	6.41	8.54	9.11	6.30	7.65	11.8	8.0
CaO	6.18	5.41	7.20	7.12	7.82	5.7	4.7
Na_2O	1.32	1.86	1.27	3.09	2.04	1.3	1.7
K_2O	7.27	6.90	7.06	5.37	7.18	7.0	11.7
P_2O_5	2.12	0.90	2.61	0.88	0.98	1.2	1.5
H_2O^+	1.34	1.14	1.26	0.20	1.36	2.8	1.2
H_2O^-	0.22	0.08	0.18	1.16	—	—	0.05
Total	100.00	100.01	100.00	99.20	99.81	99.9	100.09
Atomic ratios							
Mg/(Mg+Fe*)	0.63	0.70	0.67	0.55	0.70	0.77	0.70
K/(K+Na)	0.78	0.71	0.79	0.53	0.70	0.77	0.82
K/Na	3.6	2.4	3.6	1.1	2.3	3.4	4.6
K/Al	0.66	0.59	0.69	0.42	0.69	0.85	1.27

1: Navajo minette (ALBERT *et al.*, 1986); 2: Average of 284 lamproite analyses (BERGMAN, 1987); 3: average of 11 lamproites from Gaussberg (SHERATON and CUNDARI, 1980).

* Total iron given as FeO or Fe^{2+}.

earth elements (REE) were analyzed by instrumental neutron activation analysis (NAA) at Chemex Laboratory Inc (CLI). The remaining trace elements were analyzed by inductively coupled plasma spectrometry (ICP) at CLI.

Major element abundances of the ultrapotassic dykes are given in Table 4. The dyke rocks, as a whole, are characterized by extremely high K_2O (up to 7.27 wt%), moderate SiO_2 (49.7-54.7 wt%) , and high MgO (6.3-9.1 wt%). Except for sample K79112911-1, the ultrapotassic nature of the dykes is indicated by high K/Na (up to 3.6), K/Al (up to 0.69) and K/(K+NA) (up to 0.69) ratios. Mg/(Mg+Fe) ratio ranges from 0.55 to 0.70 suggesting slightly evolved composition.

Analytical results of trace elements are listed in Table 5. Overall, the dykes are characterized by high concentrations of incompatible elements relative to N-MORB (PEARCE, 1983). There are variable, but consistently high concentrations of the incompatible elements Ba (1840-5710 ppm), Rb (170-210), Th (5-22), and Sr (789-2040). Abundances of compatible elements are comparable to MORB (SCHILL-ING *et al.*, 1983). For example, Ni (84-150 ppm), Co (27-34), and Cr (135-230) are present at variable levels. The dykes are characterized by enhanced REE abundances, where $La_N = 198$-413 and strongly fractionated patterns ($La_N/Yb_N =$ 32.6-52.8) (Fig. 2). Samples 84011313 and Y80B12 show slightly negative Eu

Table 5. Trace element abundances (ppm) of metamorphosed dykes from Innhovde and Yamato Mountains.

Sample No. Locality	84011313 Innhovde	Y80B12 Yamato Mt.	Y80B30 Yamato Mt.	K79112911-2 Yamato Mt.
Y	130	75	98	76
Zr	735	583	459	391
Nb	6	19	12	48
Be	0.5	2.5	4.5	2.5
V	85	129	133	122
Cr	180	346	135	230
Co	27	29	34	30
Ni	150	116	84	92
Zn	144	140	146	170
Rb	210	190	200	170
Sr	868	1285	2040	789
Mo	<1	<1	<1	5
Ag	0.5	0.5	0.5	0.5
Cd	2.0	1.5	2.0	2.0
Ba	5530	2400	5710	1840
W	<10	<10	<10	<10
Pb	26	30	22	28
Bi	<2	<2	<2	<2
U	2	5	2	5
Th	6	22	5	10
La	136	65	73	87
Ce	258	156	146	178
Pr	<5	<5	<5	<5
Nd	128	92	95	82
Sm	15	12	12	10
Eu	3.0	2.9	3.8	3.3
Gd	<50	<50	<50	<50
Tb	1.6	0.8	1.2	0.7
Dy	10	4	8	4
Ho	<1	<1	<1	<2
Er	<20	<20	<20	<20
Tm	<1	<1	<1	<1
Yb	2.0	1.1	1.5	1.1
Lu	0.4	0.3	0.3	0.2

Y, Zr and Nb were analyzed by XRF. REE, U and Th by NAA. Other trace elements by ICP.

anomaly whereas other two samples exhibit positive Eu anomaly. The dykes show negative spikes for Nb and Ti in elemental variation diagram (Fig. 3). These negative spikes are characteristics of island-arc rocks and also of lamproite and minette (MITCHELL and BERGMAN, 1991; ROCK, 1991).

5. Discussion

Because all distinguished mineralogical and geochemical features of the ultrapotassic rock are susceptible to metamorphism, it is increasingly difficult to

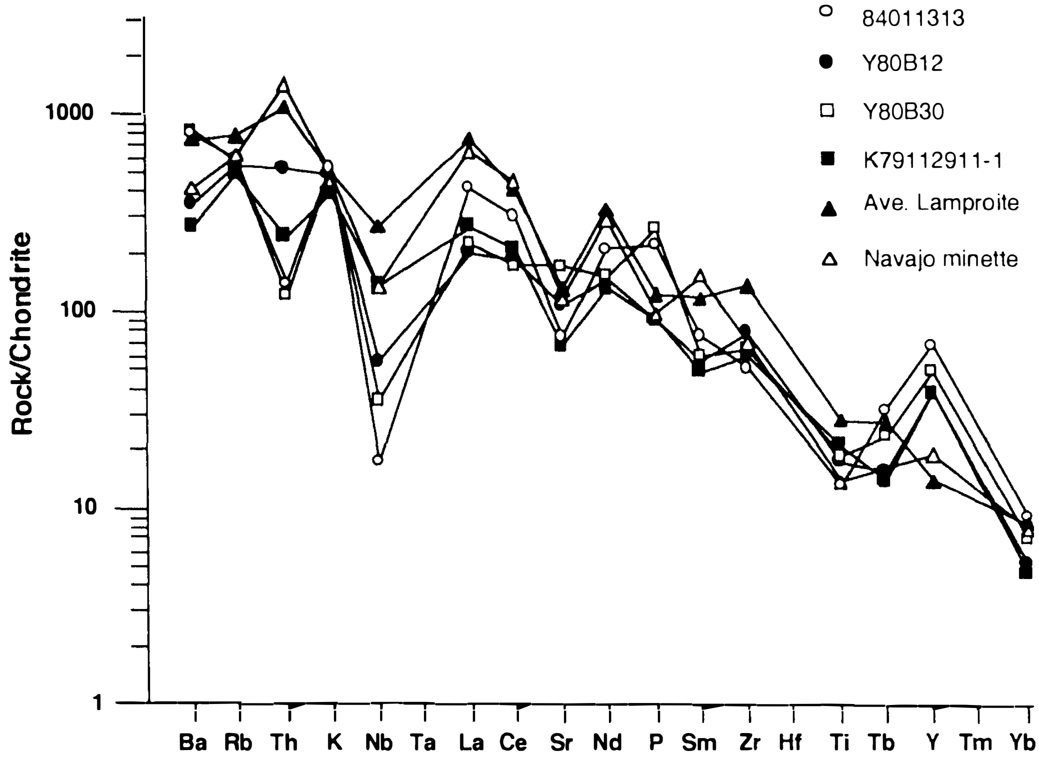

Fig. 2. Spiderdiagram patterns for the metamorphosed ultrapotassic dyke rocks, normalized according to THOMPSON *et al. (1984). The dyke rocks exhibit similar normalized pattern to that of average lamproite (*BERGMAN*, 1987) and potassium-rich minette from Navajo, Arizona (*ALBERT *et al., 1986).*

identify and classify metamorphosed ultrapotassic rocks occurring in high grade metamorphic terrains. Chemical change during metamorphism might occur in the dyke rocks studied during metamorphism of amphibolite grade. However, all of the rocks consistently exhibit high concentration of mobile elements (K, Rb, Ba) and immobile elements (Zr, Nd, Y) and they show similar normalized patterns of elemental abundances (Figs. 2, 3). These features suggest that chemical modification during metamorphism is negligible and the rocks well preserve chemical characteristics of igneous precursors.

The whole rock compositions of the dykes (Tables 4 and 5) suggest that their igneous precursors are ultrapotassic mafic rocks. Their geochemistry is within the range of ultrapotassic rocks by FOLEY *et al.* (1987) who defined ultrapotassic rocks with >3 wt% K_2O, >3 wt% MgO, and K/Na>2. FOLEY *et al.* (1987) subdivided ultrapotassic rocks into four groups based on their major element chemistry, which tend to occur in distinct tectonic settings: in continental regions (Group I, lamproite), in continental rift systems (Group II, kamafugites) and in island arc environments (Group III). Group IV includes some potassium-rich minette and rocks of lamproite affinity and is transitional between Groups I and III (FOLEY *et al.*, 1987; FOLEY and VENTURELLI, 1989).

In the discrimination diagram by FOLEY *et al.* (1987), all of the rocks studied are plotted in the transitional field (Group IV) between the fields of Group I and

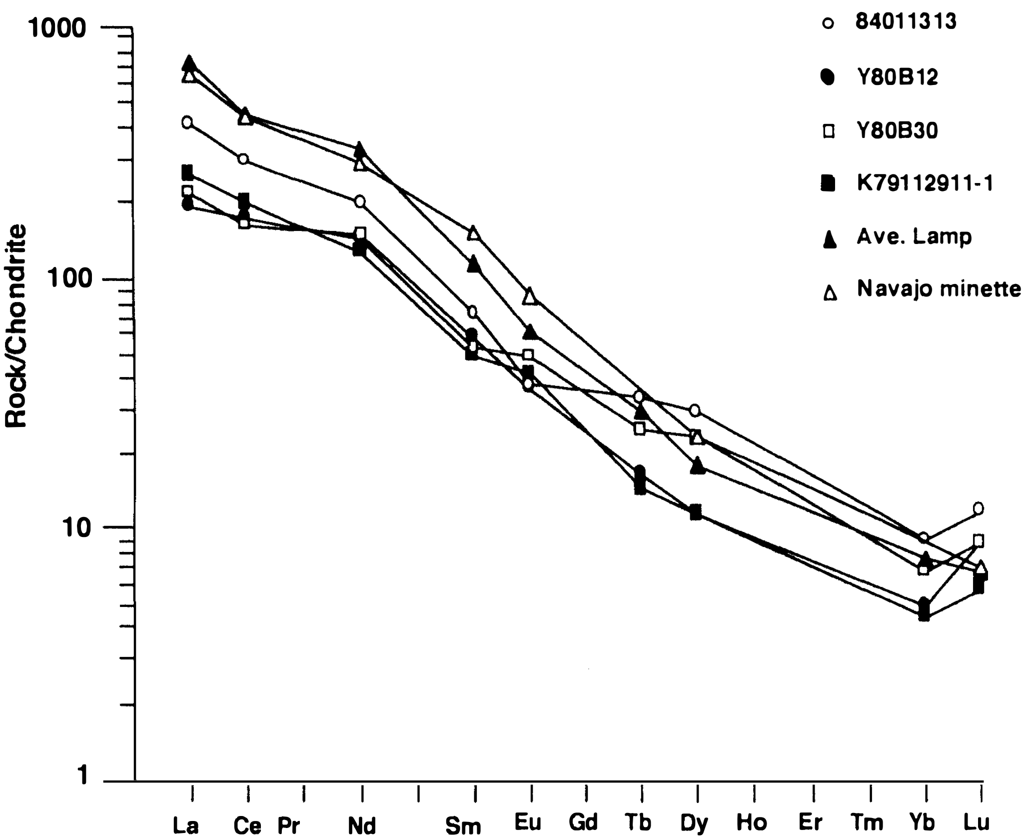

Fig. 3. Chondrite normalized REE pattern for the metamorphosed ultrapotassic rocks, comparing with that of average lamproite (BERGMAN, 1987) and Navajo minette (ALBERT et al., 1986).

Group III (Fig. 4). An exception is sample 79112911-1 which is within the region of Group III. In the discriminate diagram by BERGMAN (1987), the rocks studied are plotted within the field of lamproite and also included within the lamprophyer field (Fig. 5). As discussed by MITCHELL and BERGMAN (1991), minette, which is classified as calk-alkali lamprophyre by ROCK (1984, 1991), is geochemically similar to phlogopite-lamproite, and some potassium-rich minette is indistinguishable from phlogopite-lamproite on the basis of geochemistry alone. Mineralogical data are essential to further classify correctly the dyke rocks studied (*cf*. MITCHELL and BERGMAN, 1991) but mineralogy of igneous precursors of the dyke rocks totally disappeared. It is not clear as to whether the dyke rocks are classified as metamorphosed lamproite or minette.

It is widely accepted that ultrapotassic magmas of minette and/or lamproite compositions are derived by partial melting of enriched lithospheric mantle (*cf*. MITCHELL and BERGMAN, 1991; GIBSON *et al*., 1993). They occur in a wide range of tectonic settings and several tectonic setting models have been proposed for the ultrapotassic magma genesis (*cf*. MITCHELL and BERGMAN, 1991). For example, potassium-rich minettes have been reported from Navajo which is located at the flank of the Rio Grande rift (GIBSON *et al*., 1993), and lamproite and its affinity have been described from the west Mediterranean region under post collision tectonic

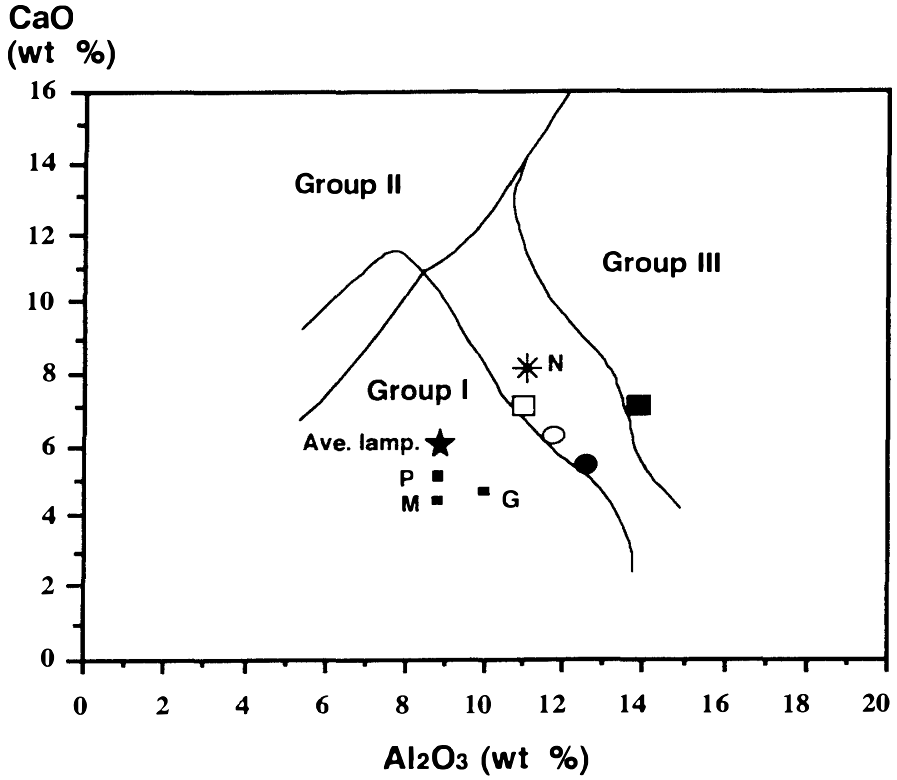

Fig. 4. Discrimination diagram for ultrapotassic mafic and ultramafic igneous rocks on the basis of their CaO and Al_2O_3 contents (after FOLEY et al., 1987). The metamorphosed ultrapotassic dyke rocks from eastern Queen Maud Land are plotted in the transitional field between the fields of Group I and Group III. An exception is sample 79112911-1 which is within the field of Group III. Ave. lamp = average lamproite composition (BERGMAN, 1987), P = Priestley Peak, M = Mount Bayliss (SHERATON and ENGLAND, 1980), G = Gaussberg (SHERATON and CUNDARI, 1980).

environments (MITCHELL and BERGMAN, 1991; FOLEY and VENTURELLI, 1989). It is noteworthy that the geochemical characteristics of the dykes studied show remarkable similarity to those of minette from Navajo (RODEN and SMITH, 1979; ALBERT *et al.*, 1986; GIBSON *et al.*, 1993) and to those of lamproite and its affinity from the west Mediterranean region (FOLEY and VENTURELLI, 1989).

In East Antarctica, lamproites have been described from three isolated localities (Fig. 1): Gaussberg (SHERATON and CUNDARI, 1980; TINGEY *et al.*, 1983); Priestley Peak (SHERATON *et al.*, 1987; SHERATON and ENGLAND, 1980); Mount Bayliss (SHERATON and ENGLAND, 1980; BLACK and JAMES, 1983). The Gaussberg lamproite is the youngest lamproite activity known (Quaternary; TINGEY *et al.*, 1983). The latter two lamproites are dated as 413-430 Ma (SHERATON and ENGLAND, 1980) and 482 Ma (BLACK and JAMES, 1983) respectively. These Paleozoic lamproites are interpreted to have been associated with an initial fracturing of Gondwana prior to the rifting that separated East Antarctica from India (SHERATON *et al.*, 1987).

The ~500 Ma event in East Antarctica has been interpreted as a deformation-free thermal event (*cf.* TINGEY, 1991). However, recent recognition of ~500 Ma

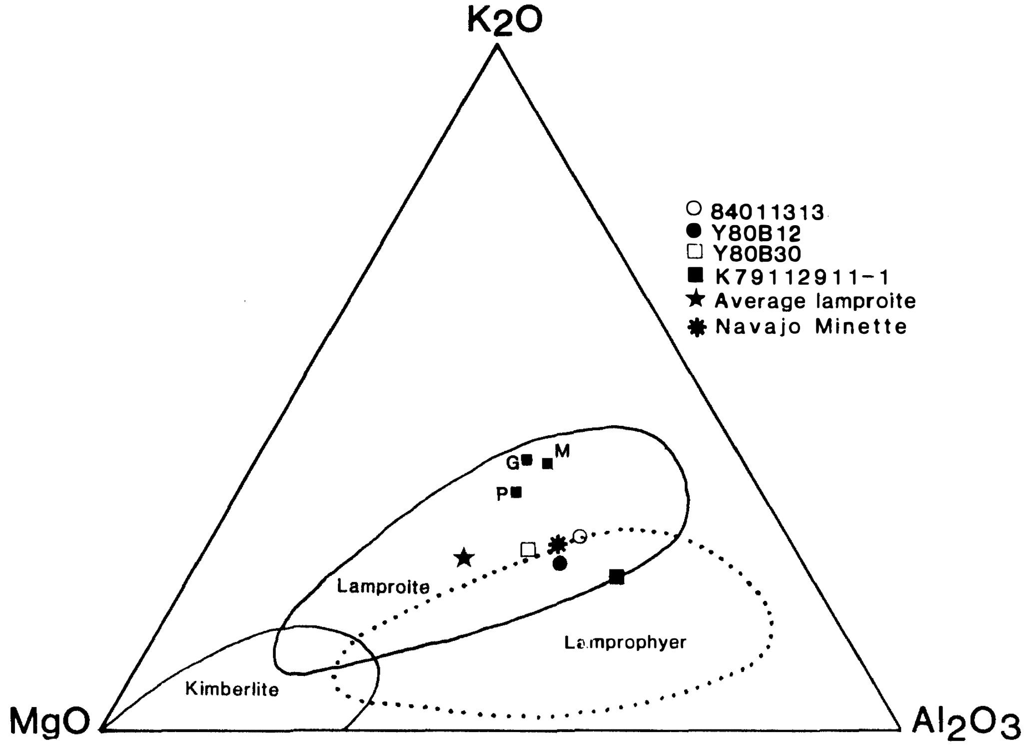

Fig. 5. Discrimination diagram of lamproite, kimberlite and lamprophyer on the basis of their K_2O, MgO and Al_2O_3 contents (after BERGMAN*, 1987). The metamorphosed ultrapotassic dykes from eastern Queen Maud Land are within the lamproite- and lamprophyer-field. Abbreviations are given in Fig. 4.*

orogeny in eastern Queen Maud Land, being coeval to the metamorphic ages of ~500 Ma for Highland Vijayan and Wanni Complexes of Sri Lanka, lead to new interpretation that this Cambrian orogeny was associated with the amalgamation of east and west Gondwana during the Pan-African orogeny (SHIRAISHI *et al*., 1992, 1994).

The ultrapotassic dykes were emplaced about a few tens million years after the ~500 Ma major orogenic event. Nearly isothermal decompressive *P-T-t* path and collision tectonic environment is well constrained for Cambrian metamorphism in the LHC (HIROI *et al*., 1991). The orogeny was associated with overthickning of lithosphere by collision of east and west Gondwana (SHIRAISHI *et al*., 1992, 1994). During post orogenic relaxation periods, partial melting of rebounding overthickened lithosphere could generate ultrapotassic magmas. The ultrapotassic dykes in eastern Queen Maud Land are best interpreted as a manifestation of post orogenic ultrapotassic igneous activity linked to the Pan-African orogeny.

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