Polar Geosci., 11, 143-153, 1998

PETROGENESIS OF THE TONALITIC ROCKS FROM THE SØR RONDANE MOUNTAINS, EAST ANTARCTICA

Yasuo IKEDA[1] and Kazuyuki SHIRAISHI[2]

[1]*Hokkaido University of Education at Kushiro, Shiroyama 1-chome, Kushiro 085-8580*
[2]*National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*

Abstract: Tonalitic rocks (*ca.* 1000 Ma) from the Sør Rondane Mountains, East Antarctica, are characterized by relatively high Na_2O/K_2O (0.6-24), K/Rb (76-1638), Sr/Y (5-60), and $(La/Yb)_N$ (1-29), and relatively low CaO/Na_2O (0.4-4) and low initial $^{87}Sr/^{86}Sr$ ratio (0.7024). They are chemically similar to trondhjemites (1000 Ma) from the Lützow-Holm Complex and to Archean tonalite-trondhjemites. Trace element modeling of the partial melting of MORB suggests that tonalitic rocks were derived by partial melting of a basaltic source material under garnet amphibolite stability *P-T* conditions. We suggest that a young hot subducting plate along the Sør Rondane Mountains at 1000 Ma may have reached elevated temperatures which initiated melting of the slab and generated the tonalitic rocks.

key words: East Antarctica, MORB, slab, Sør Rondane Mountains, tonalite

1. Introduction

The Sør Rondane Mountains consist mainly of Proterozoic metamorphic rocks (1000-1100 Ma) and various plutonic rocks with minor mafic dike rocks (~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; TAINOSHO *et al.*, 1992; ARAKAWA *et al.*, 1994) (Fig. 1). The late Proterozoic to early Paleozoic magmatisms in the Sør Rondane Mountains have raised special interest in the genesis and the tectonic significance related to the "Pan African event" (SAKIYAMA, *et al.*, 1988; TAKAHASHI *et al.*, 1990). However, geochemical characteristics and petrogenesis of the igneous rocks (protolith) from the Sør Rondane Mountains have not been well investigated except for the early Paleozoic mafic dike rocks (IKEDA *et al.*, 1995). In this paper, we discuss genesis of the metamorphosed plutonic rocks, in particular the late Proterozoic tonalite, on the basis of the geochemical data including major, REE and other minor elements and published isotope data.

2. Geological Setting of Tonalitic Rocks

The Sør Rondane Mountains are divided into two terranes (SHIRAISHI *et al.*, 1997): Northeast terrane and Southwest terrane. The Northeast terrane is underlain mainly by granulite facies metamorphic rocks of pelitic and intermediate compositions, whereas the Southwest terrane is underlain by amphibolite facies and lower grade metamorphic rocks mainly of intermediate to basic composition. The two terranes are inferred to be divided by a tectonic boundary.

Plutonic rocks in the Sør Rondane Mountains occur in both terranes and are divided into older (late Proterozoic) and younger (early Paleozoic) type rocks (SAKIYAMA *et al.*, 1988; SHIRAISHI *et al.*, 1997) (Fig. 1). The older plutonic rocks are composed of tonalitic rock, quartz diorite, granodiorite and trondhjemite. They have foliation parallel to the structure of the surrounding metamorphic rocks. The younger plutonic rocks, consisting of syenite, quartz syenite and granite, occur as stocks and dikes.

The tonalitic rock which is the main constituent of the Southwest terrane is distributed over a roughly 100×20 km area and is exposed in a belt running east to west (SHIRAISHI *et al.*, 1997). The northern margin of the pluton is subparallel to a major shear zone called the "Main Shear Zone" (KOJIMA and SHIRAISHI, 1986), whereas the southern margin is obscured by the continental ice sheet.

Tonalitic rocks are medium- to coarse-grained gneissose rocks containing various proportions of mafic schistose rock (green schist: epidote-chlorite and/or chlorite-epidote-biotite schist). Typical gneissose tonalitic rock is composed of bluish green hornblende, biotite, epidote, plagioclase and quartz. It rarely contains garnet and K-feldspar with accessory apatite, zircon, ilmenite and rare magnetite. Hornblende and biotite show a preferred orientation. Secondary chlorite, epidote, magnetite and saussuritized plagioclase are common. It shows pronounced mylonitic texture, with plagioclase and K-feldspar porphyroclasts having asymmetric pressure shadow tails, but

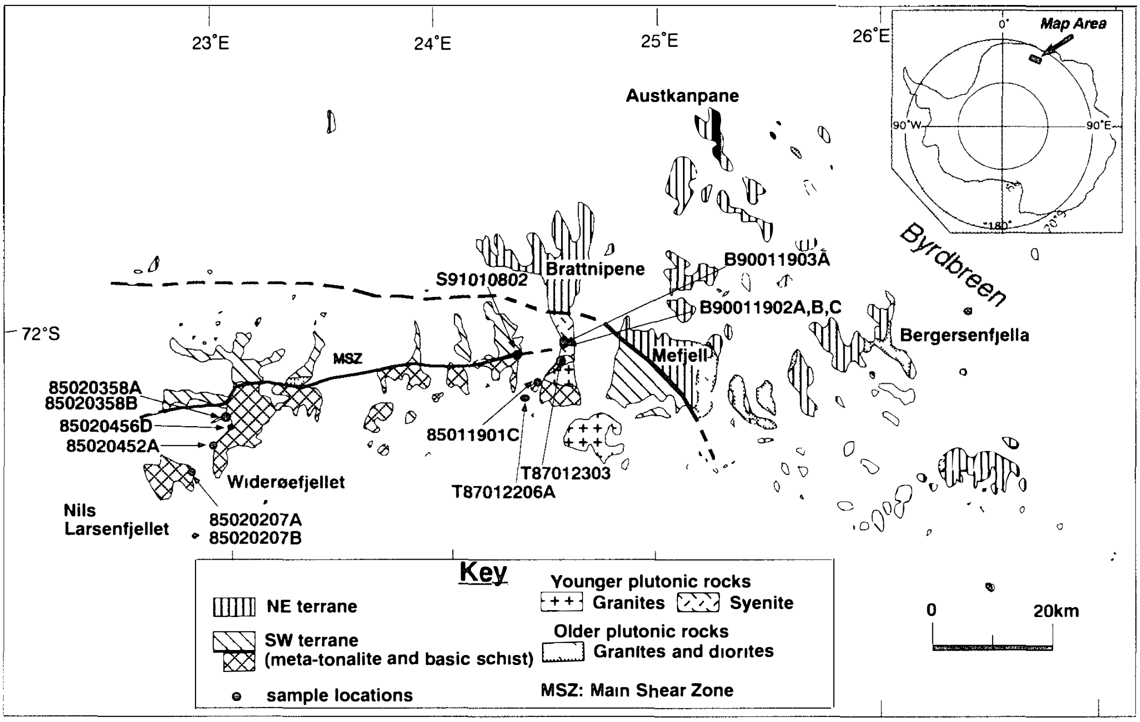

Fig. 1. Sample localities of tonalitic rocks and simplified geological map in the western and central parts of the Sør Rondane Mountains.

idiomorphic features only rarely remain in the plagioclase. As mylonitization increases, the proportions of epidote and chlorite increase, and plagioclase is more saussuritized, whereas the proportions of hornblende and biotite decrease. Therefore, epidote, zoisite and chlorite, as well as saussuritized plagioclase, are secondary products, probably under the greenschist facies condition related to the mylonitization.

The mafic rock forms thin layers up to 1 m wide and lens-shaped blocks, ribbons, and schlieren-like dark inclusions up to 1 m long, with their long axes oriented parallel to the foliation. Both the tonalite and the mafic rock are generally mylonitized in various degree by later deformation which is related to the formation of the Main Shear Zone. In the area where the effect of mylonitization is relatively weak, bundles of mafic layers and lenses tend to form narrow zones a few to tens of meters wide in the tonalitic rocks. The mineral assemblage of the mafic rock is identical with that of the tonalite. It is not uncommon for the mafic rock to consist entirely of secondary minerals; in such schistose rocks, chlorite displays crenulation cleavage which was formed probably during retrograde metamorphism.

The isotopic ages (Rb-Sr whole rock and U-Pb zircon ages) of the tonalitic rocks are 950–996 Ma (Pasteels and Michot, 1968; Takahashi *et al.,* 1990). These ages (~1000 Ma) are close to the Sm-Nd whole rock and U-Pb zircon ages of the trondhjemites from the Lützow-Holm Complex (Shiraishi *et al.,* 1994, 1995).

The tonalitic rocks as a whole define a crude calc-alkaline trend (Sakiyama *et al.,* 1988). The initial $^{87}Sr/^{86}Sr$ ratio of the tonalitic rock is as low (0.70237) as that of MORB (Takahashi *et al.,* 1990), and is also similar to that (0.70275) of the trondhjemites from the Lützow-Holm Complex (Shiraishi *et al.,* 1995). Takahashi *et al.* (1990) and Arakawa *et al.* (1994) suggest that the tonalitic rock was produced as a result of partial melting of an immature crust such as a primitive island arc, and was generated in a depleted mantle on the basis of the isotopic data.

3. Samples and Analysis

The analyzed tonalitic rocks which are less affected by mylonitization were collected from a large area of the Southwest terrane (Fig. 1). Major elements were analyzed with Inductively Coupled Plasma Emission Spectrometry (ICP), and trace elements including REE were analyzed with Inductively Coupled Plasma Mass spectrometry (ICP-MS) at Activation Laboratories Ltd. (Actlabs Ltd.).

4. Results

Results for major and trace element abundance in the tonalitic rocks are presented in Tables 1 and 2.

The tonalitic rocks range from 45 to 76 wt% in silica. The basaltic chemical compositions may reflect a mixed mineral population derived from the tonalitic rocks and the mafic inclusions.

On the Ab-An-Or classification diagram (Barker, 1979), most of the tonalitic rocks lie in the tonalite field (Fig. 2).

The tonalitic rocks are characterized by high Na_2O/K_2O (0.6–24), K/Rb (76–

Table 1. Major element abundances in the tonalitic rocks from the Sør Rondane Mountains.

Sample	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
SiO_2	45.61	50.59	50.96	55.99	56.45	56.84	58.01	59.02	61.10	67.62	72.01	75.92
TiO_2	0.83	0.96	0.49	0.66	0.65	0.61	0.47	0.51	0.50	0.53	0.24	0.26
Al_2O_3	16.26	18.40	15.98	18.09	17.63	17.53	15.69	17.40	17.09	14.05	13.18	11.60
Fe_2O_3*	17.71	12.41	12.78	7.18	7.24	7.08	10.05	5.86	5.55	4.91	4.98	3.81
MnO	0.29	0.27	0.21	0.11	0.11	0.08	0.16	0.10	0.08	0.05	0.13	0.06
MgO	4.85	2.56	5.35	3.88	3.88	3.28	3.19	2.85	2.94	0.30	0.47	0.17
CaO	10.72	10.55	9.29	7.86	8.10	7.85	8.66	6.73	6.83	1.69	4.21	1.84
Na_2O	1.54	2.28	1.69	3.99	3.72	4.01	2.03	4.47	4.01	3.34	3.08	4.63
K_2O	0.33	0.25	0.07	0.32	0.41	0.31	0.22	1.03	0.21	5.97	0.55	0.58
P_2O_5	0.09	0.32	0.07	0.17	0.17	0.17	0.10	0.15	0.16	0.09	0.05	0.02
Total	98.23	98.59	96.89	98.25	98.36	97.76	98.58	98.12	98.47	98.55	98.90	98.89
Or-Ab-An C.I.P.W. norm (mol%)												
Or	1.97	1.18	0.32	1.45	1.78	1.34	0.76	4.42	0.76	20.59	1.33	1.38
Ab	13.94	16.29	11.56	27.46	24.60	26.29	10.72	29.14	22.04	17.51	11.33	16.75
An	36.79	31.22	27.30	23.39	22.24	21.12	19.43	17.69	17.15	3.34	8.40	3.69

Sample: (1) 85020207B, (2) S91010802, (3) 85020358A, (4) T87012206A, (5) 85011901C, (6) B90011903A, (7) 85020207A, (8) B90011902C, (9) T87012303, (10) 85020456D, (11) 85020358B, (12) 85020452A.

* Total iron as Fe_2O_3. Analyst: ACTLAB Ltd.

1638), and Sr/Y (5–60) and low CaO/Na_2O (0.4–4 except for one sample) ratios. These geochemical features are similar to trondhjemite suites from the Lützow-Holm Complex (Na_2O/K_2O=3.7–9.3, K/Rb=356–2219, Sr/Y=5–767, CaO/Na_2O=0.5–1.4: IKEDA *et al.,* 1997) and high-Al Archean tonalite-trondhjemites-granodiorite (TTG) (DEFANT and DRUMMOND, 1990; DEFANT *et al.,* 1991). The high-Sr and low-Y signature such as the high-Al Archean TTG of the tonalitic rocks and trondhjemites is illustrated in Fig. 3. However, the tonalitic rocks from the Sør Rondane Mountains have lower Sr/Y ratios and higher concentrations of Y than those of trondhjemites from the Lützow-Holm Complex.

In general, the tonalitic rocks from the Sør Rondane Mountains and trondhjemites from the Lützow-Holm Complex exhibit similar fractionated chondrite normalized REE patterns with high $(La/Yb)_N$ ratios (1–29 for tonalitic rock and 2–46 for trondhjemite), and small or no Eu anomalies (Fig. 4). On the $(La/Yb)_N$ *vs.* Yb_N diagram of Fig. 5, the tonalitic rocks and trondhjemites lie in the high-Al Archean TTG. In comparison with the trondhjemites from the Lützow-Holm Complex, the tonalitic rocks are lower in $(La/Yb)_N$ values and higher in Yb_N.

5. Origin of the Tonalitic Rock Magma

The tonalitic rocks from the Sør Rondane Mountains posses characteristics consistent with derivation from a mafic, mantle-derived source, such as low K and Rb abundance and primitive initial $^{87}Sr/^{86}Sr$ ratio such as MORB (0.7024; TAKAHASHI *et*

Table 2. Trace element abundances in the tonalitic rocks from the Sør Rondane Mountains.

Sample	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Y	16.6	18.5	7.2	18.3	19.4	24.3	13.0	15.2	13.6	14.0	8.6	15.8
Zr	7.0	15.4	20.0	98.3	73.2	132.3	21.1	146.7	103.1	69.7	18.6	123.1
Nb	1.1	1.1	0.6	3.2	2.4	2.5	1.1	3.3	2.0	3.8	1.1	2.0
V	376.0	85.0	209.0	142.0	142.0	153.0	197.0	102.0	108.0	-	14.0	-
Cr	54.0	27.0	44.0	51.0	62.0	47.0	24.0	21.0	42.0	11.0	22.0	32.0
Co	56.5	41.9	56.9	54.4	50.2	28.4	80.1	23.7	67.7	72.9	70.8	69.8
Ni	14.0	35.0	21.0	31.0	30.0	19.0	-	9.0	24.0	13.0	8.0	17.0
Zn	110.0	86.0	87.0	34.0	56.0	58.0	58.0	74.0	39.0	-	61.0	34.0
Rb	3.4	6.4	1.6	4.2	7.3	2.5	5.0	41.4	1.4	30.2	12.9	9.8
Sr	84.3	271.2	193.8	636.8	620.7	633.2	172.9	893.7	634.2	112.0	150.4	114.9
Ba	38.7	55.4	14.3	107.1	113.3	137.4	74.4	170.1	122.1	391.3	146.0	215.3
Pb	-	8.0	-	-	6.0	-	-	22.0	-	-	-	-
U	0.1	0.6	0.4	0.1	0.2	0.8	0.3	1.4	0.1	1.4	0.7	0.6
Hf	0.2	0.4	0.5	2.2	1.8	2.9	0.6	3.5	2.3	2.2	0.6	3.2
Th	0.2	0.8	1.0	1.4	1.7	2.6	0.9	3.0	0.1	6.1	1.4	1.3
Ta	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.4	0.1	0.1
La	2.8	6.1	2.7	12.3	11.7	14.9	3.9	54.6	13.1	17.2	5.6	11.7
Ce	6.9	15.1	5.9	29.4	28.7	35.7	8.8	32.5	28.7	32.2	10.8	22.5
Pr	0.9	1.8	0.6	3.4	3.3	4.3	1.0	5.3	3.2	3.0	1.0	2.3
Nd	5.5	10.2	3.2	18.2	16.8	23.8	5.4	21.8	16.4	13.0	4.7	11.3
Sm	1.8	2.9	0.9	3.8	3.8	5.6	1.5	3.8	3.3	2.5	1.0	2.6
Eu	0.6	1.2	0.3	1.1	1.1	1.4	0.6	1.1	1.0	0.8	0.7	1.3
Gd	2.2	3.2	1.0	3.5	3.4	4.5	1.7	3.0	2.8	2.0	1.1	2.6
Tb	0.4	0.5	0.2	0.5	0.6	0.7	0.3	0.4	0.4	0.3	0.2	0.4
Dy	2.4	2.7	1.0	2.7	2.7	3.4	1.8	2.1	2.1	1.7	1.0	2.2
Ho	0.6	0.6	0.2	0.6	0.6	0.8	0.4	0.5	0.4	0.4	0.3	0.5
Er	1.8	1.7	0.7	1.7	1.8	2.2	1.4	1.3	1.2	1.4	0.9	1.5
Tm	0.3	0.3	0.1	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.1	0.2
Yb	1.8	1.7	0.8	1.7	1.6	2.0	1.4	1.3	1.2	1.6	1.2	1.5
Lu	0.3	0.3	0.1	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.3

Sample: (1) 85020207B, (2) S91010802, (3) 85020358A, (4) T87012206A, (5) 85011901C, (6) B90011903A, (7) 85020207A, (8) B90011902C, (9) T87012303, (10) 85020456D, (11) 85020358B, (12) 85020452A.

Analyst: ACTLAB Ltd.

al., 1990). These rocks have shown high $(La/Yb)_N$ with no Eu anomaly, or only a small negative or positive anomaly, and high Sr/Y ratios. These geochemical characteristics match those of igneous rocks considered to be products of slab melting rather than the result of fractional crystallization from a tholeiitic parent magma (DEFANT and DRUMMOND, 1990; DRUMMOND and DEFANT, 1990; JOHNSON *et al.*, 1997).

The presence of residual garnet and amphibole will lead to melts with Y and Yb concentrations of ≤ 18 and 1.9 ppm, respectively, and high Sr/Y and La/Yb ratios (DRUMMOND and DEFANT, 1990; DEFANT and DRUMMOND, 1990). Low to moderate K/

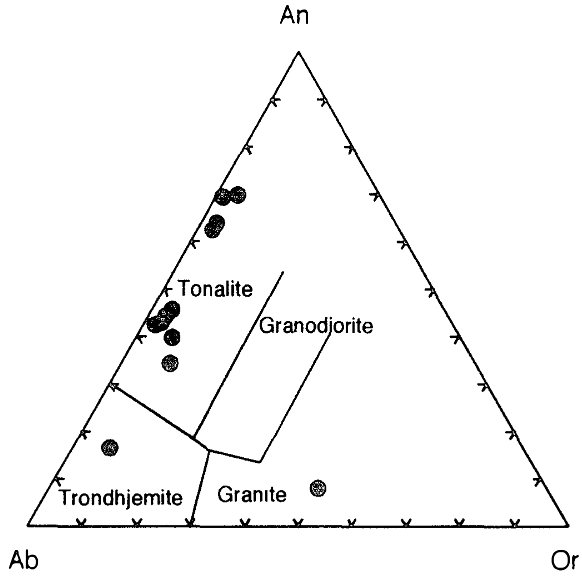

Fig. 2. Classification of the tonalitic rocks from the Sør Rondane Mountains according to their molecular normative An-Ab-Or compositions after BARKER *(1979).*

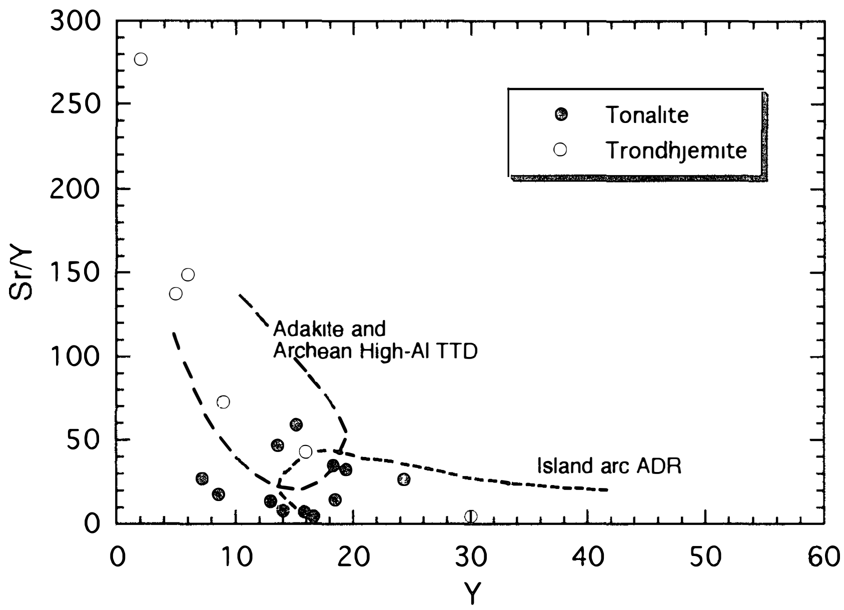

Fig. 3. Sr/Y vs. Y diagram for tonalitic rocks from the Sør Rondane Mountains and trondhjemites from the Lützow-Holm Complex (after IKEDA *et al., 1997) with fields for adakite and Archean high-Al TTD (tonalite-trondhjemite-dacite) and island-arc ADR (andesite-dacite-rhyolite), after* DEFANT *and* DRUMMOND *(1990) and* DEFANT *et al. (1991).*

Rb ratios (*ca.* 400–600) common to the Archean granitoids (high Al-type) are thought to be a function of hornblende extraction because of its greater affinity for K relative to Rb (ARTH and HANSON, 1975; GLIKSON, 1979). On the other hand, high K/Rb (~1000) samples are interpreted to represent slab melt components and probably include predominant refractory garnet under higher temperature and pressure conditions than

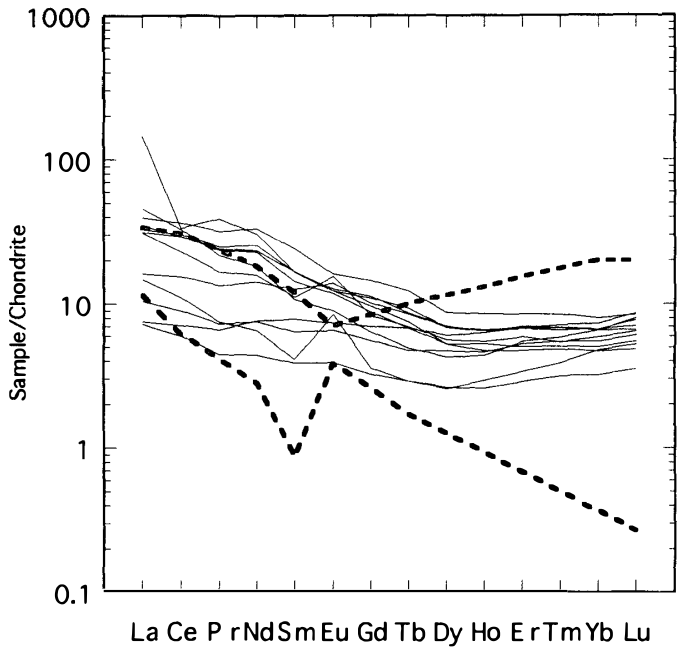

Fig. 4. Chondrite-normalized REE patterns for tonalitic rocks from the Sør Rondane Mountains (solid lines) and the compositional range of the trondhjemites from the Lützow-Holm Complex (broken lines; IKEDA et al., 1997). Chondrite normalization factors are those of MASUDA et al. (1973) and MASUDA (1975).

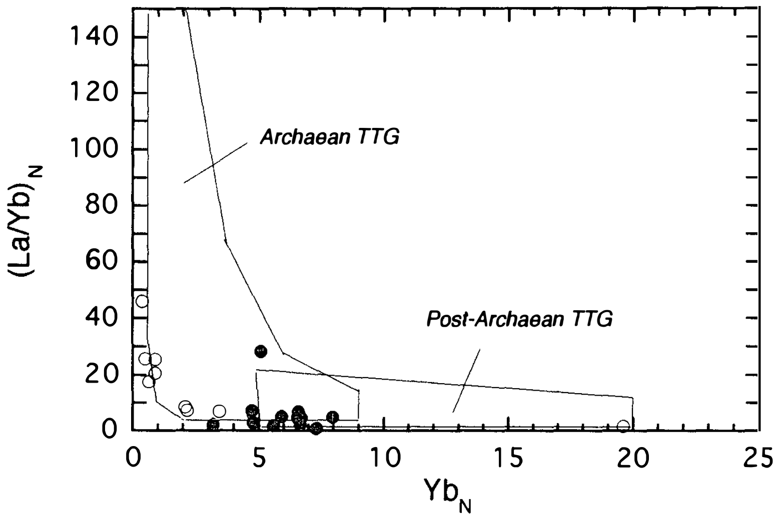

Fig. 5. $(La/Yb)_N$ vs. Yb_N diagram for the tonalitic rocks from the Sør Rondane Mountains and the trondhjemites from the Lützow-Holm Complex (after IKEDA et al., 1997). Symbols are same as in Fig. 3. Fields for Archean TTG (tonalite-trondhjemite-granodiorite) and post-Archean TTG are indicated following LUAIS and HAWKESWORTH (1994).

the hornblende stability field (DRUMMOND and DEFANT, 1990).

For the sake of consistency with a bach partial meting model, the partition coefficients, residual mineralogy, and source composition (basalt source derived from 20

% partial melting of primitive mantle) presented by LUAIS and HAWKESWORTH (1994) were used. Examples of successful models that used the residual mineral compositions of 45% plagioclase, 50% hornblende, 2% clinopyoxene, and 3% garnet (garnet amphibolite) and 50% clinopyoxene and 50% garnet (eclogite) are presented by LUAIS and HAWKESWORTH (1994). Partial melting of eclogite enhances a degree of trace element fractionation, with strong LREE enrichment and depletion of HREE, leading to higher La/Yb ratios and lower Yb concentrations compared to partial melting of garnet amphibolite (LUAIS and HAWKESWORTH, 1994).

On a diagram of La/Yb *vs.* Yb (Fig. 6), the observed data of the tonalitic rocks from the Sør Rondane Mountains and trondhjemites from the Lützow-Holm Complex show good agreement with the calculated models of partial melting of the garnet amphibolite and the eclogite, respectively. On the $(Ce/Yb)_N$ *vs.* Ce_N diagram (Fig. 7), the tonalitic rocks and trondhjemites are also produced by variable degrees of partial melting of the garnet amphibolite and the eclogite residue, respectively. The scattered data on these diagrams (Figs. 6 and 7) display the effect of variable residual garnet with partial melting. These geochemical features suggest that the trondhjemite melts could have formed from eclogite sources as discussed in IKEDA *et al.* (1997), whereas the tonalitic rocks have formed from a source with less garnet such as garnet amphibolite.

Some investigators, ATHERTON and PETFORD (1993), PETFORD and ATHERTON (1996), BARNES *et al.* (1996) and JOHNSON *et al.* (1997), suggest that such high-Al trondhjemite, tonalite and adakite-like volcanic rocks can be produced by partial melting of underplated basaltic crust (metabsasic source) in an area of thick continental crust (~50–60 km). Initial $^{87}Sr/^{86}Sr$ ratios for the underplated basaltic crust range from

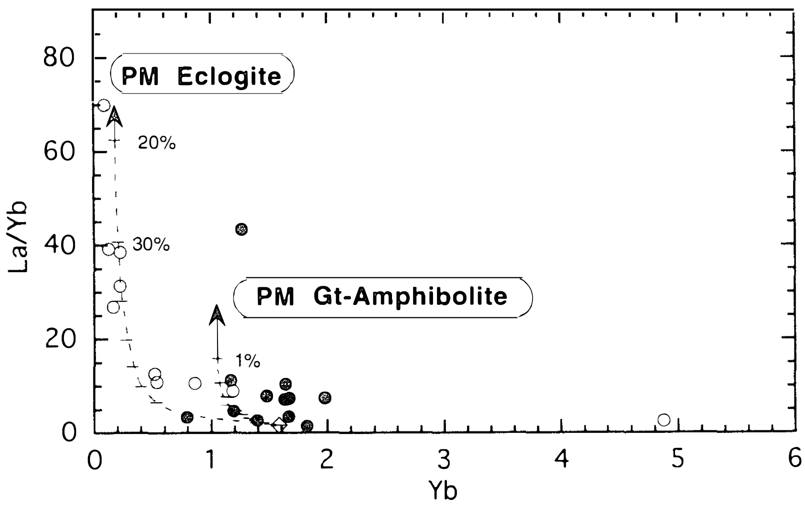

Fig. 6. La/Yb vs. Yb diagram for the tonalitic rocks from the Sør Rondane Mountains and the trondhjemites from the Lützow-Holm Complex (after IKEDA et al., 1997). Symbols are same as in Fig. 3. Bach partial melting curves from a MORB source are represented: partial melting of garnet amphibolite (45% plagioclase, 50% hornblende, 2% clinopyroxene, and 3% garnet in the residue), and partial melting of eclogite (50% garnet and 50% clinopyroxene in the residue). Numbered tick marks indicate percent fusion. The data sources for the calculations of the partial melting models are from LUAIS and HAWKESWORTH (1994).

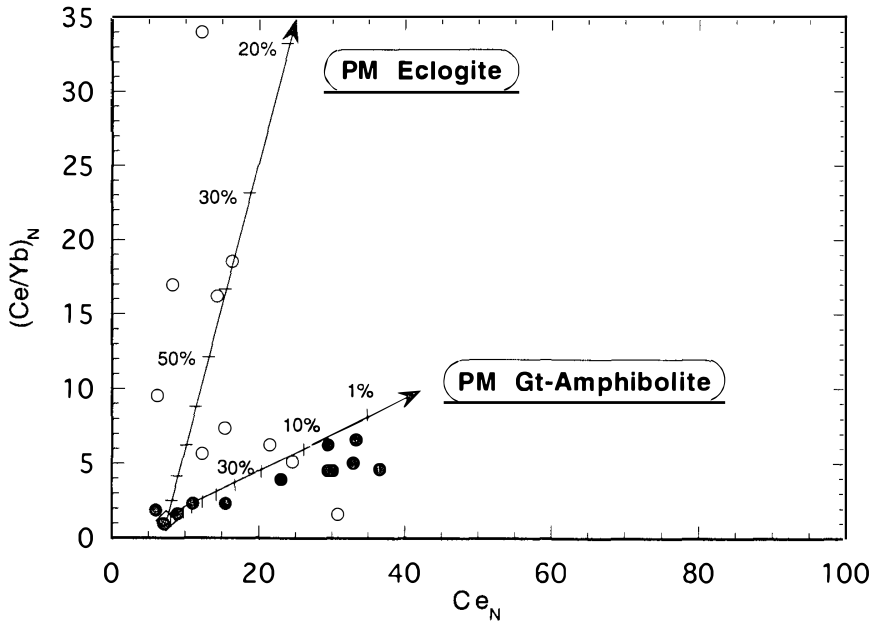

Fig. 7. (Ce/Yb)$_N$ vs. Ce$_N$ diagram for the tonalitic rocks from the Sør Rondane Mountains and the trondhjemites from the Lützow-Holm Complex (after IKEDA *et al., 1997). Symbols are same as in Fig. 3. Partial melting curves and numbered tick marks are as in Fig. 6.*

0.7031 to 0.7057 (PETFORD and ATHERTON, 1996; BARNES *et al.*, 1996; JOHNSON *et al.*, 1997). On the other hand, the initial Sr isotope ratio for the tonalitic rocks from the Sør Rondane Mountains (0.7024; TAKAHASHI *et al.*, 1990) is typical of depleted mantle-derived magmas such as N-MORB ($\approx$0.7025; SUN and McDONOUGH, 1989). These isotopic compositions suggest that partial melting of N-MORB that yields a garnet amphibolite residue may play a dominant role in generation of the tonalitic rock magma from the Sør Rondane Mountains as well as the trondhjemites from the Lützow-Holm Complex produced by partial melting of subducted oceanic crust with an eclogite residue (IKEDA *et al.*, 1997).

DRUMMOND and DEFANT (1990) proposed that Cenozoic high-Al trondhjemite-tonalite-dacite suites are produced above a young hot subduction zone (<20–30 Ma), where temperatures are hot enough to induce melting in the slab. Thus the genesis of the magmatism in the two different terranes at 1000 Ma, the tonalitic rock from the Sør Rondane Mountains and high-Al trondhjemite from the Lützow-Holm Complex, seem to be dynamically related to tectonic settings in which young, relatively hot oceanic crust subducted under the Gondwana continental margin, such as instances where an oceanic ridge is subducted or is present near the trench.

Acknowledgments

We are much indebted to the geologists who participated in JARE-26, -28, and -31 for their kind permission to use their samples. A part of this work was supported by Grants in Aid for Scientific Research of the Ministry of Education, Japan to Profs. H. KAGAMI (No. 07304041) and K. SHIRAISHI (No. 08640584).

References

ARAKAWA, Y., TAKAHASHI, Y. and TAINOSHO, Y. (1994): Nd and Sr isotope characteristics of the plutonic rocks in the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **7**, 49–59.

ARTH, J.G. and HANSON, G.N. (1975): Geochemistry and origin of the early Precambrian crust of northeastern Minnesota. Geochim. Cosmochim. Acta, **39**, 325–362.

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.

ATHERTON, M.P. and PETFORD, N. (1993): Generation of sodium-rich magmas from newly underplated basaltic crust. Nature, **362**, 144–146.

BARKER, F. (1979): Trondhjemites: Definition, environment and hypotheses of origin. Trondhjemites, Dacites and Related Rocks, ed. by F. BARKER. Amsterdam, Elsevier, 1–12.

BARNES, C.G., PETERSEN, S.W., KISTLER, R.W., MURRAY, R. and KAYS, M.A. (1996): Source and tectonic implications of tonalite-trondhjemite magmatism in the Klamath Mountains. Contrib. Mineral. Petrol., **123**, 40–60.

DEFANT, M.J. and DRUMMOND, M.S. (1990): Derivation of some modern arc magmas 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 genesis via both slab melting and differentiation: Petrogenesis of La Yeguada volcanic complex, Panama. J. Petrol., **32**, 1101–1142.

DRUMMOND, M.S. and DEFANT, M.J. (1990): A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons. J. Geophys. Res., **95**, 21503–21521.

GLIKSON, A.Y. (1979): Early Precambrian tonalite-trondhjemite sialic nuclei. Earth Sci. Rev., **15**, 1–73.

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., 37–44.

IKEDA, Y., SHIRAISHI, K. and KAGAMI, H. (1995): Geochemical characteristics of mafic dike rocks from the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **8**, 49–64.

IKEDA, Y., SHIRAISHI, K. and YANAI, K. (1997): Petrogenesis of the meta-trondhjemites from Cape Hinode, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **10**, 102–110.

ISHIZUKA, H. 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.

JOHNSON, K., BARNES, C.G. and MILLER, C.A. (1997): Petrology, geochemistry, and genesis of high-Al tonalite and trondhjemites of the Cornucopia stock, Blue Mountains, northeastern Oregon. J. Petrol., **38**, 1585–1611.

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.

LUAIS, B. and HAWKESWORTH, C. (1994): The generation of continental crust: An integrated study of crust-forming processes in the Archaean of Zimbabwe. J. Petrol., **35**, 43–93.

MASUDA, A. (1975): Abundances of monoisotopic REE, consistent with the Leedey chondrite values. Geochem. J., **9**, 183–184.

MASUDA, A., NAKAMURA, N. and TANAKA, T. (1973): Fine structures of mutually normalized rare-earth patterns of chondrites. Geochim. Cosmochim. Acta, **37**, 239–248.

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.

PASTEELS, P. and MICHOT, J. (1968): Nouveaux resultats geochronologiques obtenus par la methode U-Pb sur des zircons des monts Sør-Rondane (Antarctique). Ann. Soc. Geol. Belg., **91**, 283–303.

PETFORD, N. and ATHERTON, M. (1996): Na-rich partial melts from newly underplated basaltic crust: The Cordillera Blanca Batholith, Peru. J. Petrol., **37**, 1491–1521.

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

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., 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. , ELLIS, D.J., HIROI, Y., FANNING, C.M., MOTOYOSHI, Y. and NAKAI, Y. (1994): Cambrian orogenic belt in East Antarctica and Sri Lanka: Implications for Gondwana assembly. J. Geol., **102**, 47–65.

SHIRAISHI, K., KAGAMI, H. and YANAI, K. (1995): Sm-Nd and Rb-Sr isochron ages for meta-trondhjemites from Cape Hinode, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **8**, 130–136.

SHIRAISHI, K., OSANAI, Y., ISHIZUKA, H. and ASAMI, M. (1997): Geological map of Sør Rondane Mountains. Antarct. Geol. Map Ser., Sheet 35. Tokyo, Natl Inst. Polar Res.

SUN, S.-S. and MCDONOUGH, W.F. (1989): Chemical and isotopic systematics of oceanic basalts: Implications for mantle compositions and processes. Magmatism in the Ocean Basins, ed. by A.D. SAUNDERS and M.J. NORRY. London, Geol. Soc., 313–345.

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.

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.

(Received February 19, 1998; Revised manuscript accepted June 2, 1998)