Proc. NIPR Symp. Antarct. Geosci., **10**, 102–110, 1997

PETROGENESIS OF THE META-TRONDHJEMITES FROM CAPE HINODE, EAST ANTARCTICA

Yasuo IKEDA[1], Kazuyuki SHIRAISHI[2] and Keizo YANAI[3]

[1]*Hokkaido University of Education at Kushiro, 15–55, Shiroyama 1-chome, Kushiro 085*
[2]*National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173*
[3]*Faculty of Technology, Iwate University, 3–5, Ueda 4-chome, Morioka 020*

Abstract: Meta-trondhjemites (*ca.* 1000 Ma) from Cape Hinode, Lützow-Holm Complex (LHC), East Antarctica are characterized by relatively high Al (Al_2O_3>15% at 70% SiO_2) and Sr, and low Y and Yb contents, which are chemically similar to Archaean trondhjemites and adakites. Trace element modelings of the partial melting of MORB suggest that igneous protoliths of the meta-trondhjemites were derived by partial melting of a basaltic source material under garnet stability *P-T* conditions. We suggest that a young hot subducting plate along LHC at 1000 Ma may have reached elevated temperatures which initiated melting of the slab.

key words: eclogite, Lützow-Holm Complex, MORB, slab, trondhjemite

1. Introduction

The Lützow-Holm Complex is a medium-pressure type metamorphic belt which extends for 300 km along the Prince Olav Coast and Lützow-Holm Bay region. The metamorphic grade increases from the upper amphibolite-facies in the east to granulite-facies in the southwest (HIROI *et al.*, 1991). Cape Hinode is situated on the eastern part of the Prince Olav Coast (Fig. 1) where it forms part of the upper amphibolite facies zone.

Meta-trondhjemite is the dominant rock type in the area; it overlays an area of 4 km×5 km, occupying about 80% of the whole outcrop area (YANAI and ISHIKAWA, 1978; SHIRAISHI *et al.*, 1995). Other rock types are mainly pelitic gneisses and amphibolites with minor calc-silicate rocks. However, the field relationship between the meta-trondhjemite and the surrounding gneisses is not always evident.

Extensive zircon U-Pb dating for the metamorphic rocks except for the meta-trondhjemite indicates that the main high-grade regional metamorphism occurred in the range of 520–550 Ma (SHIRAISHI *et al.*, 1992, 1994). Rb-Sr and Sm-Nd whole rock isochron ages and SHRIMP U-Pb zircon ages for the meta-trondhjemite indicate almost same age of ~1000 Ma (SHIRAISHI *et al.*, 1992, 1994, 1995). The initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are 0.70275 and 0.51152, respectively (SHIRAISHI *et al.*, 1995). Thus SHIRAISHI *et al.* (1995) conclude that the isotopic age of ~1000 Ma indicates the time of igneous crystallization of the trondhjemite.

There are two tectonic interpretations for the meta-trondhjemite. One is that the Cape Hinode area is a tectonic window or klippe of the 1000 Ma Rayner Complex in the

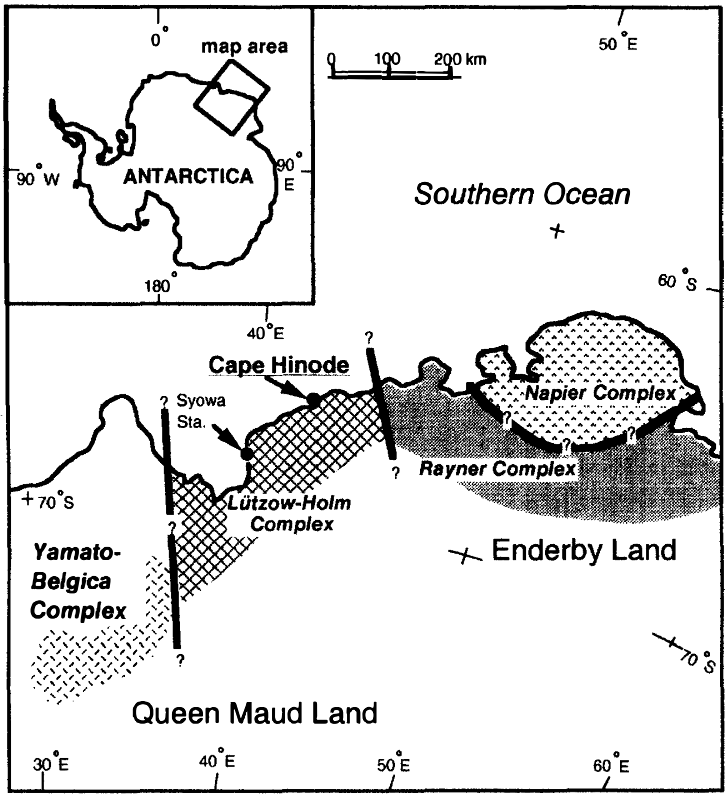

Fig. 1. Location map of the Cape Hinode and four metamorpic complexes in the Enderby Land–Queen Maud Land, East Antarctica.

east (Shiraishi *et al.*, 1994). The other is that the Cape Hinode meta-trondhjemite intruded into the surrounding gneiss sequence before the main metamorphism (Yanai and Ishikawa, 1978; Shiraishi *et al.*, 1995).

In this paper, we discus genesis of the protolith of the trondhjemite on the basis of the geochemical data including major, REE and other minor elements and published isotope data.

2. Samples

The analyzed meta-trondhjemites were the same samples as those for the Rb-Sr and Sm-Nd isotope study by Shiraishi *et al.* (1995). The meta-trondhjemites are medium- to coarse-grained rocks with mosaic texture, and consist mainly of plagioclase, quartz, biotite with or without hornblende. Some hornblende-free rocks contain garnet. The detailed mineral assemblages of the samples are listed in Shiraishi *et al.* (1995). K-feldspar is not common and occurs as antiperthite lamellae in plagioclase. Accessories are apatite, zircon and opaque minerals. Secondary muscovite, biotite, hornblende and carbonate minerals are common but subtle.

3. Sample Preparation and Analysis

Major elements and trace elements except for Rb and Sr were analysed with ICP, and Rb and Sr was analysed by the isotope dilution method by Shiraishi *et al.* (1995). REE and Th were analysed with INAA. Some samples were previously reported by Kanisawa *et al.* (1979) with wet chemical analyses and the results show consistency within the range of 3% for SiO_2 and approximately 10% of the analysed values for the other elements. Concentrations of Sm and Nd analysed with isotope dilution method by Shiraishi *et al.* (1995) are reasonably consistent with the present result.

4. Results

Results for major and trace element abundances in the meta-trondhjemites are pre-

Table 1. Representative major and trace element compositions of trondhjemites from Lützow-Holm Complex.

*	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
SiO_2	64.52	71.28	71.57	63.26	76.56	74.15	68.13	66.24	69.06	63.00
TiO_2	0.37	0.03	0.19	0.46	0.22	0.10	0.31	0.41	0.29	0.41
Al_2O_3	17.67	16.34	15.82	16.12	12.04	15.09	16.43	17.67	16.83	19.37
Fe_2O_3	3.51	0.47	2.03	4.51	2.92	1.02	2.93	3.65	2.78	3.10
MnO	0.05	0.01	0.03	0.07	0.06	0.02	0.06	0.04	0.04	0.06
MgO	1.17	0.15	0.58	2.23	0.61	0.35	0.98	1.30	1.03	1.38
CaO	5.55	4.38	3.33	5.49	2.10	3.46	4.92	5.06	4.40	3.83
Na_2O	5.30	4.69	5.21	4.04	4.01	4.68	4.69	4.86	4.64	6.16
K_2O	0.57	0.58	0.96	1.08	1.07	0.79	0.64	1.09	1.02	1.58
P_2O_5	0.14	0.02	0.07	0.12	0.04	0.03	0.15	0.16	0.10	0.03
LOI	0.61	0.29	0.68	0.73	0.35	0.54	0.50	0.40	0.44	0.40
Total	99.46	98.23	100.47	98.11	99.98	100.23	99.74	100.88	100.63	99.32
Cr	27.5	18.1	18.8	59.4	33.8	27.2	22.6	23.9	33.1	34.3
Ni	18	10	11	29	20	15	14	18	16	7
V	38	2	17	64	12	7	38	35	28	24
Zn	40	10	31	50	19	16	34	45	41	62
Th	0.1	0.1	0.1	0.5	2.7	0.2	0.1	0.2	0.2	-
Hf	2.2	1.3	2	2.5	3.8	2.7	2.8	2.5	2.2	0.7
Y	6	<1	2	9	30	<1	5	16	2	<1
Zr	65	42	73	96	139	93	104	100	91	23
Rb	2.19	2.17	12.6	25.2	15.2	14.7	3.01	18.00	19.3	30.4
Sr	891	767	554	653	141	646	687	681	723	657
Ba	315	415	629	556	562	422	349	735	714	918
La	6.6	4.3	6.9	9.2	12.7	4.7	5.9	10.7	8.5	6.3
Ce	15	6	14	21	30	8	12	24	16	12
Nd	7	2	6	11	13	3	6	14	5	4
Sm	1.45	0.2	0.93	2.17	2.75	0.42	1.12	3.21	0.84	0.61
Eu	0.63	0.33	0.39	0.70	0.61	0.39	0.53	0.99	0.48	0.37
Tb	0.2	0.1	0.1	0.3	0.6	0.1	0.2	0.6	0.1	0.1
Yb	0.52	0.16	0.22	0.86	4.88	0.12	0.54	1.19	0.22	0.09
Lu	0.07	0.02	0.03	0.12	0.76	0.02	0.09	0.16	0.03	0.01

* (1)73123103, (2)74010105, (3)73123106, (4)74010107, (5)74010113, (6)74010115, (7)73123116, (8)74010606, (9)74010701, (10)73123106S

Analyst: ACTLAB Ltd. except for Rb and Sr. Rb and Sr are after Shiraishi *et al.* (1995).

sented in Table 1. SHERATON (1984) found that chemical changes in metamorphic rocks are not significantly affected by high-grade metamorphism (amphibolite to granulite facies). Thus the analytical results of the meta-trondhjemites are potentially useful in the characterization of magma type.

The meta-trondhjemites range in silica from 63 to 76 wt%. They are characterized by low K_2O content (0.57–1.58%), low Y content (1–16 ppm except for one sample), and low Yb_N values (0.4–4.8 except for one sample) and high Na_2O/K_2O (3.7–9.3), high K/Rb (356–2219), and low CaO/Na_2O (0.52–1.36) ratios.

Compared with the trondhjemite trend defined by BARKER and ARTH (1976) on a K-Ca-Na diagram, compositions of the meta-trondhjemites do not lie on the trend because of their low K_2O (Fig. 2). These low K_2O compositions are similar to suites from other Archaean cratons, such as Swaziland (HUNTER, 1979) and Zimbabwe (LUAIS and HAWKESWORTH, 1994), in that they lie on the new sodic trend defined by LUAIS and HAWKESWORTH (1994) (Fig. 2).

Figure 3 illustrates the variation Yb-Al_2O_3 diagram which is used to classify trondhjemites originating in oceanic environments (high Yb and low Al content) and in continental environments (low Yb and high Al contents) (ARTH, 1979). A large number of the meta-trondhjemites plot in a continental environment field such as high-Al Archean trondhjemites (Fig. 3).

The meta-trondhjemites exhibit fractionated chondrite normalized REE patterns with high $(La/Yb)_N$ ratios (Fig. 4). The $(La/Yb)_N$ vs. Yb_N diagram of Fig. 4 is also used for distinguishing Archaean granitoids from post-Archaean granitoids (JAHN *et al.*, 1981; MARTIN, 1986; LUAIS and HAWKESWORTH, 1994). The High $(La/Yb)_N$ ratios and low Yb_N values of the Cape Hinode meta-trondhjemites are similar to those of Archaean granitoids.

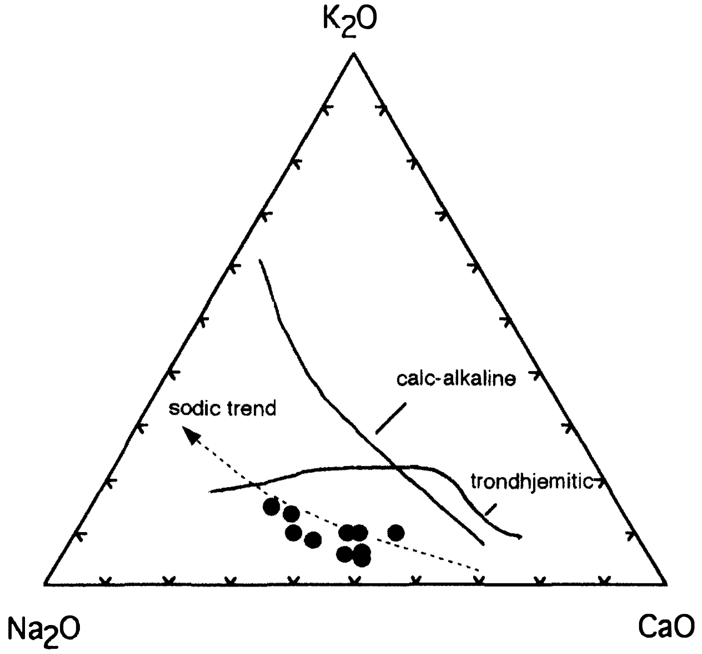

Fig. 2. K_2O-Na_2O-CaO diagram for comparison of the meta-trondhjemites from the Cape Hinode with trondhjemitic and calc-alkaline trends (BARKER and ARTH, 1976) and a new sodic trend of Archaean granitoids defined by LUAIS and HAWKESWORTH (1994).

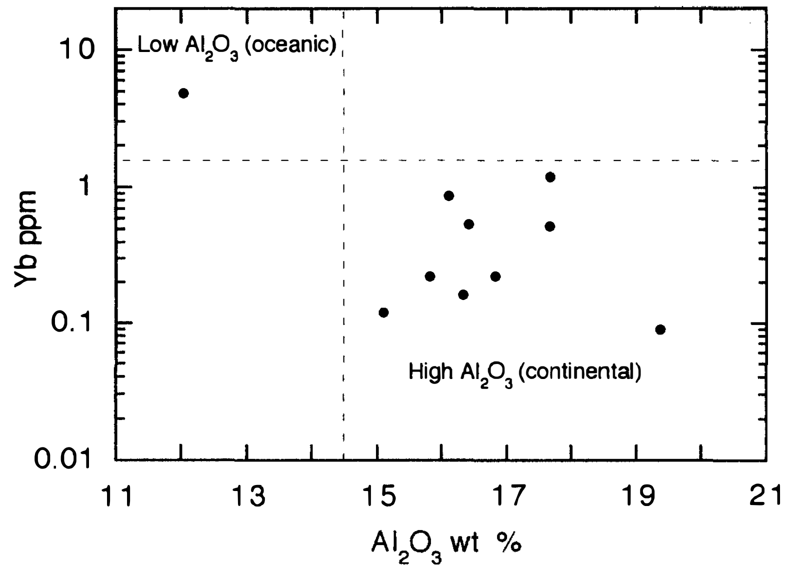

Fig. 3. Yb vs. Al_2O_3 diagram for the meta-trondhjemites from the Cape Hinode. Separations of low Al type and high Al type are defined by ARTH *(1979).*

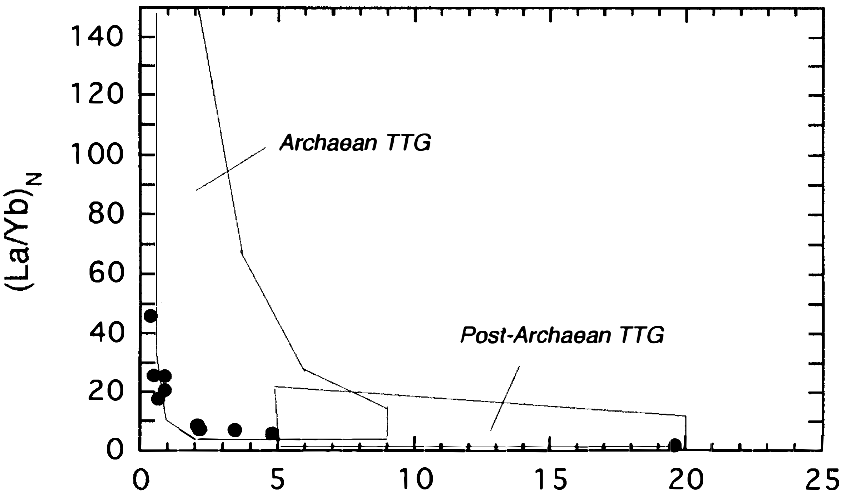

Fig. 4. $(La/Yb)_N$ vs. Yb_N diagram for the meta-trondhjemites from the Cape Hinode. Fields of Archaean TTG (tonalite-trondhjemite-granite) and post-Archaean TTG are shown in LUAIS *and* HAWKESWORTH *(1994).*

5. Petrogenesis of the Meta-trondhjemites

JAHN *et al.* (1981) and MARTIN (1986) have shown that the low Yb_N values (Yb_N<9) for Archaean granitoids are the result of partial melting of subducted metamorphosed basalt with amphibole and/or garnet in the residue. Experimental work of RAPP *et al.* (1991) has shown that the partial melting of metamorphosed tholeiite (amphobolite, garnet- amphobolite, or eclogite) will generate felsic melts relatively high in Al (Al_2O_3

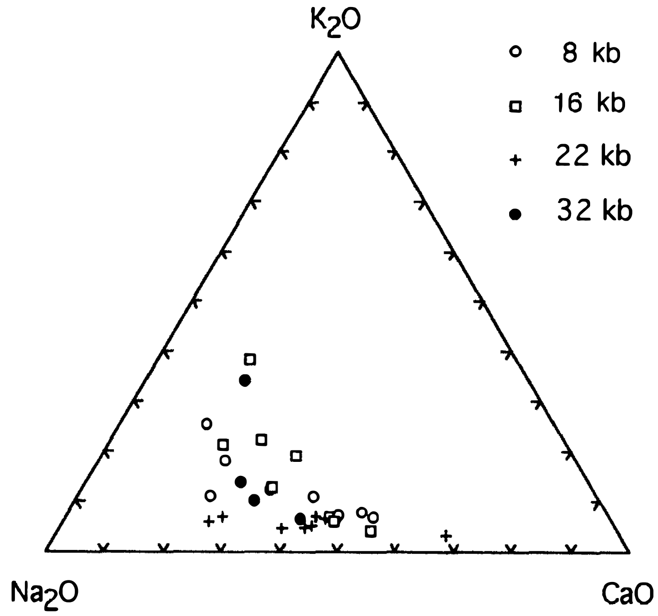

Fig. 5. K_2O-Na_2O-CaO diagram for experimental data of RAPP *et al. (1991).*

> 15% at 70% SiO_2) and the enrichment of Na relative to Ca and K as shown by the sodic trend in Fig. 2 (Fig. 5).

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/Rb ratios (*ca.* 400–600) common to the Archaean 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 involved predominant refractory garnet under higher temperature and pressure conditions than hornblende stability field (DRUMMOND and DEFANT, 1990).

Geochemical characteristics of the meta-trondhjemites from Cape Hinode (high Al and Na and low Y and Yb concentrations, and high Na/K, K/Rb, Sr/Y, and La/Yb ratios) are consistent with their derivation by partial meting of the subducted basaltic lithosphere.

A curve in the La/Yb vs. Yb diagram (Fig. 6) for the meta-trondhjemites indicate a partial melting of eclogite with 50% garnet in the residue (LUAIS and HAWKESWORTH, 1994). Increasing degree of 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 amphibolite and garnet amphibolite (LUAIS and HAWKESWORTH, 1994). The observed data show good agreement for the calculated model of LUAIS and HAWKESWORTH (1994) (Fig. 6).

The high-Sr and low-Y signature of the meta-trondhjemites is illustrated in Fig. 7, using the partial melting model of DEFANT and DRUMMOND (1990) for altered MORB, leaving an eclogite restite. The geochemical modeling for the meta-trondhjemites sug-

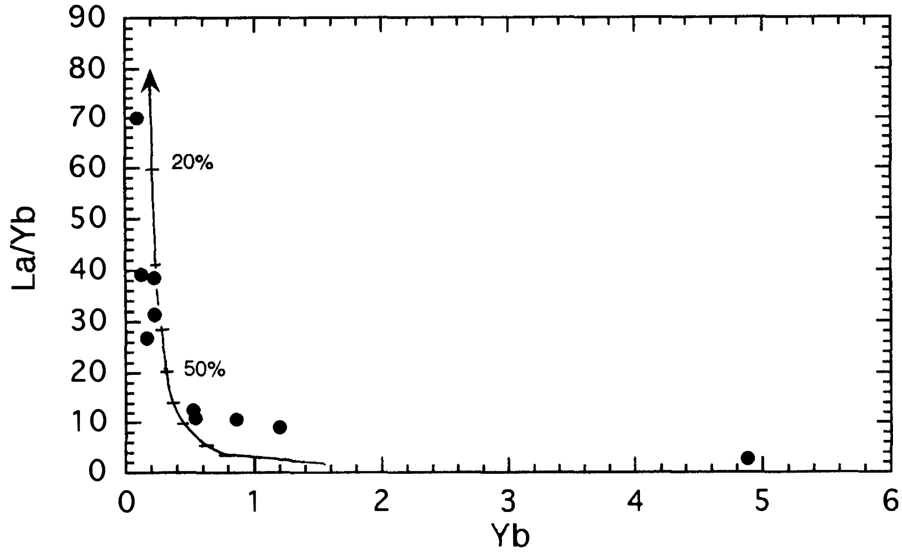

Fig. 6. La/Yb vs. Yb diagram for the meta-trondhjemites from the Cape Hinode. A partial melting line of LUAIS *and* HAWKESWORTH *(1994) is indicated: partial melting model of eclogite (50% garnet+50% clinopyroxene), with 50% garnet in the residue.*

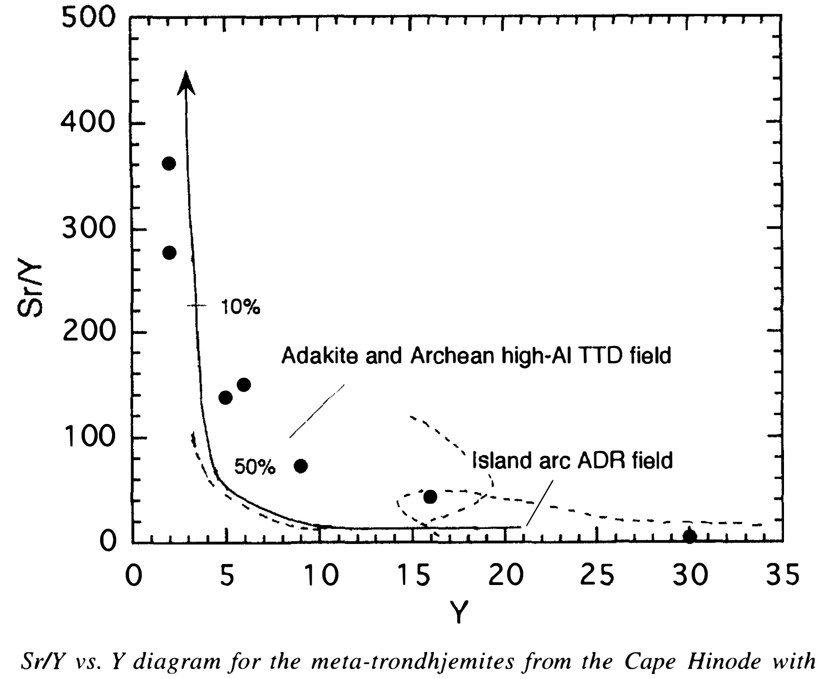

Fig. 7. Sr/Y vs. Y diagram for the meta-trondhjemites from the Cape Hinode with partial melting curve for altered MORB leaving eclogite (garnet: 50%, clinopyroxene: 50%) residue of DEFANT *and* DRUMMOND *(1990). Also shown are fields for adakite and Archean high-Al TTD (tonalite-trondhjemite-dacite) and island-arc ADR (andesite-dacite-rhyolite) from* DEFANT *and* DRUMMOND *(1990) and* DEFANT *et al. (1991).*

gests that these rocks are also derived by partial melting of a basaltic source, leaving a eclogite restite.

In summary, partial melting of a subducted oceanic crust with a eclogite residuum may play a dominant role in the generation of the trondhjemite magma of Cape Hinode.

ATHERTON and PETFORD (1993) suggest that such a high-Al trondhjemite and adakite-like volcanic rocks can be produced by partial melting of uderplated basaltic crust in area of thick continental crust (~50–60 km). The crustal melting, however, seems an unlikely model in LHC area, because experimental *P-T* conditions of eclogite residue stability require 22–32 kb (>60 km depth) in a temperature range (1025–1150°C) (RAPP *et al.*, 1991). A low initial Sr isotope ratio of the meta-trondhjemites (=0.7027; SHIRAISHI *et al.*, 1995) similar to that of MORB also supports the partial meting model of subducted oceanic crust.

DRUMMOND and DEFANT (1990) proposed that Cenozoic high-Al trondhjemit-tonalite-dacite suites are produced avobe a young hot subduction zone (<20–30 Ma), where temperatures are hot enough to induce melting in the slab. The slab-melting origin of the high-Al trondhjemite magma such as the Cape Hinode trondhjemite seems also to relate to subducted a hot oceanic lithosphere. Thus the petrogenesis of the trondhjemite magma of Cape Hinode at 1000 Ma introduces important constraints on Gondwana structure.

Acknowledgments

We are much indebted to Prof. S. KANISAWA of Tohoku University for his kind offer of his stock of the sample powders. Dr. Y. MOTOYOSHI of National Institute of Polar Research helped us in the preparation of samples and examination of the analytical results with XRF. This study was supported by a grant from the Ministry of Education, Sports and Culture to KS (08640584).

References

ARTH, J. G. (1979): Some trace elements in trondhjemites—Their implications to magma genesis and paleotectonic setting. Trondhjemites, Dacites, and Related Rocks, ed. by F. BARKER. Amsterdam, Elsevier, 123–132.

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

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

BARKER, F. and ARTH, J. G. (1976): Generation of trondhjemitic-tonalitic liquids and archaean bimodal trondhjemitic-basalt suites. Geology, **4**, 596–600.

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.

HIROI, Y., SHIRAISHI, K. and MOTOYOSHI, Y. (1991): Late Proterozoic paired metamorphic complexes in East Antarctica, with special reference to the tectonic significance of ultramafic rocks. Geological Evolution of Antarctica, ed. by M.R.A. THOMSON *et al.* Cambridge, Cambridge Univ. Press, 83–87.

HUNTER, D. R. (1979): The role of tonalitic and trondhjemitic rocks in the crustal development of Swaziland and the eastern Transvaal, South Africa. Trondhjemites, Dacites, and Related Rocks, ed. by F. BARKER. Amsterdam, Elsevier, 301–322.

JAHN, B. J., GLICKSON, A. Y., PEUCAT, J. J. and HICKMAN, A. H. (1981): REE geochemistry and isotopic data of Archaean silicic volcanics and granitoids from the Pilbara Block, Western Australia: Implications for the early crustal evolution. Geochim. Cosmochim. Acta, **45**, 1633–1652.

KANISAWA, S., YANAI, K. and ISHIKAWA, K. (1979): Major element chemistry of metamorphic rocks of the Cape Hinode district, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **14**, 164–171.

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.

MARTIN, H. (1986): Effect of steeper Archaean geothermal gradient on geochemistry of subduction-zone magmas. Geology, **14**, 753–756.

RAPP, R. P., WATSON, E. B. and MILLER, C. F. (1991): Partial melting of amphibolite/eclogite and the origin of Archean trodhjemites and tonalites. Precambrian Res., **51**, 1–25.

SHERATON, J. W. (1984): Chemical changes associated with high-grade metamorphism of mafic rocks in the East Antarctic Shield. Chem. Geol., **47**, 135–157.

SHIRAISHI, K., HIROI, Y., ELLIS, D. J., FANNING, C. M., MOTOYOSHI, Y. and NAKAI, Y. (1992): The first report of a Cambrian orogenic belt in East Antarctica—An ion microprobe study of the Lützow-Holm Complex. Recent Progress in Antarctic Eath Science, ed. by Y. YOSHIDA *et al.* Tokyo, Terra Sci. Publ., 67–73.

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.

YANAI, K. and ISHIKAWA, T. (1978): Geological map of Cape Hinode, Antarctica. Antarct. Geol. Map Ser., Sheet 21 (with explanatory text 6 p.). Tokyo, Natl Inst. Polar Res.

(Received January 30, 1997; Revised manuscript accepted April 18, 1997)