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Sm-Nd garnet ages of retrograde garnet bearing granulites from Tonagh Island in the Napier Complex, East Antarctica: A preliminary study

Masaaki Owada[1], Yasuhito Osanai[2], Toshiaki Tsunogae[3], Takuji Hamamoto[4], Hiroo Kagami[4], Tsuyoshi Toyoshima[4] and Tomokazu Hokada[5,*]

[1]*Department of Earth Sciences, Yamaguchi University, Yoshida 1677-1, Yamaguchi 753-8512 (owada@sci.yamaguchi-u.ac.jp)*
[2]*Department of Earth Sciences, Okayama University, Tsushima-naka 3-1-1, Okayama 700-8530*
[3]*Institute of Geoscience, the University of Tsukuba, Tennoudai 1-1-1, Tsukuba 305-8571*
[4]*Graduate School of Science and Technology, Niigata University, Ikarashi 2-chome, Niigata 950-2181*
[5]*National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*

Abstract: Proterozoic Sm-Nd garnet ages were dated from a garnet-bearing quartzo-feldspathic gneiss (Grt-felsic gneiss) and an iron rich garnet-pyroxene gneiss (Fe-rich Grt-Py gneiss) in the northern part of Tonagh Island, the Napier Complex. The Grt-felsic gneiss occurs as a member of layered gneiss. The Fe-rich Grt-Py gneiss appears as a block in the felsic gneiss. Since the layered gneiss contains a critical mineral assemblage of ultrahigh-temperature (UHT) metamorphism such as sapphirine+quartz, the Grt-felsic and the Fe-rich Grt-Py gneisses have undergone UHT metamorphism whose age is believed to be Late Archaean. The inclination line connecting with garnet and whole rock in the Grt-felsic gneiss yields an age of 1897 Ma in the Sm-Nd system. The internal isochron using garnet, pyroxenes and whole rock for the Fe-rich Grt-Py gneiss gives an age of 1557±35 Ma. Both Sm-Nd internal isochron ages correspond to Early Proterozoic. Garnet-quartz symplectite and quartz occur between orthopyroxene and plagioclase in the Grt-felsic gneiss. This texture indicates the following reaction: orthopyroxene+plagioclase=garnet+quartz. The garnet in the Fe-rich Grt-Py gneiss occurs as interstitial mineral with small grained clinopyroxene and quartz. Taking reaction textures into account, the garnet forming reactions in the Grt-felsic and the Fe-rich Grt-Py gneisses would occur during retrograde events after UHT peak metamorphism. The ages of *c.* 1900 and *c.* 1550 Ma would therefore reflect tectonothermal events in the Napier Complex.

key words: Napier Complex, Sm-Nd garnet age, Proterozoic, retrograde metamorphism

1. Introduction

The Napier Complex is one of the oldest crusts among Archaean terranes. The tonalitic precursor of the orthogneiss formed an initial crust *c.* 3800 to 3900 Ma, as

* Present address: Department of Geology, National Science Museum, 3-23-1 Hyakunin-cho, Shinjuku-ku, Tokyo 169-0073.

revealed by ion microprobe U-Pb analysis of zircon grains (Black *et al.*, 1986a, b; Harley and Black, 1997). The Proterozoic Rayner Complex surrounds the Napier Complex. The Rayner Complex contains reworked Archaean crust of the neighboring Napier Complex (*e.g.* Sheraton *et al.*, 1987).

The dominant rock of the Napier Complex is pyroxene- and garnet-bearing felsic gneiss of igneous origin (orthogneiss), with subordinate amounts of mafic gneiss, ultramafic rock and siliceous, aluminous and iron-rich metasedimentary rocks (Sheraton *et al.*, 1987). The metamorphic rocks consist of ultrahigh-temperature (UHT) granulite facies mineral assemblages, characterized by spinel-quartz, sapphirine-quartz and orthopyroxene-sillimanite-quartz associations. The metamorphic *P-T* conditions of the UHT rocks are up to 11 kbar and 1100°C (*e.g.* Harley and Hensen, 1990).

The timing of UHT peak metamorphism of the Napier Complex is regarded as late Archaean (DePaolo *et al.*, 1982; Black *et al.*, 1983, 1986b; McCulloch and Black, 1984; Owada *et al.*, 1994: Tainosho *et al.*, 1994, 1997; Osanai *et al.*, 1995; Harley and Black, 1997; Shiraishi *et al.*, 1997; Asami *et al.*, 1998; Hokada, 1999; Suzuki, 2000). The UHT metamorphic rocks contain retrograde minerals involving garnet (Sandiford, 1985; Harley and Hensen, 1990). The *P-T* conditions of retrograde metamorphism show 4–9 kbar and 600°–850°C (Hokada *et al.*, 1999). Proterozoic igneous activities occur as dikes in the Napier Complex. Some meta-tholeiitic dikes cutting the foliations of the host UHT rocks have mineral assemblages corresponding to upper amphibolite to granulite facies (Ishizuka *et al.*, 1998; Ishizuka and Suzuki, 2000; Tsunogae *et al.*, 1999). The *P-T* conditions of meta-tholeiitic dikes are similar to those of the retrograde metamorphism of UHT metamorphic rocks. However, the ages of the retrograde metamorphic events in UHT metamorphic rocks are not fully understood.

We performed age determination using the internal isochron method in the Sm-Nd system to detect timing of tectonothermal events after UHT metamorphism in the Napier Complex.

2. Geological outline of Tonagh Island

Tonagh Island is located at the southern part of Amundsen Bay (Fig. 1). The island is divided into five geological units from Unit I to V (Osanai *et al.*, 1999; Toyoshima *et al.*, 1999) (Fig. 1). East to west trends with steeply dipping shear zones bound each unit. A geological map of Tonagh Island is shown in Osanai *et al.* (1999). The island is dominated by mafic to felsic gneisses. A dolerite dike, named Amundsen dike, cuts the host gneisses and the shear zone, it has a chilled margin.

Unit I is underlain by a layered gneiss, which is a combination of the following rock types on the scale of several centimeters to meters in thickness: mafic, felsic, aluminous, ultramafic and calcsilicate rocks. Units II and III are characterized by the presence of thick mafic gneisses. Units IV and V are widely underlain by orthopyroxene bearing felsic gneiss with trace amounts of mafic, pelitic and quartz-magnetite gneisses. In addition to these gneisses, meta-ultramafic rocks are locally exposed on the island. Two samples for age determination were collected from Unit I. Detailed geological map and structural characteristics of Unit I are given by Osanai *et al.* (1999).

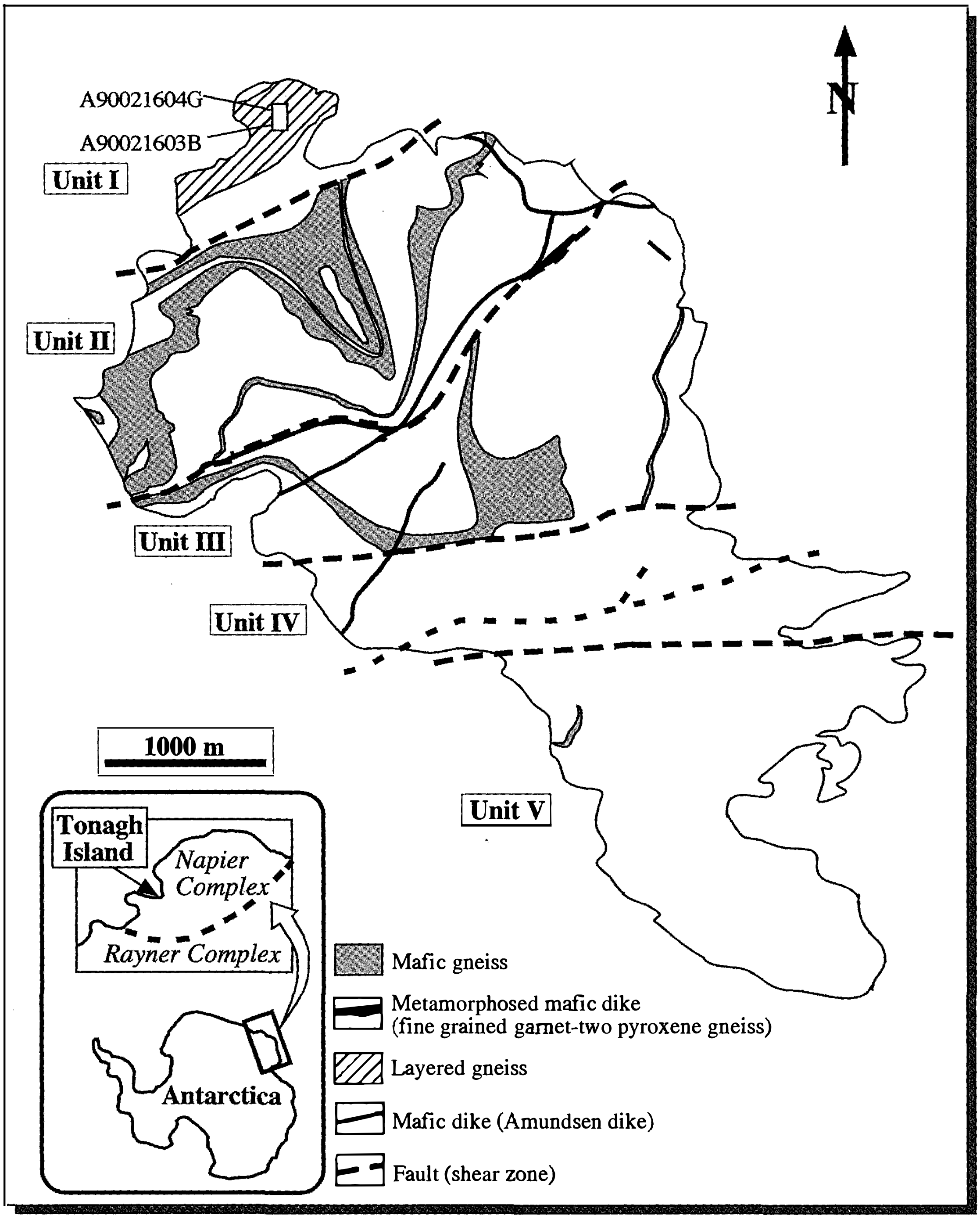

Fig. 1. Simplified geological map and unit division of Tonagh Island.

3. Description of analyzed samples

A cross-section of Unit I with sampling sites and occurrence of the layered gneiss is given in Fig. 2. The mafic and felsic gneisses expand in the direction of the strike. Sample A90021603B is garnet-bearing quartzo-feldspathic gneiss (Grt-felsic gneiss), and A90021604G is iron rich garnet-pyroxene gneiss (Fe-rich Grt-Py gneiss). The Grt-felsic gneiss (A90021603B) is accompanied by mafic and pelitic gneisses, and shows medium

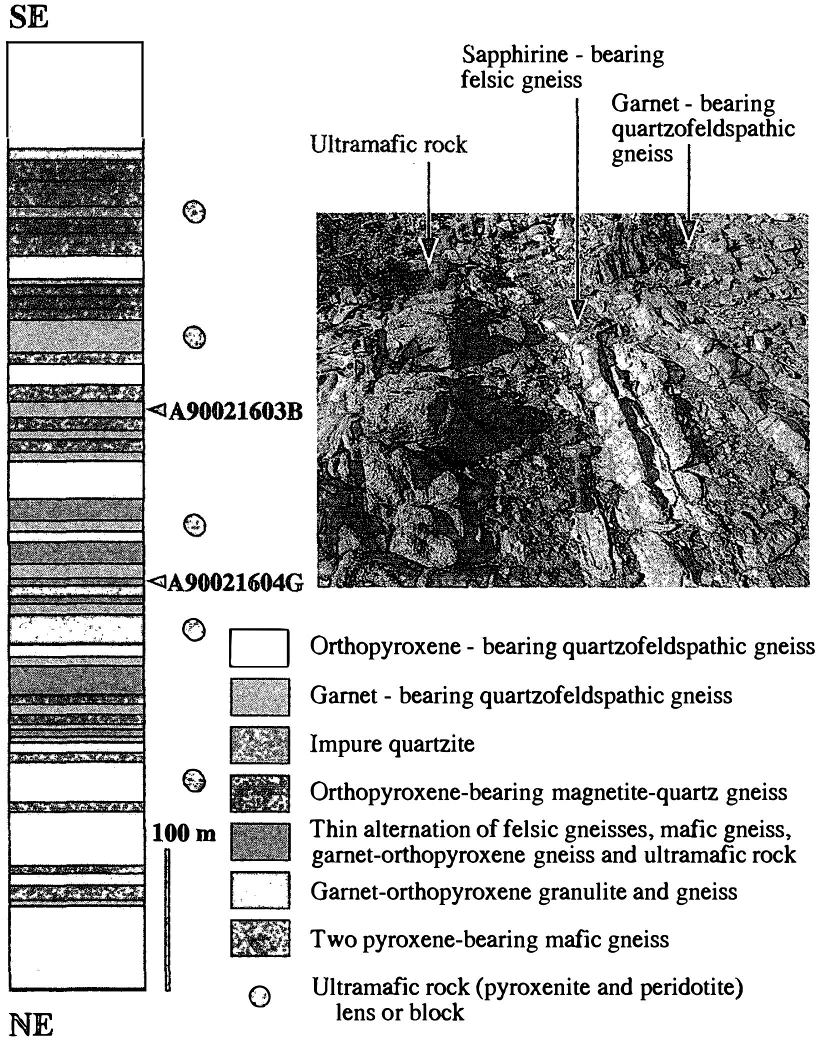

Fig. 2. Cross section of Unit I with sample location for isotope analyses. The section was modified from Osanai et al. (1999). Occurrence of layered gneiss is also shown.

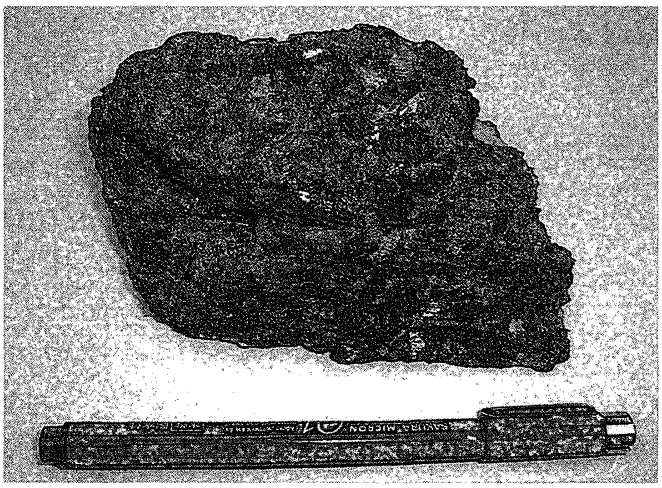

Fig. 3. Hand specimen sample of the Fe-rich Grt-Py gneiss.

Table 1. Bulk rock and mineral chemistry of the Grt-felsic gneiss and the Fe-rich Grt-Py gneiss.

Sample No.	A90021603B	A90021604G
	bulk	bulk
wt %		
SiO_2	55.10	48.08
TiO_2	1.14	0.32
Al_2O_3	16.11	2.95
Fe_2O_3	13.51	36.55
MnO	0.19	1.90
MgO	4.34	5.06
CaO	5.59	6.75
Na_2O	0.88	0.00
K_2O	1.57	0.00
P_2O_5	0.12	0.08
ppm		
Ba	260	<40
Cr	147	210
Nb	15	<2
Ni	94	170
Rb	12	<2
Sr	132	13
V	216	61
Y	50	13
Zr	95	49

Sample No.	A90021603B						A90021604G					
	Grt	Grt	Opx	Opx	Pl	Pl	Grt	Grt	Pig	Pig	Aug	Aug
wt %												
SiO_2	39.07	38.28	50.98	52.26	56.67	55.51	38.33	38.28	47.38	47.99	49.37	49.04
TiO_2	0.01	0.06	0.05	0.00	0.02	0.01	0.03	0.11	0.05	0.16	0.03	0.13
Al_2O_3	22.65	22.12	1.50	1.05	28.18	28.52	19.52	19.29	0.39	0.19	0.26	0.52
Cr_2O_3	0.01	0.00	0.02	0.01	0.00	0.00	0.09	0.06	0.00	0.02	0.02	0.04
FeO	27.29	28.21	28.66	26.01	0.06	0.08	29.91	29.70	37.91	35.52	22.02	22.28
MnO	0.78	0.64	0.20	0.15	0.00	0.00	4.75	4.18	1.81	1.56	0.93	0.98
MgO	5.43	4.09	18.57	20.09	0.02	0.00	1.05	1.29	6.68	6.51	6.08	5.77
CaO	6.36	6.95	0.37	0.34	9.26	9.56	7.09	7.36	5.49	7.78	20.89	20.24
Na_2O	0.00	0.01	0.01	0.00	6.35	6.55	0.00	0.00	0.07	0.04	0.15	0.15
K_2O	0.01	0.00	0.02	0.01	0.26	0.23	0.00	0.01	0.00	0.01	0.01	0.00
O	12	12	6	6	32	32	12	12	6	6	6	6
Si	2.994	2.994	1.949	1.977	10.103	9.965	3.076	3.081	1.965	1.976	1.974	1.973
Ti	0.001	0.003	0.001	0.000	0.003	0.001	0.002	0.007	0.001	0.005	0.001	0.004
Al	2.046	2.039	0.068	0.047	5.921	6.034	1.847	1.830	0.019	0.009	0.012	0.025
Cr	0.001	0.000	0.001	0.000	0.000	0.000	0.006	0.004	0.000	0.001	0.000	0.001
Fe	1.749	1.845	0.916	0.823	0.008	0.012	2.008	1.999	1.315	1.223	0.736	0.750
Mn	0.050	0.042	0.007	0.005	0.000	0.000	0.323	0.285	0.064	0.054	0.032	0.033
Mg	0.620	0.477	1.058	1.133	0.006	0.000	0.125	0.155	0.413	0.399	0.363	0.346
Ca	0.523	0.582	0.015	0.014	1.768	1.839	0.610	0.635	0.244	0.343	0.895	0.873
Na	0.000	0.002	0.000	0.000	2.193	2.279	0.000	0.000	0.005	0.003	0.012	0.012
K	0.001	0.000	0.001	0.000	0.059	0.052	0.000	0.001	0.000	0.000	0.000	0.000
Tot. cation	7.983	7.984	4.016	3.999	20.061	20.183	7.996	7.996	4.026	4.016	4.025	4.016

Bulk rock chemistry was determined with XRF at Yamaguchi and Kochi Universities. Electron microprobe analyzer (Shimadzu V-6) at Yamaguchi University determined mineral chemistry. The mineral data were obtained under conditions of 15 kV accelerating voltage and 15 nA sample current. Total Fe as Fe_2O_3 and FeO for bulk rocks and minerals, respectively. Grt: garnet, Opx: orthopyroxene, Pl: plagioclase, Pig: pigeonite, Aug: augite.

grain with gray color. The Fe-rich Grt-Py gneiss (A90021604G) occurs as a lens in the felsic gneiss, and is coarse grain with black color (Fig. 3).

Bulk rock and mineral compositions of the Grt-felsic and the Fe-rich Grt-Py gneisses are listed in Table 1. Analytical procedures are as follows. Major and minor elements were analyzed with XRF at the Center of Instrumental Analysis of Yamaguchi University. Mineral compositions were determined with a wavelength dispersion electron probe microanalyzer (Shimadzu V-6) at the Center of Instrumental Analysis of Yamaguchi University. The data were obtained under conditions of 15 kV accelerating voltage and 15 nA probe current for quantitative analyses. An acceleration voltage of 15 kV and probe current of 80 nA, dwell time of 200 ms and beam diameter of 2 μm (A90021603B) and 5 μm (A90021604G) were used for Yb compositional mapping.

The Grt-felsic gneiss consists mainly of plagioclase, quartz, orthopyroxene and garnet with trace amounts of apatite, zircon and opaque minerals. Biotite occurs as secondary minerals. Garnet-quartz symplectite and quartz occur between orthopyroxene and plagioclase (Fig. 4). This indicates reaction texture of orthopyroxene+plagioclase producing garnet+quartz.

The Fe-rich Grt-Py gneiss is composed of iron-rich pyroxene (pigeonite, augite), garnet, and trace amounts of quartz, apatite and opaque minerals. Garnet occurs as an interstitial mineral between pyroxenes (Fig. 5). Modal percentages of pyroxene (pigeonite+augite) and garnet are 85% and 14%, respectively. Small-grained clinopyroxene (augite) and quartz also coexist with garnet (Fig. 5).

Compositional mapping for Yb as a representative REE of the Grt-felsic and the Fe-rich Grt-Py gneisses is shown in Fig. 6. Chemical compositions of constituent minerals such as garnet and orthopyroxene in the Grt-felsic gneiss and garnet and pigeonite in the Fe-rich Grt-Py show homogeneity. Judging from texture combined with mineral chemistry, especially in REE, these minerals probably reached equilibrium during garnet forming reactions.

We separated garnet from the Grt-felsic gneiss, and garnet and pyroxene from the Fe-rich Grt-Py gneiss, and performed Sm-Nd garnet dating on each sample.

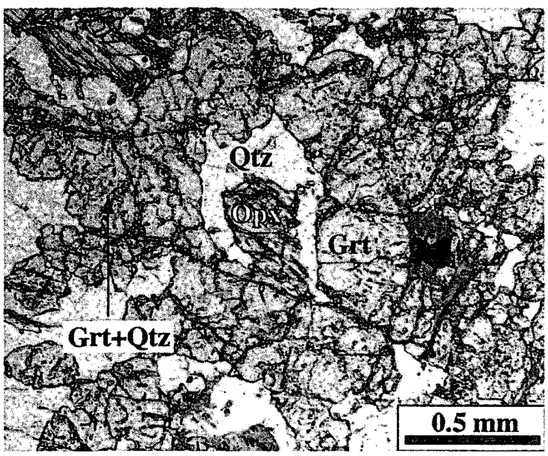

Fig. 4. Photomicrograph of the Grt-felsic gneiss (plane polarized light: PPL). Mineral abbreviations are the same as in Table 1.

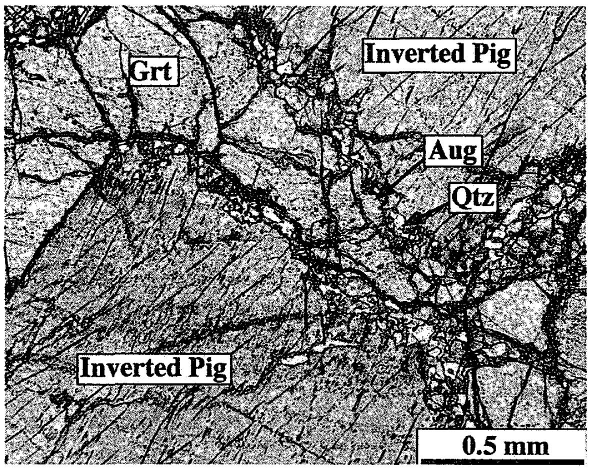

Fig. 5. Photomicrograph of the Fe-rich Grt-Py gneiss (PPL). Mineral abbreviations are the same as in Table 1.

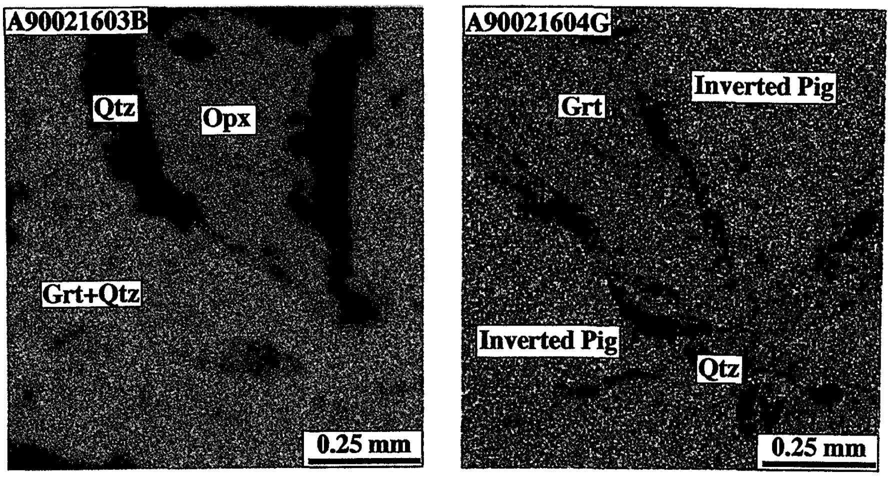

Fig. 6. Compositional mapping of Yb. Constituent minerals of both samples are homogeneity regarding to Yb.

4. Analytical procedure

The extraction procedure of Sm and Nd from rocks and minerals has been described by Kagami *et al.* (1987). $^{143}Nd/^{144}Nd$ ratios were measured with MAT 261 mass spectrometer at the Institute for Study of the Earth's Interior, Okayama University. $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd=0.7219$. The blanks for the whole procedure were Sm<0.03 ng and Nd<0.22 ng. Measured $^{143}Nd/^{144}Nd$ ratios were reported relative to $^{143}Nd/^{144}Nd=0.512640$ for BCR-1 (Wasserburg *et al.*, 1981). Concentrations of Sm and Nd were determined by isotope dilution using ^{149}Sm-^{150}Nd mixed spikes. We estimate an error of 0.1% for the Sm/Nd ratios of each sample based on reproducibility of the data.

The isochron ages and initial isotope ratios for Nd were calculated by a computer program devised by Kawano (1994) using the least square method of York (1966). The decay constant of ^{147}Sm is 0.00654/Ga (Lugmair and Marti, 1978). Input errors are as follows: $^{147}Sm/^{144}Nd=0.1\%$ and $^{143}Nd/^{144}Nd=0.01\%$. We used the following chondritic uniform reservoir (CHUR) parameters for the calculation of initial εNd values: $^{143}Nd/^{144}Nd$ (present)=0.512638, $^{147}Sm/^{144}Nd$ (present)=0.1966.

5. Results

Analytical results of these samples are listed in Table 2 and isochron diagrams are shown in Figs. 7 and 8. The inclination line connecting garnet and whole rock in the Grt-felsic gneiss yields an age of 1897 Ma in the Sm-Nd system (Fig. 7). The initial Nd isotopic ratio corrected by this age is 0.50946. The value corresponds to −14.2 as the initial εNd (εNdI). The internal isochron for the Fe-rich Grt-Py gneiss gives an age of 1557±35 Ma with an initial ratio of 0.50971±0.00010 (εNdI=−20.7) (Fig. 8). The $^{147}Sm/^{144}Nd$ ratio of the whole rock sample is smaller than that of the orthopyroxene. This ratio can be explained by the effect of apatite because of its high Nd and Sm contents and Nd/Sm ratio compared to orthopyroxene.

Mork and Mearns (1986) reported Sm-Nd internal isochron ages of metamorphosed

Table 2. Sm-Nd isotopic analyses of the Grt-felsic gneiss and the Fe-rich Grt-Py gneiss.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ error
A90021603B					
Whole rock	8.89	46.2	0.1164	0.510914	0.000014
Grt	17.1	30.5	0.3401	0.513706	0.000014
A90021604G					
Whole rock	1.61	7.45	0.1302	0.510944	0.000010
Pyroxene	0.78	3.18	0.1484	0.511049	0.000011
Garnet	2.88	2.35	0.7425	0.517174	0.000019

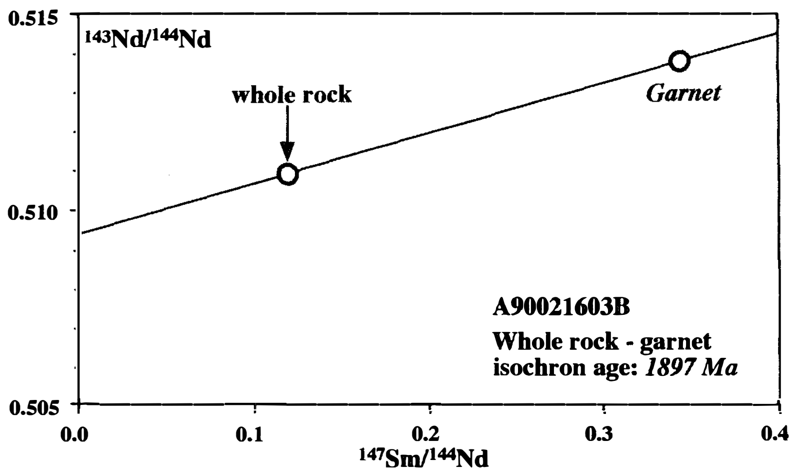

Fig. 7. Isochron diagram of the Grt-felsic gneiss.

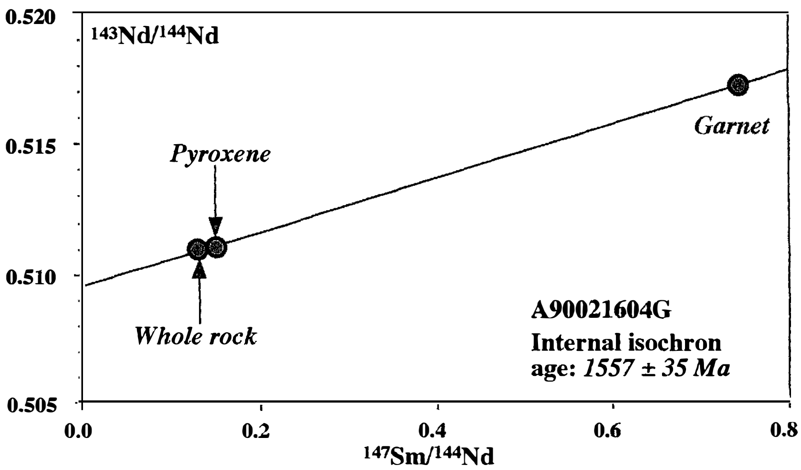

Fig. 8. Isochron diagram of the Fe-rich Grt-Py gneiss.

gabbro in the Flemsoy (Norway) and discussed resetting of the Sm-Nd system caused by metamorphic reactions. They inferred that Sm-Nd mobility was related to metamorphic reactions. Taking reaction textures and chemical composition of Yb into account, the isotopic data obtained here could be required to produce Sm-Nd isotopic equilibrium between the product phases.

6. Discussion

Sapphirine-bearing aluminous gneisses occur as thin layers intercalated with the felsic and mafic gneisses in Unit I (Osanai *et al.*, 1999). As already described, the Fe-rich Grt-Py gneiss appears as a block within the felsic gneiss. On the basis of occurrence of the metamorphic rocks in Unit I, Osanai *et al.* (1999) inferred that the layered gneisses involving metamorphosed blocks underwent UHT metamorphism at the time of peak metamorphism.

Timing of peak metamorphism of the Napier Complex is considered to be prior to 2500 Ma proposed by numerous datings, although the exact age is still controversial (DePaolo *et al.*, 1982; Harley and Black, 1997; Hokada, 1999; Suzuki, 2000). The internal isochron ages obtained here are Proterozoic.

A number of reaction textures are preserved in the UHT metamorphic rocks in the Napier Complex. Hokada *et al.* (1999) described the variety of reaction textures in the sapphirine-bearing aluminous rocks. In these reactions, garnet exsolutions occur as thin films at the grain boundaries of pyroxene grains. The garnet forming reactions had a specified effect with decreasing Al_2O_3 content in orthopyroxene. Taking reaction textures and mineral compositions into account, Hokada *et al.* (1999) inferred that the temperature of the production of garnet exsolutions is lower than that of the UHT peak metamorphism.

The estimation of metamorphic temperatures for the garnet+orthopyroxene pairs in the Grt-felsic gneiss are based on the garnet-orthopyroxene Fe-Mg exchange reaction (Harley, 1984; Sen and Bhattacharya, 1984). These thermometers yield the temperature conditions from 600° to 700°C. The pressure estimates give from 4 to 6 kbar using the above estimated temperatures for the garnet-orthopyroxene-plagioclase-quartz geobarometer (Newton and Perkins, 1982). These *P-T* conditions are similar to those of retrograde metamorphism for UHT metamorphic rocks from Tonagh Island proposed by Hokada *et al.* (1999). As already described, the following reaction texture appears in the Grt-felsic gneiss: orthopyroxene+plagioclase=garnet+quartz. This reaction indicates isobaric cooling (Harley and Hensen, 1990; Tsunogae *et al.*, 1999). The garnet forming reaction in the Grt-felsic gneiss would therefore reflect a retrograde event after the UHT metamorphism.

Proterozoic igneous activities in the Napier Complex formed the so-called “Amundsen dike”. Sheraton and Black (1981) have carried out geochemical and geochronological studies on the Amundsen dike. Recently, Suzuki *et al.* (2000) performed Sm-Nd whole rock isochron dating for meta-tholeiitic dikes with an age of *c.* 1900 Ma in the Mt. Riiser-Larsen region, 40 km northeast of Tonagh Island. Mineral assemblages of the dikes correspond to upper amphibolite to lower granulite facies (Ishizuka and Suzuki, 2000). Therefore, Suzuki *et al.* (2000) inferred that the isochron age was regarded as formation and intrusion of the meta-tholeiitic dikes after the UHT metamorphic event. The Sm-Nd mineral isochron age of the Grt-felsic gneiss resembles the formation age of the meta-tholeiitic dike, suggesting that the age of *c.* 1900 Ma may reflect a tectonothermal event involving tholeiitic magma activity in the Napier Complex.

The garnet grains in the Fe-rich Grt-Px gneiss that yield the age of *c.* 1550 Ma appear at the grain boundaries of pyroxene grains. The garnet grains in this gneiss might also be present at a retrograde stage after the peak metamorphic event because of the occurrence of garnet (Figs. 5 and 6).

Archaean cratons older than 3000 Ma are distributed in Antarctica (Enderby land) and India. Figure 9 shows a reconstructed map of eastern Gondwana, including the Archaean and Proterozoic terranes of India and Antarctica. The ages of the Napier Complex obtained here are also shown in this figure. Kelly *et al.* (1999) reported U-Pb SHRIMP dating of zircon grains in the five samples from the Oygarden Group in the Rayner Complex, situated on near the eastern boundary of the Napier Complex in western Kemp Land. There are the following four age clusters obtained from these

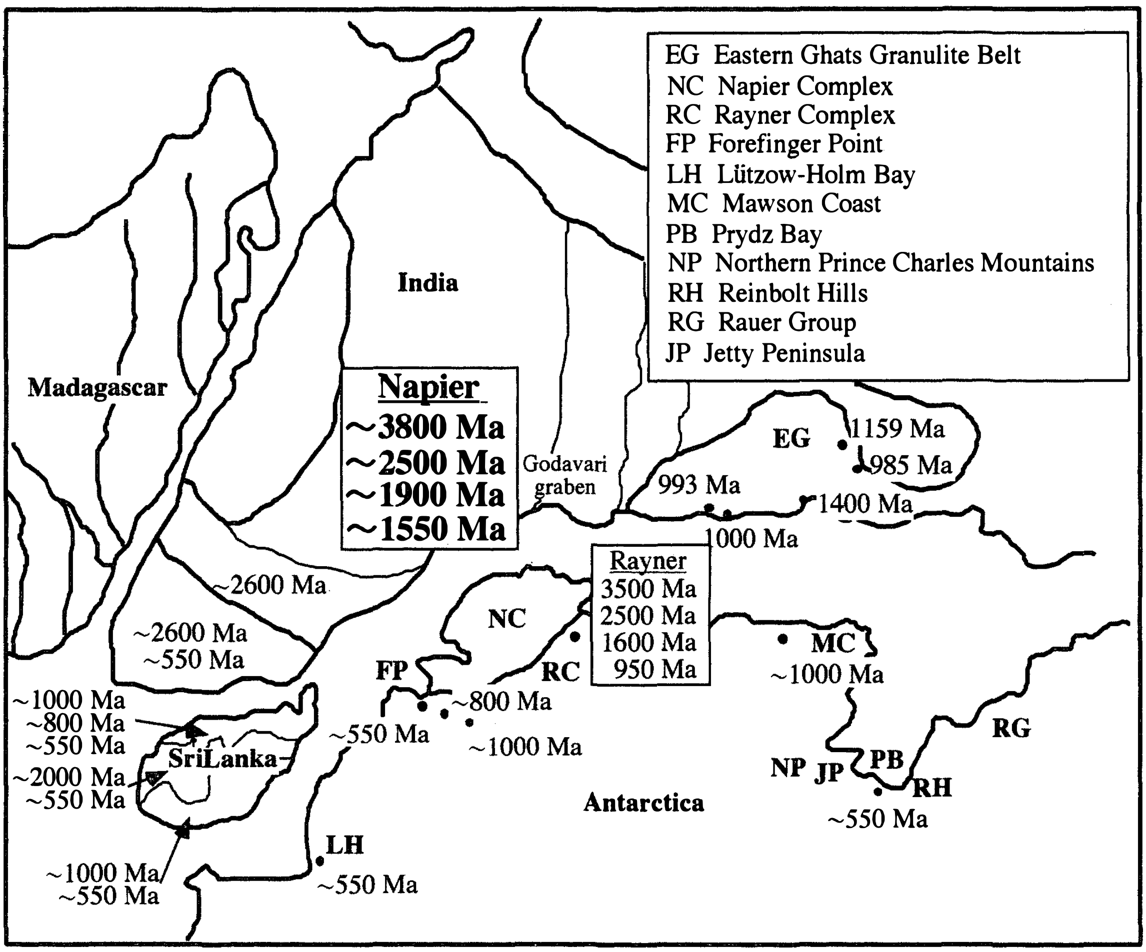

Fig. 9. Schematic reconstruction map of East Gondwanaland with isotopic ages of the metamorphic rocks (Shaw et al., 1997). Sm-Nd internal isochron ages obtained in this study are also shown. The enclosed U-Pb SHRIM data set, marked Rayner, is quoted from Kelly et al. (1999).

samples: *c*. 3500 Ma, *c*. 2500 Ma, *c*. 1600 Ma and *c*. 950 Ma. On the basis of the dating combined with structural criteria, Kelly *et al*. (1999) inferred that the Oygarden Group was dominated by an Archaean crust that was reworked during the *c*. 950 Ma Rayner tectonic event. The age of *c*. 1600 Ma in the Rayner Complex is similar to the Sm-Nd mineral isochron age of the Fe-rich Grt-Py gneiss from Tonagh Island. A tectonic event of *c*. 1550–1600 Ma, therefore, would be locally retained in the Archaean crust around Enderby Land and west Kemp Land.

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