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ISOTOPIC EQUILIBRATION AGE OF Sm-Nd WHOLE-ROCK SYSTEM IN THE NAPIER COMPLEX (TONAGH ISLAND), EAST ANTARCTICA

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Abstract: Whole-rock measurements of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ are reported for gneisses which had undergone granulite-facies metamorphism in Tonagh Island from the Napier Complex, East Antarctica. Felsic and ultramafic gneisses in adjacent outcrops yield a well-defined isochron age of 2458 ± 61 Ma with an initial ratio of 0.50897 ± 0.00004 (initial $\varepsilon Nd = -9.5 \pm 0.7$). These gneisses show a granuloblastic microfabric overprinted by a pervasive intercrystalline texture. The negative εNd value suggests that the isochron age indicates re-equilibration of the isotopic system on a whole-rock scale at 2458 ± 61 Ma. On the other hand, mafic gneisses which crop out as thin layers alternated with pelitic and felsic gneisses yield an isochron with an age of 3708 ± 533 Ma. The mafic gneisses display a uniform granuloblastic texture. The age of 3708 Ma is older than *c*. 3070 Ma, which has been regarded as the earliest tectonothermal age in the complex. εNd values at 3708 Ma for individual mafic gneiss range from $+1.3$ to $+3.3$. The values are within the range of Archaean komatiites and basalts, suggesting that the mafic gneisses were derived from the depleted mantle at *c*. 3700 Ma.

1. Introduction

The Napier Complex is an Archaean metamorphosed craton in the East Antarctic Shield. It consists of very high temperature (VHT) granulite facies assemblages, characterized by spinel-quartz, sapphirine-quartz and orthopyroxene-sillimanite-quartz associations (*e.g.*, SHERATON *et al*., 1980, 1987). The *P-T* conditions of the granulites are up to 11 kbar and 1000°C (HARLEY and HENSEN, 1990). The dominant rock-types are pyroxene- and garnet-bearing quartz-feldspathic gneiss of igneous origin (orthogneiss), with subordinate mafic granulite, pyroxenite and various siliceous, aluminous and ferruginous metasediments (SHERATON *et al*., 1980, 1987). Granitic intrusive rocks and mafic dikes are also present (SHERATON and BLACK, 1981).

The tonalitic precursor of the orthogneiss had intruded into the crust at 3927 ± 10 Ma, as revealed by ion microprobe U-Pb analysis of zircon (BLACK *et al*., 1986a). The age of the earliest deformation and VHT granulite facies metamorphism (D_1-M_1) in the complex

(JAMES and BLACK, 1981 ; HARLEY, 1983) has been dated at 3070±34 Ma (SHERATON and BLACK, 1983), followed by D_2-M_2 (*c.* 2900 Ma) and D_3-M_3 (*c.* 2460 Ma) (*e.g.* BLACK *et al.*, 1986b), each of which produced distinctive fabrics (JAMES and BLACK, 1981 ; BLACK *et al.*, 1983a).

The Sm-Nd whole-rock isochron integrating orthogneisses and mafic gneisses indicates a very imprecise age of 3500±700 Ma due to a limited variation in Sm/Nd ratio (BLACK and McCULLOCH, 1987). This apparent age encompasses the time of primitive crust formation (*c.* 3930 Ma) and that of D_1-M_1 (*c.* 3070 Ma) as well.

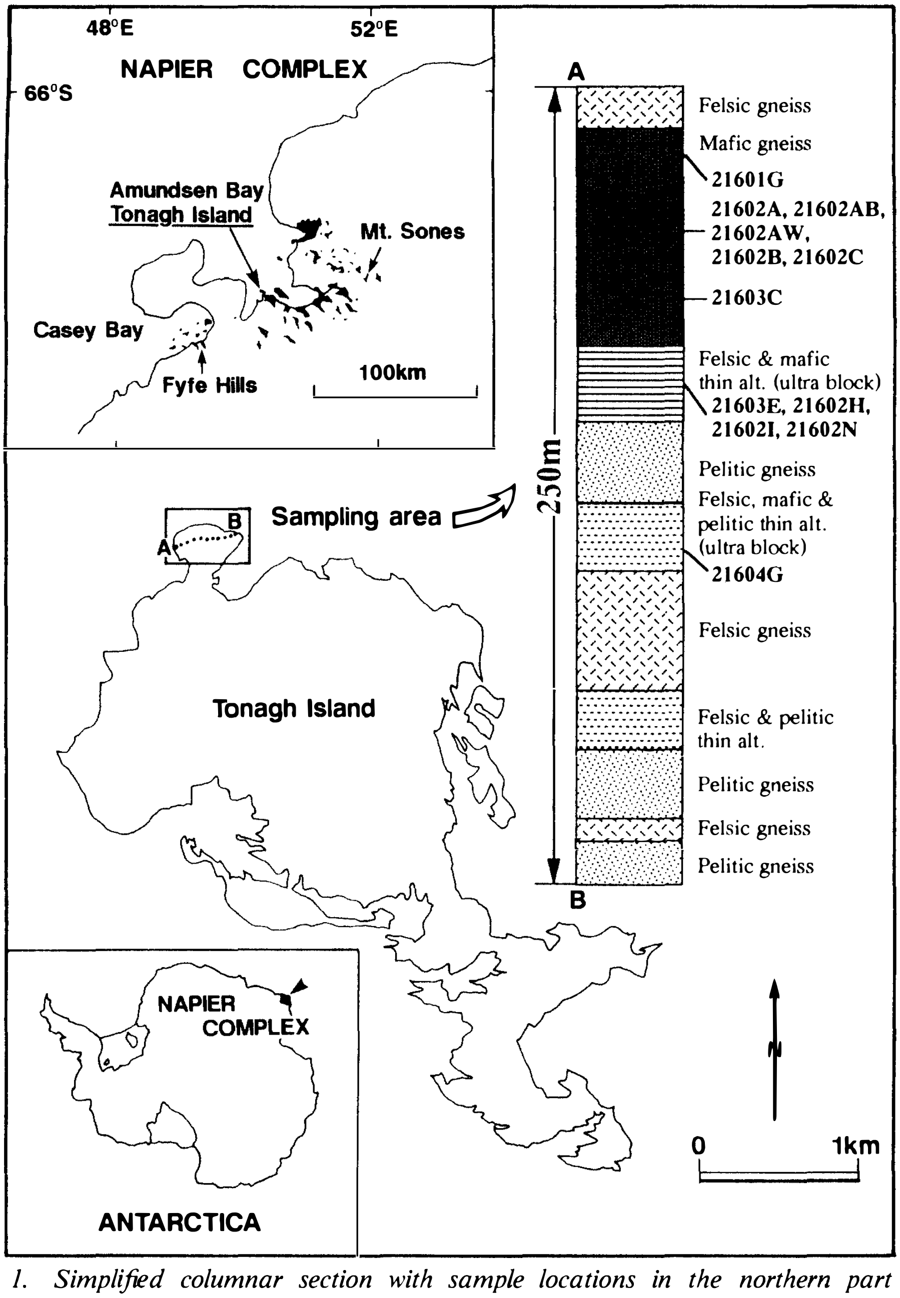

Fig. 1. Simplified columnar section with sample locations in the northern part of Tonagh Island.

The 31st Japanese Antarctic Research Expedition carried out a geological survey for one week at Tonagh Island in the southern end of Amundsen Bay (OSANAI *et al*., 1991), as shown in Fig. 1. In this paper, we measured Sm-Nd isotopic values for mafic, felsic and ultramafic gneisses collected from the northern part of Tonagh Island (Fig. 1), and give the isotopic equilibration ages for these rocks, with discussion of their implication for the crust formation and tectonothermal events of the Napier Complex.

2. Outline of Geology

The geology of the Napier Complex has been described extensively (SHERATON *et al*., 1987; BLACK *et al*., 1983a, b; HARLEY and BLACK, 1987) and geological histories are summarized by HARLEY and HENSEN (1990, Table 12.1).

Tonagh Island consists mainly of orthopyroxene gneiss, garnet-orthopyroxene gneiss, magnetite-orthopyroxene gneiss and "layered gneiss" (see below). The general trend of metamorphic foliation for these rocks strikes NE-SW to NS and dips 30°W. The ductile shear zone shows mainly ENE-WSW trending, steeply dipping at the North-western part of Tonagh Island. The orthopyroxene gneiss is widely exposed on the southern side of the shear zone, whereas various types of rocks crop out on the northern side of the zone. Many dolerite dikes are distributed throughout Tonagh Island.

The northern part of Tonagh Island is underlain by granulite facies "layered gneiss". The "layered gneiss" is a combination of the following five rock types on a scale of 15–50 m in thickness: felsic gneiss, mafic gneiss, pelitic gneiss, calc-silicate gneiss and meta-ironstone. Minor ultramafic gneiss occurs as small blocks in the felsic and the pelitic

Table 1. Mineral assemblages of granulites in the northern part of Tonagh Island.

Napier Complex	
Felsic gneiss	Opx+Qtz+Kfs±Pl
	Opx+Grt+Qtz+Kfs±Pl
	Opx+Cpx+Grt+Qtz+Pl±Kfs
	Opx+Cpx+Qtz+Kfs
Mafic gneiss	Opx+Cpx+Pl
	Opx+Cpx+Grt+Pl+Qtz
	Opx+Grt+Pl
Pelitic gneiss	Grt+Qtz+Kfs±Pl
	Grt+Sil±Crd+Qtz+Kfs±Pl
	Grt+Sil+Spr±Crd+Spl+Qtz+Kfs±Pl
	Grt+Opx+Crd+Qtz+Kfs±Pl
	Grt+Opx+Sil+Qtz+Kfs±Pl
	Grt+Opx+Spl±Spr+Qtz+Kfs+Pl
	Grt+Opx±Spr+Sil±Crd+Qtz+Kfs+Pl
	Opx+Sil+Spr±Spl+Qtz+Pl±Kfs
Calc-silicate gneiss	Cpx+Wo+Cal+Qtz
Meta-ironstone	Mt+Opx+Qtz
	Mt+Opx±Cpx+Qtz
Uitramafic gneiss	Cpx+Opx±Spl
	Opx+Grt±Cpx±Pl

gneisses. Mineral assemblages of these rocks are given in Table 1.

3. Petrography of Samples

Twelve samples were collected from four localities (A90021601, A90021602, A90021603, and A90021604; sample numbers are abbreviated to 21601, etc., hereafter) in the northern part of Tonagh Island (Fig. 1). Major and trace element compositions were measured with XRFs of Yamaguchi and Kochi Universities. Results are listed in Table 2. Each sample was collected within a distance of up to 40 m.

The mafic gneisses (21601G, 21602A, 21602AB, 21602AW, 21602B, 21602C and 21603C) consist mainly of plagioclase, orthopyroxene and clinopyroxene. Granuloblastic fabric overprinted by a relatively pervasive intercrystalline deformation texture in 21601G (Fig. 2A) is distinctively different from those of the other mafic gneisses which show a uniform granuloblastic fabric (Figs. 2B and 2C). Sample 21602B occurs as a dike which cuts the metamorphic foliation of the neighboring mafic gneisses. Constituent minerals of 21602B are up to 0.5 mm in grain size, whereas those in the other mafic gneisses are 1.5 to 2.0 mm (Fig. 2). Moreover, orthopyroxene of 21602B shows X' = green and Z' = pale pink with paleochroism, whereas that of the other mafic gneisses is colorless. These petrographic features are reflected in the bulk chemistry, viz. the FeO/MgO ratio of 21602B is higher than that of the other mafic gneisses (Table 2).

The felsic gneisses (21603E, 21603H and 21603I) are subdivided into two lithofacies: garnet-bearing quartz-dominant and feldspar-rare type (21603E), and garnet-free orthopyroxene-bearing quartz-feldspathic type (21603H and 21603I). The latter characteristically contains mesoperthite (Fig. 2D). All the felsic gneisses display the granuloblastic fabric overprinted by heterogeneous mylonitic deformation (Fig. 2D).

Samples 21303N and 21604G are ultramafic gneisses. Sample 21603N consists mainly of clinopyroxene and orthopyroxene with small amounts of brown spinel inclusion in clinopyroxene. It shows a uniform granuloblastic fabric overprinted by intercrystalline deformation texture (Fig. 2E). Sample 21604G is characterized by large amounts of garnet, orthopyroxene and small amounts of clinopyroxene and plagioclase. It displays granuloblastic fabric overprinted by pervasive intercrystalline deformation texture (Fig. 2F). Modal percentages of the granuloblastic garnet and orthopyroxene are 13.9% and 84.6%, respectively. Opaque minerals appear in garnet and orthopyroxene as inclusions.

4. Analytical Procedure

Sm-Nd isotope analyses were done on twelve whole rocks. Extraction of Sm and Nd from rock powders has been described by KAGAMI *et al.* (1987). Mass spectrometric analyses follow the procedure of KAGAMI *et al.* (1987, 1989). $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Blanks for the whole procedure were 0.04 ng in Sm and 0.40 ng in Nd. $^{143}Nd/^{144}Nd$ results are reported relative to $^{143}Nd/^{144}Nd = 0.512640$ to the BCR-1 (WASSERBURG *et al.*, 1981). Sm and Nd contents of each sample were determined using a ^{149}Sm-^{145}Nd mixed spike. Sm and Nd contents of BCR-1 were 6.61 ppm and 28.9 ppm, respectively. We estimate an error of 0.1% for the Sm/Nd ratios of each sample based on reproducibility of the data. We used the following chondritic

Table 2. Chemical compositions for mafic gneiss, felsic gneiss and ultramafic gneiss.

Sample	21601G	21602A	21602AB	21602AW	21602B	21602C	21603C	21603E	21603H	21603I	21603N	21604G
SiO_2 (wt%)	54.82	58.88	53.90	66.26	52.77	50.36	53.30	94.42	77.02	71.17	56.38	48.08
TiO_2	0.45	1.18	1.13	1.15	1.37	1.11	0.33	0.10	0.06	0.05	0.07	0.32
Al_2O_3	12.86	11.88	10.68	13.61	13.48	8.72	3.49	2.45	14.33	18.13	0.99	2.95
Fe_2O_3**	10.59	12.28	14.49	6.55	15.11	15.03	12.24	0.36	0.34	0.41	9.14	36.55
MnO	0.17	0.15	0.18	0.06	0.21	0.23	0.21	0.00	0.00	0.01	0.21	1.90
MgO	10.51	6.64	8.22	2.46	5.23	14.76	23.71	0.24	0.23	0.18	27.99	5.06
CaO	8.87	6.57	7.57	5.30	9.51	8.10	6.84	0.83	4.44	5.08	2.82	6.75
Na_2O	2.03	2.45	2.09	2.91	2.64	1.17	0.32	0.41	2.90	4.88	0.00	0.00
K_2O	0.40	0.42	0.44	0.42	0.65	1.03	0.00	0.10	1.28	1.44	0.01	0.00
P_2O_5	0.08	0.22	0.19	0.19	0.24	0.26	0.04	0.04	0.02	0.03	0.00	0.08
Total	100.78	100.67	98.89	98.91	101.21	100.77	100.48	98.95	100.62	101.38	97.61	101.69
FeO*/MgO	0.91	1.66	1.59	2.40	2.60	0.92	0.46	1.35	1.33	2.05	0.29	6.50
Ba (ppm)	83	419	346	474	304	344	<40	84	519	557	<40	<40
Cr	829	689	926	26	101	2149	5408	162	125	111	2124	210
Nb	4	14	13	16	8	7	<2	<2	<2	3	<2	<2
Ni	195	203	198	105	65	800	738	46	32	34	906	170
Rb	11	<2	<2	<2	14	44	<2	<2	13	18	<2	<2
Sr	85	118	111	145	231	141	18	25	152	202	11	13
V	224	197	220	144	350	227	105	10	6	557	108	61
Y	22	57	91	31	38	29	13	7	8	7	6	13
Zn	76	93	126	51	110	96	151	4	5	17	155	127
Zr	65	238	287	348	114	114	38	240	9	439	14	49

*Total iron given as FeO. **Total iron given as Fe_2O_3.
All data are determined by XRF.

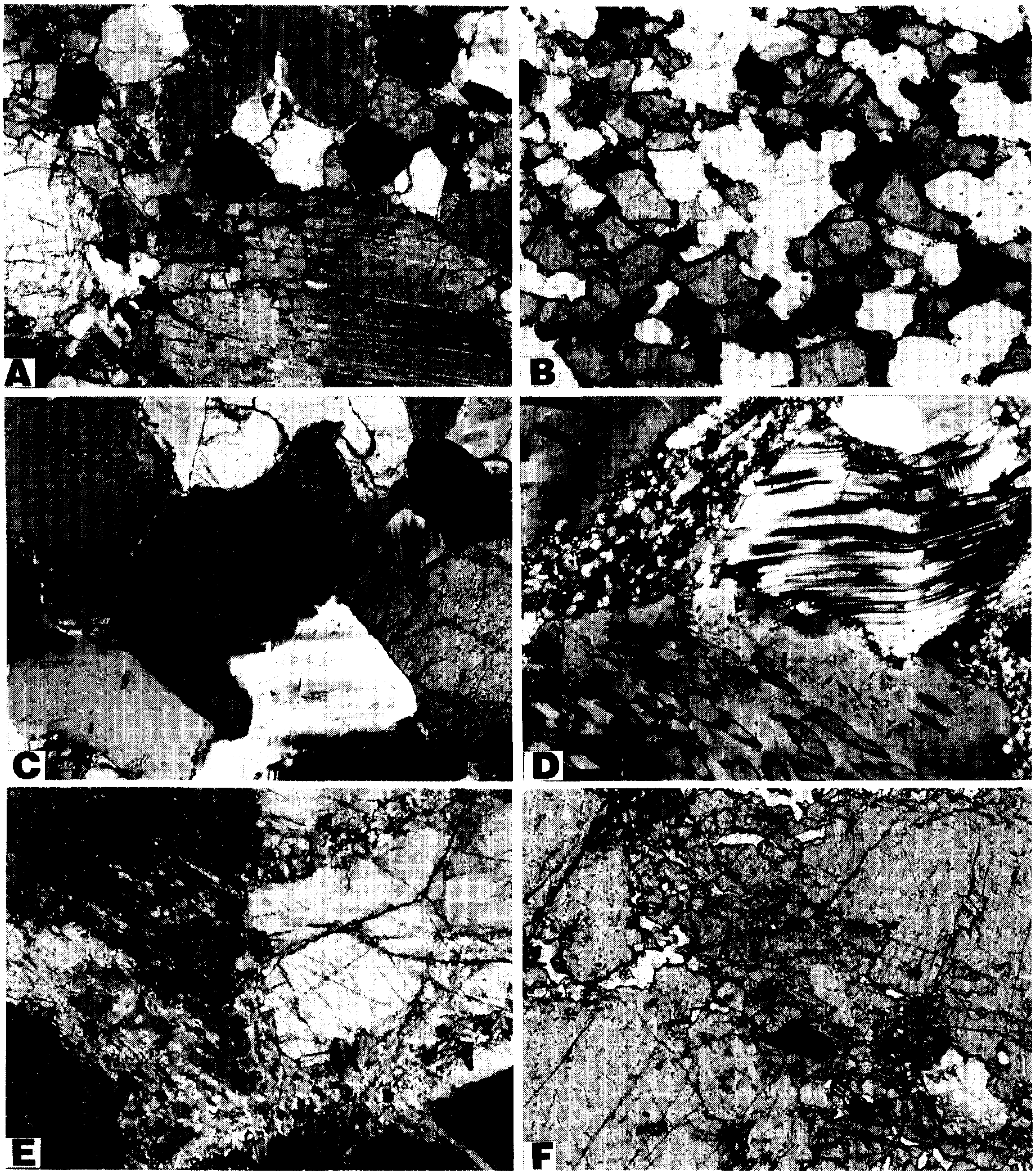

Fig. 2. Microfabric of the samples. Each photograph covers an area of 2.5 × 1.7 mm. A : Sample 21601G, mafic gneiss showing a uniform granuloblastic fabric overprinted by an intercrystalline deformation texture (cross polarized : XPL). B : Sample 21602B, mafic gneiss displaying a granuloblastic microfabric (plane polarized light : PPL). Constituent minerals are significantly small in grain size comparing with the other mafic gneisses (see A and C). C : Sample 21603C, mafic gneiss showing the uniform granuloblastic microfabric (XPL). D : Sample 21603H, felsic gneiss showing mesoperthite with heterogeneous mylonitic texture (XPL). E : Sample 21603N, ultramafic gneiss displaying the granuloblastic microfabric overprinted by the intrercrystalline deformation texture (XPL). F : Sample 21604G, ultramafic gneiss showing similar overprinted fabric to A (PPL).

uniform reservoir (CHUR) parameters for calculation of initial εNd values: $^{143}Nd/^{144}Nd$ (present)=0.512638, $^{147}Sm/^{144}Nd$ (present)=0.1966, $\lambda^{147}Sm = 6.54\times10^{-12}y^{-1}$.

5. Results

Isotopic results are listed in Table 3. The whole rock data are shown in an isochron diagram (Fig. 3). If we pay attention to the location and mineralogy of each sample, two isochrons can be obtained (Figs. 3a and 3b). Samples 21603E, 21603H, 216031 and 21603N, which show granuloblastic fabrics overprinted by intercrystalline deformation

Table 3. Sm-Nd isotopic analyses with model ages (T_{CHUR} and T_{DM}) for mafic gneiss, felsic gneiss and ultramafic gneiss.

Napier complex Sample name	Rock type	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ $\pm 2\sigma$	Sm (ppm)	Nd (ppm)	$T_{(CHUR)}$ (Ma)	$T_{(DM)}$ (Ma)
21601G	Mafic gneiss	0.1520	0.511498±09	3.12	12.4	3860	4060
21602A	Mafic gneiss	0.1222	0.510977±06	11.1	54.7	3380	3600
21602AB	Mafic gneiss	0.1279	0.511015±05	12.7	59.9	3570	3770
21602AW	Mafic gneiss	0.1100	0.510660±09	3.96	21.8	3450	3640
21602B	Mafic gneiss	0.1483	0.511805±11	5.16	21.1	2610	3130
21602C	Mafic gneiss	0.1473	0.511585±14	5.14	21.1	3230	3580
21603C	Mafic gneiss	0.1295	0.511109±13	1.71	7.99	3450	3680
21603E	Felsic gneiss	0.1004	0.510609±10	1.66	10.0	3190	3400
21603H	Felsic gneiss	0.0619	0.509972±14	1.18	11.6	3000	3180
216031	Felsic gneiss	0.0726	0.510128±14	3.34	27.9	3060	3250
21603N	Ultramafic gneiss	0.1614	0.511576±13	1.50	5.63	4540	4560
21604G	Ultramafic gneiss	0.1302	0.510944±10	1.61	7.45	3850	4000

DM parameters are adapted from McCULLOCH and BLACK (1984); $^{143}Nd/^{144}Nd$ (present)=0.513151 ($\varepsilon Nd_{(present)} = +10$), $^{147}Sm/^{144}Nd$ (present)=0.2134 and $f^{Sm/Nd} = 0.085$.

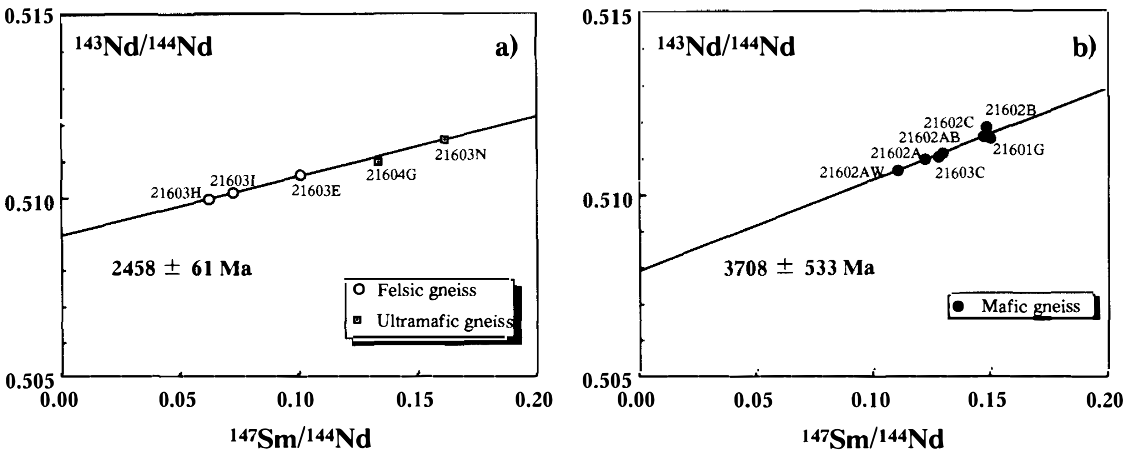

Fig. 3. $^{143}Nd/^{144}Nd$-$^{147}Sm/^{144}Nd$ diagram for rocks from Tonagh Island. a) The samples (21603E, 21603H, 216031 and 21603N) from the same location yield a well-defined isochron age of 2458±61 Ma. b) The samples (21602A, 21602AB, 21602AW, 21602C and 21603C) indicate an imprecise isochron with an age of 3708±533 Ma.

texture, were collected from the same locality. These samples give a well-defined isochron with an age of 2458±61 Ma (MSWD=0.06) and an initial ratio of 0.50897±0.00004 (initial εNd=−9.5±0.7), as shown in Fig. 3a.

The inclination of the line connecting samples with the uniform granuloblastic fabric (21602A, 21602AB, 21602AW, 21602B, 21602C, and 21603C) yields an age of 4240±829 Ma. As already described, occurrence and petrological character of 21602B are different from the other mafic gneisses. Excluding 21602B, we recalculated the age. These samples yield an isochron with an age of 3708±533 Ma (MSWD=0.53) and an initial ratio of 0.50794±0.00046, which corresponds to the initial εNd=2.6±4.8 (Fig. 3b). The large error should be attributed to the narrow variation of Sm/Nd ratio. Sample 21604G (ultramafic gneiss) is plotted below the 2458±61 Ma isochron, whereas sample 21601G (mafic gneiss) is plotted between the 2458±61 Ma isochron and the 3708±533 Ma one (Figs. 3a and 3b).

6. Discussion

The whole-rock isochron of the four samples (21603E, 21603H, 21603I and 21603N) indicates an age of 2458±61 Ma. Similar ages have been reported for rocks from the Casey Bay-Fyfe Hills region (40 km west of Tonagh Island, Fig. 1), *i.e.*, Rb-Sr whole-rock analyses (2463±35 Ma; BGACK *et al.*, 1983b, 2460±35 Ma; McCULLOCH and BLACK, 1984), a U-Pb zircon age (2456+8/−5 Ma; BLACK *et al.*, 1983a). Moreover, two ages have been reported from Mount Sones (60 km east of Tonagh Island, Fig. 1), *i.e.*, a Sm-Nd whole-rock isochron age of 2410±100 Ma (BLACK and McCULLOCH, 1987) and an ion-microprobe U-Pb zircon age of 2479±23 Ma (BLACK *et al.*, 1986a). These ages correspond to the D_3-M_3 tectonothermal event of the Napier Complex, widely accepted by previous authors (SHERATON *et al.*, 1987; BLACK *et al.*, 1983a, b, 1986a, b; HARLEY and BLACK, 1987; HARLEY and HENSEN, 1990).

The initial $^{143}Nd/^{144}Nd$ ratio of the 2458±61 Ma isochron indicates 0.50897±0.00004 (initial εNd=−9.5). This εNd value is extremely low compared with that of CHUR. The initial ratios of the Sm-Nd whole-rock isochron can provide constraints on the time of crust formation (McCULLOCH and BLACK, 1984). The large negative εNd value (εNd=−9.5) obtained here suggests that these rocks have a long time crustal history before 2458 Ma.

The samples plotted on the 2458±61 Ma isochron are composed of different types of rocks and apparently show the granuloblastic fabric overprinted by heterogeneous intercrystalline deformation and mylonitic recrystallization features. The typical D_3-M_3 fabric shows heterogeneous intercrystalline deformation and mylonitic recrystallization under the microscope (JAMES and BLACK, 1981; BLACK *et al.*, 1983b). The microfabric feature of the samples plotted on the 2458±61 Ma isochron resembles the D_3-M_3 fabric, suggesting that these samples had been deformed by the D_3-M_3 event. The Sm-Nd whole-rock isochron age of 2458±61 Ma is probably equivalent to the age of the D_3-M_3 tectonothermal event. Therefore, this isochron age and the initial ratio indicate a major period of re-equilibration of the isotopic system on a whole-rock scale at 2458±61 Ma, and this is the secondary isochron.

It is essential to estimate the timing of initial crust formation in this area. The whole-rock Sm-Nd isotopic ratios for the five mafic gneisses which show only granuloblastic fabric yield an imprecise isochron age of 3708±533 Ma with the initial ratio of 0.50794±0.00046 (initial εNd=2.6±4.8).

The εNd values normalized to 3708 Ma of the individual mafic gneiss, except for 21601G and 21602B, range from +1.3 to +3.3. These are close to the εNd(DM) at the time of 3708 Ma and are within εNd values of middle Archaean komatiites and basalts in the world (Fig. 4). Furthermore, model ages of depleted mantle (T_{DM}) for the samples plotted on the 3708±533 Ma isochron show T_{DM}=3580 to 3770 Ma (Table 3). Therefore, the age of *c*. 3700 Ma would indicate the formation of the mafic gneisses derived from the depleted mantle.

The ages newly determined here with previous works for the Napier Complex are summarized in Table 4. It was not possible to date the other ages (*c*. 3100 Ma and *c*. 2900

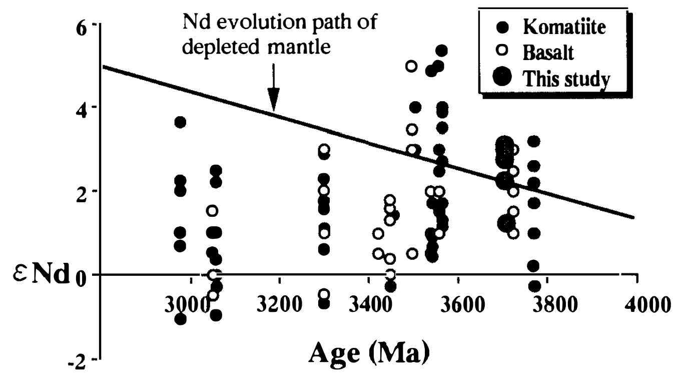

Fig. 4. εNd vs. age (Ma) diagram compiled from Archaean komatiites and basalts. The εNd(3708 Ma) values of the mafic gneisses plotted on the 3708±533 Ma isochron are within those of Archaean komatiites and basalts. Data taken from GRUAU *et al. (1990),* KAGAMI *and* KOIDE *(1987) and* SHIREY *and* HANSON *(1986), and sources therein.*

Table 4. Summaly of the tectonothermal ages for the Nepier Complex.

Age (Ma)	Method	Source	Event (1, 2, 3 and this study)
3927±10	U-Pb (z, S)	(4)	Orthogneiss precursor
<u>3708±533</u>	<u>Sm-Nd (wr)</u>	This study	<u>Formation of mafic rocks</u>
c. 3100	Rb-Sr (wr)	(5)	[D_1-M_1] Very high temperature metamorphism (VHT)
	Sm-Nd (wr)	(6)	
c. 2900	U-Pb (z, S)	(4)	[D_2-M_2] VHT, Isobaric cooling
	Rb-Sr (wr)	(7)	
c. 2460	U-Pb (z, S)	(4)	[D_3-M_3] Granulite to amphibolite Isothermal decompression
	U-Pb (z)	(7, 8)	
	Rb-Sr (wr)	(7, 8, 9)	
	Sm-Nd (wr)	(10)	
<u>2458±61</u>	<u>Sm-Nd (wr)</u>	This study	

Ages with underline are obtained here (see text). Other data are taken from 1; BLACK (1988), 2; SHERATON *et al.* (1987), 3; HARLEY and HENSEN (1990), 4; BLACK *et al.* (1986a), 5; SHERATON and BLACK (1983), 6; MCCULLOCH and BLACK (1984), 7; BLACK *et al.* (1986b), 8; BLACK *et al.* (1983a), 9; BLACK *et al.* (1983b) and 10; BLACK and MCCULLOCH (1987). S; SHRIMP, z; zircon and wr; whole-rock.

Ma) in this study. Since the tectonothermal event of D_3-M_3 seems to have been strong enough to re-equilibrate the isotopic systems of almost the entire Napier Complex, the event was dated repeatedly for the rocks from many locations of the complex (DePaolo *et al*., 1982 ; Black and McCulloch, 1987).

The formation ages of the ultramafic gneisses (samples 21603N and 21604G) are expected to be older than *c*. 3700 Ma because these rocks occur as blocks in the felsic and the pelitic gneisses accompanied by mafic gneiss. On the basis of this assumption, the time of initial crust formation in this area would be older than *c*. 3700 Ma.

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