Rb-Sr and Sm-Nd Ages from the Highland Complex of Sri Lanka

By Hiroo KAGAMI,^{*1)} Masaaki OWADA,^{*2)} Yasuhito OSANAI,^{*3)}
Kazuyuki SHIRAISHI,^{*4)} and Yoshikuni HIROI^{*5)}

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Abstract : Metagneous rocks from Gampola and Nuwara Eliya belong to the Highland Complex of Sri Lanka. Rb-Sr and Sm-Nd age data and initial Sr and Nd isotopic ratios document several geological events. (1) Separation of crustal material began in the late Archean. (2) Partial melting of crust took place on a large scale at ca. 2400 Ma, leaving metagneous rocks as restite after extraction of felsic magmas. (3) High-grade metamorphism related to the Pan-African orogeny occurred at 520 Ma. (4) Partial melting of crustal material proceeded on a local scale at 490 Ma-480 Ma, producing slight disturbance to the Rb-Sr whole-rock system.

Key words : Highland Complex of Sri Lanka; metagneous rocks; Rb-Sr age; Sm-Nd age.

Introduction. As Sri Lanka was situated inside of the Gondwana supercontinent prior to breakup, its geological relationships are important for Gondwana reconstruction. Sri Lanka consists mainly of high-grade metamorphic rocks which have been subdivided using Nd model ages into three major lithologic units. From west to east these are; 1, the Wannai Complex (2000 Ma-1100 Ma, mean 1600 ± 200 Ma), 2, the Highland Complex (3400 Ma-2000 Ma, mean 2500 ± 300 Ma) and 3, the Vijayan Complex (1800 Ma-1000 Ma, mean 1300 ± 200 Ma) (Fig. 1).^{1),2)}

The Wannai Complex, which records amphibolite-facies metamorphism, is composed of granitic gneisses and migmatite, granitoid rocks and metasedimentary rocks. The Highland Complex is composed of metagneous rocks of largely granitic composition, and metasedimentary rocks which generally occur as paragneiss, orthogneiss and charnockite. These rocks underwent upper amphibolite- to granulite-facies metamorphism. The Vijayan Complex records upper

amphibolite- to granulite-facies metamorphism.³⁾ It is composed of granitoid rocks, granitic migmatite and gneisses, and less common amphibolite and meta-sedimentary rocks.

Many researchers have shown that the Highland Complex has a different geological history from the Wannai and Vijayan Complexes.^{4),5)} The Highland Complex underwent regional high-grade metamorphism, and has a long history (in excess of 2000 Ma) compared with those of the other two complexes (less than 2000 Ma). Available geochronological data from the Highland Complex can be summarized as follows^{3),5),6)}; (1) initial crust was formed from 3000 Ma to 2000 Ma, (2) sedimentation and igneous activity (basic lava flows, basic sills and dykes) took place ca. 2000 Ma, (3) the earliest plutonism (mainly granitic magmas) occurred between 1940 Ma and 1800 Ma, (4) high-grade regional metamorphism and plutonism took place between 670 Ma and 450 Ma (Pan-African orogeny). Although geological events of Pan-African age have been analyzed in detail,⁵⁾ events prior to 2000 Ma have been relatively neglected by researchers.

In this paper, we present new Rb-Sr and Sm-Nd age data for metagneous rocks from quarries at Gampola and Nuwara Eliya, and discuss the crustal evolution of the Highland Complex.

Petrography of the analyzed samples. The nine analyzed samples were collected from quarries around Gampola (samples 1 to 4) and a quarry in Nuwara Eliya (samples 5 to 9) (Fig. 1). Precise positions of

^{*1)} Institute for Study of the Earth's Interior, Okayama University, Misasa, Tottori 682-01, Japan.

^{*2)} Department of Earth Sciences, Yamaguchi University, Yamaguchi 753, Japan.

^{*3)} Department of Earth Sciences and Astronomy, Fukuoka University of Education, Fukuoka 811-41, Japan.

^{*4)} National Institute of Polar Research, Itabashi-ku, Tokyo 173, Japan.

^{*5)} Department of Earth Sciences, Chiba University, Chiba 260, Japan.

Fig. 1. Sample localities.

quarries are shown on the attached map of Hiroi and Motoyoshi (1990).⁷⁾ These metaigneous rocks of the Highland Complex are free from alteration and mylonitic deformation.

Sample 1 is a garnet-bearing felsic gneiss, consisting mainly of quartz, mesoperthite, plagioclase, orthopyroxene and garnet, and a small amount of biotite. Some biotite forms a foliation, whereas another type surrounds mafic minerals, such as garnet and orthopyroxene. Samples 2, 3 and 4 were collected from a section of the same quarry where there is pronounced compositional banding due to variation in the amounts of orthopyroxene, hornblende, biotite, garnet and felsic minerals. The former two samples are garnet-bearing orthopyroxene amphibolites. These rocks consist mainly of hornblende, orthopyroxene, plagioclase and garnet with small amounts of quartz, K-feldspar and carbonate minerals. Sample 4, which is in contact with sample 2, is a garnet-bearing felsic gneiss, which is mainly composed of felsic minerals. Mafic minerals are garnet, hornblende and biotite. The garnets show porphyroblast features, whereas the other two minerals are smaller and have hypidiomorphic texture.

Samples 5 to 9 were collected from Nuwara Eliya quarry. Most typical of the rocks in this quarry are the

Fig. 2. Rb-Sr whole-rock isochron diagram. Open circles; Gampola, closed circles; Nuwara Eliya. Circles with bar are biotite-bearing rocks.

well banded samples 5 and 8. Sample 6 is a two-mica granite which occurs in parallel with clinopyroxenite sheet. Sample 9 is coarse-grained leucocratic band. These rocks (samples 6, 9 and clinopyroxenite) occur as concordant lenticular sheets about 5 m long and 0.1–0.2 m thick. Sample 7 is a melanocratic schlieren about 20 cm long and several centimeters thick. The five samples are divided into two groups; pyroxene amphibolite and K-feldspar-rich felsic rocks. The pyroxene amphibolites (samples 7 and 8) consist mainly of hornblende, clinopyroxene, orthopyroxene and garnet, and a small amount of plagioclase. The K-feldspar-rich felsic rocks (samples 5 and 9) consist mainly of K-feldspar, quartz, plagioclase and orthopyroxene, and small amounts of garnet, biotite and hornblende. Sample 6 is a two-mica granite which consists of K-feldspar, quartz and plagioclase with subordinate biotite and muscovite. Zircon is a common phase, as rounded grains.

Analytical procedure. Extraction procedures for Rb, Sr, Sm and Nd have been discussed elsewhere.⁸⁾ Isotopic analyses were performed on a MAT261-type (modified from MAT260) mass spectrometer equipped with five Faraday cups. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios to $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$. The measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for NBS987 during this study was 0.710220 ± 0.000010 (2σ ,

Table I. Analytical results. Numbers in parentheses in the localities column represent the name of rock specimens. F*; felsic fraction, G*; garnet, M*; mafic fraction (hornblende, biotite and a small amount of garnet). Numbers in parentheses for $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios represent analytical reproducibility in terms of 2σ , referring to the last digits. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were calculated using an age of 2415 Ma.

Sample No.	Localities	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Initial $^{87}\text{Sr}/^{86}\text{Sr}$	$T_{\text{DM}}(\text{Ma})$
1	Gampola 2153	80.1	264	0.8816	0.74088(2)	6.64	33.6	0.1196	0.511437(23)	—	2770
2	Gampola 2154(0)	20.9	72.7	0.8356	0.74865(2)	20.5	109	0.1134	0.511341(17)	0.71948	2740
3	— 2154(1)	15.2	114	0.3870	0.73140(2)	10.6	48.0	0.1336	0.511654(18)	0.71790	2840
4	— 2154(2)	223	189	3.446	0.80445(2)	7.01	44.1	0.0960	0.511077(19)	—	2680
	— 2154(2)F*	—	—	—	—	5.75	47.9	0.0725	0.510992(12)	—	—
	— 2154(2)G*	—	—	—	—	21.7	21.1	0.6203	0.512890(17)	—	—
	— 2154(2)M*	—	—	—	—	76.7	325	0.1427	0.511248(10)	—	—
5	Nuwara Eliya 2157(0)	32.3	179	0.5251	0.73737(2)	8.26	44.6	0.1120	0.511345(19)	0.71905	2700
6	— 2157(1)	185	209	2.561	0.75111(2)	17.9	170	0.0634	0.511189(20)	—	—
						17.6	168	0.0632			
7	— 2157(2)	22.6	55.6	1.182	0.76023(2)	46.1	249	0.1119	0.511223(21)	0.71906	2870
8	— 2157(3)	96.3	159	1.762	0.78044(2)	12.8	67.7	0.1140	0.511180(19)	0.71904	3000
9	— 2157(4)	183	212	2.516	0.78510(1)	4.06	21.9	0.1122	0.511147(18)	—	3000

Fig. 3. Sm-Nd whole-rock isochron diagram. Open circles; Gampola, closed circles; Nuwara Eliya.

N=3). Rb and Sr concentrations were measured by isotope dilution using a ^{87}Rb - ^{86}Sr mixed spike. $^{143}\text{Nd}/^{144}\text{Nd}$ ratios in Table I are reported relative to $^{143}\text{Nd}/^{144}\text{Nd}=0.512640$ for BCR-1 (USGS standard).⁹⁾ Sm and Nd concentrations were measured by isotope dilution using a ^{149}Sm - ^{145}Nd mixed spike. We estimate an error of 0.5% for the Rb/Sr ratios and 0.1% for the Sm/Nd ratios of each sample based on reproducibility of the data. We use the following CHUR (Chondritic Uniform Reservoir) parameters for calculation of initial ϵNd value; $^{147}\text{Sm}/^{144}\text{Nd}_{(\text{present})}=0.1966$, $^{143}\text{Nd}/^{144}\text{Nd}_{(\text{present})}=0.512638$. Model ages (T_{DM}) using depleted mantle were calculated by the following parameters; $^{147}\text{Sm}/^{144}\text{Nd}_{(\text{present})}=0.2136$, $^{143}\text{Nd}/^{144}\text{Nd}_{(\text{present})}$

$=0.513153$ ($\epsilon\text{Nd}=+10$). Rb-Sr and Sm-Nd isochron ages were calculated using the equation of York (1966)¹⁰⁾ and the following decay constants; $\lambda^{87}\text{Rb}=1.42\times 10^{-11}\text{y}^{-1}$ and $\lambda^{147}\text{Sm}=6.54\times 10^{-12}\text{y}^{-1}$. Analyzed data with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and model ages (T_{DM}) are shown in Table I.

Results. Metagneous rock data from Gampola and Nuwara Eliya are highly scattered on a Rb-Sr isochron diagram (Fig. 2). However, biotite-free mafic rocks (samples 5, 7 and 8) from Nuwara Eliya define an isochron with an age of 2415 ± 2 Ma. Biotite-free rocks from Gampola (samples 2 and 3) also plot on this isochron. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios of these rocks calculated using 2415 Ma range from 0.7179 to 0.7195

Fig. 4. Sm-Nd whole rock-mineral isochron of sample 4 from Gampola. Felsic fraction; quartz, plagioclase and K-feldspar, Mafic fraction; hornblende, biotite and minor garnet, Wr; whole rock. Numbers in parentheses indicate sample number.

(mean 0.7189 ± 0.0006 , Table I). These values are extremely high compared with estimated CHUR (0.7015) and N-MORB mantle source mantle (0.7006) compositions at this age.

Biotite-bearing and K-feldspar-rich felsic rocks from Nuwara Eliya and Gampola plot to the right of the 2415 Ma isochron. The slope of the line connecting samples 5 and 6 (Nuwara Eliya) yields an age of 480 Ma. Sample 6 (two-mica granite) and sample 9 (coarse-grained leucocratic rock) occur as concordant lenticular sheets in dominant rocks (samples 5 and 8) at Nuwara Eliya.¹¹⁾

Samples collected from along the road between Gampola and Nuwara Eliya were analyzed for Sm and Nd isotopes. Data from Gampola give a well defined isochron age of 2330 ± 30 Ma with an initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.50960 ± 0.00002 (Fig. 3). The latter ratio corresponds to an initial ϵNd value of -0.4 ± 0.3 . On the other hand, samples from Nuwara Eliya do not give an isochron. Sample 5, which is one of the main rock types at Nuwara Eliya, plots close to the isochron, suggesting a similar age to the 2330 Ma of the Gampola samples; however, another dominant rock type (sample 8) plots away from the isochron. The slope of the line connecting samples 5 and 6 corresponds to an age of 490 Ma, which is coincident with the Rb-Sr age of 480 Ma for the same samples.

For sample 4, we have also analyzed Sm and Nd concentrations and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios for whole rock, garnet, mafic (hornblende, biotite and a small amount

Fig. 5. Sr evolution lines for biotite-free metaigneous rocks. G; Gampola, N; Nuwara Eliya.

of garnet) and felsic fractions (plagioclase, K-feldspar and quartz). These give a well defined isochron age of 525.1 ± 5.8 Ma (Fig. 4). In view of the mineral assemblages from Gampola, the 525 Ma age is assigned to the last granulite-facies metamorphism. Isotopic equilibration for Sri Lankan rocks occurred on a centimeter scale only during high-grade metamorphism.¹²⁾ Accordingly, Rb-Sr and Sm-Nd whole-rock systems were not significantly disturbed at granulite-facies metamorphism. In other words, the ages obtained by Rb-Sr and Sm-Nd whole-rock isochrons might temporally define a significant event prior to the Pan-African orogeny.

Discussion. As described above, the Nuwara Eliya samples (samples 5, 7 and 8) give a Rb-Sr whole rock isochron age of 2415 Ma (Fig. 2). Biotite-bearing samples 6 and 9 plot away from this isochron, with this scatter probably being caused by a ca. 480 Ma event, as described below. However, even if these two samples are excluded, samples 5, 7 and 8 do not give a Sm-Nd whole rock isochron (Fig. 3). Strontium easily attains isotopic equilibrium during certain conditions of metamorphism and magmatism, compared to neodymium. Thus, it is likely that Nd isotopic equilibrium for the Nuwara Eliya rocks was not attained at 2300 Ma-2400 Ma.

The assumption of an age of 2330 Ma yields an

Fig. 6. Regions in Gondwana supercontinent which were affected by Pan-African orogeny (simplified from McElhinny, 1973¹³). Stippled parts represent areas subjected to the Pan-African orogeny. Names of cratons are given. Reconstruction of the Gondwana supercontinent is after Lawver and Scotese (1987).¹⁴

initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio by 0.50960 for Gampola rocks, which corresponds to a near CHUR value of -0.4 in terms of ϵNd . The Rb-Sr whole rock age obtained from biotite-free mafic rocks is 2415 Ma which is close to the Sm-Nd whole rock isochron age of 2330 Ma. U-Pb zircon ages of about 2400 Ma, using SHRIMP, have been reported from metabasite and metaquartzite collected from the Highland Complex.^{5),12)} However, the significance of this age has not been discussed in detail. Cooray (1994)³⁾ and Kröner *et al.* (1994)⁵⁾ summarized geochronological data of the Highland Complex and stated that sedimentation took place at ca. 2000 Ma. However, analyzed samples in this study are not metasedimentary rocks but metaigneous rocks. The mean initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (2415 Ma) obtained from biotite-free rocks is 0.7189, which is extremely high compared to CHUR (0.7015). Taking this into account, the age of 2300–2400 Ma is not a primary age when these rocks were formed initially from primitive mantle like CHUR.

In order to deduce the primary age of mantle-derivation, model ages (T_{DM}) were calculated using a depleted mantle like N-MORB source (Table I). The calculated model ages are in the range from 3000 Ma to 2600 Ma (mean 2830 Ma) which are within the range of 3100 Ma to 2100 Ma (except for one data) reported by Milisenda *et al.* (1994).²⁾ The T_{DM} of 3100 Ma to 2100 Ma after Milisenda *et al.* (1994)²⁾ are recalculated values using a $^{147}\text{Sm}/^{144}\text{Nd}_{(\text{present})}$ ratio of 0.2136 as a value of depleted mantle, because they used 0.2188.

The model ages suggest that separation of Gampola and Nuwara Eliya crustal material from depleted mantle took place in the late Archean.

Rb and Sr isotope data for biotite-free mafic rocks define an isochron with an age of 2415 Ma and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7189 ± 0.0006 , as mentioned above. The gradients of the lines (Sr evolution) connecting present $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and their initial ratios (2415 Ma) are less steep than those of the lines connecting their initial ratios and the ratios of depleted mantle at T_{DM} (Fig. 5). A change in gradient of these Sr evolution lines implies a change of Rb/Sr ratio (e.g. sample 2, from 1.4 to 0.3), which suggests that a significant geological event occurred at about 2400 Ma. One possibility is the extraction of felsic magma with a high Rb/Sr ratio. The products of such a magma would be expected to have a high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. According to this model, the rocks from Gampola and Nuwara Eliya are considered to be restite after extraction of felsic magma. If so, model ages (" T_{DM} ") may give a maximum age for separation of the precursor from the depleted mantle.¹¹⁾ However, even if separation of the precursor from the depleted mantle occurred at a later time than the calculated T_{DM} , the geological event at 2400 Ma caused a change from high to low Rb/Sr.

Prior to continental drift, Africa, Antarctica and India were situated in the vicinity of Sri Lanka (Fig. 6). Ages of 2400 Ma have been reported from these continents,^{6),15)–18)} corresponding to the latest stages

of the Limpopo orogeny in Africa and the Insel orogeny of Antarctica.^{15),16)} Although the orogeny in India has not been formally named, similar Nd model ages for charnockites have been reported from the Kerala Khondalite Belt in southern most India.¹⁹⁾

The metaigneous rock sample 4 from Nuwara Eliya yields a Sm-Nd whole rock-mineral isochron age of 525.1 ± 5.8 Ma (Fig. 4). Similar ages have been reported not only from the Highland Complex, but also from the Wannai and Vijayan Complexes.^{4),5),12)} Furthermore, these ages, indicative of Pan-African orogeny, have been reported from the Gondwana supercontinent (Fig. 6) and also from rocks which underwent the Caledonian orogeny in the Laurasia supercontinent. Thus, metaigneous rocks from Nuwara Eliya underwent high-grade metamorphism during the Pan-African orogeny. Although this orogeny must have been one of the biggest events in earth history, its causes have not yet been clarified.

Rocks from Nuwara Eliya underwent partial melting on a local scale at 490 Ma to 480 Ma, when two-mica granite (sample 6) was formed from sample 5-type source material, which is supported by major and minor element chemistry.¹¹⁾ Rb-Sr whole-rock systems of the metaigneous rocks from Nuwara Eliya (and probably Gampola) were slightly disturbed by this geological event.

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