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^{40}Ar-^{39}Ar AGES OF DOLERITE DYKES FROM SRI LANKA

Yutaka TAKIGAMI[1], Masaru YOSHIDA[2] and Minoru FUNAKI[3]

[1]*Kanto Gakuen University, 200 Fujiagu, Ohta 373-8515*
[2]*Department of Geosciences, Faculty of Science, Osaka City University, Sugimoto 3-chome, Sumiyoshi-ku, Osaka 558-8585*
[3]*National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*

Abstract: Two ^{40}Ar-^{39}Ar ages were obtained for dolerites from Sri Lanka which had been dated by the K-Ar method as 143–152 Ma. ^{40}Ar-^{39}Ar ages, which are more reliable than the K-Ar ages, are 160–170 Ma. These ages are important for constraining the scenario of break-up of Gondwana in the early Jurassic period.

key words: ^{40}Ar-^{39}Ar age, Sri Lanka, Gondwana

1. Introduction

In southeast Sri Lanka, unmetamorphosed dolerite dykes cut the Vijayan Complex, which is one of the Precambrian high-grade metamorphic terrains (Fig. 1). YOSHIDA *et al.* (1989) reported two K-Ar ages of 152.2±7.6 Ma and 143.3±7.2 Ma for these dykes from the Gallodai area. From a paleomagnetic study, they concluded that, if Sri Lanka was rotated on a map in order to attach it to Antarctica at Lützow-Holm Bay, the virtual geomagnetic pole position became to fit that obtained from the study of the Ferrar dolerite of Antarctica (FUNAKI, 1983). However, the ^{40}Ar-^{39}Ar age of Ferrar dolerite has been dated to be 176.6±1.8 Ma (HEIMANN *et al.*, 1994), which is older than the K-Ar ages of the above mentioned dykes. Hence, in order to clarify the cause of the apparent difference in the ages, we dated the dykes by the ^{40}Ar-^{39}Ar method.

2. Samples and Experiments

Dolerite dyke samples (Samples A–F) were collected within an area of 300 m in scale from the Gallodai area (Fig. 1) by YOSHIDA *et al.* (1989). Two samples (Samples E and F) selected from those used for the K-Ar (Samples C and F) and paleomagnetic studies in YOSHIDA *et al.* (1989) are used for this ^{40}Ar-^{39}Ar study. Constituent minerals of the dolerites are mostly plagioclase and clinopyroxene with minor amounts of amphibole, biotite, micrographic aggregates of quartz and potash feldspar, and opaque minerals (YOSHIDA *et al.*, 1989). Although these samples are generally fresh, plagioclase of sample F is slightly altered in comparison with that of sample E under a microscope. ELLIS and ABEYSINGHE (1987) reported the Gallodai dyke as quartz-normative tholeiite from a geochemical study.

Core blocks taken for paleomagnetic studies were crushed and sieved to 30–60

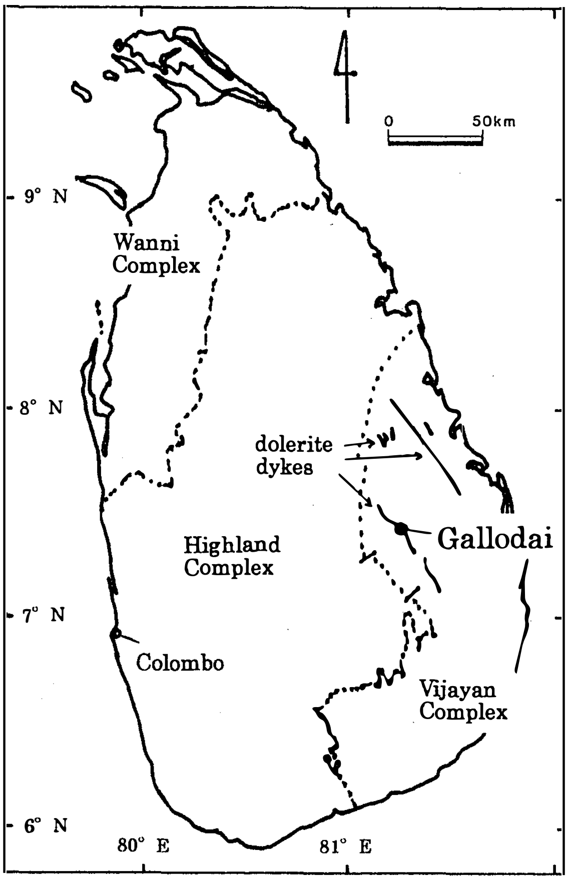

Fig. 1. Distribution of dolerite dykes in Sri Lanka (modified after Yoshida *et al., 1989).*

mesh. After washing by acetone, these sieved samples were wrapped in thin Al foil and stacked in a vacuum sealed quartz tube together with age standard samples EB-1 (biotite separated from JG-1, standard sample prepared from a Japanese granodiorite by the Geological Survey of Japan; K=6.69±0.09 wt%; 91.4±0.5 Ma; Iwata, 1998). K_2O and CaF_2, which are used for determining correction factors for the K- and Ca- derived interference Ar isotopes to ^{40}Ar, ^{39}Ar and ^{36}Ar, were also sealed in the same quartz tube. After fast neutron irradiation of about 10^{18} n/cm^2 in JMTR (Japan Material Testing Reactor), samples were heated in a Mo furnace using the induction heater. Ar gases were purified with the heated Ti and analyzed on a mass spectrometer (VG3600) at the Radio Isotope Center, University of Tokyo. Temperatures were controlled by the output power of the induction heater and monitored with an optical pyrometer at the top of Mo furnace.

After correcting for the effects of the mass discrimination and K- and Ca- derived Ar isotopes, ages were calculated by comparing the $^{40}Ar^*/^{39}Ar_k$ ($^{40}Ar^*$ and $^{39}Ar_k$ mean the radiogenic ^{40}Ar and K-derived ^{39}Ar, respectively.) obtained for samples with that of the standard sample.

Table 1. Analytical data of ^{40}Ar-^{39}Ar studies.

Sample E (weight=0.0343g; J=0.003952±0.000028)

Temperature (°C)	^{40}Ar ($\times 10^{-6}$ cm^3/g)	$^{36}Ar/^{40}Ar$ ($\times 10^{-4}$)	$^{37}Ar/^{40}Ar$ ($\times 10^{-2}$)	$^{38}Ar/^{40}Ar$ ($\times 10^{-3}$)	$^{39}Ar/^{40}Ar$ ($\times 10^{-2}$)	$^{40}Ar^{*}/^{39}Ar_K$ (1)	^{39}Ar (%)	Age (2) (Ma)	K/Ca (3)
600	0.311	23.47	5.603	2.294	2.940	10.65	2.1	74.36	0.524
		±0.33	±0.066	±0.023	±0.006	±0.33		±2.34	
700	0.523	9.324	1.957	2.232	3.515	20.66	4.3	141.6	1.796
		±0.133	±0.024	±0.022	±0.005	±0.12		±1.2	
800	1.63	11.03	1.139	1.738	2.732	24.71	10.3	168.1	2.398
		±0.15	±0.013	±0.006	±0.006	±0.17		±1.6	
900	1.29	4.352	1.455	1.999	3.461	25.21	10.4	171.3	2.378
		±0.079	±0.027	±0.026	±0.014	±0.12		±1.4	
1000	1.63	1.920	1.481	8.225	3.880	24.33	14.7	165.7	2.619
		±0.033	±0.017	±0.080	±0.006	±0.06		±1.2	
1100	2.03	1.315	2.456	2.475	3.979	24.21	18.7	164.9	1.620
		±0.027	±0.029	±0.025	±0.011	±0.08		±1.2	
1200	1.59	2.605	3.872	2.357	3.995	23.21	14.7	158.3	1.031
		±0.057	±0.045	±0.023	±0.006	±0.07		±1.2	
1300	1.66	3.632	7.481	2.208	3.891	23.19	14.9	158.2	0.519
		±0.101	±0.087	±0.022	±0.008	±0.11		±1.3	
1500	1.18	6.350	12.39	2.093	3.628	22.84	9.9	155.9	0.292
		±0.269	±0.14	±0.022	±0.006	±0.24		±1.9	

Sample F (weight=0.0314g; J=0.003861±0.000027)

Temperature (°C)	^{40}Ar ($\times 10^{-7}$ cm^3/g)	$^{36}Ar/^{40}Ar$ ($\times 10^{-4}$)	$^{37}Ar/^{40}Ar$ ($\times 10^{-3}$)	$^{38}Ar/^{40}Ar$ ($\times 10^{-3}$)	$^{39}Ar/^{40}Ar$ ($\times 10^{-2}$)	$^{40}Ar^{*}/^{39}Ar_K$	^{39}Ar (%)	Age (Ma)	K/Ca
600	10.2	10.47	20.94	2.484	3.869	17.90	35.3	120.5	1.847
		±0.14	±0.25	±0.024	±0.007	±0.12		±1.1	
700	9.76	7.363	8.989	2.037	3.456	22.65	30.2	151.2	3.844
		±0.103	±0.108	±0.020	±0.005	±0.10		±1.2	
800	2.59	3.467	8.906	2.128	3.774	23.79	8.8	158.5	4.236
		±0.069	±0.142	±0.021	±0.007	±0.07		±1.2	
900	1.60	4.278	8.544	2.096	3.674	23.78	5.3	158.5	4.299
		±0.103	±0.192	±0.021	±0.009	±0.10		±1.2	
1000	1.21	3.274	8.383	2.146	3.775	23.93	4.1	159.4	4.503
		±0.109	±0.286	±0.021	±0.007	±0.10		±1.2	
1100	0.886	3.796	8.102	2.127	3.737	23.76	3.0	158.4	4.611
		±0.158	±0.271	±0.024	±0.013	±0.15		±1.4	
1200	0.665	0.8123	8.383	2.266	4.119	23.70	2.5	157.9	4.912
		±0.4203	±0.367	±0.026	±0.015	±0.32		±2.3	
1300	0.802	0.9449	5.826	2.260	4.151	23.41	3.0	156.1	7.125
		±0.4864	±0.509	±0.027	±0.017	±0.36		±2.5	
1500	2.07	n.d. (4)	11.01	2.336	4.278	23.97	7.9	159.7	3.886
			±0.30	±0.030	±0.023	±0.48		±3.3	

± in values are errors of one standard deviation.

^{36}Ar, ^{37}Ar, ^{39}Ar and ^{40}Ar values in this table are not corrected for interference Ar isotopes derived from K and Ca. Ages and other values have been corrected for interference Ar isotopes by using following values; $(^{40}Ar/^{39}Ar)_K$=0.03000±0.00274, $(^{39}Ar/^{37}Ar)_{Ca}$=0.0007328±0.0000178, $(^{36}Ar/^{37}Ar)_{Ca}$=0.0004228±0.0000821.

(1) $^{40}Ar^{*}$ and $^{39}Ar_K$ mean the radiogenic ^{40}Ar and K-derived ^{39}Ar, respectively.

(2) Ages were calculated by using following constants. $\lambda_e=0.581\times 10^{-10}/y$, $\lambda_\beta=4.962\times 10^{-10}/y$, $^{40}K/K=1.167\times 10^{-4}$ (STEIGER and JÄGER, 1977).

(3) K/Ca ratios were calculated from $^{39}Ar_K/^{37}Ar_{Ca}$, where $^{37}Ar_{Ca}$ means Ca-derived ^{37}Ar.

(4) "n.d." means not detected.

3. Results and Discussion

Analytical data are listed in Table 1 and age spectra and K/Ca plots are shown in Fig. 2.

For sample E, we have obtained an age of 169.7±1.6 Ma for 800 and 900°C fractions (released ^{39}Ar is 20.7%). The total fusion age is 160.3±1.1 Ma. The ages for higher temperature fractions are slightly younger than those for 800 and 900°C fractions. These descending ages might occur due to the redistribution of radiogenic ^{40}Ar caused by thermal metamorphism or insufficient corrections of Ca-derived Ar because the sample has relatively high Ca contents as recognized from the low K/Ca ratios in Fig. 2. Hence, the age of this sample is conjectured to be 160–170 Ma.

For sample F, ages of 600 and 700°C fractions are younger than those of the other fractions and about 65% of ^{39}Ar are released in these temperature fractions which might correspond to the altered plagioclase. We have a plateau age of 158.6±0.6 Ma for 800–1500°C fractions whose released ^{39}Ar is 34.6% and K/Ca ratios are almost constant, around 4–5, except for the 1300°C fraction. The total fusion age of 143.0±1.1 Ma agrees well with the K-Ar age of 143.3±7.2 Ma for the same sample F reported in YOSHIDA *et al.* (1989). Since this sample shows the degassing feature of Ar from the age spectrum in Fig. 2, the plateau age would represent a meaningful age for the sample.

Considering the freshness of the samples, the present results suggest that the forma-

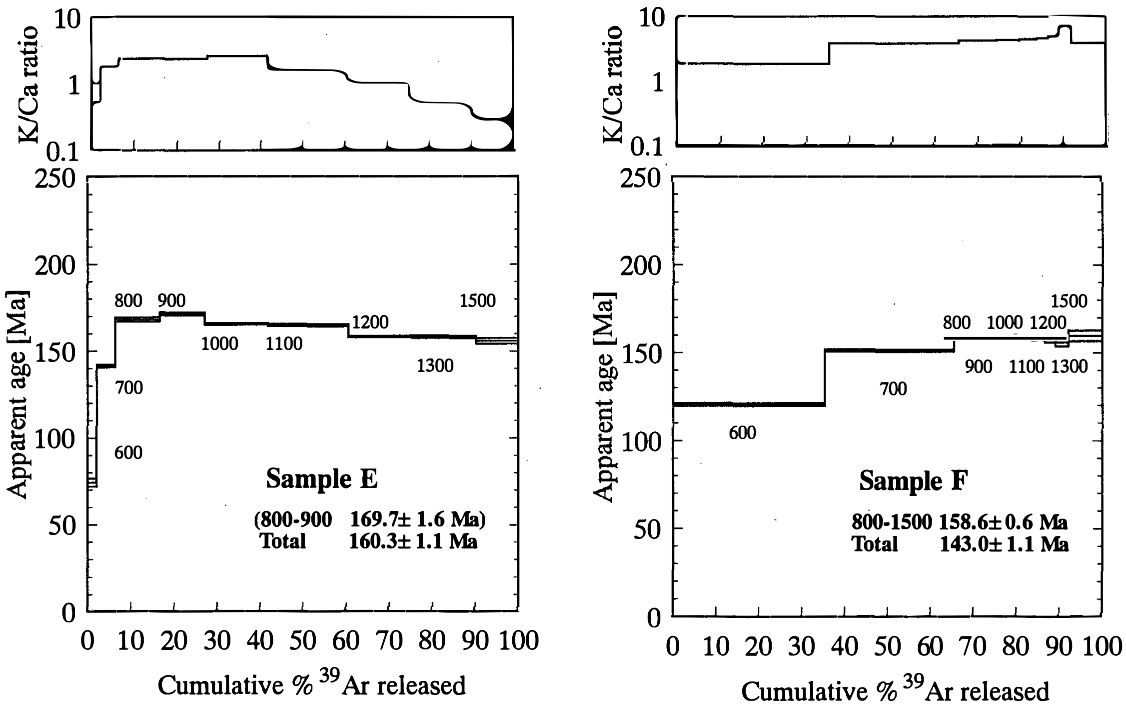

Fig. 2. ^{40}Ar-^{39}Ar age spectra and K/Ca plots. Upper part is K/Ca plot and lower part is age spectrum. K/Ca ratio differs for Ar gas degassed from different minerals or sites in the sample. Errors are included in age bands in the age spectrum and not illustrated in the K/Ca plot. Numerical figures of 600, 700, 800 ··· mean Ar degassing temperatures of 700°C, 800°C, 900°C ··· at the top of a Mo crucible, respectively.

tion age of this dolerite might be 160–170 Ma, which is older than the results of K-Ar datings.

Comparing the paleomagnetic data of this dolerite with those of Ferrar dolerite in the Transantarctic Mountains, YOSHIDA *et al.* (1989) conjectured that Sri Lanka should have been attached to Lützow-Holm Bay of East Antarctica before the disruption of Gondwana in Jurassic time and rotated to the present position. As the ^{40}Ar-^{39}Ar ages of the dolerite from Sri Lanka (160–170 Ma) become closer to that of Ferrar dolerite (176.6±1.8 Ma (HEIMANN *et al.*, 1994)) than K-Ar ages, the estimation of the position of Sri Lanka in Jurassic time from the paleomagnetic study becomes more reliable than before.

The initial rifting with the large tholeiitic magmatism in Gondwana is considered to have started about 180 Ma in South Africa (Karoo magmatism; ^{40}Ar-^{39}Ar age of 182±2 Ma, U-Pb age of 183.7±0.6 Ma) and Antarctica (Ferrar magmatism; ^{40}Ar-^{39}Ar age of 176.6±1.8 Ma, U-Pb age of 183.9±0.3 Ma) (Fig. 3) (STOREY, 1995; HEIMANN *et al.*, 1994; ENCARNACIÓN *et al.*, 1996; MINOR and MUSAKA, 1997). The sea-floor break-up had started at about 156 Ma based on magnetic anomaly M22 in the northern Mozambique Basin (SIMPSON *et al.*, 1979). During the time interval from 180 Ma to 156 Ma, there were slightly younger volcanic activities recorded at Ferrar magmatic province (173±6 Ma, 176±5 Ma, ^{40}Ar-^{39}Ar age) (BREWER *et al.*, 1992), Heimefrontfjella in western Dronning Maud Land in Antarctica (163 Ma, 172 Ma, K-Ar age) (JACOBS *et al.*, 1992) and the Karoo magmatic province (about 165 Ma, ^{40}Ar-^{39}Ar age and K-Ar age) (COX, 1988). Though Sri Lanka is far from Karoo and Dronning Maud Land (Fig. 3), the ages of the dolerite of Sri Lanka (160–170 Ma) correspond to the last stage of these initial rifting volcanic activities. As BREWER *et al.* (1992) suggested that volcanic rocks of Dronning Maud Land and younger ones of the Ferrar magmatic province have relatively lower initial $^{87}Sr/^{86}Sr$ ratios (<0.707) than those of older ones of Ferrar magmatic province (>0.709), it is interesting to measure the $^{87}Sr/^{86}Sr$ ratio of the Sri

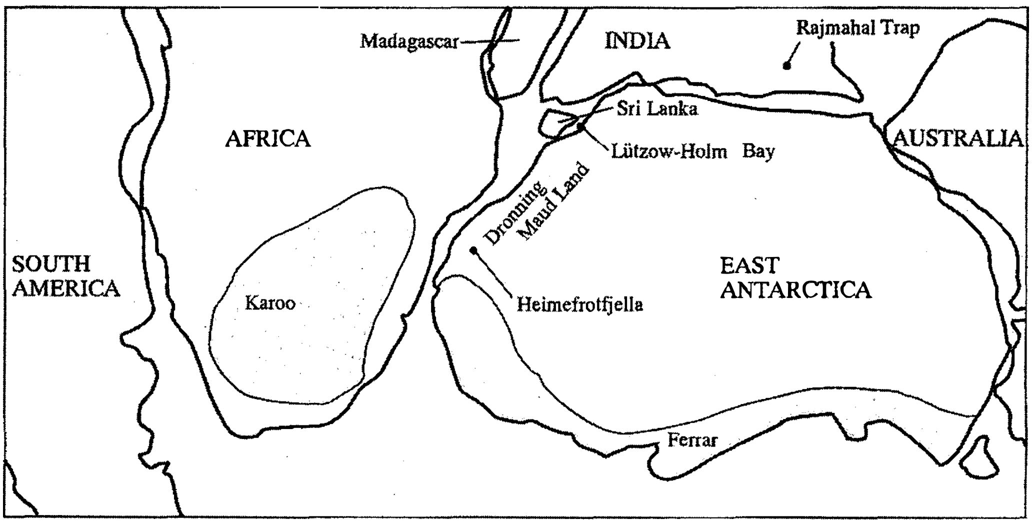

Fig. 3. Gondwana reconstruction at about 180 Ma. Karoo and Ferrar represent Karoo and Ferrar magmatic provinces, respectively (modified after STOREY, 1995).

Lanka dolerite to clarify the relationship between them and to consider the mechanism of 160–170 Ma magmatism in these areas.

BEHRENDT *et al.* (1992) proposed a theory of the propagating rift around Antarctica considering other magmatic activities such as those of Rajmahal Trap basalts whose ^{40}Ar-^{39}Ar ages are about 125–130 Ma (SAKAI *et al.*, 1997) (Fig. 3). As Sri Lanka was situated in the middle position between Karoo magmatic province and Rajimahal Trap, if the magmatism had been propagated around Antarctica, the ages of 160–170 Ma for Sri Lanka dolerites may be reasonable ages.

From the viewpoints of time and space, the dolerite of Sri Lanka must be studied more geologically and geochemically.

SHIRAISHI *et al.* (1988) found Jurassic tholeiitic boulders in the Lützow-Holm Bay region and pointed out the relation with Sri Lanka. Though the K-Ar age of a boulder is 131.8±6.9 Ma, it might represent the same igneous activities as Sri Lanka, considering that of K-Ar ages of Sri Lanka are 143–152 Ma. We need ^{40}Ar-^{39}Ar ages of boulders from the Lützow-Holm Bay region for more further discussion. Moreover, we might need to expand the research area to Madagascar, which was connected to Sri Lanka in Jurassic time.

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