

Rb-Sr, Sm-Nd ages of the Phalaborwa Carbonatite Complex, South Africa

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Abstract: We analyzed Rb-Sr and Sm-Nd isotopic compositions of whole-rock and minerals from syenite, biotite gneiss xenolith, dolerite dyke, phoscorite, and carbonatite from the Phalaborwa Carbonatite Complex located in northeastern Transvaal, South Africa. Syenite does not give significant Rb-Sr and Sm-Nd whole-rock and mineral isochron ages. Dolerite gives an Rb-Sr whole-rock and mineral isochron age of 2062 ± 74 Ma. This age overlaps with the timing of the magmatism of the Phalaborwa Carbonatite Complex. Biotite gneiss and phoscorite do not also give significant Rb-Sr and Sm-Nd isochrons. The Rb-Sr whole-rock and mineral isochron of phoscorite, however, gives an age of 2013 ± 93 Ma. The age is clearly the cooling age of this complex. Carbonatites are divided into two groups, having low and high initial Sr isotopic ratios. This coordinates with the result of S.C. Eriksson (Carbonatites, ed. by K. Bell, 1989). In addition, these groups indicate different initial Nd isotopic ratios. These suggest that carbonatite and related rocks were formed by mixing of two source magmas having different Sr and Nd isotopic compositions.

key words: Rb-Sr and Sm-Nd isochron age, phoscorite, carbonatite, Phalaborwa, South Africa

1. Introduction

In the Phalaborwa Carbonatite Complex located in northeastern Transvaal, South Africa, there is a world-wide Cu deposit (Fig. 1). Copper sulphides, magnetite, baddeleyite, apatite and uranoan thorianite have been mined from this deposit. Minor Ni, Au, Pt group metals, Ag, Se, Te, Th and U are also mined from this complex.

The geology of the Phalaborwa Carbonatite Complex has been well studied because of its high economic interest. Numerous geological, petrological, mineralogical and chronological reports have been presented for the clinopyroxenites, phoscorites and carbonatites composing the main complex (e.g. Hall, 1912a,b; Shand, 1931; Hanekom *et al.*, 1965; Palabora Mining Company, 1976; Eriksson, 1984, 1989; Reischmann, 1995).

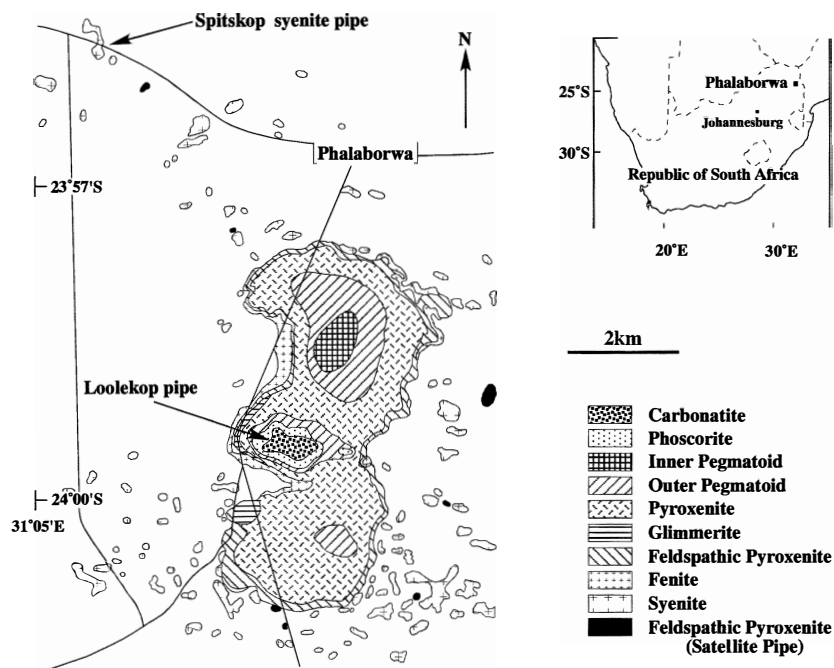


Fig. 1. Generalized geological map of the Phalaborwa Carbonatite Complex, South Africa (after Eriksson, 1984) with locations of the Spitskop syenite pipe and Loolekop pipe.

In contrast, the syenites that surround the main complex and appear as pipes have not been studied extensively, and therefore, there are few reports about the satellite bodies. Therefore, Yuhara *et al.* (2003) reported whole-rock isotopic compositions of syenite from the Spitskop pipe (Fig. 1), one of the satellite bodies of the Phalaborwa Carbonatite Complex. These syenites and related rocks are dispersed in Rb-Sr and Sm-Nd whole-rock isochron diagrams, and did not give clear whole-rock isochron ages. This suggests the necessity of whole-rock and mineral isochron ages.

In this paper, we report whole-rock and mineral Sr and Nd isotopic compositions of syenite, biotite gneiss xenolith, and dolerite from this syenite pipe, and phoscorite and carbonatite from the Loolekop pipe (Fig. 1).

2. Geological setting

The Phalaborwa Carbonatite Complex was formed by continuous intrusion of pyroxenite, syenite, ultramafic pegmatites and carbonatite into an Archaean terrain (Hall, 1912a,b; Shand, 1931; Hanekom *et al.*, 1965; Palabora Mining Company, 1976; Eriksson, 1984). The main complex is an elongated pipe-like body (Fig. 1). The Palabora Mining Company open pit (Fig. 2A), whose diameter is about 2 km, is located at the Loolekop pipe that crops out near the center of the Phalaborwa Carbonatite Complex (Fig. 1). This pipe is composed of phoscorite (a local name on the

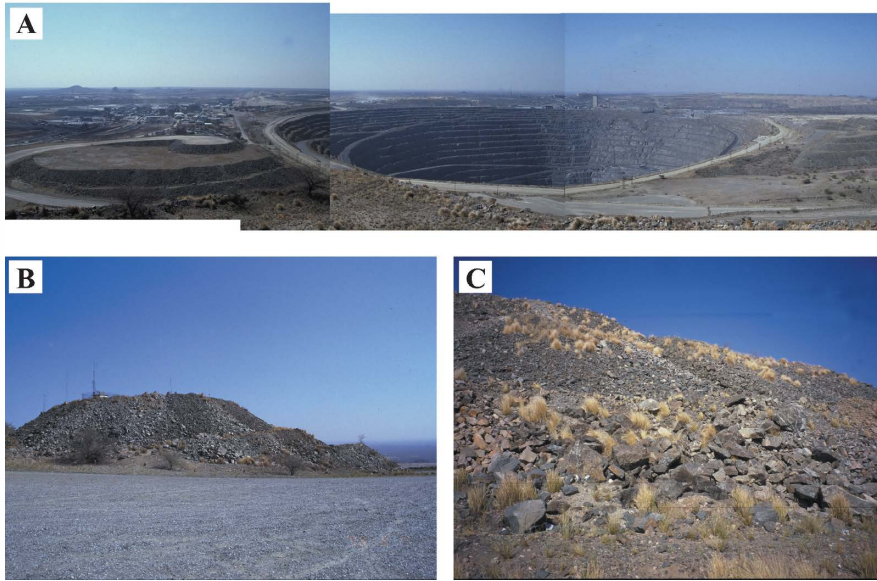


Fig. 2. Photographs of the open pit and waste of the Phalaborwa Copper Mine.
 A: Whole view of open pit. B: Whole view of waste. C: Close up view of the waste (photo B).

Phalaborwa Carbonatite Complex), banded carbonatite, and transgressive carbonatite (Palabora Mining Company, 1976). The phoscorite alternates with the banded carbonatite. The transgressive carbonatite is a dike like body cutting across these rocks. Satellite bodies are concentrated on or near the periphery of the main complex, but some occur away from the main complex, several kilometers to the northeast and northwest (Fig. 1). The rock types of satellite bodies include feldspathic pyroxenite, peralkaline syenite, peralkaline quartz syenite, peralkaline granite and trachyte. Northeast-southwest trending dolerite dykes of various sizes intruded into the main complex and satellite bodies.

It has been proposed that the timing of magmatism of the Phalaborwa Carbonatite Complex is about 2000 Ma, on the basis of an Rb-Sr isochron age of 2012 ± 19 Ma on phlogopites (Eriksson, 1984), and an U-Pb age between 2047 and 2061 Ma (Eriksson, 1984; Heaman and LeCheminant, 1993; Reischmann, 1995; Horn *et al.*, 2000; Wingate and Compston, 2000; French *et al.*, 2002) (Table 1). It has also been proposed that the activity of some of the dolerite dykes is about 1900 Ma (Briden, 1976) deduced from palaeomagnetic data. More detailed work of Briden (1976) confirms that most cross-cutting dykes in the Phalaborwa Complex are Precambrian (Palabora Mining Company, 1976; Eriksson, 1989). Eriksson (1989) showed the existence of large fenitized dolerite xenoliths and truncated dolerite dykes in the main complex, and suggested that dolerite magmatism commenced before formation of the main complex. Thus, magmatism of the dolerite continued intermittently for a long time.

Table 1. Radiometric ages of the Phalaborwa Carbonatite Complex.

Rock type	Age	Method	Reference
clinopyroxenite, carbonatite and phoscorite	2012 ± 19	Rb-Sr phlogopite	Eriksson (1984)
carbonatite and phoscorite	2047 + 11 / - 8	U-Pb thorianite and baddeleyite	Eriksson (1984)
carbonatite	2059.8 ± 0.8	U-Pb baddeleyite	Heaman and LeCheminant (1993)
	2060.6 ± 0.5	U-Pb baddeleyite	Reischmann (1995)
	2057 ± 8	U-Pb baddeleyite	Horn <i>et al.</i> (2000)
	2057.1 ± 2.6	SHRIMP baddeleyite	Wingate and Compston (2000)
	2059.6 ± 0.4	U-Pb baddeleyite	French <i>et al.</i> (2002)
	2026 + 46 / - 47	U-Th-total Pb baddeleyite	French <i>et al.</i> (2002)

3. Analyzed samples

Fine-grained syenite and biotite gneiss have been taken from the Spitskop pipe (Fig. 1; Yuhara *et al.*, 2003). The phoscorite and carbonatite of the Loolekop pipe have been taken at the waste site near the observatory commanding a view of the whole open pit (Figs. 2B, C).

Fine-grained syenite is characterized by porphyritic texture. It consists mainly of alkali-feldspar, quartz, clinopyroxene, amphibole, and accessory titanite, opaque minerals, apatite, zircon and monazite. This syenite has a modal composition of alkali-feldspar syenite (Yuhara *et al.*, 2003). Phenocrystic alkali-feldspar is euhedral to subhedral, up to 4 mm in diameter.

The biotite gneiss, which is a xenolith in the Spitskop syenite pipe, shows a banded structure (Fig. 3), with lepidoblastic and granoblastic texture (Fig. 4). It consists mainly of quartz, plagioclase, biotite, alkali-feldspar and accessory titanite, apatite, zircon, opaque minerals, and amphibole.

The phoscorite alternates with the banded carbonatite, and the boundary between both is complex (Fig. 5). They include each other. The phoscorite is holocrystalline —rock consisting mainly of olivine, apatite, magnetite, phlogopite, and a small amount

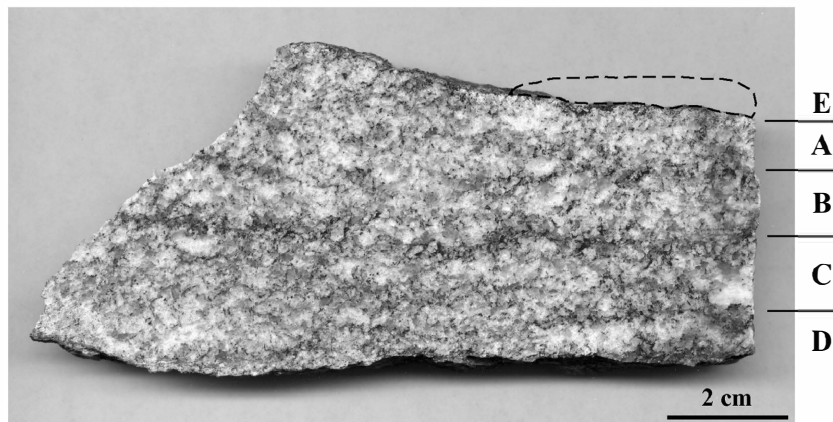


Fig. 3. Photograph of slab of biotite gneiss xenolith (98081501G) from the Spitskop syenite pipe.

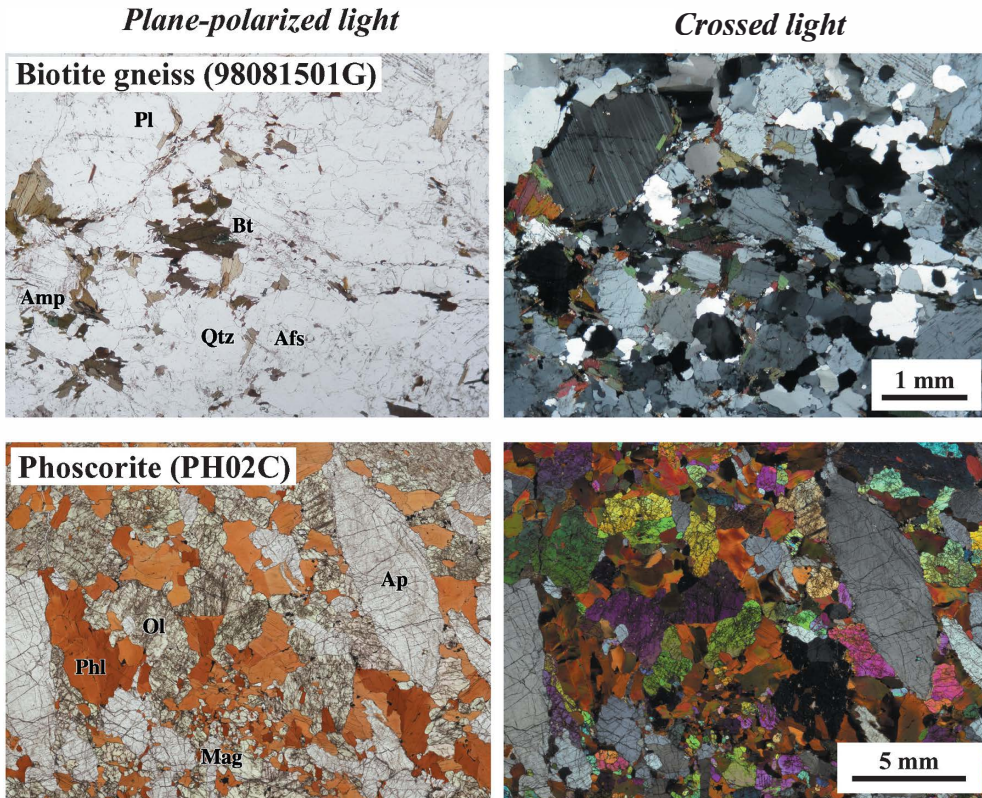


Fig. 4. Photomicrographs of biotite gneiss and phoscorite.

Pl: plagioclase, Qtz: quartz, Amp: amphibole, Bt: biotite, Afs: alkali-feldspar, Ap: apatite, Ol: olivine, Phl: phlogopite, Mag: magnetite.

of calcite (Fig. 4). Proportions of the constituent minerals of phoscorite vary considerably (Figs. 5B, C, D) from 100% magnetite to 100% olivine (Eriksson, 1989). Size of minerals also varies considerably (Figs. 5B, C, D). The size of euhedral to anhedral apatite is biggest, up to 5 cm in diameter. Euhedral to anhedral magnetite is up to 2.5 cm. Euhedral to anhedral phlogopite and olivine are less than 1 cm and 0.5 cm, respectively. Phoscorite PH03 was divided into six domains A: apatite rich domain, B: domain including apatite megacryst, C: olivine + apatite + phlogopite domain, D: mainly apatite + phlogopite domain, E: domain including magnetite megacryst, F: phlogopite + apatite + olivine domain, for analysis (Fig. 5D).

The Carbonatite consists mainly of calcite, dolomite, and a small amount of magnetite and phlogopite. PH06 is a member of banded carbonatite alternating with phoscorite. PH04 and PH05 might be members of transgressive carbonatite (Figs. 5A, B), because they do not alternate with phoscorite and include very little magnetite and phlogopite.

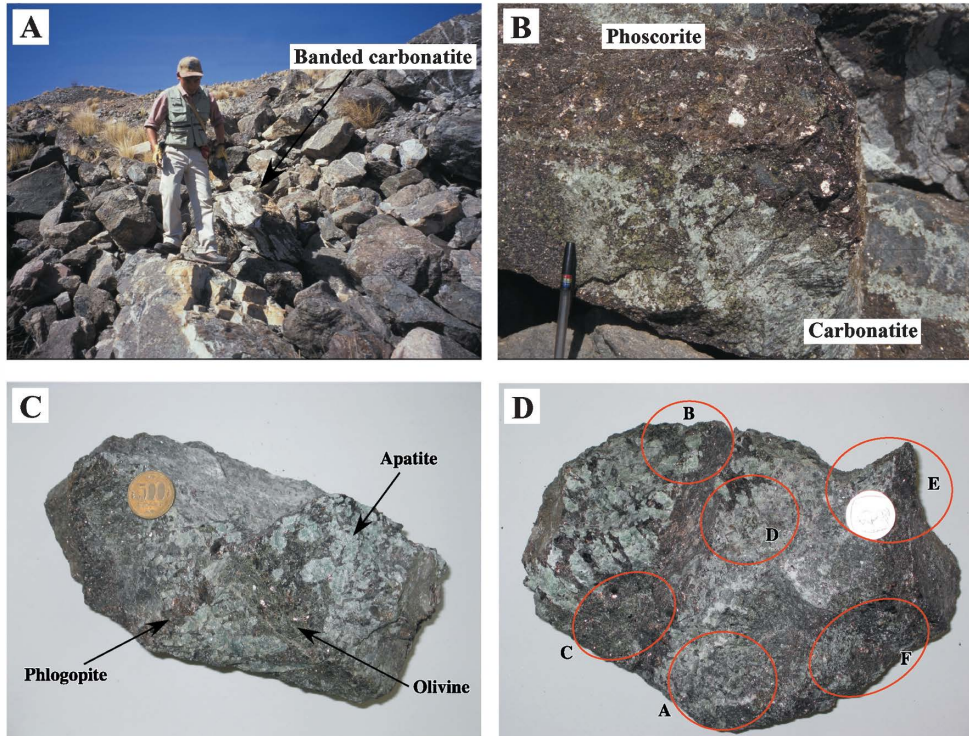


Fig. 5. Photographs of phoscorite and carbonatite.

A: Mode of occurrence of rolling stones at waste. B: Rolling stone of banded carbonatite.
 C: Minerals of phoscorite (PH02). D: Domains of analyzed phoscorite (PH03).

4. Chemistry

4.1. Analytical procedures

The major and trace element concentrations of samples were analyzed using the XRF (RIGAKU ZSX100e) at Fukuoka University by the method of Yuhara and Taguchi (2003a,b), Yuhara *et al.* (2004) and Takamoto *et al.* (2005). Their chemical compositions are given in Table 2. As, Ga, Pb, S and Th concentrations of the samples (syenites and related rocks) reported by Yuhara *et al.* (2003) were also analyzed. New data are given in the Appendix.

Clinopyroxene, amphibole, felsic fractions (mixtures of feldspars and quartz) from the fine-grained syenite and dolerite were separated with the help of an isodynamic separator and heavy liquids. Phlogopite and apatite were separated from phoscorite by hand picking. The biotite gneiss was divided into five layers (A–E) (Fig. 3).

Isotopic separation was performed at Saga University using the experimental procedure of Kawano *et al.* (1999). Isotopic analyses were performed on the thermal ionization mass spectrometer (MAT262) equipped with nine dynamic faraday cups at Niigata University. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to

Table 2. Whole-rock chemical compositions of the phoscorite and biotite gneiss.

Sample No.	PH-02F	PH-02C	PH-03A	PH-03B	PH-03C	PH-03D	PH-03E	PH-03F
SiO ₂ (wt.%)	44.86	27.98	24.74	35.40	36.78	24.78	29.31	25.29
TiO ₂	0.87	0.78	1.33	0.87	0.72	1.35	0.83	1.00
Al ₂ O ₃	3.94	3.60	2.79	3.80	2.97	3.81	1.87	4.89
Fe ₂ O ₃	8.04	6.28	5.60	7.57	7.18	6.82	8.08	6.40
MnO	0.12	0.08	0.08	0.09	0.10	0.08	0.13	0.07
MgO	16.91	11.64	10.12	14.27	14.68	11.73	15.89	12.55
CaO	16.70	27.01	30.06	22.15	23.07	26.71	24.83	24.87
Na ₂ O	0.21	0.00	0.00	0.06	0.09	0.00	0.03	0.00
K ₂ O	4.05	3.85	3.07	4.02	3.45	4.13	2.34	5.20
P ₂ O ₅	2.15	16.51	19.21	9.72	7.95	17.93	14.35	17.79
L.O.I.	0.95	0.93	1.02	0.97	2.22	1.19	1.06	0.79
Total	98.80	98.66	98.02	98.92	99.21	98.53	98.72	98.85
As(ppm)	<4	8	21	4	<4	13	8	7
Ba	762	711	773	706	608	851	429	895
Cr	158	138	240	170	154	410	617	235
Cu	n.d.	n.d.	<4	32	332	73	54	<4
Ga	7	5	<3	7	6	4	3	6
Nb	4	10	54	<5	<5	39	28	10
Ni	55	41	37	47	46	38	59	39
Pb	6	26	105	9	14	78	54	24
Rb**	254	247	194	255	209	298	139	353
S	28	58	75	57	166	89	81	46
Sr**	588	2531	2687	1432	1547	2934	2110	2333
Th	36	232	730	97	84	544	376	198
V	31	26	34	32	28	33	27	28
Y	30	139	216	79	72	185	134	144
Zn	76	57	42	65	53	54	59	57
Zr	196	3062	11670	862	251	5444	2491	1429

Sample No.	98081501G				
	A	B	C	D	E
SiO ₂ (wt.%)	70.45	72.87	72.77	73.07	69.69
TiO ₂	0.39	0.15	0.28	0.27	0.40
Al ₂ O ₃	15.34	15.42	14.84	14.46	15.48
Fe ₂ O ₃	2.57	0.97	1.76	1.74	2.71
MnO	0.02	0.01	0.01	0.01	0.02
MgO	0.83	0.34	0.57	0.58	0.87
CaO	2.23	2.24	2.20	2.09	2.21
Na ₂ O	5.82	6.04	5.70	5.57	5.83
K ₂ O	1.48	1.05	1.15	1.14	1.57
P ₂ O ₅	0.17	0.13	0.15	0.16	0.26
L.O.I.	0.40	0.30	0.33	0.37	0.53
Total	99.70	99.52	99.76	99.46	99.57
As(ppm)	<4	<4	<4	n.d.	<4
Ba	478	439	418	435	525
Cr	<4	n.d.	6	<4	<4
Cu	6	5	5	9	11
Ga	18	16	16	16	19
Nb	<5	n.d.	<5	<5	5
Ni	5	6	7	7	6
Pb	11	13	10	11	12
Rb**	73.9	35.9	53.0	55.6	80.7
S	29	16	16	31	58
Sr**	594	657	588	581	640
Th	24	39	18	23	26
V	13	5	12	10	13
Y	6	6	5	5	8
Zn	48	22	35	35	50
Zr	98	201	287	81	54

L.O.I., loss on ignition; n.d., not detected.

**Determined by isotope dilution.

$^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$, respectively. The normalized $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were corrected using the NBS-987 standard of $^{87}\text{Sr}/^{86}\text{Sr}=0.710241$. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were corrected with the Japanese standard JNdi-1 (Nd isotopic reference of the Geological Survey of Japan) of $^{143}\text{Nd}/^{144}\text{Nd}=0.512106$, which has been well-documented using the international standard La Jolla of $^{143}\text{Nd}/^{144}\text{Nd}=0.511849$ (Tanaka *et al.*, 2000). Sm, Nd, Rb and Sr concentrations were determined by an isotope dilution method using ^{87}Rb - ^{84}Sr and ^{149}Sm - ^{145}Nd mixed spikes. Rb-Sr and Sm-Nd isochron ages and initial Sr and Nd isotope ratios were calculated by the computer program of Kawano (1994) which used the equation of York (1966) and the decay constants $\lambda^{87}\text{Rb}=1.42 \times 10^{-11}/\text{y}$ (Steiger and Jäger, 1977) and $\lambda^{147}\text{Sm}=6.54 \times 10^{-12}/\text{y}$ (Lugmair and Marti, 1978). Analytical errors for $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were 0.5% (1 σ) and 0.01% (1 σ), and those for $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were 0.1% (1 σ) and 0.01% (1 σ), respectively. Detailed isotopic analytical procedures were reported by Miyazaki and Shuto (1998). The Rb-Sr and Sm-Nd isotopic data are given in Table 3.

Table 3. Rb-Sr and Sm-Nd isotopic data of rocks and minerals from the Phallaborwa Carbonatite Complex.

Sample No.	Rb(ppm)	Sr(ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}(2\sigma)^*$	Sm(ppm)	Nd(ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}(2\sigma)^*$
Fine-grained syenite								
98081501B	339	87.3	11.58	1.02098(1)	6.55	66.9	0.05830	0.510824(14)
98081501B-Cpx	13.0	143	0.2649	0.71763(1)	4.07	15.2	0.1615	0.511917(13)
98081501B-Amp	165	92.5	5.248	0.85006(1)	6.95	62.1	0.06762	0.510929(14)
98081501B-F.f.	585	54.9	33.49	1.58854(1)	0.73	4.10	0.1079	0.511437(13)
Dolerite								
98081501F-Cpx	73.2	38.0	5.670	0.88053(1)	6.57	25.9	0.1532	0.511850(13)
98081501F-Hb	34.3	83.0	1.201	0.74470(1)	8.60	34.2	0.1522	0.511861(14)
98081501F-F.f.	500	57.2	30.19	1.59344(2)	0.757	3.93	0.1166	0.511506(12)
Biotite gneiss								
98081501G-A	73.9	594	0.3603	0.71586(1)	7.51	82.4	0.05507	0.509915(14)
98081501G-B	35.9	657	0.1582	0.70991(1)	9.47	110	0.05187	0.509826(14)
98081501G-C	53.0	588	0.2609	0.71236(1)	5.65	61.2	0.05581	0.509902(14)
98081501G-D	55.6	581	0.2768	0.71313(1)	7.17	80.4	0.05394	0.509883(14)
98081501G-E	80.7	640	0.3656	0.71681(1)	7.60	80.2	0.05721	0.509925(14)
Phoscorite								
PH02F	254	588	1.251	0.73317(1)	26.8	143	0.1135	0.511239(12)
PH02C	247	2531	0.2824	0.71579(1)	161	935	0.1038	0.511119(12)
PH02-Phl	630	81.8	23.75	1.38990(1)	6.44	31.8	0.1235	0.511314(13)
PH02-Ap	0.7360	5536	0.000385	0.70709(1)	454	2690	0.1020	0.511069(51)
PH03A	194	2687	0.2087	0.71483(1)	254	1349	0.1138	0.511239(10)
PH03B	255	1432	0.5151	0.72034(1)	96.5	554	0.1052	0.511102(13)
PH03C	209	1547	0.3918	0.71766(1)	86.9	504	0.1043	0.511099(9)
PH03D	298	2934	0.2946	0.71698(1)	261	1433	0.1101	0.511156(10)
PH03E	139	2110	0.1911	0.71384(1)	151	860	0.1062	0.511106(13)
PH03F	353	2333	0.4381	0.71976(1)	186	1058	0.1062	0.511091(14)
Carbonatite								
PH04	2.01	4843	0.001198	0.71078(1)	40.6	209	0.1173	0.511206(14)
PH05	0.411	5182	0.000229	0.71090(1)	43.7	216	0.1222	0.511285(13)
PH06	0.240	8397	0.000083	0.70568(1)	58.0	337	0.1040	0.511133(9)

*bracket number indicates 2 σ error in the isotopic ratio.

Cpx: clinopyroxene, Amp: amphibole, F.f.: felsic-fractions, Hb: hornblende, Phl: phlogopite, Ap: apatite.

4.2. Major and trace elements

The phoscorite has SiO₂ content ranging from 24.7 wt% to 44.9 wt% (Table 2). Variations of P₂O₅, Cr, Cu, Nb, Pb, S, Sr, Th, Y, Zr are large. The SiO₂ content of each layer of the biotite gneiss ranges from 69.7 wt% to 73.1 wt% (Table 2). Variation of each element is small except for Rb, Zr.

4.3. Nd-Sr isotopes

Clinopyroxene, amphibole, felsic-fractions, and whole-rock sample separated from the fine-grained syenite (98081501B) give a Rb-Sr whole-rock and mineral isochron age of 1843 ± 24 Ma and Sm-Nd whole-rock and mineral isochron age of 1664 ± 180 Ma. Hornblende, clinopyroxene, and felsic-fractions separated from dolerite (98081501F) give a Rb-Sr mineral isochron age of 2062 ± 74 Ma (Fig. 6) and a Sm-Nd mineral isochron age of 1471 ± 147 Ma. Phlogopite, apatite, and whole-rock sample separated from phoscorite (PH-02) give an Rb-Sr whole-rock and mineral isochron age of 2013 ± 93 Ma (Fig. 6) and a Sm-Nd whole-rock and mineral isochron age of 1639 ± 382 Ma. Each domain of phoscorite gives an Rb-Sr isochron age of 1381 ± 285 Ma and Sm-Nd isochron age of 2202 ± 609 Ma. The biotite gneiss layers do not give clear Rb-Sr and Sm-Nd isochron ages. The Nd model ages calculated using DM (Depleted Mantle: parameters for calculation are $^{143}\text{Nd}/^{144}\text{Nd}$ (present) = 0.51315 and $^{147}\text{Sm}/^{144}\text{Nd}$ (present) = 0.2136) are in narrow range from 3.09 to 3.12 Ga (T_{DM}).

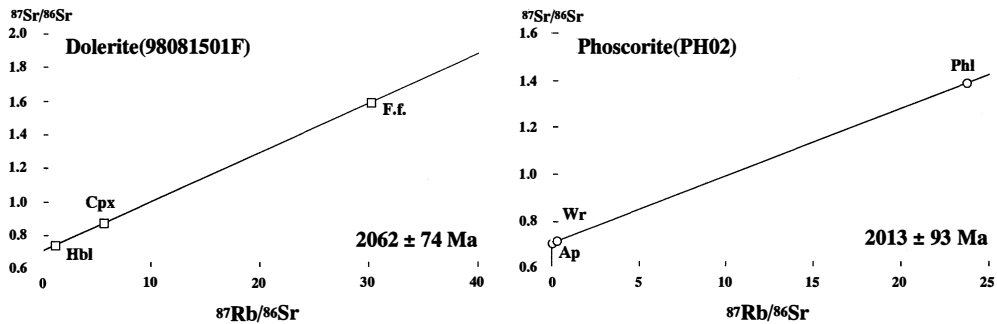


Fig. 6. Rb-Sr mineral isochron diagrams of the dolerite and phoscorite.

Hbl: hornblende, Cpx: clinopyroxene, F.f.: felsic-fractions, Wr: whole-rock, Phl: phoscorite, Ap: apatite.

Carbonatites are divided into two groups in terms of Sr isotopic ratios (Table 3). One has a high Sr isotopic ratio (0.71078 of PH04 and 0.71090 of PH05), another has a low Sr isotopic ratio (0.70568 of PH06) (Table 3). The Nd isotopic ratio of the former is higher than that of the latter (Table 3).

5. Discussion

Rb-Sr and Sm-Nd whole-rock and mineral isochron ages of the fine-grained syenite (1843 ± 24 Ma and 1664 ± 180 Ma) are younger than the timing of magmatism of the Phalaborwa Carbonatite Complex (about 2050Ma). The large age error of Sm-Nd

whole-rock and mineral isochron ages is caused by the small variation of the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio. Thus, these ages are greatly influenced by the magmatism of dolerite dykes, probably indicating an age younger than 1900 Ma, and do not indicate the timing of syenite magmatism.

Rb-Sr mineral isochron age of dolerite (2062 ± 74 Ma; Fig. 6) overlaps the timing of the Phalaborwa Carbonatite Complex magmatism. Therefore, it is hypothesized that this dolerite dyke intruded immediately after the syenite activity. The Sm-Nd mineral isochron age (1471 ± 147 Ma) is far younger than that, and has a large error caused by the small variation of the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio. This age is of low reliability, and can not indicate the timing of activity.

The Rb-Sr whole-rock and mineral isochron age of phoscorite (2013 ± 93 Ma; Fig. 6) is nearly coincident with the Rb-Sr mineral isochron age of 2012 ± 19 Ma (Eriksson, 1984) involving phlogopites obtained from clinopyroxenites, carbonatite, and phoscorite (Eriksson, 1989). The closure temperature for the Rb-Sr isotope system of biotite is $300\text{--}330^\circ\text{C}$ (Wagner *et al.*, 1977; Harrison *et al.*, 1979). Thus, these ages indicate the cooling age, when the body cooled down under 300°C . The U-Pb age between 2047 and 2061 Ma, therefore, indicates the time of magmatism of the Phalaborwa Carbonatite Complex (Eriksson, 1989). Thus, the timing of magmatism of the Phalaborwa Carbonatite Complex is about 2050 Ma. The Sm-Nd whole-rock and mineral isochron age of phoscorite (1639 ± 382 Ma) is far younger than that, and has a large error caused by the small variation of the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio. The Rb-Sr isochron age obtained by each domain of phoscorite (1381 ± 285 Ma) is far younger than Rb-Sr whole-rock and mineral isochron age, and has large error caused by dispersion. The Sm-Nd isochron age of phoscorite (2202 ± 609 Ma) is slightly older than that, and has large error caused by small variation of $^{147}\text{Sm}/^{144}\text{Nd}$ ratio. These ages are of low reliability. Thus, these isochrons should be considered pseudo-isochrons.

The biotite gneiss was brought from Archean terrane. Each layer of the biotite gneiss does not give clear Rb-Sr and Sm-Nd isochron ages. This is caused by the thermal effect of syenite for the Rb-Sr and Sm-Nd systems and by the small variation of $^{147}\text{Sm}/^{144}\text{Nd}$ ratio for Sm-Nd system. The T_{DM} of the biotite gneiss is in the narrow range from 3.09 to 3.12 Ga. This is consistent with the biotite gneiss having been brought from Archean terrane.

Two groups of carbonatite have initial Sr isotopic ratios (SrI) of 0.71074 to 0.71089 and 0.70569 calculated at 2050 Ma, respectively. Eriksson (1989) indicated that most of the SrI of carbonatite ranges from 0.70393 to 0.70680, except for one sample which has an SrI of 0.71022. The result of this study is consistent with that of Eriksson (1989). Eriksson (1989) proposed that at least two carbonatite source magmas form the carbonatites and pyroxenites, one with an $\text{SrI} < 0.7039$ and another with a high $\text{SrI} > 0.710$. Initial Nd isotopic ratios (NdI) of the two groups are 0.509623 to 0.509636 and 0.509729, respectively. SrI and NdI of carbonatites are plotted in the compositional range indicated by Eriksson (1989) (Fig. 7). SrI and NdI of phoscorite, which has an interbanded relationship, range from 0.70513 to 0.70867 and from 0.509658 to 0.509718, respectively, except for SrI of PH02F. These are isotopic data encompassed within the above two carbonatite groups (Fig. 7). The mode of occurrence of phoscorite suggests that the phoscorite is a cogenetic product with carbonatite

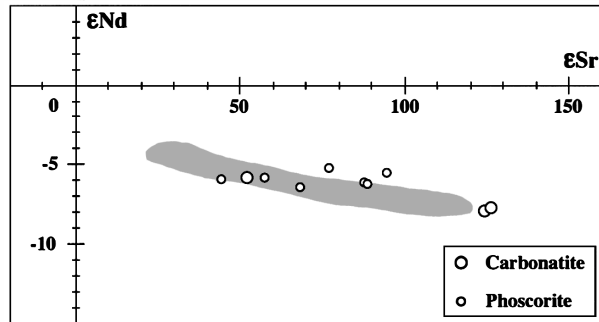


Fig. 7. Initial ϵSr vs. ϵNd diagram of carbonatite and phoscorite.

Chondritic Uniform Reservoir (CHUR) parameters for calculation of initial ϵSr and ϵNd values: $^{87}Sr/^{86}Sr(present) = 0.7045$, $^{87}Rb/^{86}Sr(present) = 0.0827$, $^{143}Nd/^{144}Nd(present) = 0.512638$, $^{147}Sm/^{144}Nd(present) = 0.1966$. The gray area is the compositional range of carbonatite reported by Eriksson (1989).

magmatism (Eriksson, 1989). Thus, these isotopic data suggest that carbonatite and related rocks obtained in this area were formed by mixing of two source magmas having different Sr and Nd isotopic compositions. Eriksson (1989) showed that the clinopyroxinite, carbonatite and phoscorite could not be the result of magmatic differentiation alone, but involve complicated magmatic processes. Our result is consistent with his interpretation.

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Appendix. Whole-rock chemical compositions of the syenite and related rocks.

Sample No.	98081501	98081502	98081503	98081504	98081505	98081501A
Rock facies	C.Sy.	A.G.	C.Sy.	F.Sy.	M.R.	C.Sy.
As(ppm)	<4	n.d.	<4	<4	<4	<4
Ga	30	19	27	28	19	24
Pb	27	17	22	31	94	29
S	110	23	92	69	26	83
Th	62	<4	32	100	135	38

Sample No.	98081501B	98081501C	98081501D	98081501E	98081501F
Rock facies	F.Sy.	M.R.	M.R.	A.G.	Do.
As(ppm)	<4	<4	<4	n.d.	<4
Ga	26	23	20	19	18
Pb	43	75	133	19	8
S	43	48	41	28	780
Th	131	171	230	<4	<4

A.G.: alkali-feldspar granite, **F.Sy.:** fine-grained syenite, **C.Sy.:** coarse-grained syenite, **M.R.:** melanocratic rock, **Do.:** dolerite. n.d.: not detected.