

## Rb-Sr age of the Sivamalai alkaline complex, Tamil Nadu

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**Abstract.** The Sivamalai alkaline complex comprises ferro-, pyroxene- hornblende- and nepheline-syenites. Field relations show that the nepheline syenites followed the emplacement of non-feldspathoidal syenites. Mineralogical data on the syenite suite have been reviewed. The Sivamalai alkaline rocks are not strongly enriched in rare-earth elements like most miaskites. Rb-Sr isotopic analyses of a suite of six samples from the various members of the complex define an isochron corresponding to an age of  $623 \pm 21$  Ma ( $2\sigma$ ) and initial Sr ratio of  $0.70376 \pm 14$  ( $2\sigma$ ). This is consistent with a model of fractional crystallization of a parent magma derived from an upper mantle source with apparently no isotopic evidence for more than one magma source for the complex. The Sivamalai alkaline complex represents a Pan-African alkaline magmatic event in the southern granulite terrane of Peninsular India.

**Keywords.** Sivamalai alkaline complex; Rb-Sr whole-rock isochron; initial strontium ratio; fractional crystallization; rare-earth element abundances.

### 1. Introduction

The Sivamalai alkaline complex (SAC) occurs in the southern granulite terrane between Moyar-Bhavani and Noyil-Cauvery lineaments (figure 1; cf. Drury *et al* 1984). It was first described by Holland (1901) and subsequently studied for its detailed structure, petrology and petrochemistry by many others (Subramaniam 1949; Bose 1968a, b, 1971; Bose and Basu 1970; Bhaskar Rao 1982; Czygan and Goldenberg 1989; Leelanandam 1993a, b). Although these studies have established the structural geometry, petrology and petrochemistry of the alkaline complex, they differ considerably in the interpretation of its field relations and magmatic history. For example, while Bose and Basu (1970) from structural analysis of primary planar and linear fabric assign a post-tectonic igneous intrusive origin, Czygan and Goldenberg (1989) ascribe the foliation to a secondary metamorphic impress. Regarding petrogenesis, Bose (1971) considers the saturated syenites and nepheline syenites as products of progressive crystallization of a syenite magma, whereas Bhaskar Rao (1982) and Leelanandam (1993a, b) invoke two separate magma sources for the two main rock groups. Czygan and Goldenberg (1989) propose that the nepheline syenite magma was primary which desilicated the country rock gneisses into syenites. Even a more directly measurable information as the age of emplacement of the complex is also not known to any useful precision. Based on only a three-point isochron insufficiently constrained by poorly radiogenic soda syenites, Crawford (1969) reported a very imprecise age of  $998 \pm 650$  Ma (recalculated with the presently accepted value of  $1.42 \times 10^{-11} \text{a}^{-1}$  for the  $^{87}\text{Rb}$  decay constant) and an initial Sr ratio of  $0.7008 \pm 0.0046$ , but indicated that the age could be as low as 700 Ma. Biotite separated from one of

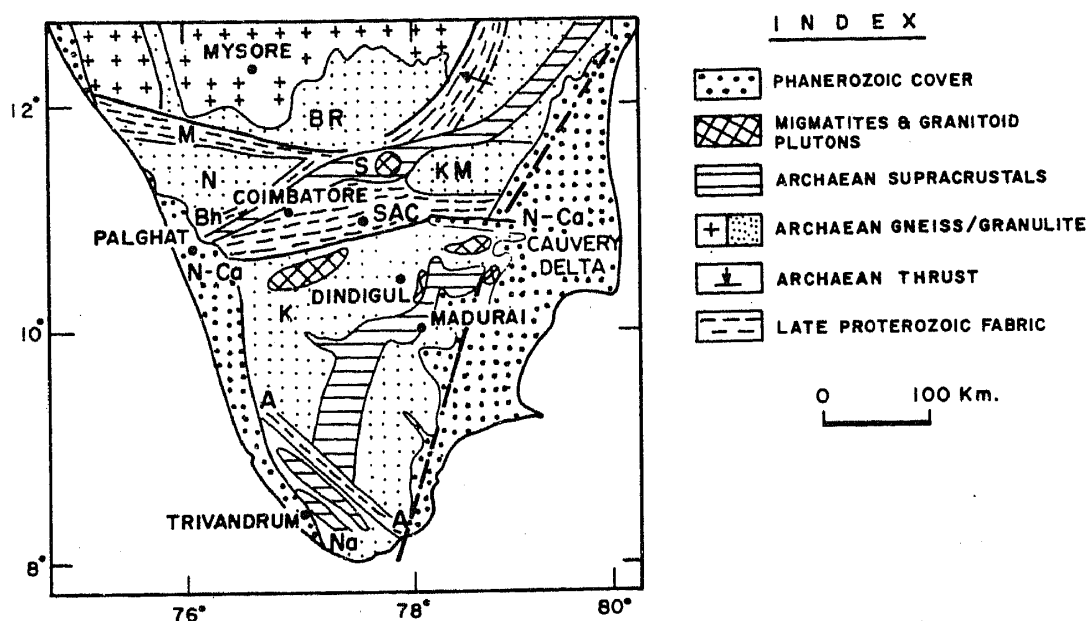


Figure 1. The geological map of the south Indian granulite terrain showing the location of Sivamalai Alkaline Complex (SAC). Granulite Massifs: N - Nilgiri, BR - Biligirirangan, K - Kodaikanal, KM - Kollimalai, Na - Nagarcoil. Shear zones: N - Ca: Noyil-Cauvery, M - Moyar, Bh - Bhavani and A - A: Achankovil.

the three whole-rocks gave an age of 510 Ma. Although this biotite age is in very broad agreement with the fission track age of  $452 \pm 92$  Ma on apatite (Nagpal *et al* 1974), it is not clear whether these apparently younger mineral ages are primary or secondary.

The purpose of the present study is primarily to obtain a more precise age of the complex occurring in the southern granulite belt, and to test the petrogenetic models proposed by others using Sr isotopic data. Detailed petrography, mineralogical composition and trace (including rare-earths) element data are presented for the samples selected for Rb-Sr isotopic analysis.

## 2. Field relations

The high-grade supracrustal rocks, gneisses and granulites in which the Sivamalai alkaline complex is emplaced are intensely folded and sheared. However, the members of the alkaline complex are free from effects of shearing and hence must have postdated the latest shear movement. The main alkalic pluton forming the Sivamalai hill occupies an oval area with a broad projection to the west as shown in figure 2 after Bose (1971). It comprises several distinct rock types in close spatial association. The main pluton comprises pyroxene-, hornblende-, and nepheline-syenites. The nepheline syenites are dominantly biotite-nepheline syenites (grading to leucosyenite) with a minor proportion of hornblende-nepheline syenite. While the contacts between the different petrographic types in the Sivamalai pluton are gradational or diffuse, the main pluton itself has a distinct geometry (of inverted cone) and a sharp and clear contact with the country rocks (Bose and Basu 1970). In contrast to the close spatial

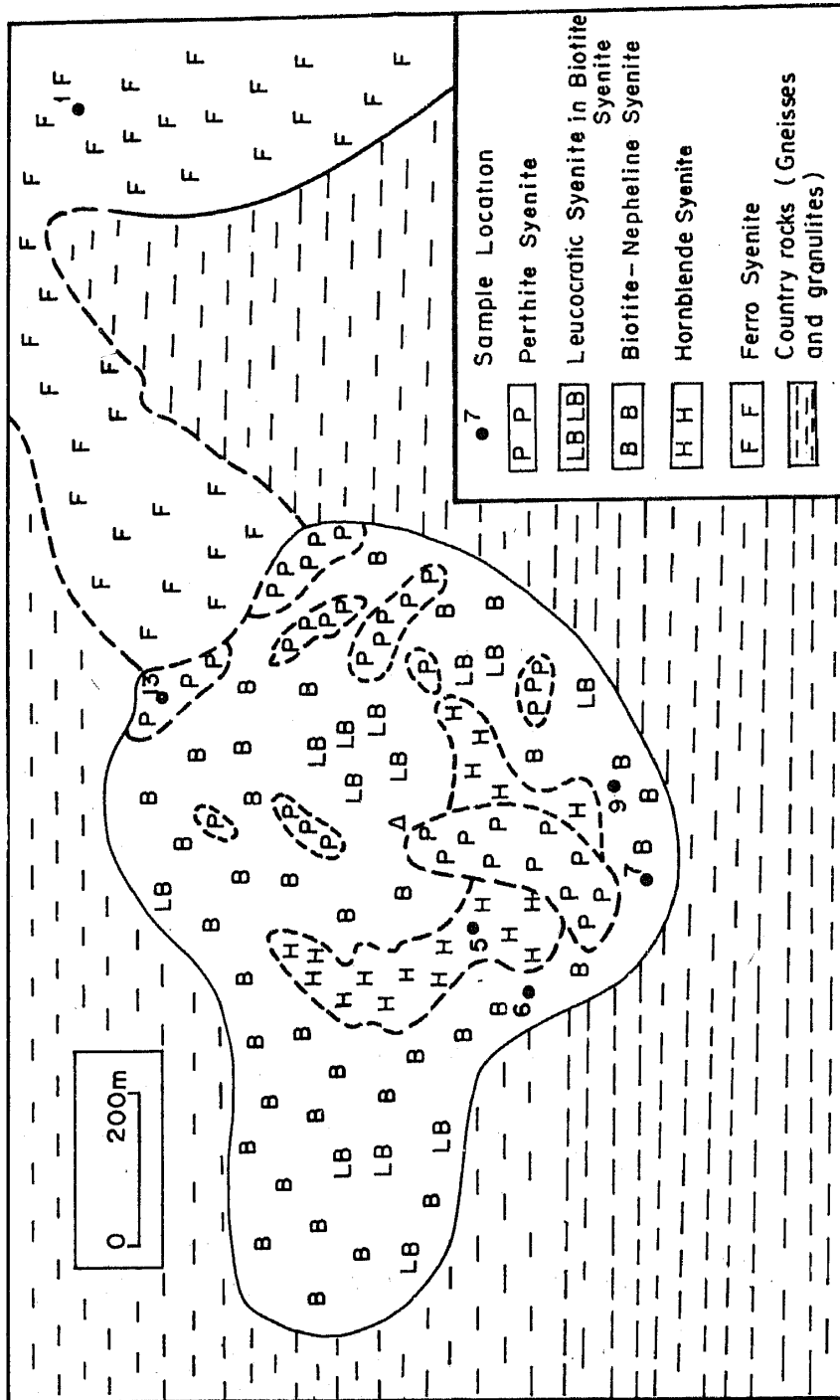


Figure 2. Lithological map of Sivamalai Alkaline Complex after Bose (1971) showing the location of samples used for dating (for detailed structural data see Bose and Basu (1970)).

association of syenites and nepheline syenites mentioned above, ferrosyenite occurs as a large intrusion (only a part is shown in figure 2) to the east and northeast of the Sivamalai hill. Cross-cutting relations between the members show that the ferrosyenite was emplaced prior to the main pluton and nepheline syenite was emplaced last. The locations of rock samples collected and analysed by us for geochronological investigations are shown in figure 2.

### 3. Analytical methods

Fresh fragments (between 5 and 8 kg each) were crushed in a steel jaw crusher and powdered in a tungsten carbide mill. Major elements except sodium were analysed by X-ray fluorescence spectrometry on lanthanum-doped fused glass beads. Na, Cr and Ni were determined by AAS and FeO by titration. Replicate analyses of international rock standards indicate accuracy of measurements within 2% for major elements and 10% for trace elements.

Rare earth and other trace elements (Sc, V, Cu, Zn, Ga, Y, Zr, Nb, Ba, Hf and Ta) were analyzed by plasma source mass spectrometry (VG PlasmaQuad) using the procedure of Balaram and Saxena (1988). International rock standards (MRG-1, BM, JG-1a and GM) analyzed in parallel with the alkaline rocks indicate analytical accuracies within 5%.

For Rb and Sr isotopic analyses, sample powders were digested in a  $\text{HNO}_3 + \text{HF}$  mixture and spiked with  $^{87}\text{Rb}$  and  $^{84}\text{Sr}$  isotopic tracers before ion exchange separation. Isotopic analyses were carried out on an automatic VG 354 thermal ionization mass spectrometer. Total process contamination for Rb and Sr was less than  $1 \times 10^{-9}$  gm. During the course of this work, NBS-987 Sr standard was run five times giving a mean  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.71028 \pm 4$ .

Chemical composition of minerals in the different rock samples was determined on a Cameca Camebax electron microprobe.

### 4. Petrography

The model compositions of the seven samples are presented in table 1. Comparison of model compositions and detailed petrographic features with those of documented rock types in the complex indicates that the selected rock samples fall into the following categories.

**SI89-1** is a ferrosyenite with a greenish grey colour and medium to fine grained hypidiomorphic granular texture. This is the only rock containing olivine. Alkali feldspar shows an abundant perthitic texture with an equal share of plagioclase. Clinopyroxene is greenish grey in colour and intergrown with orthopyroxene displaying striped pyroxene texture (see also Bose 1971; Leelanandam 1993a). Iron oxides occur as independent grains and also mottled by amphibole and/or biotites.

**SI89-13** is a sample collected from the zone identified as perthite syenite or perthosite by Bose (1971). He later regarded this rock as a variant of ferrosyenite (Bose 1972). Olivine is absent and pyroxene is similar to that in ferrosyenite. This rock is referred to as pyroxene syenite in the present work. Alkali feldspars comprise

**Table 1.** Modal compositions of Sivamalai rocks.

	1	2	3	4	5	6	7
Quartz	0.8	—	—	—	—	—	—
Olivine	—	5.0	—	—	—	—	—
Nepheline	—	—	—	—	22.7	25.0	22.5
Alkali feldspar	—	88.2	66.3	56.3	68.8	66.6	69.3
Plagioclase	38.3	2.3	26.4	10.4	—	—	—
Pyroxene	15.2	1.0	2.5	—	—	—	—
Amphibole	42.9	0.5	3.5	16.4	1.8	5.1	3.1
Biotite	0.3	1.5	0.2	12.1	3.7	0.2	1.3
Apatite	0.3	0.1	0.2	2.5	0.4	Tr.	—
Iron oxides	0.9	0.5	0.4	0.6	2.4	2.7	3.5
Calcite	0.9	0.4	0.3	0.7	—	Tr.	—
Sphene	—	—	—	0.6	—	—	—
Colour index	60	9	8	33	8	8	8

- 1: SI89-4 Gabbroic diorite.  
 2: SI89-1 Ferrosyenite.  
 3: SI89-13 Pyroxene syenite.  
 4: SI89-5 Hornblende syenite.  
 5: SI89-6 Biotite nepheline syenite.  
 6: SI89-7 Hornblende nepheline syenite.  
 7: SI89-9 Hornblende nepheline syenite.

microcline-micropertthite, cryptopertthite and albite. The rock is plagioclase-rich (inclusive of albite) which constitutes about 26% of its modal composition.

SI89-5 is a sample collected from the hornblende syenite unit of the complex. The sample chosen for geochronology is somewhat richer in mafic mineral content as compared to the large part of this rock and may be considered as mafic-rich portions of the hornblende syenite. It is characterized by allotriomorphic texture. It has about 16% of amphibole. The amphiboles are pale-green to green in colour. Alkali feldspar is perthitic and occurs as discrete grains. Perthitic lamellae are albitic in composition and sometimes merge into a rim of albite which surrounds the alkali feldspar. The discrete grains of plagioclase show polysynthetic twin lamellae and are characterized by an An content of about 12%. Apatite, calcite, sphene and iron oxides are the accessory minerals.

SI89-6, SI89-7 and SI89-9 are nepheline syenites with more than 20% nepheline. They show marked compositional banding. Amphibole and biotite bands alternate with alkali feldspar and nepheline bands. Absence of discrete plagioclase indicates hypersolvus nature. Iron oxides, calcite and apatite are accessories.

## 5. Mineralogy

The composition of minerals in the various samples have been determined by electron microprobe (data available on request from authors). The mineralogy discussed in the following is based on the new data and has been compared with the compositions published earlier (Bose 1971; Bhaskar Rao 1982; Leelanandam 1993a).

**Olivine**, present only in ferrosyenite, is a manganese-rich fayalite,  $Fa_{91.4}Fo_{5.7}Mn_{2.9}$ . Although the fayalite composition of olivine in ferrosyenite has been known (Bose 1971; Bhaskar Rao 1982; Leelanandam 1993a) the Mn component has not been reported so far. Such Mn-rich fayalitic olivines are known from other alkaline complexes (cf. Henderson *et al* 1989).

**Orthopyroxene**, occurring as discrete grains only in ferrosyenite, is eulitic in composition ( $Ca_5Mg_{18}Fe_{7.7}$ ) with  $100 \text{ Mg/Mg} + \text{Fe} + \text{Mn} = 78$ . The ferrosilite value (81) is consistent with the range 75.1 to 89.3 reported by Leelanandam (1993a).

**Clinopyroxene** occurs in ferro-, pyroxene- and hornblende syenites. Its composition varies from ferrohedenbergite ( $Ca_{4.4}Mg_9Fe_{4.7}$ ) in the ferro- and pyroxene syenite to salite ( $Ca_{4.8}Mg_{3.7}Fe_{1.5}$ ) in hornblende syenite. Leelanandam (1993a) reported identical ferrohedenbergite composition. The hedenbergite component in the clinopyroxene of the ferrosyenite goes upto 80% while the diopside component in the clinopyroxene of hornblende syenite is as much as 70%. Earlier the occurrence of hypersolvus pyroxene later unmixed to striped pyroxene (with inverted pigeonite) was reported (Bose 1968a; Leelanandam 1993a).

**Amphibole** in our samples shows compositional variations from magnesium-through iron- to soda-rich phases. The nomenclature of amphiboles is after Leake (1978). They are ferroedenitic hornblende in the ferro- and pyroxene syenite. In the hornblende syenites they are ferropargasitic in composition. The amphibole in the nepheline syenite is of alkaline group similar to katophorite but with Ca predominating over Na when the B and A sites are considered together.

**Biotite** is subordinate to the other mafic minerals. The composition of biotite varies from annite in the syenites to siderophyllite in the nepheline syenites.

**Alkali feldspar** is the most abundant constituent in the samples studied. It is represented by microcline-microperthite, cryptoperthite and albite. They show a range of orthoclase contents –  $Or_{3.1}$  to  $Or_{7.9}$ . The Ab content is 20% in ferrosyenite but as high as 66% in the pyroxene syenite. Chemical data on alkali feldspars from different members of the alkaline complex has been presented by Bose (1971).

**Plagioclase feldspar** generally appears as partially resorbed crystals in the ferro-, pyroxene and hornblende syenites and is very rare in the nepheline syenites. The most calcic plagioclase is seen in the hornblende syenite ( $Or_1Ab_{88}An_{11}$ ). An content decreases to  $An_9$  in ferrosyenite and to  $An_{7.7}$  in the pyroxene syenite, reaching the lowest values of  $An_2$  in the nepheline syenites.

**Nepheline** occurring in nepheline syenites is euhedral to subhedral, in some instances ovoidal and compositionally homogeneous mediopotassic. The amount of excess silica is quartz molecule while aluminium is deficient.

## 6. Petrochemistry

The major and trace element (including REE) data for the seven samples are given in tables 2 and 3 along with normative composition. Agpaitic-, differentiation- and solidification indices, after Sorensen (1974), Thornton and Tuttle (1960) and Kuno (1968) respectively, are also given. Chondrite normalized REE patterns are presented in figure 3.

The CIPW norms confirm the saturated to slightly oversaturated nature of the ferro-, pyroxene- and hornblende syenite. Silica undersaturated minerals like olivine

Table 2. Major element analyses and CIPW norms.

Sample No.	1	2	3	4	5	6	7
SiO <sub>2</sub>	55.08	59.38	63.86	58.04	59.18	59.92	59.16
TiO <sub>2</sub>	0.87	0.45	0.15	1.09	0.30	0.33	0.27
Al <sub>2</sub> O <sub>3</sub>	17.76	16.10	20.62	18.73	21.28	21.17	21.23
Fe <sub>2</sub> O <sub>3</sub>	2.76	2.52	0.28	2.29	1.22	1.11	0.99
FeO	5.84	8.32	0.90	5.32	3.18	2.88	3.42
MnO	0.09	0.34	0.13	0.13	0.06	0.07	0.05
MgO	4.96	1.31	0.48	1.57	0.52	0.60	0.44
CaO	6.86	1.80	1.30	3.23	1.10	1.27	1.20
Na <sub>2</sub> O	4.67	4.85	5.79	4.30	7.45	7.16	7.82
K <sub>2</sub> O	0.55	4.84	5.62	4.05	4.81	4.93	4.91
P <sub>2</sub> O <sub>5</sub>	0.11	0.17	0.10	0.70	0.15	0.18	0.11
Total	99.55	100.08	99.23	99.45	99.25	99.62	99.60
K%	0.46	4.02	4.67	3.36	3.99	4.09	4.08
AI	0.47	0.82	0.76	0.61	0.82	0.81	0.86
KSI	26.41	6.00	3.67	8.96	3.03	3.60	2.50
DI	45.34	70.94	87.69	68.06	86.21	85.89	86.66
Fe	8.32	10.59	1.15	7.38	4.28	3.88	4.31
Fe/Fe + Mg	0.63	0.89	0.71	0.82	0.89	0.87	0.91
<b>C.I.P.W. NORMS</b>							
q	2.38	1.36	4.85	7.41			
c		0.02	2.91	3.09	2.19	2.19	1.14
or	3.27	28.58	33.47	24.07	28.64	29.24	29.13
ab	39.70	41.01	49.37	36.59	50.55	51.72	47.01
an	25.99	7.81	5.84	11.51	4.51	5.14	5.26
ne					7.02	4.93	10.53
wo	3.12						
en	12.41	3.26	1.21	3.93			
fs	7.21	13.08	1.43	6.35			
fo					0.91	1.05	0.77
fa					3.46	3.07	3.96
mt	4.02	3.65	0.41	3.34	1.78	1.62	1.44
il	1.66	0.85	0.29	2.08	0.57	0.63	0.52
ap	0.26	0.40	0.24	1.67	0.36	0.43	0.26

KSI: Kuno's solidification index.

DI: Differentiation index.

AI: Agpaitic index.

(modal) in the early ferrosyenite and nepheline in the later members indicate a low level of silica content throughout the suite. Chemically the nepheline syenites are miaskitic and syenites are plumasitic (cf. Sorensen 1974). As noted by Bose (1971) from a larger set of analyses, the agpaitic index does not show much variation among the samples and is about 0.8. Although the differentiation index shows a general increase from 71 in ferrosyenite to 86 in the nepheline syenites (the last member in the suite), the variation trend within the syenite members is not regular, presumably due to inadequate number of analyses or sampling bias in the present study. The

Table 3. Trace and rare earth element analyses.

Sample No.	1	2	3	4	5	6	7
Sc	28.2	10.1	8.2	10.3	3.6	6.3	5.2
V	234.6	6.7	2.6	8.2	5.5	5.3	4.00
Cr	20.00	8.00	10.00	21.00	13.00	12.00	17.00
Co	54.2	20.3	19.9	20.2	21.2	34.7	23.1
Ni	10.00	5.00	3.00	6.00	7.00	8.00	6.00
Cu	10.5	6.6	7.8	25.2	4.1	3.1	8.9
Zn	114.6	116.8	86.8	124.6	89.6	69.1	61.6
Ga	17.00	22.5	26.4	19.7	30.1	33.3	23.9
Rb	40.00	43.00	50.00	32.00	72.00	71.00	64.00
Sr	258.00	29.00	18.00	717.00	109.00	113.00	213.00
Y	36.6	18.7	16.00	16.8	1.5	0.9	1.4
Zr	33.2	24.5	21.6	157.3	151.4	191.8	87.2
Nb	8.4	16.5	74.5	30.00	21.9	17.3	24.00
Ba	320.00	147.00	82.00	1486.00	36.00	46.00	113.00
La	30.58	32.87	33.58	42.06	4.34	3.30	6.72
Ce	58.1	61.9	84.5	77.34	9.99	7.92	13.73
Pr	6.56	6.9	9.86	8.37	1.2	0.87	1.34
Nd	32.59	34.69	49.2	37.2	5.8	4.43	6.36
Sm	5.43	5.95	8.61	6.78	0.94	0.9	1.04
Eu	1.33	1.84	1.68	4.14	0.3	0.3	0.38
Gd	6.45	5.34	7.17	7.00	0.66	0.59	1.01
Tb	1.01	0.78	0.89	0.79	0.09	0.07	0.11
Dy	5.58	3.6	4.23	3.45	0.35	0.31	0.49
Ho	1.1	0.63	0.75	0.53	0.05	0.04	0.06
Yb	2.84	1.49	1.85	0.92	0.14	0.11	0.16
Lu	0.47	0.25	0.31	0.14	0.03	0.02	0.03
Hf	2.1	1.1	2.1	4.5	5.5	7.9	2.8
Ta	0.6	1.5	2.8	1.9	0.7	0.8	1.1
REE	152.04	156.24	202.63	188.72	23.89	18.86	31.43
La <sub>N</sub> /Lu <sub>N</sub>	6.66	13.55	11.16	30.95	17.19	17.01	23.09
Eu/Eu*	0.69	1.004	0.66	1.85	1.17	1.27	1.14

trend in chemical composition shown by Bose (1971) is also reflected in the limited set of our data. For example, despite their considerable petrographic variations, our samples show very little variation in their Si content. Alumina shows a gradual increase from syenites to nepheline syenites, as also the alkalis, particularly soda. While MgO, FeO, CaO show a general decrease from ferrosyenite to nepheline syenite in our analyses, their gradual decrease is clearly evident in the data set of Bose (1971). P205 at 0.7% in our hornblende syenite sample is significantly higher than in the rest of our samples but is consistent with its higher modal apatite abundance.

The most striking aspect of the trace element data, particularly from the geochronological angle, is that while Rb varies by less than a factor of two among the rocks, Sr varies drastically from 18 to 717 ppm, the latter being in the hornblende syenite. Ba also reflects the Sr trend. The unusual Sr enrichment in the hornblende syenite relative to the other two syenites may be due to the high proportion of apatite and calcite in this rock and also the mafic-rich nature of these samples. Even though



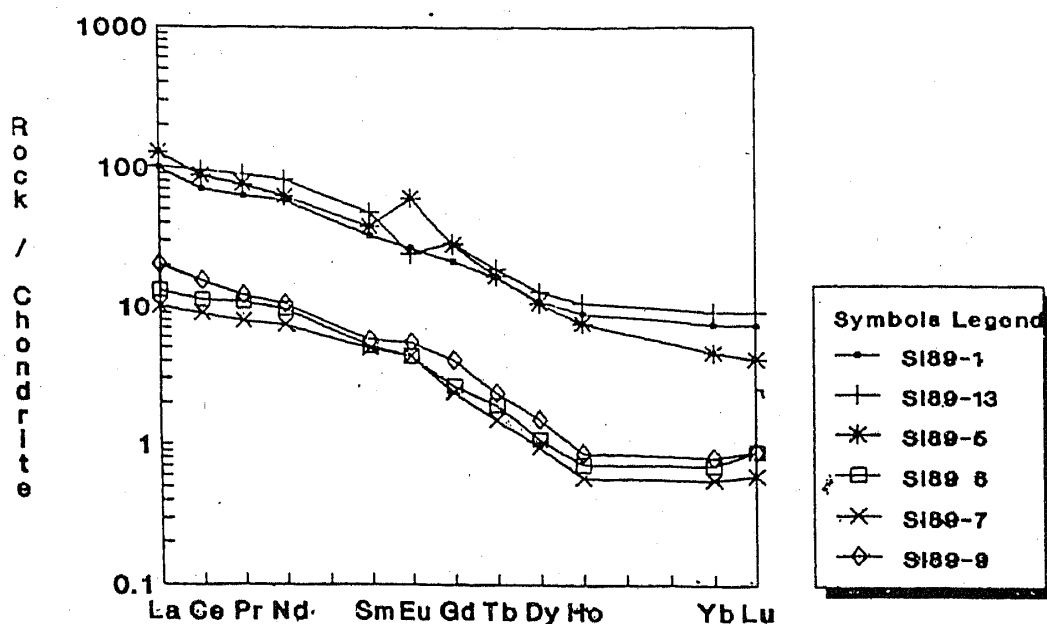


Figure 3. Chondrite normalized REE patterns for various members of the SAC.

Sc, V, Cr, Ni, Ta, Zn and Ga have very different geochemical affinities, they do not vary by more than a factor of two between the syenites and nepheline syenites. Zr is greatly enriched in the nepheline syenites.

As for the REEs, the Sivamalai alkaline rocks do not show the typical enrichment seen in alkaline rocks in general. However, the range of abundances in the nepheline syenites is similar to those in miaskites (cf. Gerasimovski 1974). The total REE are about 5–10 times enriched in the syenites relative to the nepheline syenites. But the fractionation of the LREE relative to the HREE is about the same between the two groups. The ferro-, pyroxene- and hornblende syenites are characterized by slightly LREE enriched and HREE depleted patterns. While the ferrosyenite and pyroxene syenite show negative Eu anomaly, the hornblende syenite shows positive Eu anomaly and also steeper HREE fractionation pattern. The nepheline syenites show a small positive Eu anomaly. Rb, Sr, Ba, Zr, Hf, Nb, Zn and Ga abundances reported by Czygan and Goldenberg (1989) as the average of 19 analyses of nepheline syenite samples are in good agreement with our data. They have not given any REE data for these samples for comparison with our data set.

## 7. Rb-Sr chronology

Rb and Sr isotopic data for the seven samples are given in table 4 and plotted on the Sr evolution diagram in figure 4. The data points show a good mutual spread. With the possible exception of the ferrosyenite, all points closely conform to a linear array. The straight line shown is the best fit line for all the samples based on the double error regression procedure of Williamson (1968). Interpreted as an isochron, this line yields an age of  $623 \pm 21$  Ma ( $2\sigma$ ) and initial Sr ratio ( $Sr_i$ ) of  $0.70376 \pm 0.00014$  ( $2\sigma$ ) (MSWD = 11.6). The hornblende syenite (SI89-5) has such a low Rb/Sr ratio that it constrains the  $Sr_i$  very tightly. The three syenite samples have a good mutual spread

Table 4. Results of Rb-Sr (whole-rock) isotopic analysis.

Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}^*$ (atomic)	$^{87}\text{Sr}/^{86}\text{Sr}^{**}$ (atomic)
1. SI89-4	40	258	0.047	$0.70474 \pm 4$
2. SI89-1	43	29	4.360	$0.74568 \pm 5$
3. SI89-13	50	18	7.896	$0.77551 \pm 2$
4. SI89-5	32	717	0.128	$0.70494 \pm 3$
5. SI89-6	72	109	1.895	$0.72011 \pm 5$
6. SI89-7	71	113	1.828	$0.71979 \pm 2$
7. SI89-9	64	213	0.875	$0.71076 \pm 2$

\*Error in  $^{87}\text{Rb}/^{86}\text{Sr}$  is  $< 2\%$ .

\*\*The error shown is in the last digit.

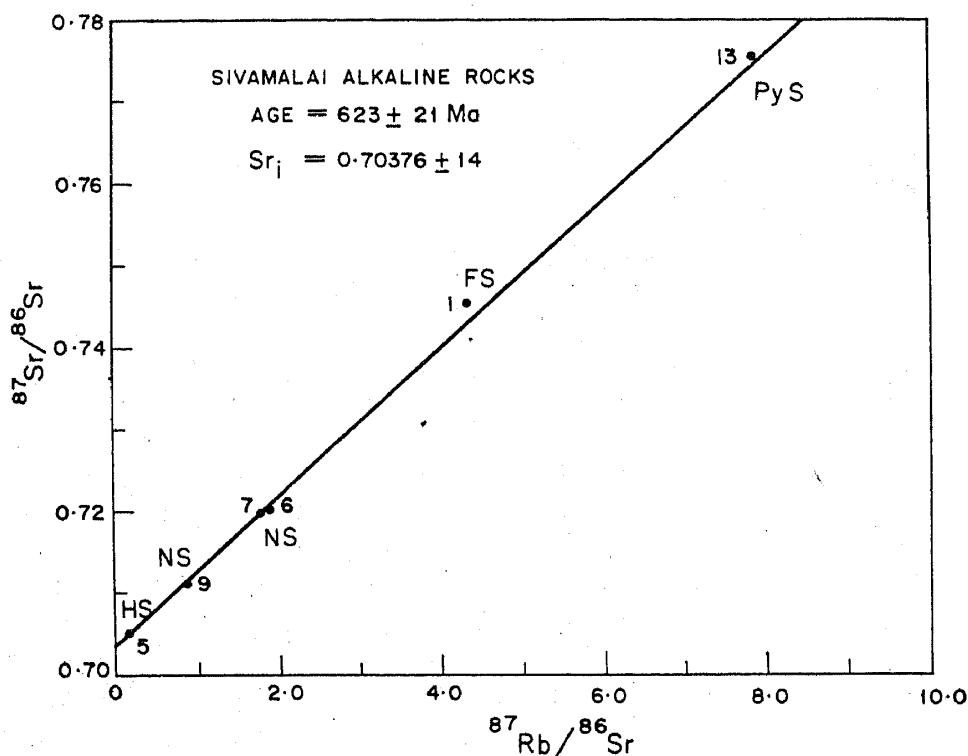


Figure 4. Rb-Sr isochron.

in their Rb/Sr ratios to define a satisfactory isochron corresponding to an age of  $656 \pm 19$  Ma and  $\text{Sr}_i$  of  $0.70374 \pm 0.00009$ . While the ages agree within experimental error, the initial ratios are virtually unchanged.

Despite the relatively small spread and radiogenic enrichment among the three nepheline syenites, regression of their Rb-Sr data gives an age of  $653 \pm 42$  Ma and  $\text{Sr}_i$  of  $0.70260 \pm 76$ . In fact the least radiogenic nepheline syenite sample (SI89-9) yields its initial ratio as 0.70296 after correction for the small radiogenic contribution. So within the resolution of the present measurements, the age and initial Sr ratios of the syenites and nepheline syenites are indistinguishable. Our preferred values for the complex are given by the combined six point isochron - namely an age of  $623 \pm 21$  Ma ( $2\sigma$ ) and initial Sr ratio of  $0.70376 \pm 0.00014$  ( $2\sigma$ ).

## 8. Discussion

The Sivamalai alkaline complex consists of a variety of syenites and nepheline syenites. Modal and major element compositions of the rocks selected for our geochronological investigations show that they represent the major rock types viz., ferro-, pyroxene- and hornblende-syenites (saturated members) and hornblende- and biotite- nepheline syenites (undersaturated members). All these rock types occur in close spatial association. The fact that they all conform closely to a linear array in a Sr evolution diagram (figure 4) implies that they have evolved for 620 Ma as isolated chemical systems from a common initial Sr composition of  $0.70376 \pm 14$ . The age defined by this common isochron is not only more precise but also very different from the  $998 \pm 650$  Ma whole-rock Rb-Sr age reported by Crawford (1969). We interpret this result as the time of emplacement of the complex. Since this whole-rock age of  $623 \pm 21$  Ma is distinctly older than the biotite Rb-Sr age of 510 Ma (Crawford 1969) and the apatite fission track age of  $452 \pm 92$  Ma (Nagpal *et al* 1974), the mineral ages may relate to a mild secondary thermal event in the complex nearly 100 Ma after its emplacement.

Apart from the coherence of the syenites and nepheline syenites reflected by their whole-rock isochron, the initial Sr ratios of the two groups calculated from the age-insensitive measured ratios are indistinguishable implying that the melts from which they crystallized had the same Sr composition close to 0.7038. This is directly compatible with the proposal of Bose (1971) on chemical and mineralogical grounds that the syenites and nepheline syenites are derived from a single syenitic magma with negligible extraneous contamination. Based on two distinct trends of differentiation in the Q-L-M diagram, Bhaskar Rao (1982) invoked two different sources for saturated and undersaturated members – pyroxene syenodiorite and barkevikite melteigite, respectively. Leelanandam (1993b) also suggested two different sources viz., tholeiitic and alkalic (malignite/meltigite) for the ferrosyenite and nepheline syenites respectively. If they were indeed formed from different melts, our results now constrain that the two magmas had the same Sr composition.

Czygan and Goldenberg (1989) have argued that the nepheline syenite magma is the only primary component of the intrusive with the syenites being the products of desilication of the host granite gneisses by the nepheline syenite magma. The field observation that the Sivamalai pluton is undeformed and has sharp contacts with the country rocks and distinct geometry is not consistent with a wholesale metasomatic conversion of the latter into syenites (Bose and Basu 1970). There is also no significant LREE enrichment in the syenites as expected for granite contaminants. Also, with such a mixed origin for the syenites, the initial Sr ratios of the syenites and nepheline syenites will most probably differ, which is not borne out by our result.

As noted earlier, the syenites and nepheline syenites have very similar chondrite normalized patterns, although the REE abundance in the former is higher by 5–10 times relative to the latter. Despite the large amount of REE data on different types of rocks (Henderson 1984) the variation of REE systematics among the comagmatic members in a single alkaline complex has not been reported so far to compare with the Sivamalai case. Since REE contents are known in some cases to progressively decrease in residual melt due to fractional crystallization (see Henderson 1984), the simplest explanation of our REE data is that fractional crystallization of the parental magma caused REE contents to decrease in a residual liquid without significant

fractionation. Sorensen (1974) attributes the depletion of REE in miaskitic syenites to the escape of gaseous constituents containing these elements from the crystallizing melt.

The  $Sr_i$  ratio of 0.70376 is nearly identical to the inferred Sr composition for the 'bulk earth' 620 Ma ago. This implies that the upper mantle source from which the syenitic parent magma was derived by partial melting was not fractionated due to any prior episodes of melt extraction. The 620 Ma age obtained for the Sivamalai complex indicates alkaline magmatic activity during the Pan-African orogeny. Thus it represents an alkaline magmatic event distinct from the middle-Proterozoic alkaline magmatic activity represented in the Eastern Ghat Mobile Belt (viz. coastal granulite belt) of the Khammam and Prakasam districts, Andhra Pradesh and Koraput district, Orissa (see Clark and Subba Rao 1971 and Subba Rao *et al* 1989). On the other hand in the southern granulite terrane (close to the Sivamalai alkaline complex) Pan-African magmatic events have been recorded. For example, the nearby Dindigul granite has almost the same age ( $626 \pm 35$  Ma) as that of the Sivamalai alkaline complex (Narayana *et al* 1988). These ages are also very similar to those found in other parts of the Pan-African belt in the Afro-Arabian shield. It is generally believed that the alkaline plutons are emplaced during the relaxation from a compressive regime to one of extension.

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