metabasites. This study therefore supports the use of metabasites as petrotectonic indicators in low- to medium-grade metamorphic terranes.

Acknowledgements

This study was funded under the Canada-Newfoundland Mineral Development Agreement 1984–1989 (project 840024), and by Natural Sciences and Engineering Research Council of Canada grants to J.V.O. and J.D.G. We thank Ken Currie, Andrew Hynes, Harold Williams and an anonymous Journal referee for reviewing various versions of the manuscript.

Appendix – Comparison of microprobe analyses with published values of natural amphibole standards K-HB and SC-HB

	K-HB			SC-HB		
	published value	probe value	S.D.	published value	probe value	S.D.
SiO_2	40.37	41.57	0.22	40.60	40.63	0.25
TiO_2	4.72	4.51	0.04	4.70	4.89	0.03
Al_2O_3	14.90	14.08	0.11	13.70	12.91	0.07
FeO	10.92	10.60	0.09	15.77	15.70	0.23
MnO	0.09	0.08	0.02	0.28	0.19	0.02
MgO	12.80	12.56	0.09	9.84	9.58	0.18
CaO	10.30	10.08	0.08	10.10	10.27	0.07
Na_2O	2.05	2.01	0.04	3.11	2.98	0.04
K_2O	2.05	2.01	0.04	1.14	1.15	0.04
n		9			5	

S.D. = standard deviation; n = number of samples.

References

Baadsgaard, H., Erdmer, P. and Owen, J.V., in prep. U-Pb and Pb-Pb geochronology of the Long Range Inlier, Newfoundland.

Bellefontaine, K.A., 1987. A geochemical and petrographic study of the deformation, metamorphism, and alteration of a deformed mafic dyke from the Long Range dyke swarm, northwestern Newfoundland. B.Sc. Thesis, St. Francis Xavier University, Antigonish, N.S. (unpublished).

Bostock, H.H., 1983. Precambrian rocks of the Strait of Belle Isle area. In: Geology of the Strait of Belle Isle, Northwestern Insular Newfoundland, Southern Labrador, and Adjacent Quebec. Geol. Surv. Can., Mem., 400: 1–73.

Bryan, W.B., Finger, L.W. and Chayes, F., 1969. Estimating proportions in petrographic mixing equations by least-squares approximation. Science, 163: 926–927.

Evans, J.L., 1978. An alkalic volcanic suite of the Labrador Trough, Labrador. M.Sc. Thesis, Memorial University of Newfoundland, St. John's, Nfld. (unpublished).

Frey, F.A., Bryan, W.B. and Thompson, G., 1974. Atlantic Ocean floor: geochemistry and petrology of basalts from Legs 2 and 3 of the Deep Sea Drilling Project. J. Geophys. Res., 79: 5507–5528.

Gast, P.W., 1968. Trace element fractionation and the origin of tholeiitic and alkaline magma types. Geochim. Cosmochim. Acta, 32: 1057–1086.

Grant, J.A., 1986. The isocon diagram – a simple solution to Gresens' equation for metasomatic alteration. Econ. Geol., 81: 1976–1982.

Greenough, J.D. and Papezik, V.S., 1986. Petrology and geochemistry of the early Mesozoic Caraquet dyke, New Brunswick, Canada. Can. J. Earth Sci., 23: 193–201.

Gresens, R.L., 1967. Composition-volume relationships of metasomatism. Chem. Geol., 2: 47–65.

Hynes, A., 1982. A comparison of amphiboles from medium- and low-pressure metabasites. Contrib. Mineral. Petrol., 81: 119–125.

Kamo, S.L., Gower, C.F. and Krogh, T.E., 1989. Birthdate for the Iapetus Ocean? A precise U-Pb zircon and baddeleyite age for the Long Range dikes, southeast Labrador. Geology, 17: 602–605.

Leake, B.E. (Compiler), 1978. Nomenclature of amphiboles. Mineral. Mag., 42: 533–563.

Lesher, C.M., Gibson, H.L. and Campbell, I.H., 1986. Composition-volume changes during hydrothermal alteration of andesite at Buttercup Hill, Noranda district, Quebec. Geochim. Cosmochim. Acta, 50: 2693–2705.

Moody, J., Meyer, D. and Jenkins, J.E., 1983. Experimental characterization of the greenschist/amphibolite boundary in mafic systems. Am. J. Sci., 283: 48–92.

Owen, J.V., 1987. Geology of the central part of the Long Range Inlier, western Newfoundland. Geol. Surv. Can., Open-File Rep. 1505.

Papezik, V.S. and Hodych, J.P., 1980. Early Mesozoic diabase dikes of the Avalon Peninsula, Newfoundland: Petrochemistry, mineralogy, and origin. Can. J. Earth Sci., 17: 1417–1430.

Papezik, V.S., Greenough, J.D., Colwell, J.A. and Mallinson, T.J., 1988. North Mountain basalt from Digby, Nova Scotia: Models for a fissure eruption from stratigraphy and petrochemistry. Can. J. Earth Sci., 25: 74–83.

Philpotts, J.A. and Schnetzler, C.C., 1970. Phenocryst-matrix partitioning coefficients for K, Rb, Sr and Ba with applications to anorthosite and basalt genesis. Geochim. Cosmochim. Acta, 34: 307–322.

Spear, F.S., 1981. An experimental study of hornblende stability and compositional variability in amphibole. Am. J. Sci., 281: 697–734.

Strong, D.F., 1974. Plateau lavas and diabase dikes from northwestern Newfoundland. Geol. Mag., 111: 501–514.

Strong, D.F. and Williams, H., 1972. Early Paleozoic flood basalts of northwestern Newfoundland: their petrology and tectonic significance. Proc. Geol. Assoc. Can., 24: 43–53.

Stukas, V. and Reynolds, P.H., 1974. $^{40}Ar/^{39}Ar$ dating of the Long Range dikes, Newfoundland. Earth Planet. Sci. Lett., 22: 256–266.

Lithos, 24 (1989) 65–79
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Late Precambrian alkaline plutons in southwest India: Geochronologic and rare-earth element constraints on Pan-African magmatism

M. SANTOSH[1], S.S. IYER[2], M.B.A. VASCONCELLOS[2] and J. ENZWEILER[3]

[1] *Centre for Earth Science Studies, P.B. 7250, Akkulam, Thuruvikkal Post, Trivandrum 695 031 (India)*
[2] *IPEN (CNEN/SP), Cidade Universitaria, Caixa Postal 11049, São Paulo (Brazil)*
[3] *Instituto de Geociências, Universidade Estadual de Campinas, Campinas, São Paulo (Brazil)*

LITHOS

Santosh, M., Iyer, S.S., Vasconcellos, M.B.A. and Enzweiler, J., 1989. Late Precambrian alkaline plutons in southwest India: Geochronologic and rare-earth element constraints on Pan-African magmatism. Lithos, 24: 65–79.

The Precambrian granulite facies terrain of southwestern India is intruded by a suite of alkali granite and syenite plutons. Rb-Sr whole-rock isotope data for the Angadimogar syenite (AM) and the Peralimala alkali granite (PM), belonging to this suite, define isochron ages of 638 ± 28 and 750 ± 40 Ma, respectively, with initial $^{87}Sr/^{86}Sr$ ratios of 0.7032 ± 0.0008 and 0.7031 ± 0.0008, respectively. These age data, together with data from previous studies, demonstrate long-lived magmatic activity in the time span from the late Proterozoic to the early Palaeozoic, broadly contemporaneous with Pan-African events in other fragments of the Gondwana supercontinent.

REE patterns are reported for four plutons of this Pan-African alkali granite-syenite suite: Chengannoor (CR), Vellingiri (VL) and the two dated intrusions (AM and PM). CR and AM are characterised by high total REE, strongly LREE-enriched patterns with no Eu anomaly, associated with low Sr, Rb, U and Th. K_2O, K_2O/Na_2O, K_2O/MgO and the agpaitic index are lower for these plutons as compared to the other two. The PM and VL intrusions have lower total REE and less strongly fractionated REE patterns, associated with high K_2O, K_2O/Na_2O and K_2O/MgO ratios, high Sr and Rb levels, but low U and Th. The geochemical patterns in these rocks compare them well with A-type granites and their tectonic relations assign affinities to magmatism of within-plate type. The alkaline magmatism manifests an extensional phase associated with the pre-rift tectonics of the Indian continent within the Gondwana assemblage. A petrogenetic model is developed for these plutons, involving decompression-induced melting of deep crustal source materials characterised by low initial $^{87}Sr/^{86}Sr$ and high K/Rb ratios.

(Received October 3, 1987; accepted August 29, 1989)

Introduction

A narrow transition zone separates the Archaean of south India into a greenschist-amphibolite facies terrain in the north and a granulite facies terrain in the south (Fig. 1, inset). The Kerala segment forms the southwestern part of the high-grade terrain and is represented dominantly by charnockites, granulite facies metasediments and migmatitic gneisses. These high-grade rocks are intruded by a number of granitic and syenitic bodies, most of which lie on or close to major late Proterozoic lineaments (Fig. 1). Within the last few years, there have been several studies of the petrology, geochemistry and geochronology of various rock formations in the northern segment of the South Indian craton. The southern high-grade region has recently been the subject of several investigations, mainly concerning thermobarometric and fluid-inclusion research, to constrain the genesis of granulites (e.g., Harris et al., 1982; Srikantappa et al., 1985; Santosh, 1986, 1987; Hansen et al., 1987). However, concerning the igneous history of the area, preliminary geochemical studies and a few mineral ages are the only available date (Odom, 1982; Santosh and Nair, 1983; Soman et al., 1983; Nair and Santosh, 1984; Santosh et al.,

0024-4937/89/$03.50

Litho, 24: 65-79, 1989

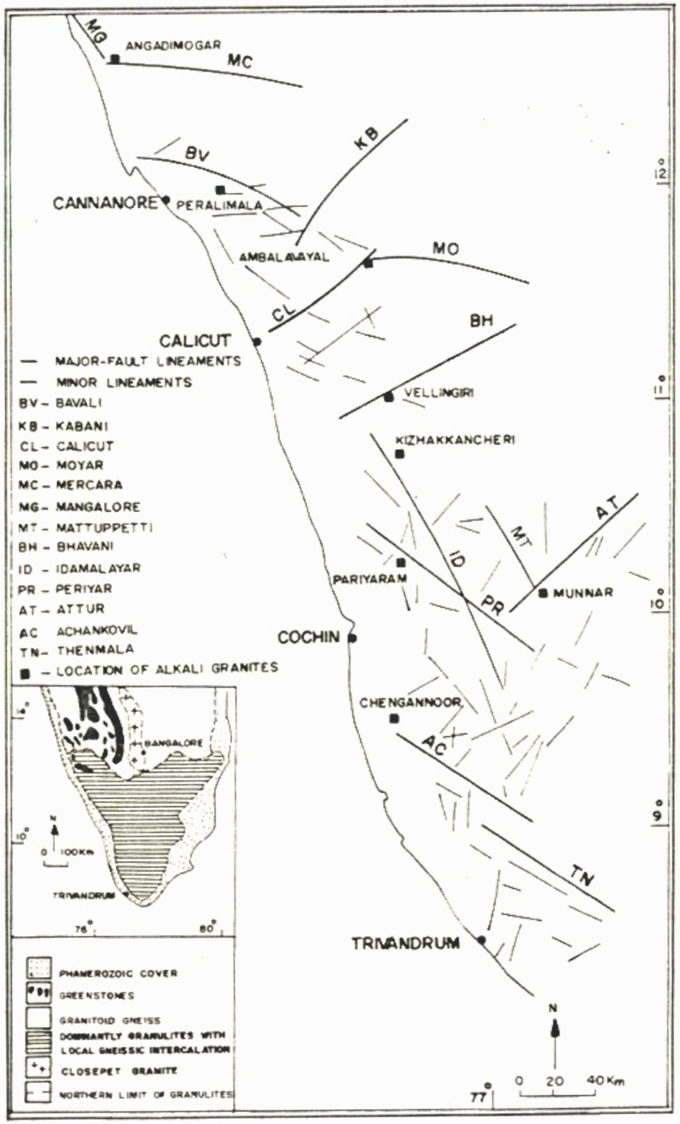

Fig. 1. Location of alkaline plutons in the Kerala region in relation to major fault-lineaments. The *inset* shows the generalised geology of south India.

1986; Santosh and Drury, 1988). Geochemical studies have shown that the magmatism was alkaline in nature. The few K-Ar and U-Pb dates on mineral separates indicate late Precambrian-early Palaeozoic ages (Odom, 1982; Nair et al., 1985). The Rb-Sr age of 678 Ma reported for the Ezhimala granite (Nair and Vidyadharan, 1982) provides no details of the isochron or the initial $^{87}Sr/^{86}Sr$ ratio. Santosh et al. (1986) reported a Rb-Sr age of 595 ± 20 Ma for the Ambalavayal granite in northern Kerala, but were unable to accurately define the initial $^{87}Sr/^{86}Sr$ ratio due to lack of analytical precision.

The late Proterozoic alkaline magmatic activity, spatially related to regional lineaments, warrants further detailed investigations on these plutons, to determine their petrogenesis and tectonic significance. This paper presents Rb-Sr isotopic age data for two representative members of the group, namely the Peralimala alkali granite (PM) and the Angadimogar syenite (AM). The rare-earth element (REE) geochemistry of these two plutons and of Chengannoor (CR) and Vellingiri (VL) plutons is also presented. From the results, we attempt to constrain the timing of the magmatic events and the petrogenetic characteristics of the alkaline magmatism so as to address the tectonic implications of these intrusives in a rifted Gondwana fragment.

Analytical techniques

The REE, U and Th analyses were carried out in the laboratories of IPEN and the Geochronological Centre, University of São Paulo, Brazil. Major elements were analysed by wet chemical techniques and trace elements (including Rb and Sr) were determined by X-ray fluorescence spectrometry (XRF), the uncertainties in the ratios are estimated as ±2%. Strontium was separated by standard ion-exchange techniques in quartz columns using highly purified acids. Samples for Sr-isotope analyses were loaded on a pre-heated single Ta filament with orthophosphoric acid and analysed in a Varian TH 5 mass spectrometer, coupled to a micro-computer system for data acquisition and processing (Kakazu et al., 1986). $^{87}Sr/^{86}Sr$ ratios were corrected for mass discrimination by normalising to $^{86}Sr/^{88}Sr = 0.1196$. Analytical details, precision and accuracy are the same as those reported in Kakazu et al. (1986) and Iyer and Santosh (1990).

REE, U and Th were determined by instrumental neutron activation analysis (INAA) (Vasconcellos and Luna, 1978; Iyer et al., 1984), using both thermal and epithermal irradiations. In the case of the thermal neutrons, a flux of $5 \cdot 10^{12}$ n m^{-2} s^{-1} was employed for 8 h, counting first after 7 days, and then again after 14 days of cooling. For epithermal irradiation, the flux was of the same order, with ca. 24 h irradiation time, and counting after cooling periods of 3 and 20 days. Samples were counted along with U.S. Geological Survey (U.S.G.S.) standards, using an Ortec Ge(Li) detector coupled to standard modular units for data acquisition and processing. Based on duplicate analysis and comparison with results for U.S.G.S. standards, the accuracy of the data presented can be taken to be of the order of ± 10% for most of the elements.

Salient features of the Kerala plutons

The general geological and mineralogical data pertaining to the four plutons are summarised in Table 1. All the intrusives are small (20–60 km^2), E-W or NW-SE elongated elliptical bodies showing sharp contacts with the country rocks. The CR pluton intrudes charnockites, whereas PM, AM and VL penetrate late Archaean gneisses intercalated with granulites in north Kerala. CR is spatially related to the NW-SE trending Achankovil lineament, considered to be a major strike-slip shear system by Drury et al. (1984). The PM pluton lies on the Bavali lineament, a major fault which has controlled the emplacement of Proterozoic anorthosite bodies, gabbros and granophyre (Nair and Santosh, 1983). AM lies close to the intersection of the Mercara fault and the Mangalore lineament. VL is spatially related to the Bhavani lineament, a Proterozoic strike-slip shear belt (Drury et al., 1984), which has controlled the emplacement of mafic and ultramafic bodies along its NE extension.

The dominant mineral constituent of all the plutons is perthitic K-feldspar. In CR, the alkali feldspar is a coarse-grained mesoperthite, whereas in others, the perthite lamellae vary from stringers and braids to coarser flames and patches. Plagioclase is subordinate, with a compositional range from albite to oligoclase. Quartz is present in minor amounts. The modal *Q-A-P* contents (Fig. 2) mainly

TABLE 1

Summary of geologic, mineralogic and geochronologic characters of the alkaline plutons

Name of pluton	Related fault-lineament(s)	Country rock	General mineralogy	Age (Ma)
Chengannoor	Achankovil	charnockite	quartz-K-feldspar-plagioclase-hornblende-biotite-sphene	550[*1]
Peralimala	Bavali	migmatic gneiss	quartz-K-feldspar-plagioclase-alkali amphibole-garnet-sphene-biotite	750[*2]
Angadimogar	Bavali, Mangalore	migmatitic gneiss	quartz-K-feldspar-plagioclase-hornblende, riebeckite-acmite-zircon-sphene	638[*2]
Vellingiri	Bhavani	migmatitic gneiss	quartz-K-feldspar-plagioclase-alkali amphibole-aegirine-garnet-sphene-phlogopite	n.d.

n.d. = not determined.

[*1] K-Ar (hornblende) age (Soman et al., 1983).

[*2] Rb-Sr (isochron) age; this study.

TABLE 2

Salient major- and trace-element characteristics of the alkaline plutons of Kerala

	Chengannoor		Peralimala			Angadimogar		Vellingiri					
	CR-2/1	CR-2/3	PM-A	PM-C	PM-E	AM-1/4	AM-1/8	VL-1/2	VL-2/2	VL-2/4	VL-3/1	VL-3/2	VL-3/3
Major elements (wt.%):													
SiO_2	70.19	69.68	63.71	65.32	63.46	62.88	61.54	63.05	62.21	60.15	64.81	63.79	62.84
TiO_2	0.30	0.32	0.06	0.06	0.09	0.12	0.68	0.17	0.17	0.13	0.02	0.65	0.72
Al_2O_3	14.78	15.80	17.82	17.85	18.87	18.86	17.84	17.84	15.80	17.33	17.33	17.33	16.82
Fe_2O_3	1.24	0.88	1.40	0.86	1.14	1.47	1.44	1.00	3.73	2.59	1.47	1.58	1.17
FeO	0.90	0.79	1.04	0.73	0.63	1.69	3.08	0.60	0.22	0.54	0.25	0.54	0.68
MnO	0.03	0.03	0.06	0.04	0.06	0.04	0.05	0.03	0.07	0.02	0.01	0.08	0.11
MgO	0.48	0.64	0.96	0.24	0.96	0.64	0.97	0.65	0.64	1.60	0.32	0.89	0.48
CaO	2.24	1.80	0.92	1.28	0.54	2.79	1.57	3.36	4.03	3.36	1.79	2.96	3.18
Na_2O	3.67	3.88	1.91	1.89	5.00	6.35	6.47	2.27	1.98	1.97	2.35	4.58	3.90
K_2O	4.85	4.79	11.40	11.31	7.94	5.05	3.84	9.66	9.93	11.37	10.61	6.38	8.63
P_2O_5	0.07	0.07	0.02	0.02	0.06	0.02	0.21	0.03	0.04	0.03	0.01	0.02	0.02
K_2O/Na_2O	1.32	1.23	5.97	5.98	1.59	0.79	0.59	4.26	5.02	5.78	4.51	1.39	2.21
K_2O/MgO	10.10	7.48	11.88	47.13	8.27	7.89	3.96	14.86	15.82	7.11	33.15	7.17	17.98
(K+Na)/Al	0.88	0.64	1.18	1.17	1.05	0.91	0.86	1.05	1.08	1.18	1.21	1.17	0.97
Trace elements (ppm):													
Ba	610	852	3253	3589	727	304	900	1721	450	784	1948	480	1016
Sr	238	193	1580	527	690	248	977	1583	1609	1415	1276	2228	1291
Rb	112	106	254	248	162	63	73	116	154	155	148	162	168
Zr	-	-	44	52	48	-	-	120	80	240	500	400	420
K/Rb	359.8	375.5	372.4	380.2	430.7	1102.6	778.1	691.4	580.3	704.5	595.3	616.3	586.9

- = below detection limit.

fall in the quartz-alkali feldspar-syenite and quartz-alkali feldspar-granite fields of Streckeisen (1976). Greenish pleochroic hornblende, riebeckite, aegirine and acmite occur in some of the samples. Garnet and sphene are common accessories in PM and VL. Apatite, zircon, biotite and calcite are other accessories. Phlogopite occurs in VL.

Out of these four plutons, age data are available only for the CR, where K-Ar dating of hornblende separates has yielded an age of 550 Ma (Soman et al., 1983), indicating an early Palaeozoic magmatic episode.

The salient geochemical features of the four plutons are given in Table 2. Only data pertaining to the samples selected for REE analyses are listed in the table, but comprehensive studies show that there is little variation in individual plutons (cf. Nair and Santosh, 1984; Santosh and Nair, 1986; Santosh and Drury, 1988). SiO_2 values are high in CR (up to 70.19%), whereas other plutons show moderate silica levels (60.15–65.32%). A notable feature is the high content of alkalies (K_2O+Na_2O up to 13.31% in PM). In all the plutons except AM, K_2O exceeds Na_2O, with K_2O/Na_2O values ranging up to 5.98 in PM. K_2O/MgO values are also high (7.11–47.13), comparable with those of alkali granites in other shield areas (Greenberg, 1981). In plots of $\log_{10}(K_2O/MgO)$ vs. SiO_2 (Fig. 3), the Kerala plutons fall close to the alkali granite field as delineated by Rogers and Greenberg (1981). The agpaitic index [(K+Na)/Al, atomic] ranges from 0.84 in CR to 1.18 in PM and VL. Except for VL-2/2, none of the samples are nepheline normative. However, many of them contain significant normative diopside and wollastonite. Low MgO (0.24–1.6%), low to moderate CaO (0.54–4.03%) and high Fe_2O_3/FeO (up to 17.4 in VL) are other common characteristics. Among the trace elements, CR and AM show moderate Sr (193–977 ppm) and low Rb (63–112 ppm), whereas PM and VL have generally high Sr (up to 2228 ppm) with moderate Rb (116–254 ppm). K/Rb values are high (339–1102) in all the plutons. VL shows a high Zr content (up to 500 ppm).

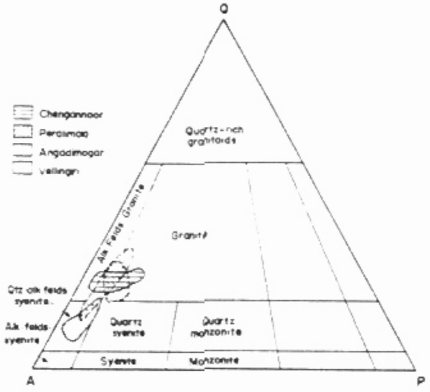

Fig. 2. *Q-A-P* plots of the modal compositions of the four alkaline plutons of the present study. The classification scheme is after Streckeisen (1976).

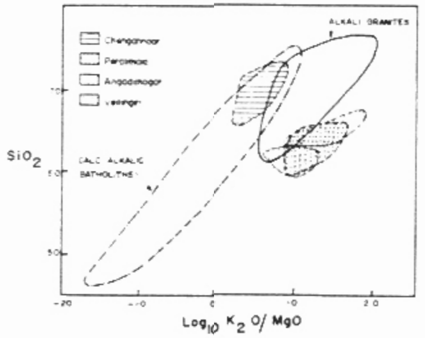

Fig. 3. SiO_2 vs. $\log_{10}(K_2O/MgO)$ relationship in the alkaline plutons. The calc-alkalic and alkali granite fields are from Rogers and Greenberg (1981).

TABLE 3

Rb-Sr analytical data for Peralimala and Angadimogar alkaline plutons, Kerala

Sample No.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Peralimala:				
PM-A	254	1580	0.465	0.7082
PM-B	196	1315	0.431	0.7077
PM-C	248	527	1.363	0.7174
PM-D	200	1538	0.376	0.7066
PM-E	162	690	0.680	0.7107
PM-F	154	788	0.565	0.7095
Angadimogar:				
AM-1/4	63	248	0.729	0.7101
AM-1/6	74	126	1.553	0.7172
AM-1/7	66	134	1.427	0.7162
AM-1/8	73	977	0.216	0.7051
AM-1/9	60	497	0.351	0.7063

Rb-Sr isotope results

The analytical data, Rb/Sr ratios and Sr-isotopic composition for the PM and AM plutons are given in Table 3. The rocks are generally rich in Sr relative to Rb, so that Rb/Sr ratios are low and rather uniform. The Rb-Sr isotopic data are plotted in isochron diagrams in Figs. 4 and 5. The decay constant for ^{87}Rb is taken as $1.42 \cdot 10^{-11}$ a^{-1} (Steiger and Jäger, 1977). When the data points are regressed according to the model of York (1969), the following results are obtained:

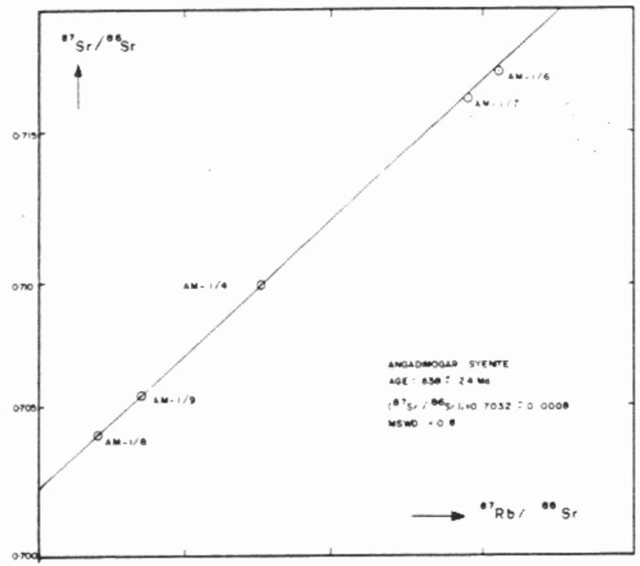

Fig. 4. Rb-Sr isochron diagram for the Angadimogar syenite.

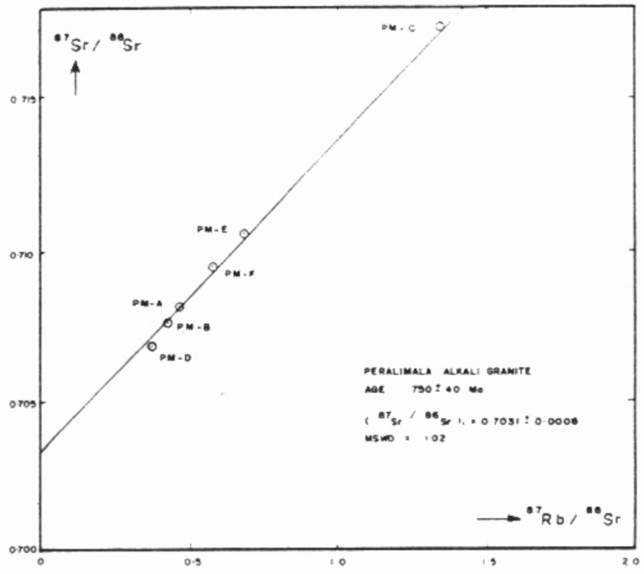

Fig. 5. Rb-Sr isochron diagram for the Peralimala alkali granite.

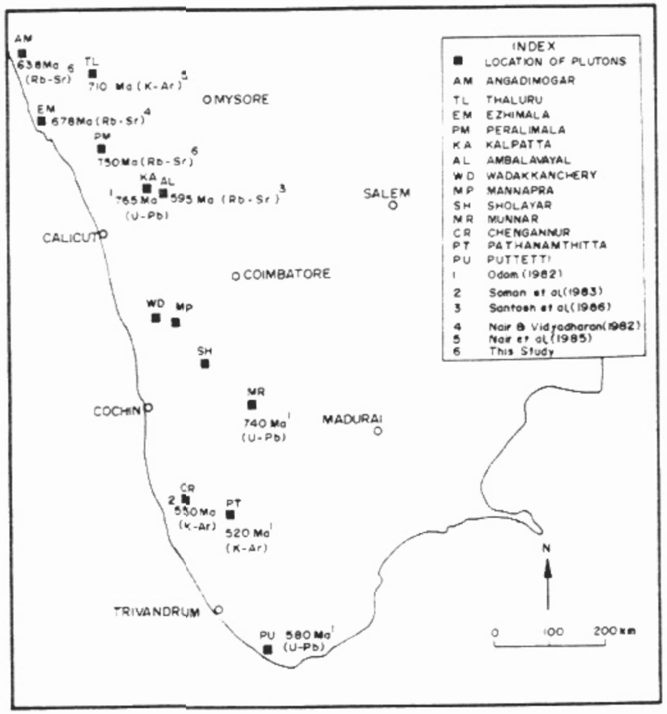

Fig. 6. Compilation of available geochronologic data for the southwestern Indian Shield pertaining to Pan-African magmatism.

Angadimogar syenite:

Age: 638 ± 24 Ma
$(^{87}Sr/^{86}Sr)_i$: 0.7032 ± 0.0008
MSWD: 0.6

Peralimala alkali granite:

Age: 750 ± 40 Ma
$(^{87}Sr/^{86}Sr)_i$: 0.7031 ± 0.0008
MSWD: 1.02

The isochrons are well fitted, with MSWD-values lower than the upper limit of 2.5 set for acceptable isochrons by Brooks et al. (1977).

The ages of the two plutons are distinct, and together with previous age determinations in the region, indicate a time span of about 200 Ma for the alkaline magmatic activity from ca. 750 to 550 Ma. The late Proterozoic ages are also correlatable with the emplacement of carbonatites and other alkaline complexes in south India (Deans and Powell, 1968; Borodin et al., 1971). Whether the period 750–550 Ma represents one episode of continuous tectonomagmatic activity or more than one episode must be determined by further geochronological studies. The available ages on the granites and syenites in the southwestern Indian Shield are compiled and shown in Fig. 6. The data indicate that the alkaline magmatism in the region spans the late Proterozoic-early Paleozoic boundary, broadly coincident with age data for the Pan-African rocks of other Gondwana fragments.

The initial Sr-isotope ratios are low for the PM (0.7031 ± 0.0008) and AM (0.7032 ± 0.0008) plutons. For VL, the Sr-isotope ratios were calculated based on an assumed age of 700 Ma, as the Rb/Sr-values were low with little dispersion. The calculations show a range between 0.706 and 0.707. It has been observed that within the late Pan-African of Arabia, initial $^{87}Sr/^{86}Sr$ ratios range from 0.7032 to 0.7093 (Gass, 1981). The values obtained for the Kerala plutons are in good agreement with these.

In addition to the classification of granites into I and S types, anorogenic alkali granites are now classified as A-type (Loiselle and Wones, 1979; White, 1979; Collins et al., 1982), which represent rift-related magmatism in shield areas. Alkali granites, in general, have a considerable range of initial $^{87}Sr/^{86}Sr$ ratios (0.703–0.712; Pitcher, 1982), the higher values signifying remelting of continental crustal rocks or contamination of mantle-derived magmas by crustal material. The low initial $^{87}Sr/^{86}Sr$ ratios in the alkaline plutons reported here indicate Rb-depleted lower-crustal or upper-mantle source.

Rare-earth elements (REE)

Analyses of REE, U and Th in representative samples from the four plutons are presented in Table 4. The CR and AM plutons have distinctly higher REE compared to PM and VL, and the REE concentration levels as well as light REE/heavy REE (LREE/HREE) ratios of these plutons show an apparent negative correlation with the agpaitic indices of the rocks. Thus, the more alkalic plutons like PM and VL have considerably lower total REE compared to the less alkaline CR and AM intrusives.

The chondrite-normalised REE patterns of the four plutons (normalisation values after Jahn et al., 1980) are shown in Fig. 7. CR and AM exhibit similar REE patterns, characterised by steep slopes from LREE to HREE [average $(Ce/Yb)_n$ ratios 31.5 and 27.1, respectively], suggesting a highly fractionated nature for these rocks, in marked contrast to PM and VL [average $(Ce/Yb)_n$ 3.9 and 2.5, respectively]. Two samples of the VL pluton (VL-2/2 and 2/4) show positive slopes from La to Lu, indicating a marked enrichment in HREE. Modal analysis of these samples has shown significant contents of garnet and zircon. These accessories are known to concentrate HREE in granitic rocks (Arth, 1976; Hanson, 1978), so that the presence of these phases may account for the high HREE levels in these samples. The $(Eu/Sm)_n$-values show a limited range in CR (0.21–0.36) and AM (0.47–0.56), whereas in PM

TABLE 4

Rare-earth elements, U and Th analyses of the alkaline plutons of Kerala

	Chengannoor		Peralimala			Angadimogar	
	CR-2/1	CR-2/3	PM-1	PM-7	PM-11	AM-1/4	AM-1/8
La (ppm)	67	49	13.8	8.7	5.6	124	204
Ce	100	63	18.6	17.1	11.0	182	274
Sm	6.3	4.2	4.9	3.8	1.15	12.9	10.4
Eu	1.3	1.5	0.72	1.05	0.30	2.28	2.18
Tb	0.52	0.43	0.57	0.84	–	0.65	0.71
Yb	0.82	n.a.	1.06	1.58	0.62	2.12	2.15
Lu	0.15	0.15	0.19	0.34	0.12	0.24	0.31
U	1.40	1.33	2.0	–	3.0	n.a.	n.a.
Th	13.6	10.1	1.94	1.94	1.58	19.4	12.6
$(La/Lu)_n$	46.3	33.8	7.4	2.6	4.7	66.6	52.3
$(Eu/Sm)_n$	0.21	0.36	0.39	0.74	0.70	0.56	0.47
$(Ce/Yb)_n$	31.5	–	4.5	2.8	4.5	32.3	21.9

	Vellingiri					
	VL-1/2	VL-2/2	VL-2/4	VL-3/1	VL-3/2	VL-3/3
La (ppm)	6.5	6.4	5.3	6.9	4.1	5.7
Ce	15.7	22.0	20.7	10.9	6.8	13.6
Sm	2.3	5.5	4.8	0.66	0.89	2.9
Eu	0.64	1.42	1.15	0.24	0.34	0.67
Tb	0.27	2.83	2.23	–	0.25	0.66
Yb	1.23	19.0	12.2	0.58	0.44	1.62
Lu	0.20	4.06	2.3	0.12	0.07	0.31
U	–	n.a.	n.a.	n.a.	–	n.a.
Th	5.1	n.a.	n.a.	n.a.	1.15	n.a.
$(La/Lu)_n$	3.3	0.16	0.23	5.8	5.9	1.9
$(Eu/Sm)_n$	0.74	0.67	0.64	0.97	1.02	0.62
$(Ce/Yb)_n$	3.3	0.30	0.43	4.8	4.0	2.1

– = below detection limit; n.a. = not analysed.

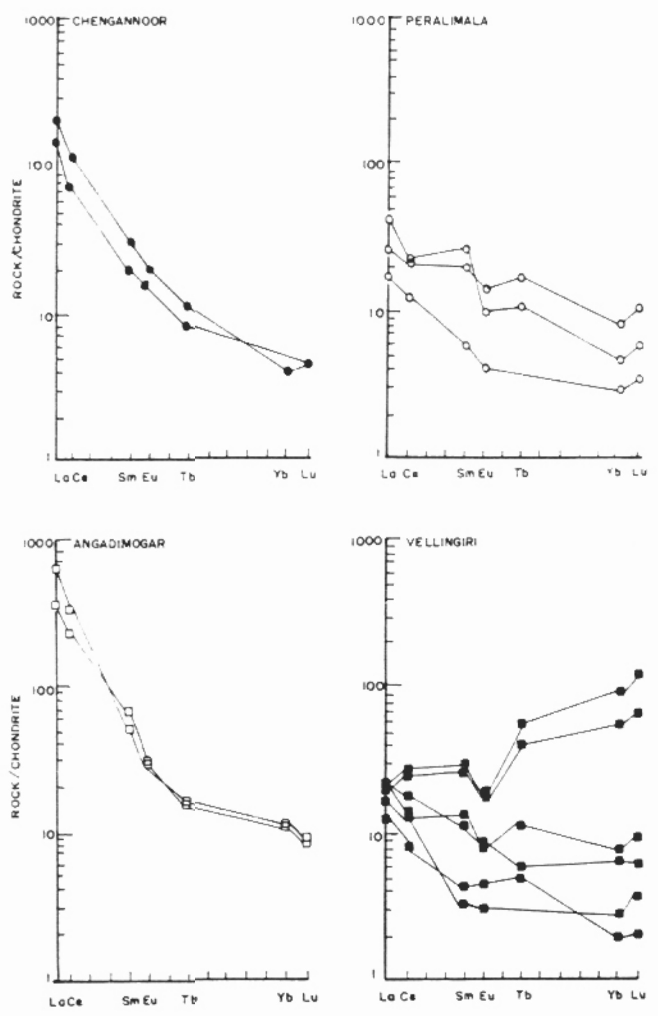

Fig. 7. Chondrite-normalised REE patterns for the alkaline plutons of Kerala.

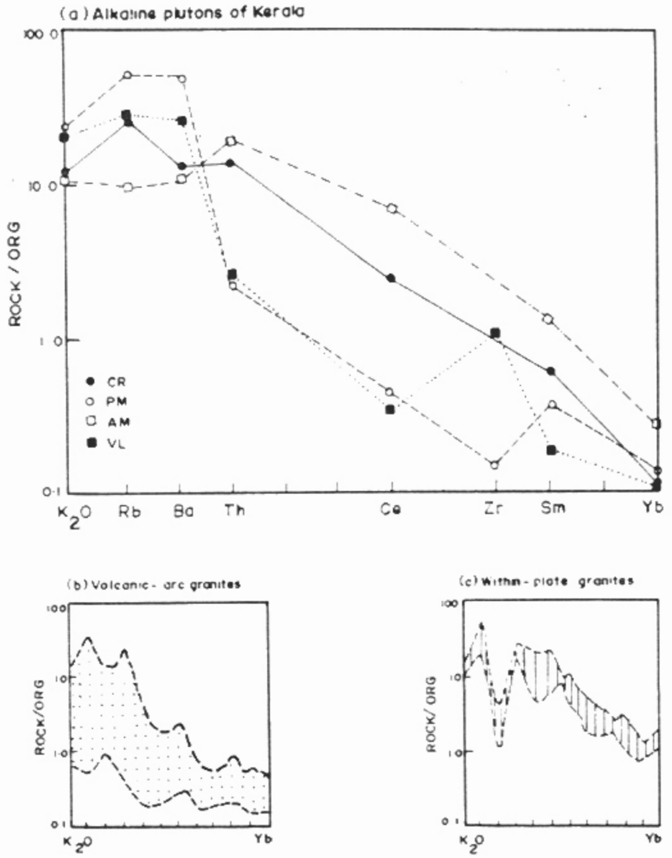

Fig. 8. Synthetic ocean-ridge granite (*ORG*) -normalised trace-element patterns of Kerala plutons (a), compared with those of volcanic-arc (b) and within-plate (c) granites (after Pearce et al., 1984).

(0.39–0.74) and VL (0.62–1.02) the ranges are significant. The majority of the REE plots of PM and VL show moderate negative Eu anomalies, indicating plagioclase fractionation. CR and AM lack Eu anomaly.

Among the radioactive elements, PM and VL show low U, Th and Th/U-values, whereas CR and AM have high Th, low U and consequently high Th/U-values. The U and Th values of all the samples of these alkaline plutons are lower than the values of >5 and >20 ppm, respectively, considered typical of peralkaline granites by Taylor et al. (1980).

Pearce et al. (1984) examined possible methods of distinguishing granites from a variety of tectonic settings and proposed a method of normalising trace-element abundances relative to an appropriate standard. The synthetic ocean-ridge granite (ORG) chosen by Pearce et al. (1984) has been taken to construct the patterns of the Kerala plutons in Fig. 8a, where they are compared with the ORG-normalised patterns of volcanic-arc (VAG) and within-plate (WPG) granites (Fig. 8b and c).

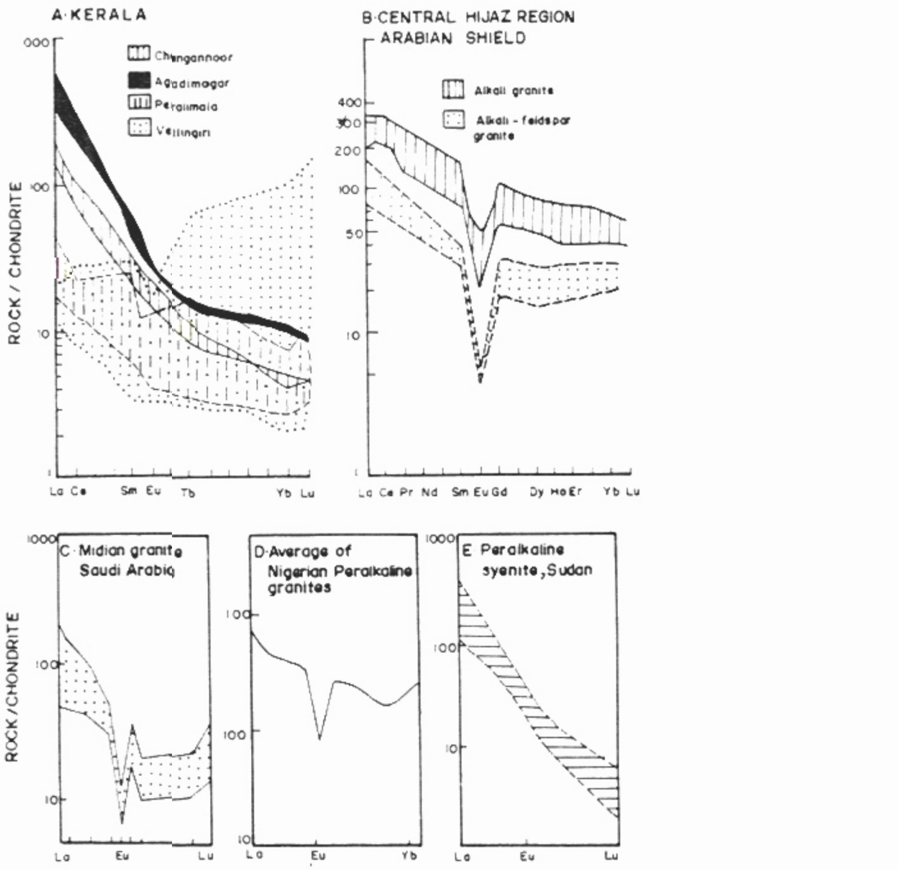

Fig. 9. Chondrite-normalised REE patterns of Kerala plutons (a), compared with those of the central Hijaz region of Arabia (b: after Jackson et al., 1984), the Midian granite of Saudi Arabia (c: after Harris and Marriner, 1980) and the peralkaline syenite of Sudan (d: after Harris et al., 1983).

The lack of a pronounced negative anomaly for Ba and the low abundances of Ce, Zr, Sm and Yb suggest affinities with VAG and COLG (collission-zone) granites. However, the petrogenetic modeling of Pearce et al. (1984) assumes that all granitic magmas derive from parents with a mantle source region. Where granites are emplaced in thick older crust, as is demonstrably the case in Kerala, contamination by earlier sial is expected, at the very least. Crustal contaminants would cause a WPG to be misclassified as VAG or COLG (cf. Santosh and Drury, 1988). From actual field setting of these plutons, they correspond more closely to WPG type.

On geochemical characteristics, the alkaline plutons of Kerala could be divided into two distinct groups, as identified from the present results. One has lower K_2O, K_2O/Na_2O, K_2O/MgO and agpaitic indices, and high $(Ce/Yb)_n$ ratios with no Eu anomaly. This group has low U and high Th values and it includes the CR and AM plutons. The PM and VL granites, on the other hand, have high K_2O, K_2O/Na_2O, K_2O/MgO and agpaitic indices, and their REE characteristics contrast with CR and AM in that they have low $(Ce/Yb)_n$ and significant negative anomalies. Two samples even show LREE-depleted patterns. U and Th values are consistently low in these rocks.

The REE patterns of the four plutons are compared with those of subalkaline and peralkaline silicic rocks from different regions in Fig. 9. Light REE (LREE) enrichment patterns are characteristic features of such rocks and the Kerala granites are similar to them. However, lack of prominent negative Eu anomaly and the rather steep LREE-enriched patterns of CR and AM distinguish these plutons from those of the Arabian Shield (Jackson et al., 1984), the peralkaline Median granite of Saudi Arabia (Harris and Marriner, 1980) and the Nigerian peralkaline granites (Bowden and Whitley, 1974). Nevertheless, their REE patterns are similar to those of a peralkaline ultrapotassic syenite from west Norway (Furnes et al., 1982), a peralkaline nepheline syenite in Sudan (Harris et al., 1983) as well as some peralkaline and subalkaline granite plutons of the Lleyn Peninsula, North Wales, U.K. (Croudace, 1982). The normalised patterns of PM and VL compare well with those of peralkaline plutons from Nigeria and the U.S.S.R. (Bowden and Whitley, 1974). Two samples of the VL pluton (2/2 and 2/4) deviate from other patterns in having LREE-depleted patterns (i.e. $(Ce/Yb)_n<1$); these are similar to the patterns in albitised riebeckite granites reported by Bowden and Whitley (1974). As mentioned earlier, the high modal contents of garnet and zircon in these two samples may account for their higher LREE levels.

Discussion and conclusions

It is now widely recognised that the tectonothermal event throughout Africa at the end of the Precambrian, for which Kennedy (1964) coined the term Pan-African, is widely represented throughout the Gondwana continents (Kröner, 1979, 1980, 1981). In NE Africa and Arabia, the final stages of cratonization in the Pan-African were marked by a switch from calc-alkaline to peralkaline magmatism (Gass, 1981). The ca. 750–550 Ma ages of the Kerala plutons are broadly coincident with those found in the Pan-African of the Afro-Arabian shield. Hence these plutons are envisaged to be imprints of a similar tectonothermal event in south India and suggest that the Pan-African thermal activity was an important aspect of the Precambrian evolution of the Indian Shield. In the context of south India's former position at the centre of the Gondwana supercontinent, the Kerala plutons warrant detailed studies in terms of geochemistry and geochronology in order to characterise the petrogenetic and tectonic history of the Indian Pan-African.

A-type granites, which the Kerala plutons resemble most, are thought to be the products of crystallization of primary magmas produced by the partial melting of relatively anhydrous lower-crustal rocks (Barker et al., 1975; Collins et al., 1982; Jackson et al., 1984). The Collins et al. (1982) model proposes partial melting of A-type granite magmas at elevated temperatures from a source depleted in water by the previous extraction of minimum-melt I-type magma. A-type magmatism is thus characterised by a source of sialic, dehydrated crust, a source of heat sufficient to partially melt this crust and a means of migration of the resulting magma.

The high K/Rb ratios (359–1102) of the Kerala plutons and their low initial $^{87}Sr/^{86}Sr$ levels (0.7031 and 0.7032) indicate Rb-depleted lower-crustal or upper-mantle source for the magma. Although the associated granulites (in which the alkaline plutons are emplaced) are not commonly depleted in Rb relative to K at their present-day level of exposure, deeper-level charnockites of different ages from the Nilgiri Hills and many other terrains have high K/Rb ratios. Hence, generation of the Kerala plutons by crustal melting cannot be ruled out. The relatively quartz-poor alkaline nature of many of the plutons may indicate deep melting because of the movement of the granite minimum in the Q-Ab-Or system to more alkaline compositions with increasing pressure (Santosh and Drury, 1988).

Harris and Marriner (1980) suggested that slightly peralkaline magmas can be generated by deep crustal partial melting under a high flux of mantle-derived volatiles. Such gas-flux transports thermal energy to produce a steep transient geotherm and abnormally high temperatures at intermediate crustal levels (Harris et al., 1982), in addition to carrying elements scavenged from along

its path. In the case of a CO_2 flux driving water vapor before it, as suggested for the carbonic metamorphism of south Indian charnockites (Santosh, 1986), high temperatures and high P_{H_2O} would induce melting at different crustal levels ahead of the dehydration front as it moves progressively to higher crustal levels, represented by the Kerala charnockites (Santosh and Drury, 1988). Of particular interest in this context are the recent carbon stable isotope studies of fluid inclusions. Thermal decrepitation of fluid inclusions in the Kerala plutons and stable isotope analysis of the released CO_2-rich fluid yield $\delta^{13}C$-values in the range of -13.6 to -7.3‰ (cf. Santosh, 1990). Carbon isotopes of fluid inclusions in the Kerala charnockites show a closely comparable range (-12.3 to -7.5‰; Santosh et al., 1988), indicating the possibility of a common "mantle connection" for the entrapped fluids.

The generation of alkaline magmas within non-orogenic zones of crustal fractures has been observed by various workers (Murthy and Venkataraman, 1964; Bowden, 1974). The spatial relationship of the Kerala granites with regional lineaments needs emphasis. Many of these lineaments are deep-seated faults or shears and are rift-related in nature (Grady, 1971; Katz, 1978; Drury et al., 1984). Peralkaline plutonism is a ubiquitous feature of pre-rift tectonics and is especially important in the early stages of extensional tectonics. Abnormal enrichment of alkalies is considered to be a key-note of rift-related magmatism (Bailey, 1974). Crustal fractures act as conduits for heat and volatile transfer from the underlying mantle. The volatile influx brings with it mobile elements, especially alkalies. A number of syenite masses, sodic anorthosites and carbonatites with Pan-African ages are emplaced along the major lineament systems in south India (Deans and Powell, 1968; Borodin et al., 1971). Since the most probable mechanism of crustal anatexis within the continental plate is decompression melting, triggered by extensional tectonics, it is inferred that the alkaline magmatic regime in the Indian Shield represents repeated attempts of the crust to break apart in the Gondwana supercontinent during the Pan-African times.

Acknowledgements

M.S. thanks the Director of Centre for Earth Science Studies for support. The late Dr. N.G.K. Nair (CESS) initiated this study and extended constant encouragement. S.S.I. thanks the IPEN authorities for facilities and support. The authors thank Paul Taylor and an anonymous referee for helpful comments which greatly aided in improving our presentation.

References

Arth, J.G., 1976. Behaviour of trace elements during magmatic processes – a summary of theoretical models and their applications. J. Res. U.S. Geol. Surv., 4: 41–47.

Bailey, D.K., 1974. Origin of alkaline magmas as a result of anatexis. In: H.S. Sørensen (Editor), The Alkaline Rocks. Wiley, New York, N.Y., pp. 436–441.

Barker, F., Wones, D.R., Sharp, W.N. and Desborough, G.A., 1975. The Pikes Peak batholith, Colorado Front Range and a model for the origin of gabbro-anorthosite-syenite-potassic granite suite. Precambrian Res., 1: 97–160.

Barker, F., Arth, J.G., Peterman, Z.L. and Friedman, I., 1976. The 1.7–1.8 b.y. old trondhjemites of south-western Colorado and northern New Mexico – geochemistry and depths of genesis. Geol. Soc. Am. Bull., 87: 189–198.

Borodin, L.S., Gopal, V., Moralev, V.M., Subramanian, V. and Ponikarov, V., 1971. Precambrian carbonatites of Tamil Nadu, south India. Geol. Soc. India, 12: 101–112.

Bowden, P., 1974. Oversaturated alkaline rocks, granites, pantellerites and comendites. In: H. Sørensen (Editor), The Alkaline Rocks. Wiley, New York, N.Y., pp. 109–123.

Bowden, P. and Whitley, J.E., 1974. Rare earth patterns in peralkaline and associated granites. Lithos, 7: 15–21.

Brooks, C., Hart, S.R. and Wendt, I., 1977. Realistic use of two error regression treatments as applied to rubidium-strontium data. Rev. Geophys. Space Phys., 10: 551–577.

Collins, W.J., Beams, S.D., White, A.J.R. and Chappell, B.W., 1982. Nature and origin of A-type granites with particular reference to south-eastern Australia. Contrib. Mineral. Petrol., 80: 189–200.

Croudace, I.W., 1982. The geochemistry and petrogenesis of the lower Palaeozoic granitoids of the Llyen Peninsula, North Wales. Geochim. Cosmochim. Acta, 46: 609–622.

Cullers, R.L. and Graff, J.L., 1984. Rare earth elements in igneous rocks of the continental crust: Predominantly basic and ultrabasic rocks. In: P. Henderson (Editor), Rare Earth Element Geochemistry. Elsevier, Amsterdam, pp. 237–274.

Deans, T. and Powell, J.L., 1968. Trace elements and strontium isotopes in carbonatites, fluorites and limestones from India and Pakistan. Nature (London), 218: 750–752.

Drury, S.A., Harris, N.B.W., Holt, R.W., Reeves-Smith, G.J. and Wightman, R.T., 1984. Precambrian tectonics and crustal evolution in south India. J. Geol., 92: 3–20.

Furnes, H., Mitchell, J.G., Robins, B., Ryan, P.D. and Skjerlie, F.J., 1982. Petrography and geochemistry of peralkaline, ultrapotassic syenite dykes of Middle Permian age, Sunnfjord, west Norway. Nor. Geol. Tiddskr., 62: 142–159.

Gass, I.G., 1981. Pan-African (Upper Proterozoic) plate tectonics of the Arabian-Nubian shield. In: A. Kroner (Editor), Precambrian Plate Tectonics. Elsevier. Amsterdam. pp. 385–405.

Grady, J.C., 1971. Deep main faults in south India. J. Geol. Soc. India. 12: 56–62.

Greenberg, J.K., 1981. Characteristics and origin of Egyptian younger granites. Geol. Soc. Am. Bull., Part II, 92: 749–840.

Hansen, E.C., Janardhan, A.S., Newton, R.C., Prame, W.K.B.N. and Kumar, G.R.R., 1987. Arrested charnockite formation in southern India and Sri Lanka. Contrib. Mineral. Petrol., 86: 225–244.

Hanson, G.N., 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. Earth Planet. Sci. Lett., 53: 26–43.

Harris, N.B.W. and Marriner, G.F., 1980. Geochemistry and petrogenesis of a peralkaline granite complex from the Midian mountains, Saudi Arabia. Lithos, 13: 325–337.

Harris, N.B.W., Holt, R.W. and Drury, S.A., 1982. Geobarometry, geothermometry and late Archaean geotherms from the granulite facies terrain of south India. J. Geol., 90: 509–527.

Harris, N.B.W., Mohammed, A.E.R.O. and Shaddad, M.Z., 1983. Geochemistry and petrogenesis of a nepheline syenite-carbonatite complex from the Sudan. Geol. Mag., 120: 115–127.

Iyer, S.S. and Santosh, M., 1990. Late Proterozoic Rb-Sr ages from the cordierite gneiss-charnockite terrain of Kerala, south India. Precambrian Res. (in press).

Iyer, S.S., Chaudhuri, A., Cordani, U.G. and Vasconcellos, M.B.A., 1984. Radioactive element distribution on the Archaean granulite terrane of Jequie Bahia, Brazil. Contrib. Mineral. Petrol., 85: 95–101.

Jackson, N.J., Walsh, J.N. and Pegram, E., 1984. Geology, geochemistry and petrogenesis of late Precambrian granitoids in the Central Hijaz region of the Arabian shield. Contrib. Mineral. Petrol., 87: 205–219.

Jahn, B.M., Auvray, B., Blais, S., Capdevila, R., Cornichet, V.F. and Hameurt, J., 1980. Trace element geochemistry and petrogenesis of Finnish greenstone belts. J. Petrol., 21: 201–244.

Kakazu, M.H., Stato, K., Moraes, N.M.P., Shihomutsu, H. and Iyer, S.S., 1986. Precisão e exatidão na espectrometro de massa aermoionica aquisicao de dados com microcomputador. In: Mass Spectrometry, Rio de Janeiro, (abstract).

Katz, M.B., 1978. Tectonic evolution of the Archaean granulite facies belt of Sri Lanka and South India. J. Geol. Soc. India, 19: 185–205.

Kennedy, W.Q., 1964. The structural differentiation of Africa in the Pan-African (±500 m.y.) tectonic episode. Res. Int. Afr. Geol., Univ. of Leeds, 8th Annu. Rep., pp. 48–49.

Kröner, A., 1979. Pan-African mobile belts as evidence for a transitional tectonic regime from intraplate orogeny to plate margin orogeny. In: S.A. Tahoun (Editor), Evolution of the Arabian-Nubian Shield, Vol. 1. Pergamon, Oxford, pp. 21–37.

Kröner, A., 1980. Pan-African crustal evolution. Episode, 2: 3–8.

Kröner, A., 1981. Precambrian plate-tectonics. In: A. Kröner (Editor), Precambrian Plate Tectonics. Elsevier, Amsterdam. pp. 57–90.

Loiselle, M.C. and Wones, D.R., 1979. Characteristics and origin of anorogenic granites. Geol. Soc. Am., Annu. Meet., Abstr. Progr., 11: 468.

Murthy, M.V.N. and Venkataraman, P.K., 1964. Petrogenetic significance of certain platform peralkaline granites of the world. In: C.H. Smith and T. Sorgenfrei (Editors), The Upper Mantle Symposium I.V.G.S. Publ., New Delhi, pp. 127–149.

Nair, N.G.K. and Santosh, M., 1983. Petrochemistry of the granite and granophyre complex, Kerala, India. Proc. Indian Acad. Sci. (Earth Planet. Sci.), 92: 129–140.

Nair, N.G.K. and Santosh, M., 1984. Petrochemistry and tectonic significance of the Peralimala alkali granite Cannanore district, Kerala. J. Geol. Soc. India, 25: 35–44.

Nair, M.M. and Vidyadharan, K.T., 1982. Rapakivi granite of the Ezhimala complex and its significance. J. Geol. Soc. India, 23: 46–51.

Nair, N.G.K., Soman, K., Santosh, M., Arkelyants, M.H. and Golubyev, V.N., 1985. K-Ar ages of three granite plutons from north Kerala. J. Geol. Soc. India, 26: 674–676.

Odom, A.L., 1982. Isotopic age determinations of rock and mineral samples from Kerala, India. U.N. New York, N.Y., Case No. 81-10084 (unpublished).

Pearce, J.A., Harris, N.B.W. and Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol., 25: 956–983.

Pitcher, W.S., 1982. Granite type and tectonic environment. In: K.J. Hsü (Editor), Mountain Building Processes. Academic Press, London, pp. 19–40.

Rogers, J.J.W. and Greenberg, J.K., 1981. Trace elements in continental margin magmatism. III. Alkali granites and their relationship to cratonization. Geol. Soc. Am. Bull., 92: 57–93.

Santosh, M., 1986. Carbonic metamorphism of charnockites in the southwestern Indian shield: a fluid inclusion study. Lithos, 19: 1–10.

Santosh, M., 1987. Cordierite gneisses of southern Kerala, India: Petrology, fluid inclusions and implications for crustal uplift history. Contrib. Mineral. Petrol., 96: 343–356.

Santosh, M., 1990. Alkaline plutons, decompression granulites and late Proterozoic CO_2 influx in South India. Mem. Geol. Soc. India, 15 (in press).

Santosh, M. and Drury, S.A., 1988. Alkali granites with Pan-African affinities from Kerala, south India. J. Geol., 96: 616–622.

Santosh, M. and Nair, N.G.K., 1983. Petrochemistry of the Chengannoor granite, Alleppey district, Kerala. J. Geol. Soc. India, 24: 291–298.

Santosh, M., Nair, N.G.K., Pande, K. and Gopalan, K., 1986. Rb-Sr geochronology of the Ambalavayal granite, Kerala. J. Geol. Soc. India, 27: 309–312.

Soman, K., Santosh, M. and Golubyev, V.N., 1983. Early Palaeozoic I-type granite from central Kerala and its bearing on possible mineralization. Indian J. Earth Sci., 10: 137–141.

Srikantappa, C., Raith, M. and Spiering, B., 1985. Progressive charnockitization of a leptynite-khondalite suite in

southern Kerala, India – evidence for formation of charnockites through decrease in fluid pressure. J. Geol. Soc. India, 26: 849–872.

Steiger, R.H. and Jäger, E., 1977. Subcommission on Geochronology: Convention on the use of decay constants in geo- and cosmo-chronology. Earth Planet. Sci. Lett., 36: 359–362.

Streckeisen, A.L., 1976. To each plutonic rock its proper name. Earth Sci. Rev., 12: 1–33.

Sukhesvala, R.N. and Viladkar, S., 1978. Carbonatites of India. Proc. 1st Int. Symp. on Carbonatites, São Paulo, pp. 277–293.

Taylor, R.P., Strong, D.F. and Kean, B.F., 1980. The Topsails igneous complex: Silurian-Devonian peralkaline magmatism in western Newfoundland. Can. J. Earth Sci., 17: 425–439.

Vasconcellos, M.B.A. and Luna, F.W.J., 1978. Activati
analysis of alkaline rocks – a comparison between d
structive and non-destructive methods. J. Radioana
Chem., 44: 55–81.

Wendlandt, R.F. and Harrison, W.J., 1979. Rare earth part
tioning between immiscible carbonate and silicate liqui
and CO_2 vapor: results and implications for the formati
of light rare earth enriched rocks. Contrib. Mineral. P
trol., 69: 409–419.

White, A.J.R., 1979. Source of granite magmas. Geol. So
Am., Abstr. Progr., 11: 539.

York, D., 1969. Least squares fitting of a straight line wi
correlated errors. Earth Planet. Sci. Lett., 5: 320–324.