Petrogenesis of granitic rocks of low- to high-grade transition zone of Krishnagiri, Dharmapuri District, Tamil Nadu

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The granitic rocks of low- to high-grade transition zone of Krishnagiri are distinctly grey coloured, exhibiting a clear gneissic banding with predominant tonalite–granodiorite composition. Ubiquitous occurrence of amphibolite enclaves in the granite suggests a genetic link between the two. The rocks are composed of quartz, plagioclase and subordinate amounts of orthoclase and microcline as light coloured minerals with hornblende and biotite as mafics. Chemically, these granitoids belong to moderate- to high-alumina type and metaluminous granite with average A/CNK value being less than unity. Magmatic parentage is discernible from the behaviour of many major and trace elements. Abundances of certain elements like TiO_2, MgO, Sr and Ni indicate a basic source. REE data support the partial melting of garnet-bearing amphibolite source in the evolution of these granitoids. The I-type characteristics and low Rb/Sr ratios suggest that the amphibolite source is possibly derived from an enriched mantle/lower crust with mafic constituents. The mineralogy and petrochemistry match well with the granites of IAG + CAG affinity.

THE Archaean rocks of India are a complex suite, comprising greenstones, low, and high-grade gneisses and granites with polyphase and polygenetic characters and ages ranging from 3300 m.y to 2500 m.y (ref. 1). On the basis of the extensive study on these rocks, it is now generally understood that they have complicated plutono-metamorphic history, heterogeneity of petrochemical composition, time–space distribution, obliterated original structures due to subsequent deformations and metasomatism. Granitic rocks, constituting a major component of the Archaean, have also undergone the tectonics. Some petrologists[2], believe that most of the granitic rocks occurring in Precambrian Cratons and Mobile Belts are better indicators of the crustal processes and compositions as these rocks are considered to owe their evolution to conditions of high temperature and abnormal crustal activity prevailing during orogenic events. Therefore, more emphasis is placed on the investigation of the Archaean granitic rocks in recent years to probe into their probable precursors. The studies, so far, carried out on the litho-units of Transition Zone in Dharmapuri District mainly concentrated on their metamorphic grade of formation[3–6]. The present study constitutes a detailed account of the granitic rocks occurring in the transition zone of Krishnagiri.

Field setting

The granitic rocks, occurring in and around the transition zone of Krishnagiri (Figure 1), are distinctly grey-coloured, exhibiting a clear gneissic banding with dominant tonalite–granodiorite composition and subordinate occurrences of granite (s.s.). Mostly, they are medium-grained with occasional fine and coarse-grained varieties. The gneissic banding, often, exhibits contortion in compositional layering which gives rise to small scale close folds with parallel fold axes. Abundant amphibolite enclaves with different shapes and sizes are present which depict a structural pause with the surrounding granitoids and are regarded as possible relics of the older crust[7]. The last phase of the igneous activity in the area is represented by the profuse development of dolerite dykes cross cutting three granitic rocks dominantly in WSW–ENE and WNW–ESE directions. The trend of the foliation, defined by parallel orientation of mafic minerals, is more or less the same throughout and is generally along the NNE–SSW direction swinging frequently to N–S with easterly dips ranging from 30° to 40°.

Petrography

The medium-grained rocks of the area exhibit distinct gneissic banding consisting of alternating bands of leucocratic and melanocratic minerals of quartz, plagioclase and subordinate amounts of potash feldspars in the former and hornblende and biotite in the latter respectively. Based on mineralogy (Table 1), three types could be recognized using IUGS systematics after Streckeisen[8], namely: (i) tonalite, (ii) granodiorite and (iii) granite (Figure 2). The granitoids fall in the IAG + CAG fields after Maniar and Piccoli[9]. In thin sections, the feldspars are mostly plagioclase (An_{14-32}) with minor amounts of orthoclase and microcline, the latter minerals are seen more in granite (s.s.). The plagioclase grains are both twinned, generally, on albite-ala law and untwinned. Sericitization of feldspars is noticed in some sections. The orthoclase is occasionally perthitic and microcline is interstitial between quartz and plagioclase grains. Myrmekitic intergrowths are rarely noticed. The mafic minerals include prevalent hornblende ($2V_x = 68–78°$; Z^$c = 17–19°$), followed by biotite which is distinctly pleochroic from brown to greenish brown. The common minor accessories are sphene, apatite and magnetite.

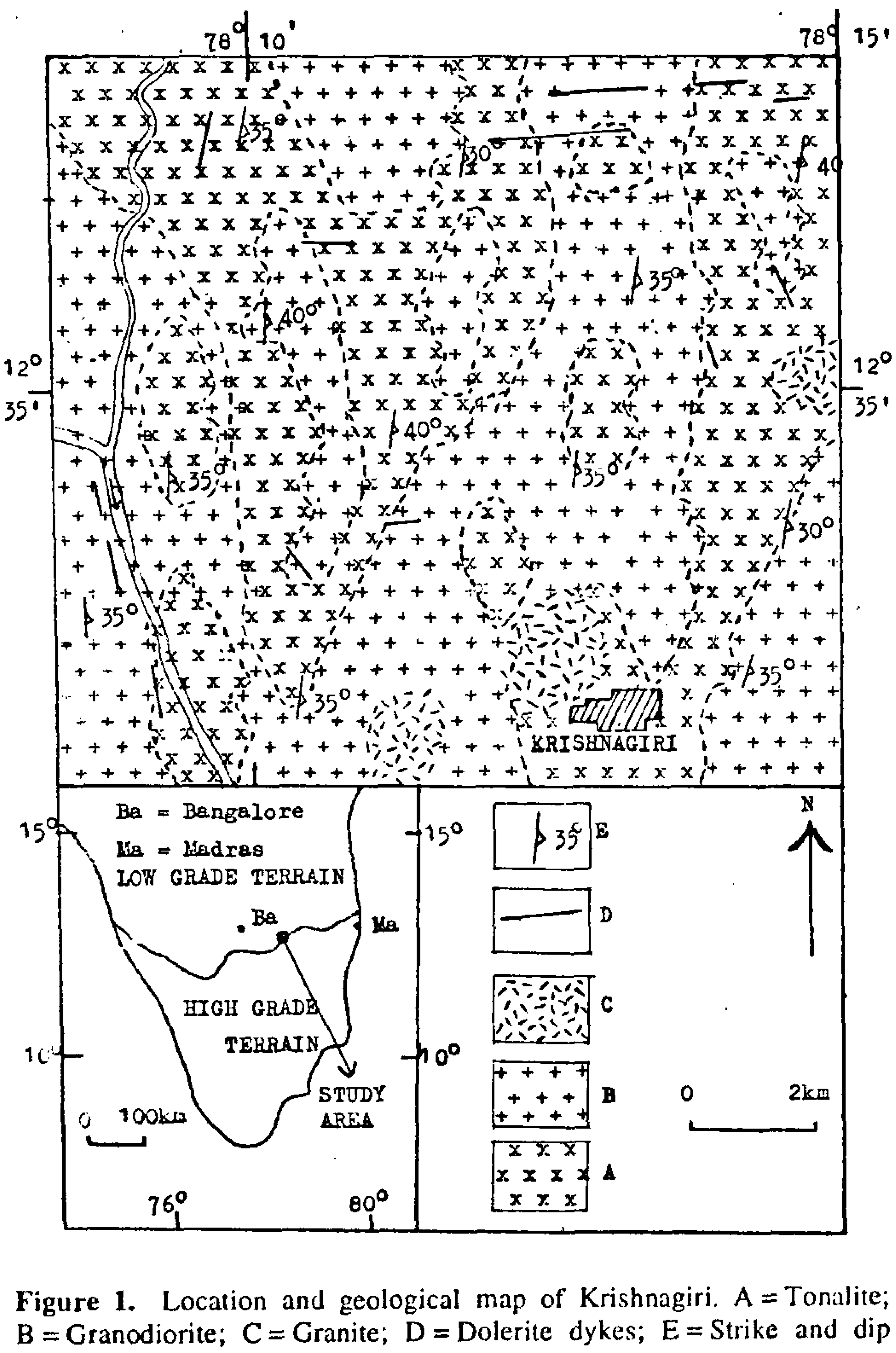

Figure 1. Location and geological map of Krishnagiri. A = Tonalite; B = Granodiorite; C = Granite; D = Dolerite dykes; E = Strike and dip of foliation.

Table 1. Modal composition of the Krishnagiri granitic rocks

Mineral	1	2	3	4	5	6	7
Quartz	23.4	34.4	31.1	32.7	26.9	22.1	26.1
Plagioclase	48.1	42.7	49.4	37.8	43.7	46.2	29.6
K-feldspar	5.5	4.9	3.4	15.5	13.4	20.2	31.3
Hornblende	16.3	11.1	7.8	10.5	9.5	6.3	7.4
Biotite	5.8	6.1	6.8	2.3	5.7	4.1	4.1
Accessories	0.9	0.8	1.5	1.2	0.8	1.1	1.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sample Nos. 1 to 3 = Tonalite; 4 to 6 = Granodiorite; 7 = Granite.

Petrochemistry

Seven representative samples were carefully selected for chemical analyses. Major elements were determined by conventional wet methods and trace elements were determined by atomic absorption spectrophotometer. Rare earth elements (REE) on selected samples were determined by using spark source mass spectrometry[10]. The precision (±5%) and accuracy were checked by using standards and by performing duplicate analyses. The chemical data of the granitic rocks of Krishnagiri are given in Table 2. Table 3 presents some diagnostic chemical parameters.

Major elements

From Table 2, it is observed that from tonalite to granite, there is a gradual increase of SiO_2, K_2O and gradual decrease of MgO, CaO, Na_2O and Sr, while the remaining oxides show fluctuations. In the differentiation index (DI) diagram (Figure 3), with increasing DI, there is an increase in SiO_2, K_2O, Ba, K/Rb, K/Ba and K/Sr and decrease in Na_2O, MgO, CaO and Sr. All the parameters trace a smooth trend against DI, suggesting that these granitoids are cogenetic. In case of the Ca–Na–K distribution, the granitoids follow a calcalkaline trend[11]. Na_2O/K_2O, which usually will be less than one in the microcline rich granites, is high and more than one (average 2.18) and seems to be controlled by the abundance of plagioclase in the rocks testifying to their dominant tonalite–granodiorite composition[12]. World-wide observations indicate that soda-rich granitoids are of Archaean age and K-rich granitoids are of Proterozoic

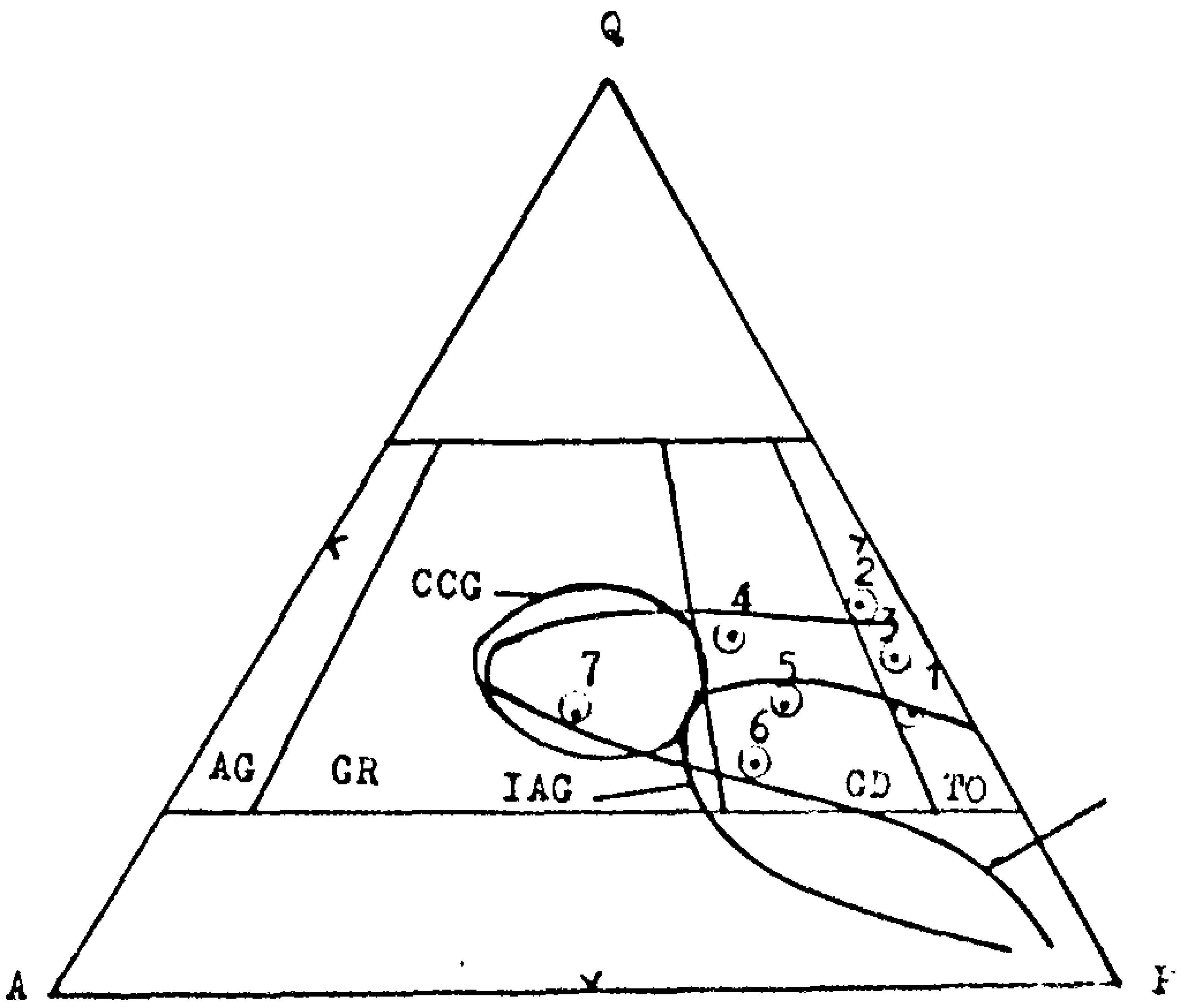

Figure 2. Modal Q-A-P plot using IUGS systematics after Streckeisen[8]. Description of the samples are as given in Table 1. IAG = Island Arc Granites; CAG = Continental Arc Granites; CCG = Continental Collision Granites. The fields are after Maniar and Piccoli[9].

and younger age[13]. The tonalite–granodiorite suites of the Shimoga–Honali, Holenarsipur and Chitradurga, having Na_2O/K_2O ratio more than one, have yielded an age older[14] than 2.5 b.y, whereas granitoids of adamellite–granite compositions from Closepet area, with the ratio less than one, are younger[15] than 2.5 b.y.

The granitoids of the area are dominantly metaluminous with A/CNK values being less than unity except for one sample which is slightly peraluminous (average A/CNK and A/NK are 0.95 and 1.68 respectively). The agpaitic index is less than one indicating subsolvus nature of these granitoids. Barker *et al.*[16] and Barker[17]

Table 2. Chemical composition of granitic rocks from the Krishnagiri area

	1	2	3	4	5	6	7	Average
SiO_2	67.10	68.78	68.30	71.35	69.66	70.59	72.08	69.69
TiO_2	0.32	0.28	0.36	0.35	0.40	0.44	0.30	0.35
Al_2O_3	15.84	15.80	15.01	14.30	15.03	14.72	14.52	15.03
Fe_2O_3	1.10	0.78	0.92	0.85	0.92	0.95	0.68	0.89
FeO	1.98	1.12	1.53	1.31	1.41	1.17	1.29	1.40
MnO	0.10	0.06	0.07	0.08	0.11	0.05	0.09	0.08
MgO	2.22	1.20	1.78	0.87	0.75	0.97	0.62	1.20
CaO	5.07	4.61	4.40	3.74	3.91	3.53	2.01	3.90
Na_2O	4.38	4.98	4.45	3.73	3.67	3.71	2.98	3.99
K_2O	1.20	1.47	1.53	2.22	2.58	2.79	3.41	2.17
P_2O_5	0.15	0.32	0.27	0.30	0.24	0.29	0.58	0.31
LOI	1.13	0.93	1.37	1.28	0.81	0.98	1.08	
Total	100.59	100.33	99.99	100.38	99.49	100.19	99.64	
Trace elements								
Rb	45	49	52	38	35	57	41	45
Ba	171	215	135	156	145	201	197	174
Sr	312	215	285	185	235	193	172	228
Ni	26	31	21	28	19	23	17	24
Cr	27	25	30	17	19	23	20	23
Y	16	12	22	15	18	19	13	16
Zr	131	165	181	156	154	172	150	158
REE								
La			31	37			41	36
Ce			28	36			31	32
Sm			5.1	4.8			5.7	5.2
Eu	ND	ND	0.95	0.75	ND	ND	1.21	0.97
Tb			0.51	0.64			0.58	0.58
Er			0.41	0.74			0.63	0.59
Yb			0.66	0.72			0.42	0.60

Description of the samples as in Table 1; ND = Not determined.

Table 3. Some diagnostic chemical parameters

	1	2	3	4	5	6	7	Average
DI	67.29	74.74	72.55	76.94	75.33	77.94	82.48	75.32
Na_2O/K_2O	3.65	3.39	2.91	1.68	1.42	1.33	0.87	2.18
A/CNK	0.89	0.87	0.88	0.92	0.94	0.94	1.18	0.95
A/NK	1.85	1.60	1.67	1.65	1.70	1.60	1.68	1.68
Agpaitic index	0.54	0.62	0.60	0.60	0.59	0.63	0.60	0.60
Ba/Sr	0.55	1.00	0.47	0.84	0.62	1.04	1.15	0.81
K/Rb	222	251	248	489	620	408	700	420
Ca/Sr	117	154	112	145	108	132	85	122
Rb/Sr	0.14	0.23	0.18	0.21	0.15	0.29	0.24	0.21
REE	–	–	66.63	80.65	–	–	80.54	75.94
$(LREE/HREE)_N$	–	–	10.69	9.44	–	–	12.29	10.81
La_N/Yb_N	–	–	28.47	31.14	–	–	59.16	39.59
La_N/Sm_N	–	–	3.33	4.23	–	–	3.95	3.84
Ce_N/Yb_N	–	–	9.64	11.36	–	–	16.78	12.59
Ce_N/Y_N	–	–	4.34	8.18	–	–	8.19	6.90
Eu/Eu*	–	–	0.66	0.50	–	–	0.82	0.66

Description of the samples as in Table 1.

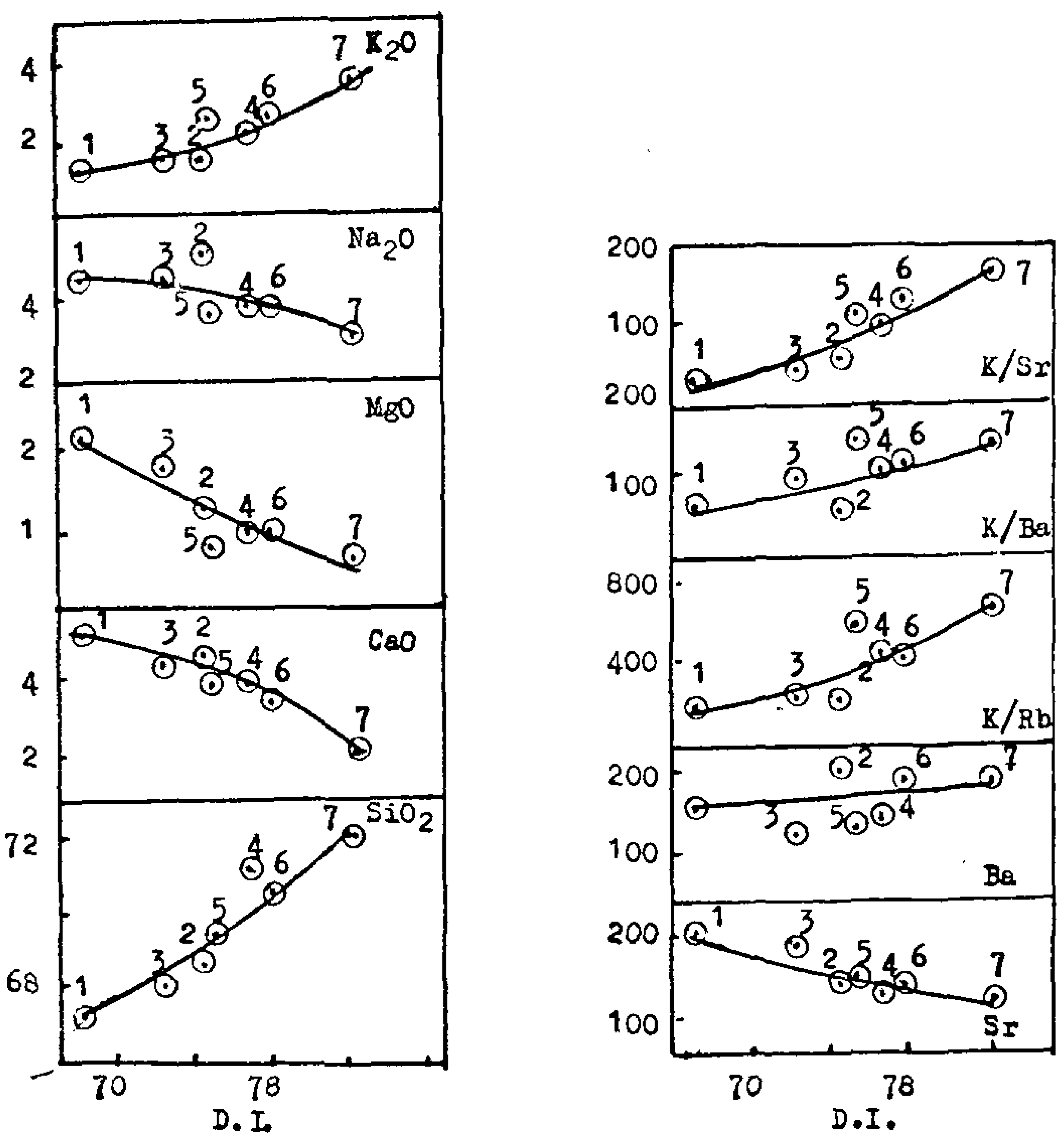

Figure 3. Plots of the major and trace elements against differentiation index (DI), for the granitic rocks of Krishnagiri. Symbols as in Figure 2.

have classified the granitic rocks into high alumina and low alumina types using weight percentages of SiO_2 and Al_2O_3. Barker[17] has indicated 15% Al_2O_3 at 70% SiO_2 as the dividing point for these two types. Recently, Sarvothaman[18] has suggested, after an elaborate study, that the specifically calculated SiO_2/Al_2O_3 ratio depicts an unequivocal demarcation between low- and high-alumina types. The SiO_2/Al_2O_3 ratio for the granitic rocks of Krishnagiri ranges from 4.24 to 4.99, thereby assigning them to moderate to high-alumina type.

Trace elements

Barium. Ba shows generally moderate values varying from 135 to 215 ppm averaging 174 ppm. The K/Ba ratio, depicting wide fluctuations from 57 to 150 and averaging 106, shows an increase with increase in DI (Figure 3). Ba/Sr ratios of these granitoids are low to moderate with the average value of 0.81. Similar value is reported for Marginal Gneiss Suite (average 0.97) of Holenarsipur Belt of Karnataka[19].

Rubidium. Rb values in the present granitic rocks show scatter very narrowly from 35 to 57 ppm and correlating with the low potash content of the rocks. The average value of 45 ppm in this suite is fairly comparable to the Kaptipada tonalite–granodiorite suite of Singhbhum Craton (average 60 ppm)[7] and mean Archaean High alumina tondhjemite (average 44)[20]. The K/Rb values show wide variations from 222 to 700 with the average value of 420.

Strontium. Sr levels in the present case depict appreciable fluctuations (from 172 to 312 ppm) showing depletion towards higher SiO_2 levels and sympathetic with behaviour of Ca. The values are (average 228 ppm) correlating well with the Ca content (average 2.80) of this suite. The average Rb/Sr ratio of 0.21 is closely comparable to those of Phases I and II of Singhbhum granitoid with tonalite–granodiorite composition (average 0.21)[21], of tonalite–granodiorite suite of Kaptipada (average 0.19)[7] and of equigranular granitoid suite of the Bonai Pluton (average 0.21)[22].

Nickel. Ni content of this suite ranges from 17 to 31 ppm with an average value of 24 ppm, which is fairly similar to the concentrations reported for the trondhjemites of Hassan District (average 19 ppm)[23] and for tonalites of Dharwar Craton (average 16.5 ± 4.9 ppm)[24].

Chromium. Cr values, varying from 17 to 30 ppm, show decrease towards increase in SiO_2.

Yttrium. The granitic rocks of the area show lower values of Y ranging from 12 to 22 ppm averaging 16 ppm. Y_N depicts negative correlation with Ce_N/Y_N, which probably suggests the role of garnet in the formation of granitic precursors[25]. A positive correlation is seen between Y and TiO_2 (Figure 4).

Zirconium. The concentration of Zr shows limited range of variations from 131 ppm to 181 ppm averaging 158 ppm, which is moderately low like other Archaean gneisses[20]. Similar to Y, Zr also exhibits a linear correlation with TiO_2 (Figure 4).

Rare earth elements. The granitic rocks show narrow ranges in REE abundances (66.63–80.65 ppm). Ce_N/Yb_N ratio ranges from 9.64–16.78 averaging 12.59. La_N/Yb_N ratio exhibits very high values ranging from 28.47 to 59.16, whereas, La_N/Sm_N values show a limited range of variation (3.33–4.23).

The chondrite normalized REE patterns in these granitoids show a highly fractionated nature with a conspicuous LREE enrichment and HREE depletion (Figure 5). Generally, they show slight to moderate negative Eu anomaly with Eu/Eu* ratio ranging from 0.50 to 0.82.

Discussion and conclusion

The calc-alkaline affinity of the grey granitic rocks of the area suggests their emplacement under thick continental crustal conditions indicating greater temperatures in the lower crust, a situation capable of generating

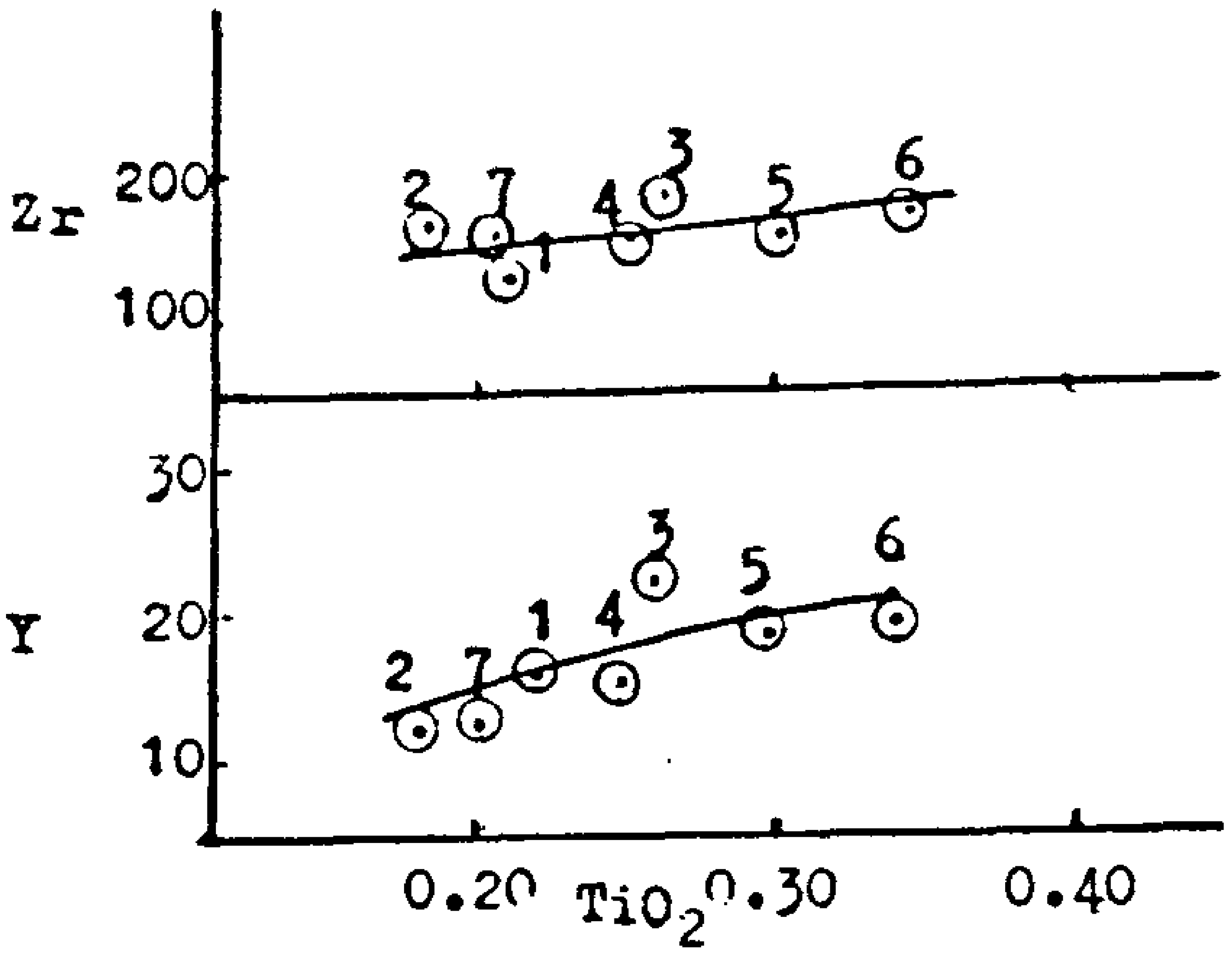

Figure 4. TiO_2 versus Y and Zr diagram. The samples show a linear correlation between the elements. Symbols as in Figure 2.

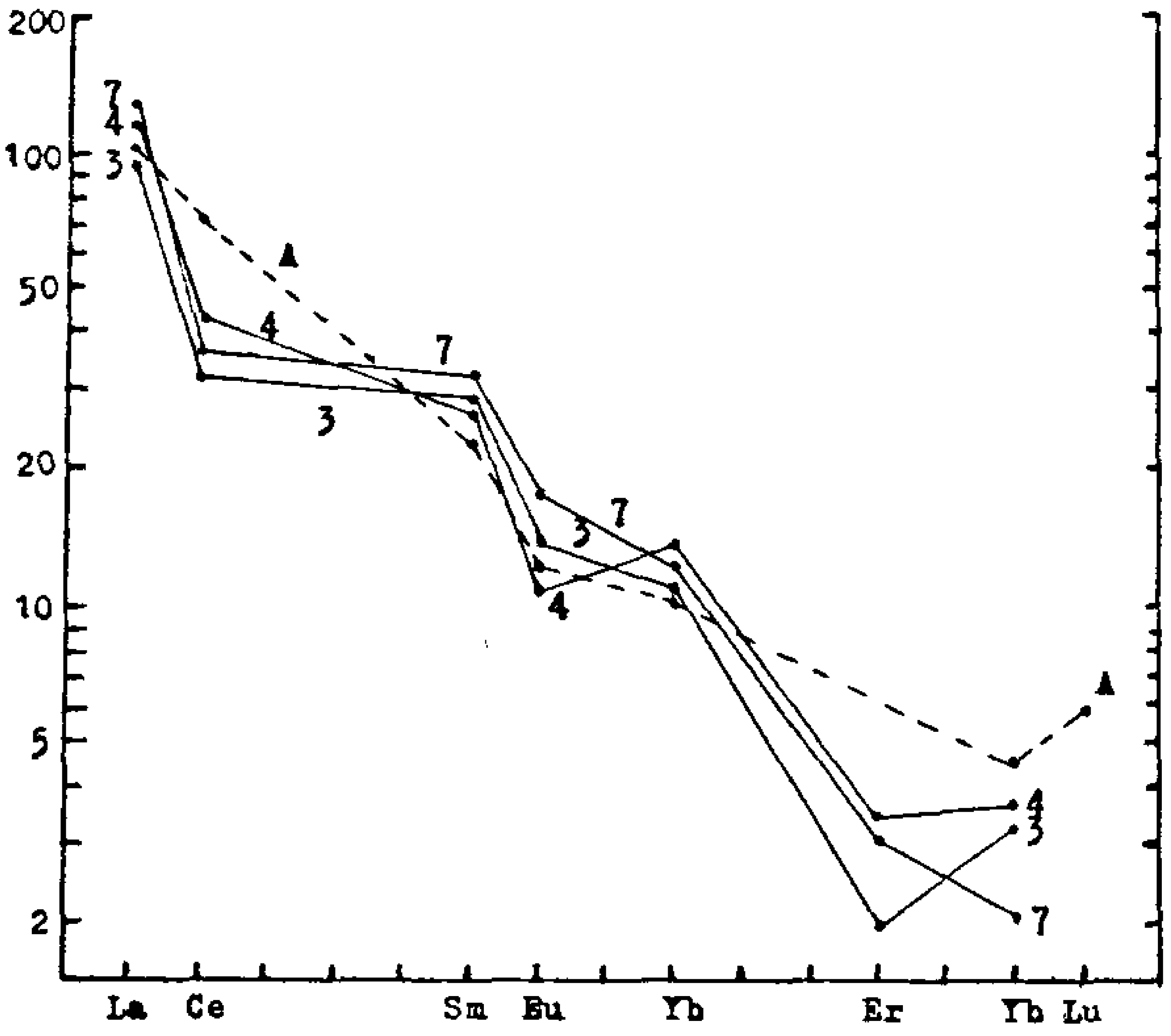

Figure 5. Chondrite normalized REE abundances of granitoids of Krishnagiri. Description of the samples as in Figure 2. A = sample no. KP-5 of Kaptipada[7].

large volumes of tonalitic magmas. The phenomenon appears characteristic of early stages of many magmatic cycles recorded in shields[17,26–28]. Many workers[11,20,28] advocated different models for the origin of calc-alkaline orthogneisses. They are:

(a) the nature of source rocks – various mantle compositions, gabbros, wet basalts, amphibolites, simatic and sialic granulitic crust, greywackes, other sediments, etc.
(b) the process – partial melting and fractional crystallization of variable nature and degree involving garnet, amphibole and/or plagioclase as residual or fractionating phases.

The general high content of certain oxides like TiO_2, MgO and trace elements such as Sr and Ni in these granitioids suggests the presence of mafic components in the source region[29]. The higher values of these elements reflect the characteristics of a magma evolving probably from an amphibolite-bearing source. A similar source has been invoked for the granitic rocks of India[7,23,30]. The amphibolite enclaves are considered to be relics of a basaltic crust and suggest as a source for the tonalite–granodiorite suite of Nuk Gneiss[31]. Amphibolite, occurring as enclaves, has been regarded as the source for the various tonalite–granodiorite suites of India[7,22,23].

The highly fractionated REE patterns with high LREE/HREE ratios suggest the role of hornblende/garnet in the source rocks of Krishnagiri granitoids[32,33]. The moderate to high Ce_N/Y_N ratios (4.34–8.19) imply that Y is retained in residual garnet[34]. Positive correlation of Y and Zr with TiO_2, negative correlation between Y_N and Ce_N/Y_N and high LREE/HREE ratio are in conformity with equilibration between melt and solid that is controlled generally by garnet[35–37]. Also granitoids which are considered to have residual garnet in their partial melt have Ce_N/Yb_N ratio[38–40] more than 10. This ratio in the granitoids of the area ranges from 9.64 to 16.78, supporting the presence of garnet in the residual melt.

Possible mechanisms have been explored, regarding the process of formation of the granitic rocks of Krishnagiri. The subordinate occurrence of granite (s.s.) in the present area precludes the formation by ensialic anatexis. The absence of petrographic features like albitization of plagioclase and replacement of plagioclase by potash feldspar rule out the process of metasomatism as well. Also the model of fractional crystallization is set aside as there is distinct absence of intermediate rocks, like syenites and/or diorites and also there is no continuous order of basic to acidic rocks except for quartz-rich granites (s.l.). The most appropriate mechanism appears to be partial melting of basic rocks. It has been envisaged that the formation of cumulates during the fractional crystallization of a basic magma of mantle derivation emplaced into the lower crust in a tensional tectonic environment liberates hidden heat which brings about partial melting in the lower crust[16,41]. Ellis and Thompson[42], after conducting partial melting experiments, have observed that a suite of calc-alkaline rocks can originate by melting of amphibolites or basalt (or similar basic rocks) and that during the partial melting of basic rocks, say at 1000°C and one atmosphere pressure, the melts produce metaluminous granites and are, therefore, diopside normative, whereas at 5 kb pressure range, basic rocks may give rise to melts of metaluminous granites at temperatures far below 1000°C. The granitic rocks of the area are dominantly metalu-

Table 4. Comparative statement of some diagnostic parameters of granitoids of Krishnagiri and Kaptipada (south-eastern part of Singhbhum Craton, Orissa)

Parameter	Krishnagiri area	Kaptipada area
Field association	Ubiquitous amphibolite enclaves present	Presence of dominant amphibolite enclaves
Type of granitoid	Dominant tonalite–granodiorite	Tonalite–granodiorite
Mineralogy	Qz + plag. + K-feld. + hornb. + biotite	Qz + plag. + K-feld. + hornb. + biotite epi + chlorite
I- or S-type	I-type	I-type
Petrochemistry		
K_2O/Na_2O	0.59	0.50
$CaO/Na_2O + K_2O$	0.64	0.60
TiO_2	0.35	0.43
Rb/Sr	0.21	0.19
REE	66–80	67–101*
LREE/HREE	High	High*
Eu/Eu†	0.50–0.82	0.70†

*Sample nos of Kaptipada KP-1, KP-2 and KP-5 (Table V)[7].
†Inferred from the sample no. KP-5 (Table V)[7].

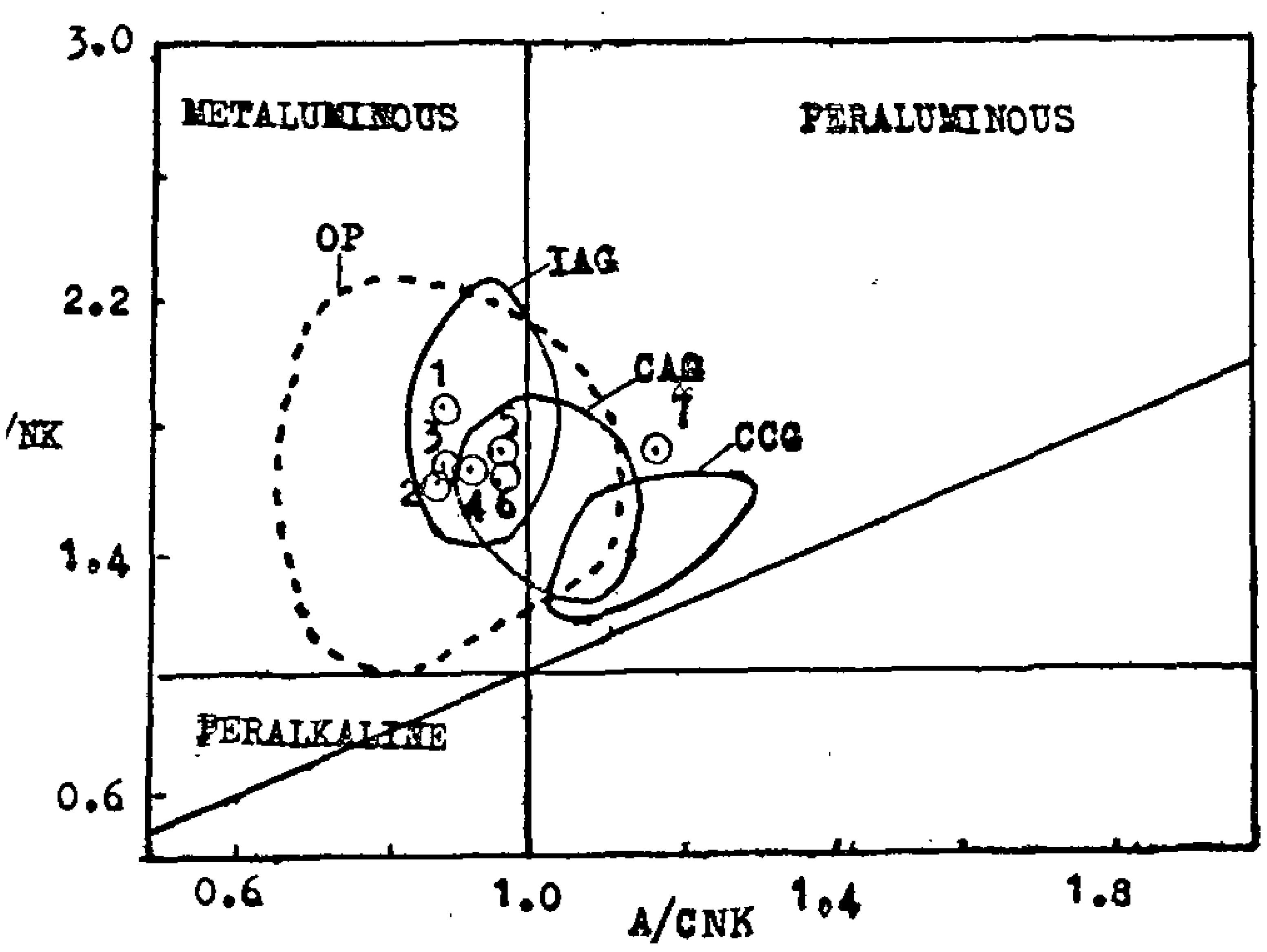

Figure 6. A/NK versus A/CNK binary plot. IAG = Island Arc Granites; CAG = Continental Arc Granites; CCG = Continental Collision Granites; OP = Oceanic Plagiogranites. Fields are after Maniar and Piccoli[9]. Symbols as in Figure 2.

minous with the average ASI value less than unity. In view of the above contention, the process of partial melting of amphibolite source appears to be more tenable in the evolution of the granitic suite in this area. The same process has been attributed to the origin of similar granitic rocks in several parts of Peninsular India[7,23,33].

Several occurrences of I- and S-type granites are reported in the Indian shield by Dhanaraju *et al.*[13]. Most of the following features indicate I-type characteristics[13,43,44] for the granitoids in this region: (i) high Na_2O content, (ii) average molar A/CNK ratio is 0.95, indicating metaluminous nature, (iii) average molar A/NK ratio is 1.67, (iv) dominant diopside normative, (v) regular inter-elemental behaviour, (vi) biotite and hornblende as mafic minerals, (vii) ubiquitous amphibolite enclaves and (viii) presence of sphene and apatite as common accessories.

Geochemical signatures in granitic rocks are controlled by their source characteristics[45]. These granitoids might have inherited the petrochemical features probably from an 'enriched' mantle or lower crust, with mafic constituents[29,30]. The above assumption is supported by the high abundances of certain elements in these granitoids as mentioned earlier and I-type lineages with lower Rb/Sr ratio. The I-type granitoids are genetically related to the mantle source[43]. Similar source characteristics have been invoked for the tonalite–granodiorite suite of the Kaptipada area having the same petrological features[7] as that of the granitoids of the present area (Table 4).

Maniar and Piccoli[9] have devised a number of discriminant diagrams using major element chemistry in order to know the geotectonic environment in which granitic rocks are emplaced. In the diagram employing A/NK versus A/CNK ratios, a clear demarcation of Island Arc Granites (IAG), Continental Arc Granites (CAG) and Continental Collision Granites (CCG) could be made effectively. In the binary diagram employing the above ratios (Figure 6), the granitic rocks of the Krishnagiri area plot themselves in IAG + CAG field, which has already been attested in the modal diagram (Figure 2). The IAG + CAG granites have A/CNK values less than 1.15, which is highlighted in the present granitic rocks. The authors[9] further rule out the possibility of discriminating between IAG and CAG based on the major elements.

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ACKNOWLEDGEMENTS. This paper forms a part of the Ph D thesis of one of the authors (C.G.C), submitted to the University of Madras in 1987. We thank Drs U. S. Ramachandran, S. Ramanathan, and C. Navaneethakrishnan for their valuable suggestions and encouragement. The help of Dr V. Balasubramanian, in carrying out the chemical analyses, is sincerely acknowledged. We thank the unknown referee whose constructive comments have substantially improved the paper.

Received 30 October 1995, revised accepted 21 May 1996