CORRESPONDENCE

Petrological and Geochemical Constraints on the Evolution of the Alkaline Complex of Koraput in the Eastern Ghats Granulite Belt, India

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Abstract

The Koraput Alkaline Complex in the high-grade Eastern Ghats Belt, India, is synkinematically emplaced in a pull-apart structure and far from the Bastar cratonic margin. The suite comprises four distinct members, namely, mafic syenite, felsic syenite, nepheline syenite and perthite syenite. Fe-rich orthopyroxene rims on olivine in mafic syenite indicate iron-enrichment in the early stage of differentiation. With plagioclase of andesine composition it could be described as alkali-norite, the plutonic equivalent of hawiite. Felsic syenite with both alkali-feldspars and plagioclase of oligoclase composition could be described as two-feldspar syenite, the plutonic equivalent of mugearite. Albitic rims on nepheline indicates subsolvus reaction. Chemical trends in amphiboles and plagioclase feldspars, progressively more ferroan and more sodic respectively, are strong indications of mineral fractionation in the Koraput suite. Chemical trends in the variation diagrams are compatible with feldspar fractionation in the Koraput suite. A weak Fe-enrichment trend in the early stage of differentiation, as observed in the AFM diagram, is compatible with that of the alkali-basalt series. Nb anomalies, both positive and negative, are indicative of crustal contamination as expected in synkinematic plutons. In terms of Gondwana assembly and break up, the alkaline complexes are supposed to represent rift-related magmatism along the continental margin. In spite of petrological evidence of the magmatic character of the Koraput Complex, anorogenic setting is contra-indicated by mesoscopic and microscopic fabrics, more akin to synkinematic intrusion during F_2 folding in the host country rocks. The Proterozoic alkaline complexes in the Eastern Ghats Belt, could alternatively trace the path of moving Gondwana continent over mantle plumes.

Key words: Synkinematic pluton, alkaline complex, Eastern Ghats, alkali-basalt series, mantle plume.

Introduction

Several exposures of alkaline complex have been reported from the high-grade Eastern Ghats Belt, India (Leelanandam, 1998). For such plutonic complexes, the relation between tectonism and magmatism is generally obscured and most of these reports do not provide field structural data. In a recent publication Bhattacharya and Kar (2004) have provided field structural data for the Koraput Complex. They have described the complex as bounded by shear zones in the host metapelitic granulites and thus its emplacement in a pull-apart structure has been suggested. This is in sharp contrast to the model of continental rift, the ensialic linear rift zone (Leelanandam, 1998). The Proterozoic alkaline complexes in the Eastern Ghats Belt, tracing the path of moving Gondwana continent over mantle plume, is a more viable alternative (Foland and Faul, 1977).

On the petrological front preliminary results on the Koraput Complex were published more than three decades ago by Bose (1970). In a recent review Leelanandam (1998) criticized the petrogenetic scenario proposed by Bose (1970). Objections to Bose's interpretation pertain to the identification of alkali-gabbros on the one hand and on the other to the proposed petrogenetic link between alkali gabbros and nepheline syenites. Leelanandam (1998) also observed that most of the reports of alkaline rocks in the Eastern Ghats Belt, lack information on the chemical trends in pyroxenes and amphiboles as well as compositions of coexisting nepheline and alkali-feldspar pairs. Another important controversy pertains to interpretation of the fabrics, magmatic or deformation induced in some of these complexes (Panda et al., 1993; Bhattacharya et al., 2004).

In the present article we present comprehensive petrological and geochemical data, including mineral-compositional data, from the different rock units of the Koraput Complex and try to resolve the controversy on the petrogenesis.

Geological setting

Eastern Ghats Belt

The high-grade Eastern Ghats Belt along the east coast of India, and bounded by Singhbhum and Bastar Cratons to the north and west respectively, could be described as a compressional orogen (Bhattacharya, 1997; Bhattacharya and Sen, 2003). Isoclinal and rootless F_1 folds with NE-SW trending steep axial plane foliation, S_1 and common structural repetitions suggest a regional NW-SE directed compression and shortening during development of the first generation folds (Bhattacharya, 1997). The lithologic make-up of this belt could be described in terms of three broad groups, namely, metapelitic granulites, charnockite-enderbite gneisses and associated granulites, and migmatitic gneisses. Additionally, a transition zone occurs along significant length of the western margin (Ramakrisnan et al., 1998). Anorthosites and alkaline complexes are other important rock types in this high-grade belt (Fig. 1).

Study area

The Koraput Complex occurs as a lozenge-shaped intrusion into the country rocks, which is dominantly of metapelitic granulites and with minor bands of mafic granulites (cf. Fig. 1 in Bhattacharya and Kar, 2004). The country rocks of metapelitic granulites are characterised by a strong gneissosity (S_1) and folding of this gneissosity on mesoscopic and large scales. Intrusive contacts, particularly of melanocratic syenite against pelitic granulites with a pervasive gneissic foliation is common (cf. Fig. 3a in Bhattacharya and Kar, 2004). On the evidence of two sets of mylonitic foliation in the metapelites at the contact region, Bhattacharya and Kar (2004) described the Koraput Complex to have been emplaced in a pull-apart structure.

Petrography

Four lithological varieties could be recognized, namely, mafic syenite, felsic syenite, nepheline syenite and perthite syenite. Felsic syenite and nepheline syenite form bulk of

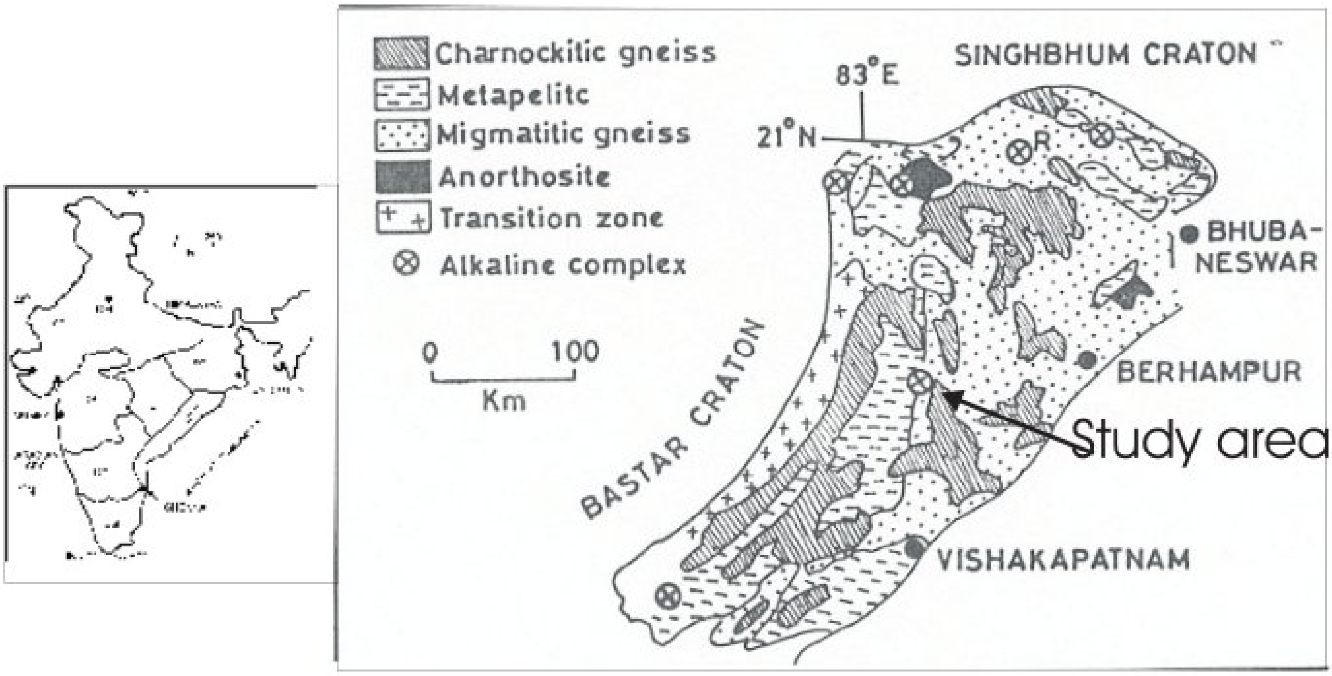

Fig. 1. Generalized geological map of the Eastern Ghats Belt, showing locations of the alkaline complexes, including the Koraput Complex (study area). Inset map of India showing crustal segments: AC–Aravalli Craton; SC–Singhbhum Craton; BC–Bastar Craton; DB–Deccan Basalt; DC–Dharwar Craton; EG–Eastern Ghats; SG–Southern Granulites.

Table 1. Summary of mineral composition in the Koraput Alkaline Complex.

Rock	MS	FS	NS	PS
Pargasitic amphibole X_{Mg}	0.56	0.36	0.25	0.25
Taramite X_{Mg}	–	–	0.25	–
Biotite X_{Mg}	–	0.39	0.30	0.33
Plagioclase X_{Na}	0.60	0.74	0.96	0.95
Olivine Fo	47	–	–	–
Clinopyroxene Ac	5.37	–	–	–
Nepheline Ne	–	–	76	–

the lozenge-shaped body, while mafic syenite occurs as minor bands concordant with the magmatic foliation in the host felsic syenite, and perthite syenite occurs as thin band, mostly along the eastern margin. Mineral assemblages in the syenite varieties are:

Mafic syenite: Ol+Cpx+Amp+Plg+Opq±Opx±Bio±K-fls
Felsic syenite: Plg+K-fls+Bio+Amp+Opq±Cpx
Nepheline syenite: Perth+Neph+Bio+Amp+Opq+Plg±K-fls
Perthite syenite: Perth+K-fls+Amp+Opq±Bio±Plg

Mafic to felsic proportion varies between 70:30 and 60:40 in the mafic syenite, between 30:70 and 20:80 in the felsic syenite, between 5:95 and 10:90 in the nepheline syenite and between 5:95 and 15:85 in the perthite syenite (Table 1 in Bhattacharya and Kar, 2004).

In addition to hornblende, two other varieties of amphibole, namely brown amphibole and green amphibole, are observed.

Important textures include, (a) orthopyroxene corona on olivine in mafic syenite (Fig. 2a); (b) euhedral nepheline cluster with calcite, biotite and amphibole in nepheline syenite (Fig. 2b); (c) secondary albitic rim on perthite at nepheline contact in nepheline syenite (Fig. 2c).

Mineral Chemistry

Minerals were analyzed on a Jeol Jxa-8600 M microprobe at the USIC, University of Roorkee, India. 15 kV accelerating voltage, 2×10^{-8} amp sample current and 2-μm beam diameter were used.

In table 1 we present a summary of mineral compositions from the rocks of the alkaline complex, in order to illustrate chemical characterization of solid solutions and inter-mineral relationships.

Amphibole

Both high-alumina and low-alumina varieties are found and according to the classification scheme of Leake et al. (1998), amphibole in the mafic syenite and in the felsic syenite is pargasite; taramite in nepheline syenite; pargasite and actinolite in perthite syenite. From mafic syenite through felsic syenite and nepheline syenite to perthite syenite amphiboles are progressively more ferroan, consistent with Fe-enrichment on differentiation.

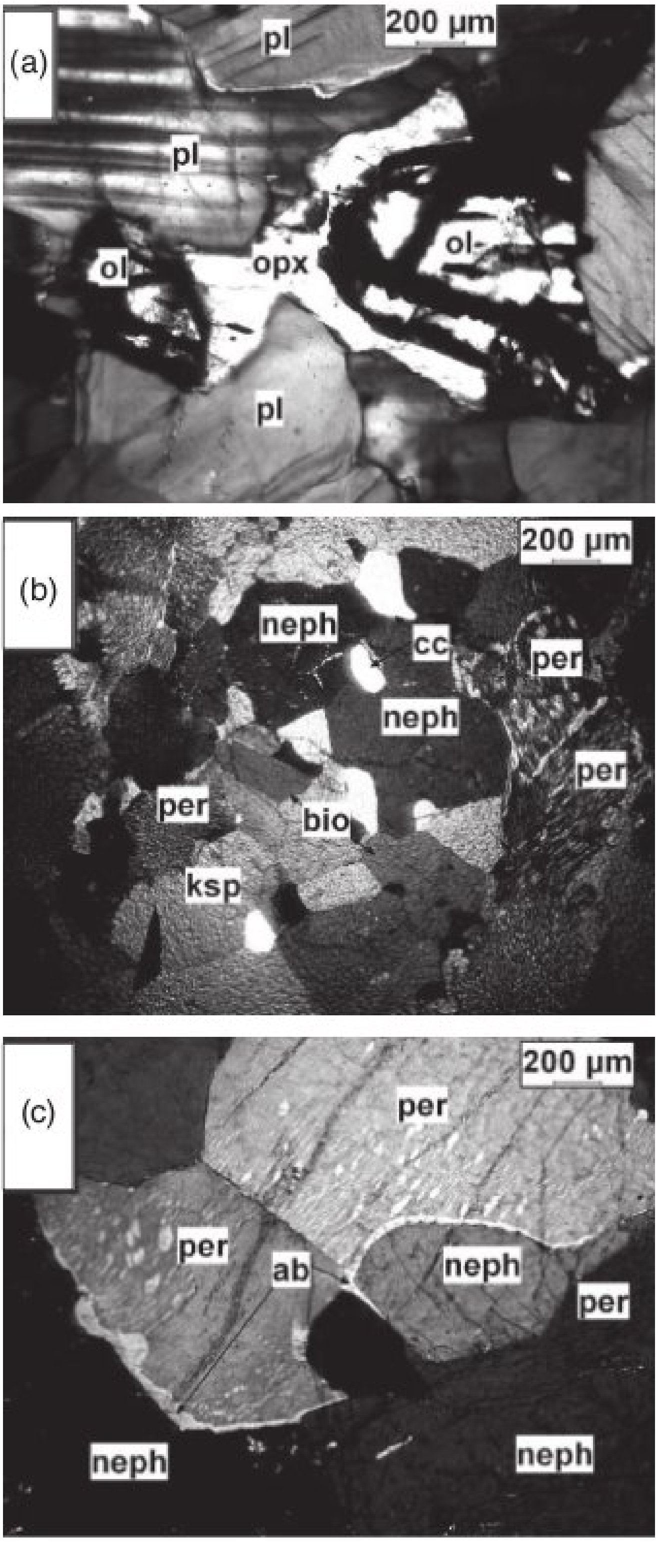

Fig. 2. Photomicrographs. (a) Shows orthopyroxene rim on olivine, in mafic syenite; (b) shows euhedral nepheline in nepheline syenite; (c) shows albitic rim on perthite in nepheline syenite.

Biotite

Biotite in nepheline syenite, felsic syenite and perthite syenite are annite-phlogopite solid solutions, but rich in annite component, about 70%, typical of alkaline rocks.

Feldspars

Plagioclase feldspar in the mafic syenite variety is of andesine composition ($X_{An} = 0.4$); in the felsic syenite plagioclase of oligoclase composition ($X_{An} = 0.25$); while those in the nepheline syenite is of albite ($X_{Ab} = 0.96$). Increasing sodic character of the plagioclase, together with decreasing mafic mineral content is consistent with differentiation products from alkali-basalt magma (Wilson, 1989). Alkali feldspars are mostly perthites, but some K-feldspar grains are also found ($X_K = 0.84$). Perthites coexisting with nepheline, vary from $X_K = 0.86$ to 0.94 hosts and $X_{Na} = 0.94$ to 0.95 blebs. From mafic to felsic syenites, a clear feldspar fractionation trend can be visualized: plagiclase fractionation followed by two feldspar fractionation and ultimately to single alkali feldspar (Cox et al., 1979).

Clinopyroxene

In the mafic syenite clinopyroxene is augite, with about 4 to 5% acmite component.

Olivine

Olivine in the mafic syenite is of intermediate composition between forsterite and fayalite.

Nepheline

Nepheline is a solid solution of nepheline and kalsilite, with about 24% kalsilite component.

On the basis of the above mineral compositions, the four syenite varieties could be named as alkali-norite (plutonic equivalent of hawiite with andesine), two-feldspar syenite (plutonic equivalent of mugearite with oligoclase), nepheline syenite and perthite syenite, respectively.

Rock Chemistry

Major and trace element analyses by XRF spectrometry were carried out at the USIC, Gauhati University.

Table 2. Bulk composition of the Koraput Alkaline Complex.

Sample no	21C	47A	74C	52E	28B	54B	23	46B	22	69	74D	30A	68	30B	66A	44D	74A	70
Rock	MS	MS	MS	MS	MS	FS	FS	FS	NS	NS	NS	NS	NS	PS	PS	PS	PS	PS
SiO_2	46.83	46.53	48.74	59.87	48.88	52.48	51.79	49.77	60.96	58.49	59.74	55.19	63.96	56.85	58.28	63.64	61.71	67.41
Al_2O_3	7.02	7.34	12.81	17.12	9.63	13.68	15.24	13.34	17.53	17.49	18.92	17.04	19.66	17.17	15.45	16.34	15.47	18
Fe_2O_3	17.3	17.96	14.68	2.31	15.78	12.67	10.9	14.31	3.7	4.35	4.47	8.08	2.21	8.64	7.35	3.65	7.12	1.17
MnO	0.27	0.23	0.2	0.07	0.26	0.18	0.15	0.2	0.07	0.1	0.09	0.14	0.07	0.16	0.14	0.06	0.14	0.01
MgO	5.07	7.04	2.51	2.06	3.2	2.11	1.77	1.88	1.88	2.04	1.31	1.9	0.53	1.94	2.58	2.34	1.8	0.73
CaO	8.94	14.63	11.05	7.66	11.01	8.78	9.31	10.15	1.84	2.31	2.7	4.36	0.75	2.87	3.83	2.29	1.84	0.92
Na_2O	0.72	0.14	0.69	2.28	0.09	1.83	0.28	0.84	3.12	3.89	2.12	2.15	2.97	1.77	1.12	0.67	1.99	2.95
K_2O	3.32	0.55	2.73	5.94	3.16	2.72	2.56	1.4	7.89	7.99	7.31	7.35	7.91	7.44	7.08	7.53	7.17	6.68
TiO_2	5.06	3.54	3.44	0.09	4.64	2.33	3.37	3.48	0.43	0.41	0.63	1.32	0.09	0.78	1.17	0.71	0.6	0.18
P_2O_5	3.72	0.35	0.57	0.16	3.45	1.57	1.74	2	0.35	0.42	0.37	0.52	0.06	0.61	0.6	0.46	0.04	0.03
Trace elements (in ppm)																		
Ba	1037	636	496	709	615	383	601	1010	200	1056	400	415	608	439	820	615	667	1183
Rb	66	26	90	79	92	129	50	14	112	162	198	256	275	172	168	149	253	177
Sr	1499	668	1025	1439	1117	729	2431	2867	1275	1557	647	1451	224	672	485	1368	61	39
Y	37	51	53	49	77	43	25	20	3	12	15	19	5	21	65	22	44	5
Zr	146	408	415	340	220	413	63	88	103	144	218	281	552	234	249	159	674	39
Nb	55	38	89	67	125	147	56	18	24	53	76	96	66	134	350	107	140	12
Cr	5	464	30	302	14	6	5	5	11	25	12	8	18	2	25	10	10	11
Ni	86	441	5	706	16	36	2	2	2	2	2	2	2	2	5	7	2	2
Zn	159	327	263	258	315	173	114	166	5	31	53	134	36	121	111	5	84	2
Normative compositions																		
Q	7.56	3.24	6	6.99	12.61	8.88	17.96	14.7	4.26	0	9.91	0	12.59	4.74	9.73	21.9	11.38	21.25
C	0	0	0	0	0	0	0	0	1.21	0	3.48	0	5.01	2.39	0.3	3.92	1.15	4.3
Or	20.35	3.38	16.85	36.1	18.99	16.61	15.78	8.63	47.92	48.72	44.52	44.77	47.83	45.23	43.26	45.79	43.71	40.37
Ab	6.31	1.23	6.08	19.82	0.77	15.95	2.47	7.41	27.1	30.41	18.45	18.71	25.65	15.38	9.78	5.82	17.33	25.48
An	6.35	18.43	24.82	19.51	16.8	21.73	34.24	29.83	7.55	6.93	11.64	15.6	3.65	10.89	15.97	9.25	9.33	4.8
Ne	0	0	0	0	0	0	0	0	0	1.89	0	0	0	0	0	0	0	0
Di	12.79	45.85	24.82	15.76	13.88	11.13	2.64	8.96	0	2.43	0	3.24	0	0	0	0	0	0
Hy	27.72	19.95	13.17	1.53	19.81	17.33	16.22	18.94	10.39	0	9.94	11.52	5	18.38	17.26	10.99	15.79	3.52
Ol	0	0	0	0	0	0	0	0	0	8.02	0	2.44	0	0	0	0	0	0

NS–Nepheline syenite; MS–Mafic syenite; FS–Felsic syenite; PS–Perthite syenite.

Operating condition for XRF machine was 20/40 kV for major oxides and 55/60 kV for trace elements. Nominal analysis time was 300 seconds for all major oxides and 100 seconds for each trace elements. For the XRF analyses the overall accuracy (% relative standard deviation) for major and minor oxides are given as less than 5% and for trace elements is less than 12%. The average precision is reported as better than 1.5%.

Major elements

In table 2, we present XRF analytical data of eighteen samples of the Koraput alkaline complex; of these five are from alkali-norite, three are from two-feldspar syenite, four are from nepheline syenite and five are from perthite (single alkali feldspar) syenite.

Alkali norites are quartz normative, although no modal quartz was detected. Normative Di:Hy is variable as also normative An:Or, this could be due to variable contents of amphibole and biotite and/or K-feldspar contents. Overall, these are critically saturated in silica. Two-feldspar syenites are also quartz normative; normative Hy:Di>1, normative An:Or>1. Among the nepheline syenites both Q and Ol/Ne normtive varieties are found. Q normative samples also have normative C and Hy. These variations in normative compositions could be due to variable proportions of nepheline and perthite. Perthite syenites have normative Q, C and Hy, also high normative Or, consistent with their single alkali feldspar mineralogy.

In the variation diagrams (Fig. 3a-e), good positive correlation between SiO_2–Al_2O_3 and SiO_2–K_2O are observed; but K_2O increases only up to 55% SiO_2. On the other hand good negative correlation between SiO_2–Fe_2O_3, SiO_2–CaO and SiO_2–TiO_2 are observed. These co-variations are consistent with feldspar fractionation outlined in the previous section (Cox et al., 1979).

In the AFM plot (Fig. 4), Fe-enrichment at the early stage fractionation could be recognized and this trend could discriminate between calc-alkaline and tholeiitic trend; however, Fe-enrichment is feeble in the present case, as expected in the alkali-basalt series (Bose, 1997). The dashed line represents the alkali-basalt series after Nocolds (1954).

Trace elements

In all the syenite varieties LILE, Rb, Ba, Sr and K are enriched between 10 and more than100 times against primitive mantle (Fig. 5a-d). The high concentration of incompatible elements and enhanced concentrations in the felsic members by fractionation are typical of continental alkaline complexes (Philpotts, 1990). Also notable is the high concentration of HFSE elements, particularly in the mafic syenite: Nb: 38 to 125 ppm; Y: 37 to 77 ppm; and Zr: 146 to 415 ppm, and this is

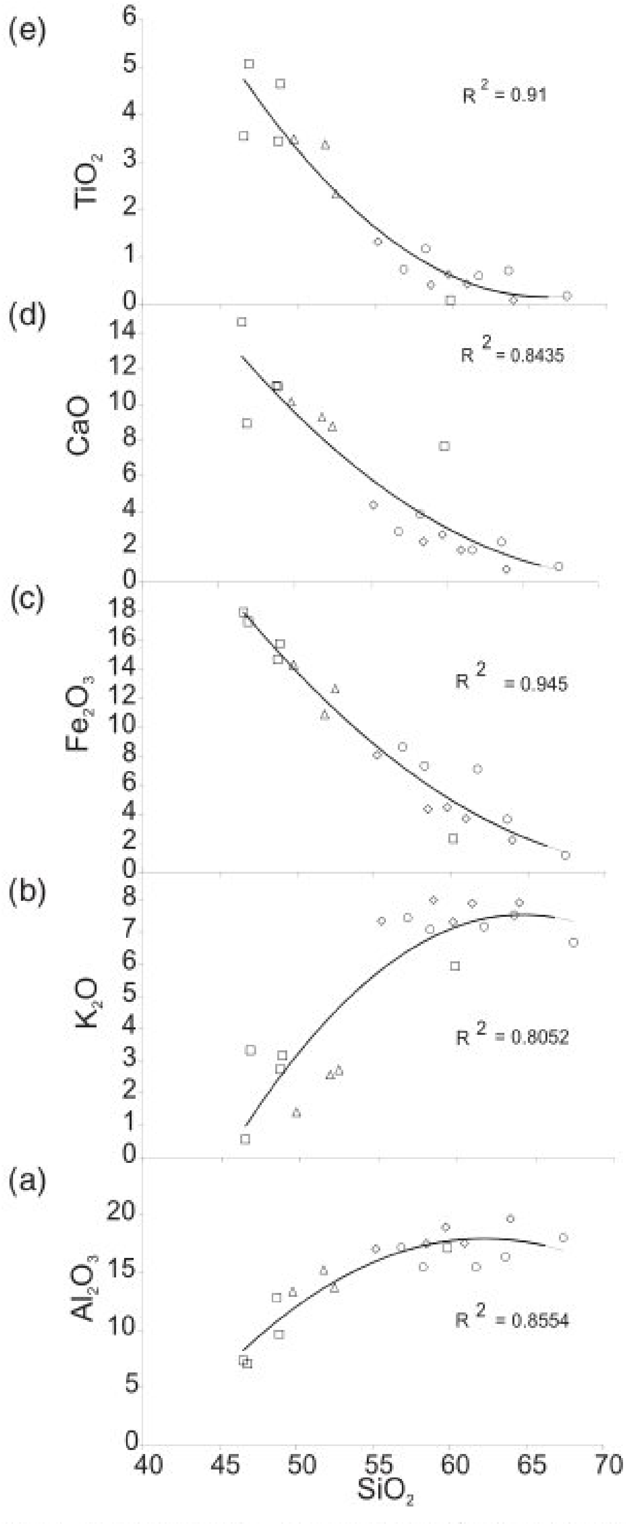

Fig. 3. (a) SiO_2 versus Al_2O_3 variation diagram for the Koraput suite. Symbols: Square–mafic syenite; Triangle–felsic syenite; Diamond–nepheline syenite; Circle–perthite syenite. (b) SiO_2 versus K_2O variation diagram for the Koraput suite. Symbols as in figure 3a. (c) SiO_2 versus Fe_2O_3 variation diagram for the Koraput suite. Symbols as in figure 3a. (d) SiO_2 versus CaO variation diagram for the Koraput suite. Symbols as in figure 3a. (e) SiO_2 versus TiO_2 variation diagram for the Koraput suite. Symbols as in figure 3a.

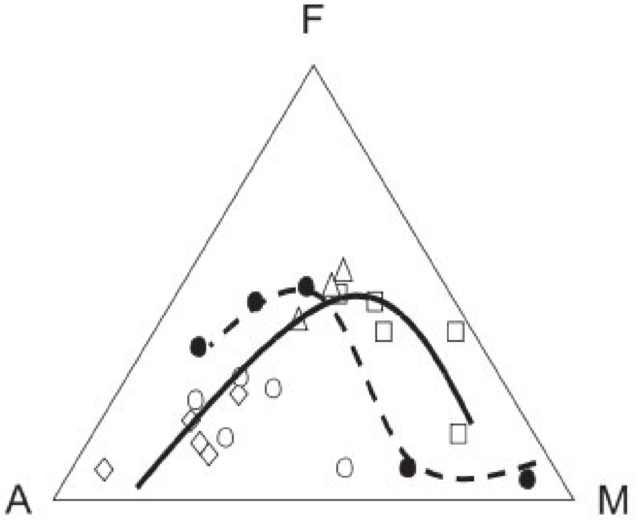

Fig. 4. AFM ternary variation diagram for the Koraput suite. Filled circle and dashed line for the data of Nocolds (1954). Other symbols as in figure 3a.

comparable to within-plate basic sodic magma (Sun and McDonough, 1989). However, when all the syenite varieties are considered, wide variation in all these HFSE elements and some incompatible elements, particularly Rb (14 to 275 ppm) and Sr (39 to 2867 ppm) are not amenable to interpretation by simple fractionation. Moreover, variation of SiO_2 and Sr are not related, which argues against fractionation of the magma. The Nb anomaly varies between positive and negative and possibly reflects crustal contamination (negative anomaly) of mantle-derived (positive anomaly) melts (Condie et al., 1987; Saunders et al., 1992) Large Sr and Ti negative anomalies may be interpreted by fractionation of plagioclase and a Ti-rich mineral (Srivastava and Singh, 2003). Overall the trace element signatures could have resulted from crustal contamination of a fractionating magma. Enrichment of incompatible elements and Ti, probably suggest the magma was derived from an enriched mantle source (Condie et al., 1987).

Discussion

Many field features, particularly shear fabrics and shear lenses in most of the syenite varieties suggest synkinematic intrusion (Bhattacharya and Kar, 2004). Some mineral compositional data, namely, progressively more ferroan amphibole from mafic syenite through felsic syenite to nepheline syenite and perthite syenite on the one hand, and progressively more sodic plagioclase feldspar, are indicative of magma fractionation/differentiation trend.

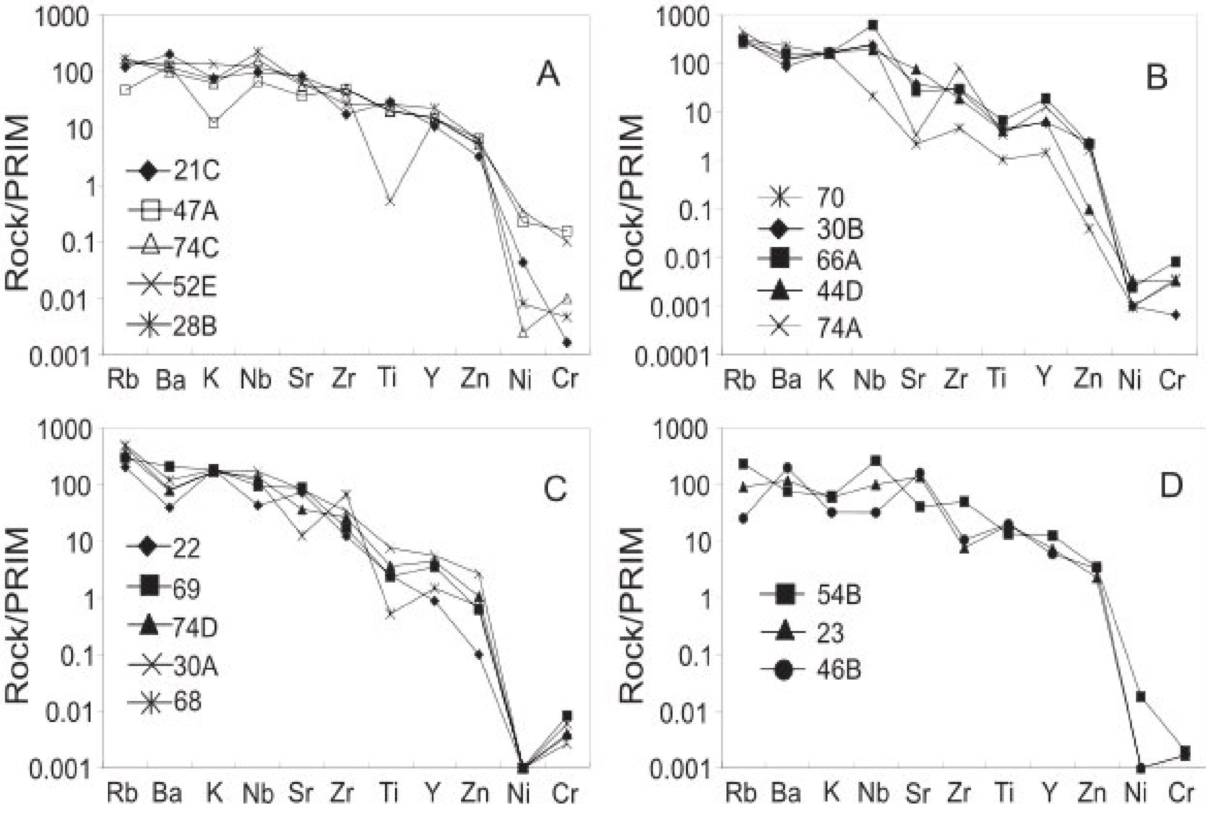

Fig. 5. Primitive mantle normalized multi-element spider plot of the alkaline complex of Koraput. A–mafic syenite; B–felsic syenite; C–nepheline syenite; D–perthite syenite. Normalization according to Sun and McDonough (1989).

A weak trend of iron enrichment in the early stage of differentiation can be observed in the AFM plot and this could be designated as that of alkali-basalt series (Bose, 1997). However, trace element signatures are not typical of a fractionating magma. Some degree of crustal contamination is indicated by Nb anomalies and could be related to deformation during emplacement.

Considering all these features, the Koraput Alkaline Complex could be described as a crustally contaminated (synkinematic intrusion) differentiated suite.

The identification of alkali-gabbro by Bose (1970) was criticized by Leelanandam (1998), on two counts. First objection relates to lack of ophitic texture in the mafic syenites. Our observations testify to lack of magmatic textures, but this could be due to synkinematic intrusion. The second objection relates to plagioclase composition, andesine rather than labradorite, as in gabbros. We would prefer to call the mafic syenite as alkali-norite (plutonic equivalent of hawiite with andesine), felsic syenite as two-feldspar syenite (plutonic equivalent of mugearite with oligoclase), nepheline syenite and perthite syenite respectively. Finally, that mafic syenites of the Koraput Complex are not inclusions on the one hand, and on the other, bulk chemical and mineralogical data presented suggest that nepheline syenites and perthite syenites are the end stage differentiation products of alkali-basalt series. We also conclude that the Koraput Alkaline Complex, an integral part of the high-grade Eastern Ghats belt, intruded synkinematically with late deformation and unrelated to either rifting or break up of East Gondwana. More comprehensive isotopic data from the alkaline complexes of the Eastern Ghats Belt, could verify the alternative proposal of plume related magmatism in this part of the Gondwana.

Acknowledgments

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