Evaluation of phase chemistry and petrochemical aspects of Samchampi–Samteran differentiated alkaline complex of Mikir Hills, northeastern India

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The Samchampi–Samteran alkaline complex occurs as a plug-like pluton within the Precambrian granite gneisses of Mikir Hills, Assam, northeastern India and it is genetically related to Sylhet Traps. The intrusive complex is marked by dominant development of syenite within which ijolite–melteigite suite of rocks is emplaced with an arcuate outcrop pattern. Inliers of alkali pyroxenite and alkali gabbro occur within this ijolite–melteigite suite of rocks. The pluton is also traversed by younger intrusives of nepheline syenite and carbonatite. Development of sporadic, lumpy magnetite ore bodies is also recorded within the pluton. Petrographic details of the constituent lithomembers of the pluton have been presented following standard nomenclatorial rules. Overall pyroxene compositions range from diopside to aegirine augite while alkali feldspars are typically orthoclase and plagioclase in syenite corresponds to oligoclase species. Phase chemistry of nepheline is suggestive of Na-rich alkaline character of the complex. Biotite compositions are typically restricted to a uniform compositional range and they belong to ‘biotite’ field in the relevant classification scheme. Garnets (developed in syenite and melteigite) typically tend to be Ti-rich andradite, which on a closer scan can be further designated as melanites. Opaque minerals mostly correspond to magnetite. Use of Lindsley’s pyroxene thermometric method suggests an equilibration temperature from $\sim 450^{\circ}$ – 600° C for melteigite/alkali gabbro and $\sim 400^{\circ}$ C for syenite. Critical assessment of other thermometric methods reveals a temperature of equilibration of $\sim 700^{\circ}$ – 1350° C for ijolite–melteigite suite of rocks in contrast to a relatively lower equilibration temperature of $\sim 600^{\circ}$ C for syenite. Geobarometric data based on pyroxene chemistry yield an equilibration pressure of 5.32–7.72 kb for ijolite, melteigite, alkali pyroxenite, alkali gabbro and nepheline syenite. The dominant syenite member of the intrusive plug records a much higher (~ 11 kb) equilibration pressure indicating a deeper level of intrusion. Major oxide variations of constituent lithomembers with respect to differentiation index (D.I.) corroborate a normal magmatic differentiation. A prominent role of liquid immiscibility is envisaged from field geological, petrographic and petrochemical evidences. Tectonic discrimination diagrams involving clinopyroxene chemistry strongly suggest within plate alkaline affinity for the parental magma which is in conformity with the regional plume tectonics.

1. Introduction

The initial and waning stages of Continental Flood Basalt (CFB) volcanisms are marked by

alkaline magmatic intrusions which represent various differentiating phases of the main flood basalt event (Basu *et al* 1993; Renne *et al* 1996; Ray and Pande 2001; Nambiar 2007). An association

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between alkaline magmatism and carbonatite is well documented (Le Bas 1987, 1989; Gittins 1989; Bailey 1995; Bell *et al* 1998) and it is spatially and temporally associated with continental flood basalts (CFB), which are generally interpreted as manifestation of plume activities (Heaman *et al* 2002; Bell 2001, 2002).

In northeastern India, the Sylhet Traps are exposed in a narrow, 80 km long and 4 km wide east-west trending belt. This belt is part of Bengal–Sylhet–Rajmahal flood basalt province and is located along the southern margin of the Shillong Plateau having a maximum thickness of 550–650 m (Mazumder 1986). Bakshi (1995) has considered Sylhet Traps to mark the beginning of Kerguelen plume activities beneath the Indian Plate (Nambiar 1988; Bakshi 1995; Nandy 2001; Mahoney *et al* 1983; Veena *et al* 1998; Kent *et al* 2002) around 117 Ma. The Kerguelen hotspot was situated close to the eastern Indian margin 100–120 Ma ago and was responsible for the extrusion of Rajmahal basalts exposed over the Gondwana Supergroup and Sylhet basalts and related alkaline-carbonatite magmatism of Shillong Plateau (Coffin *et al* 2002; Kent *et al* 2002).

The Shillong Plateau of northeastern India underwent an extensive basic and alkaline-carbonatite magmatic activity during early Cretaceous (Kumar *et al* 1996; Srivastava *et al* 2005). A spatial and temporal association of this magmatism with Kerguelen hotspot-mantle plume system of Indian Ocean has been proposed (Ray *et al* 1999; Kent *et al* 2002). The ultramafic-mafic-alkaline-carbonatite intrusive complexes representing late stage differentiation of Sylhet Trap magmas occur as small, isolated, circular bodies along a NE trending zone in Shillong Plateau (Mamallan *et al* 1994; Srivastava and Sinha 2004, 2007) (figure 1). One important differentiation centre is represented by the Samchampi (26°13'N : 93°18'E)–Samteran (26°11'N : 93°25'E) alkaline complex, which occurs as a near circular, plug-like [funnel shaped intrusive magmatic bodies, commonly emplaced into the brittle upper crust, elliptical and subcircular in cross section, are called plugs (Best 2003)] in intrusive body emplaced into the Precambrian basement gneisses of the Mikir Hills, in the Karbi–Anglong district of Assam (Kumar *et al* 1989; Nag *et al* 1999). The intrusions, emplaced in a granitic host rock, span a broad compositional lithospectrum embracing syenites (covering large part of the area), ultramafics (alkali pyroxenite), mafics (ijolite, melteigite, shonkinite, malinite), carbonatite, vanadium bearing titaniferous magnetite ore bodies. Small pockets of phosphatic, non-clastic sedimentary rocks overlie the pluton. A zone of fenitization encircles the complex.

Till date for the Samchampi–Samteran alkaline complex, only rudimentary petrological data are available in the literature (Kumar *et al* 1989; Nag *et al* 1999). Knowledge of mineral chemistry for different lithotypes and the genetic correlation among them is unknown. Here we report for the first time, mineral chemical compositions from the rocks of the Samchampi–Samteran alkaline complex to decipher the P–T condition of equilibration of different constituent lithomembers of the area. Mineral chemical parameters have been considered to delineate the tectonic setting of the complex. Whole rock geochemical data (after Kumar *et al* 1989; Nag *et al* 1999) have been used to describe the geochemical characters and petrogenetic aspects of the intrusive complex. In this paper we combine field evidences, mineralogical and geochemical observations to present a cogent petrogenetic model which in turn would be useful for understanding broad tectonic setting of this type of differentiation centres present in NE India possibly linked up with Sylhet Traps.

2. Geological overview: Mode of occurrence and field relations

Alkaline magmatism is mostly concentrated in relatively stable, intracratonic platforms facilitated by major lithospheric uparch or lineaments. The emplacement and distribution of ultramafic–mafic–alkaline–carbonatite complexes are controlled by deep-seated faults and rift-like extension zones with abruptly decreasing thickness of the continental lithosphere (Frolov 1973; Woolley 1989). The Shillong Plateau forms a part of the NE extremity of the Indian peninsular shield. It is roughly rectangular in shape, covers an area of about 40,000 km² and is considered as an uplifted horst-like feature, bounded by the E–W trending Dauki and Brahmaputra fault systems in the south and the north, respectively. The western and eastern fringes of the plateau are bordered by the N–S trending Jamuna fault system and the NW–SE trending Kopili fracture zone respectively, the latter separating the Shillong Plateau from the Mikir Hills (Evans 1964; Desikachar 1974; Nandy 1980, 2001; Acharya *et al* 1986; Gupta and Sen 1988). Linear fracture patterns along the Assam–Meghalaya belt, directed towards NE–SW and ENE–WSW and subparallel to Kalyani Lineament and Sarhed fault (figure 2) (Nandy 1980, 2001; Nag *et al* 1999) are loci of major alkali emplacements and seismic activity. The Samchampi (26°13'N: 93°18'E)–Samteran (26°11'N: 93°25'E) alkaline complex occurs as a near circular plug-like intrusion within the Precambrian granite gneisses of Mikir Hills in Karbi–Anglong district

Figure 1. Regional geological and tectonic framework of the Shillong Plateau (Srivastava and Sinha 2004).

Figure 2. Map featuring major lineaments and faults defining the alkaline complexes of Assam–Meghalaya belt (after Nag *et al* 1999).

of Assam, northeastern India and it is linked with some of the major structural features of north-eastern India. The pluton was emplaced at about 15 km south of the E–W trending Kalyani Lineament (figure 2). This lineament possibly merges with the deep-seated regional fracture defined by Barapani Lineament (figure 2) (Das *et al* 1995; Nag *et al* 1999) further to the west. The geological framework of the Samchampi–Samteran alkaline complex is given in figure 3. The intrusive complex comprises a broad compositional lithospectrum including syenite, ijolite–melteigite, alkali pyroxenite, alkali gabbro, nepheline syenite and carbonatite. Syenite constitutes the dominant lithomember of the complex within which the ijolite–melteigite suite of rocks has been emplaced with an arcuate outcrop pattern (figure 3). Field observations record a sharp contact between syenite and ijolite–melteigite rocks. Alkali pyroxenite and alkali gabbro occur as inliers within the ijolite–melteigite suite and the field relation suggests that they are older than the latter. In the field, lumpy vanadium bearing titaniferous magnetite ore bodies are exposed as isolated intrusives within the syenite host rocks (figure 3). Dykes and dykelets of nepheline syenite and carbonatite occur as later intrusives cutting across the syenite and ijolite–melteigite rocks. Their spatial relationship suggests that they represent the youngest intrusive lithomember of the complex.

3. Petrography and mineralogy

Distinct petrographic features of the constituent lithomembers of the complex are described below.

3.1 Syenite

Megascopically, syenites are hard, massive and leucocratic. K-feldspar, plagioclase, clinopyroxene, amphibole and carbonates constitute the essential mineral composition of the rocks, while biotite, sphene, apatite and opaque occur as accessory minerals. In syenite, clinopyroxene is in the range $Wo_{38-48}En_{17-35}Fs_{17-45}$ and composition of K-feldspar shows the range $Or_{70-96}Ab_{5-28}An_{0-2}$. In some samples, garnet is present as a major constituent. In sample SAJ 4A (syenite) clinopyroxene grains occur as inclusion within garnet ($And_{91-96}Gr_{1-6}Py_{0.7-1.2}Sp_{1.4-1.6}Uv_{0.16-0.4}$) (figure 4a) suggesting the earlier origin of clinopyroxene and replacement of clinopyroxene by garnet possibly due to metasomatic reactions. Biotite grains are formed at the expense of clinopyroxene grains. The rock is holocrystalline, coarse grained, equigranular and shows an overall hypidiomorphic granular texture with local development of perthitic intergrowths. Composition of plagioclase blebs in perthite is $Or_1Ab_{81}An_{18}$. Modal compositions of the representative samples of this rock type (table 1) occupy the field of 'Alkali feldspar syenite' in the Q–A–P diagram (Streckeisen 1976).

3.2 Ijolite–melteigite suite of rocks

Ijolite–melteigite rocks of the investigated area are hard, massive and dominantly melanocratic in hand specimen. Nepheline and clinopyroxene represent essential mineralogy of these rocks. In some samples, biotite, garnet and carbonates are present as major constituents. Subordinate

Figure 3. Geological map of Samchampi–Samteran ultramafic–mafic–alkaline–carbonatite complex. Inset map shows location of study area in the map of India.

amounts of K-feldspar, sphene, apatite and opaque represent the accessory mineral phases. Biotite grains have formed along the boundaries of clinopyroxene in some samples. In ijolite–melteigite rocks, clinopyroxene composition shows the range $Wo_{45-48}En_{30-36}Fs_{15-26}$ with $mg\#$ ranging from 0.68 to 0.83. K-feldspar in ijolite (SAJ 3) shows the composition $Or_{98}Ab_{1.7}An_{0.3}$. In sample SAJ 3 (ijolite), nepheline occurs as distinct inclusion within clinopyroxene (figure 4b) while in sample SAJ 17 (melteigite), clinopyroxene occurs as inclusion within nepheline (figure 4c). These distinct petrographic features suggest that in ijolite–melteigite rocks, two generations of clinopyroxene are present. The earlier formed clinopyroxene occurs as inclusion within nepheline while the late formed clinopyroxene contains inclusion of nepheline in it. Garnet grains, in some cases, have developed at the expense of both clinopyroxene and biotite grains. In melteigite (SAJ 17) composition of garnet is $And_{83}Gr_9Py_6Sp_{1.8}Uv_{0.2}$. The ijolite–melteigite rocks are holocrystalline,

coarse grained and show an overall hypidiomorphic granular texture. Local development of poikilitic texture has also been observed where clinopyroxene grains are enclosed by relatively larger plate of nepheline. In some places, intergrowth texture is exhibited by vermicular nepheline grains intergrown within K-feldspar base (figure 4d). The independent nepheline grains locally maintain optical continuity with the vermicular nepheline intergrowths suggesting that K-feldspar has replaced nepheline in these rocks. Similar K-feldspar–nepheline replacement phenomenon has been described from Khariar alkaline complex of Orissa, India (Madhavan *et al* 1989). Representative modal compositions (table 1) occupy the Feldspathoid–Alkali feldspar (F–A) arm of the F–A–P triangular diagram and the plots correspond to the field of ‘Foidolites’ (Streckeisen 1976). Further consideration of colour index (C.I.), modal mafic and foid (vol.%) indicates that both ijolite and melteigite varieties are present, following IUGS classification scheme for foidal mafic rocks (Streckeisen 1976).

Figure 4. (a) BSE image showing inclusion clinopyroxene (Cpx) within melanite in syenite. Occurrence of K-feldspar and sphene is also noted. (b) BSE image showing inclusion of nepheline within clinopyroxene (Cpx) in ijolite. (c) BSE image showing inclusion clinopyroxene (Cpx) within nepheline in melteigite. Occurrence of magnetite along the grain boundary of Cpx is also noted.

3.3 Alkali pyroxenite

Megascopically, alkali pyroxenite rocks are hard, massive and melanocratic. They are holocrystalline, coarse grained and equigranular. Clinopyroxene occurs as essential and the most dominant

mineral constituent with the compositional range $Wo_{41-45}En_{33-35}Fs_{20-26}$. Accessory minerals include K-feldspar ($Or_{88.8}Ab_{11.2}$), nepheline and carbonates with sphene, apatite, biotite and opaque. These rocks show an overall hypidiomorphic granular texture but cumulus texture is locally developed. Clinopyroxene is the cumulus phase and nepheline occurs in the intervening spaces representing the intercumulus phase. Average modal compositions of the representative alkali pyroxenite samples have been presented in table 1.

3.4 Alkali gabbro

The alkali gabbro rock bodies are hard, massive and melanocratic in hand specimen. These rocks are essentially composed of clinopyroxene ($Wo_{46-47}En_{37-40}Fs_{14-15}$), K-feldspar ($Or_{97.5}Ab_{2.5}$) and nepheline with lesser amounts of biotite. Carbonates are present in some samples. Accessory phases include subordinate amounts of sphene, apatite and opaque. The overall textural pattern is defined by a poikilitic relationship where clinopyroxene is enclosed within K-feldspar (figure 4e). The modal compositions (table 1), occupy the F-A arm of the F-A-P triangle and correspond to the field of 'Foid syenite' (Streckeisen 1976). Following Streckeisen's (1976) criteria, the alkali gabbro may further be subdivided into malginit and shonkinite (table 1).

3.5 Minor intrusives: Nepheline syenite and carbonatite

Megascopically, nepheline syenites are hard, massive and mesocratic. The essential mineralogical composition is represented by K-feldspar ($Or_{83}Ab_{17}$) and nepheline. Clinopyroxene ($Wo_{43-44}En_{31-32}Fs_{25-26}$) occurs as major mafic constituent. Subordinate amounts of biotite, carbonates, sphene and apatite represent the accessory phases. In some samples, minor occurrence of ferruginous alteration of mafic minerals has been noticed. An overall hypidiomorphic granular textural pattern has been documented. Poikilitic texture is developed locally, where clinopyroxene grains are enclosed by nepheline depicting a poikilitic relationship. The modal plots occupy the F-A arm of the F-A-P triangle and belong to the field of 'Foid syenite' where foid is being represented by nepheline (Streckeisen 1976).

Carbonatites are essentially composed of carbonate minerals with apatite and minor amounts of biotite and clinopyroxene. Opaque minerals represent the accessory phase. These rocks are coarse grained and sovitic. Carbonate grains are arranged in a granular mosaic pattern defining an overall hypidiomorphic granular texture (figure 4f). These

Table 1. Average modal (vol.%) composition of the different intrusives.

	Syenite	Melanite bearing syenite	Ijolite	Melteigite	Alkali pyroxenite	Alkali gabbro		Nepheline syenite	Carbonatite
	* <i>n</i> = 9	* <i>n</i> = 3	* <i>n</i> = 8	* <i>n</i> = 5	* <i>n</i> = 3	* <i>n</i> = 2	* <i>n</i> = 2	* <i>n</i> = 4	* <i>n</i> = 4
K-feldspar	69.6	73.3	8.2	—	1.2	20.4	27.9	56.6	—
Plagioclase	3.1	5.8	—	—	—	—	—	—	—
Nepheline	—	—	44.7	17.9	2.8	10.2	20.3	22.7	—
Clinopyroxene	10.3	Trace	33.3	56.7	92.6	64.2	33.7	17.9	6.5
Amphibole	8.2	7.4	0.3	—	—	—	—	—	—
Biotite	1.8	—	9.4	5.9	0.5	2.9	11.5	0.7	11.4
Garnet	—	10.7	—	6.3	—	—	—	—	—
Carbonate	3.6	1.2	1.4	10.4	1.7	—	1.4	1.7	71.3
Sphene	1.3	0.9	1.0	0.4	0.8	2.3	1.7	—	—
Apatite	0.2	0.4	0.8	0.7	0.2	0.3	0.8	0.3	8.5
Opaque	1.9	0.3	1.0	1.7	0.1	—	2.7	0.1	2.4

**n* = number of data.

rocks have >50% vol. of carbonate minerals (conforming to general classification scheme proposed by Middlemost 1985, p. 222).

3.6 Vanadium bearing titaniferous magnetite ore bodies

Megascopically, the rocks are hard, massive and deep brown in colour. These rocks are dominantly composed of magnetite associated with hematite. Pronounced effects of martitization are evident where magnetite has been oxidized and replaced by haematite which occurs as lamellae. Box-work type intergrowth textural pattern has been observed in martitized grains.

4. Mineral chemistry

Quantitative chemical analyses of constituent mineral phases have been undertaken at Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, USA. Major element compositions of constituent minerals were analysed by wavelength dispersive spectrometry (WDS) on a JEOL JXA-733 electron probe micro analyzer (WDS) with computer control. A fully focused beam operating with beam energy of 15 keV and a probe current of 300 nA was used. Typical counting times were 20–40 seconds and 1 σ standard deviations of the counts were 0.5–1%. Synthetic as well as natural standards were used during the analyses.

4.1 Pyroxene

The mineral chemical data obtained from twelve pyroxene analyses representing the alkaline felsic

(syenite, nepheline syenite) and alkaline mafic-ultramafic (ijolite, melteigite, alkali gabbro and alkali pyroxenite) members of the presently investigated Samchampi–Samteran Complex have been furnished in table 2. The pyroxenes are classified on the basis of ‘Q’ and ‘J’ relations (Morimoto *et al* 1988). In the Q–J classificatory diagram (figure 5a; Morimoto 1989), the pyroxenes of syenite, melteigite and alkali gabbro occupy the ‘Quad’ field and are thus Quad, whereas the pyroxenes from alkali pyroxenite, ijolite and nepheline syenite fall in the field of Ca–Na pyroxenes and are designated as non-Quad pyroxenes. The Quad pyroxenes are mostly diopside in composition (figure 5b) while the non-Quad pyroxenes largely cluster in the aegirine-augite field (figure 5c). Further in the Di–Hd–En–Fs diagram (Morimoto *et al* 1988; Rock 1990), pyroxene compositions corresponding to melteigite, alkali gabbro and syenite follow the ‘alkaline trend’ (Dobosi 1987) while lone plot of pyroxene corresponding to syenite follows the ‘mildly alkaline trend’ (Dorais *et al* 1991) (figure 5d).

4.2 Feldspar

Altogether eleven mineral-chemical analyses of feldspar from three constituent lithomembers of the study area, viz., syenite, alkali pyroxenite and alkali gabbro have been presented in table 3. Out of eleven analyses, nine correspond to K-feldspar while rest two represent plagioclase. Alkali feldspar data are available for syenite, ijolite, alkali pyroxenite, alkali gabbro and nepheline syenite. In the Or–Ab–An triangular diagram (figure 6), the data-plots corresponding to syenite, ijolite, alkali pyroxenite, alkali gabbro and nepheline syenite reflect an orthoclase composition.

Table 2. *EPM analyses of pyroxene.*

Sample	SAJ 11		SAJ 17	SAJ 19	
Analysis	1	2	3	4	5
Rock type	AP	AP	M	M	M
SiO ₂	52.39	53.21	49.87	51.28	53.24
TiO ₂	0.21	0.16	0.68	0.38	0.09
Al ₂ O ₃	0.91	0.69	2.55	2.59	0.51
FeO	4.85	3.33	7.72	4.97	6.90
Fe ₂ O ₃	6.74	10.47	6.06	4.40	2.84
Cr ₂ O ₃	0.07	0.08	0.02	0.01	0.03
MnO	0.54	0.53	0.51	0.28	0.55
MgO	11.10	9.62	9.26	12.15	12.23
CaO	19.78	16.29	20.08	22.39	22.24
Na ₂ O	2.66	4.72	2.11	1.31	1.29
Total	99.25	99.10	98.86	99.75	99.91
O = 6					
TSi	1.974	2.003	1.913	1.918	1.993
TAl	0.026	—	0.087	0.082	0.007
TFe ₃	—	—	—	—	—
M ₁ Al	0.015	0.031	0.029	0.032	0.015
M ₁ Ti	0.006	0.004	0.020	0.011	0.002
M ₁ Fe ₃	0.191	0.296	0.175	0.124	0.080
M ₁ Fe ₂	0.153	0.105	0.247	0.155	0.216
M ₁ Cr	0.002	0.002	0.001	—	0.001
M ₁ Mg	0.624	0.540	0.530	0.677	0.682
M ₂ Fe ₂	—	—	0.001	—	—
M ₂ Mn	0.017	0.017	0.017	0.009	0.017
M ₂ Ca	0.799	0.657	0.825	0.897	0.892
M ₂ Na	0.194	0.345	0.157	0.095	0.094
Sum-cat	4	4	4	4	4
Q	1.58	1.30	1.60	1.73	1.79
J	0.39	0.69	0.31	0.19	0.19
WO	44.79	40.68	46.01	48.17	47.25
EN	34.97	33.43	29.52	36.37	36.15
FS	20.24	25.89	24.47	15.46	16.60
WEF	80.38	65.68	83.77	90.16	90.60
JD	1.39	3.23	2.28	2.01	1.51
AE	18.23	31.09	13.95	7.83	7.89
mg#	0.80	0.84	0.68	0.81	0.76

AP: Alkali pyroxenite; M: Melteigite.

Plagioclase occurs in syenite as exsolution blebs within perthite. The analysed plagioclase of syenite corresponds to oligoclase species (An_{18.4}–An_{18.5}) (table 3).

4.3 Nepheline

Nepheline data are available for melteigite and nepheline syenite (table 4). The analyzed nepheline compositions are characterized by a higher proportion of Na₂O (ranging from 15.44–15.95 wt.%) with relatively lesser amounts of K₂O (ranging from 6.70–7.59 wt.%), thereby reflecting an overall sodic nature. The Na/(Na + K) ratio of nepheline in both melteigite and nepheline syenite is identical (0.76).

Thus, the representative Na/(Na + K) ratios suggest a soda-rich, alkaline character of the Samchampi–Samteran intrusives with prominent influence of silica-undersaturation (Dawson *et al* 1995).

4.4 Biotite

Representative electron probe compositions of biotite from four lithomembers of the study area, namely, ijolite, melteigite, alkali pyroxenite and nepheline syenite have been presented in table 5. The mineral chemical data reveal overall uniform biotite chemistry in all the four lithotypes. The analyzed biotite compositions represent a characteristic higher proportion of K₂O ranging from

Table 2. (Continued).

Sample	SAJ 25		SAJ 3	SAJ 47	SAJ 4A	SAJ 4B	
Analysis	6	7	8	9	10	11	12
Rock type	NS	NS	I	S	S	AG	AG
SiO ₂	52.72	52.81	52.91	49.85	50.45	52.97	52.94
TiO ₂	0.51	0.60	–	–	0.52	0.25	0.29
Al ₂ O ₃	0.47	0.47	0.46	0.64	1.06	0.67	0.63
FeO	6.84	6.00	3.85	23.11	4.48	7.29	4.77
Fe ₂ O ₃	7.24	8.60	8.21	1.65	5.99	1.44	3.37
Cr ₂ O ₃	0.03	0.03	–	–	0.04	0.02	–
MnO	0.38	0.43	0.58	1.79	0.43	0.56	0.47
MgO	9.86	9.72	10.81	5.59	11.48	12.40	13.33
CaO	18.87	18.42	19.80	17.58	22.09	21.98	21.43
Na ₂ O	3.13	3.52	3.06	0.41	1.54	1.17	1.53
Total	100.04	100.61	99.68	100.61	98.07	98.75	98.77
O = 6							
TSi	1.987	1.979	1.985	1.981	1.931	2.000	1.986
TAl	0.013	0.021	0.015	0.019	0.048	–	0.014
TFe ₃	–	–	–	–	0.021	–	–
M ₁ Al	0.007	–	0.006	0.011	–	0.030	0.014
M ₁ Ti	0.014	0.017	–	–	0.015	0.007	0.008
M ₁ Fe ₃	0.205	0.242	0.232	0.049	0.152	0.041	0.095
M ₁ Fe ₂	0.216	0.188	0.121	0.608	0.143	0.224	0.137
M ₁ Cr	0.001	0.001	–	–	0.001	0.001	–
M ₁ Mg	0.554	0.543	0.605	0.331	0.655	0.698	0.745
M ₂ Fe ₂	–	–	–	0.160	–	0.007	0.012
M ₂ Mn	0.012	0.014	0.018	0.060	0.014	0.018	0.015
M ₂ Ca	0.762	0.740	0.796	0.749	0.906	0.889	0.861
M ₂ Na	0.229	0.256	0.223	0.031	0.114	0.086	0.111
Sum_cat	4	4	4	4	4	4	4
Q	1.53	1.47	1.52	1.85	1.71	1.82	1.76
J	0.46	0.51	0.45	0.06	0.23	0.17	0.22
WO	43.57	42.83	44.93	38.25	47.92	47.39	46.15
EN	31.68	31.45	34.13	16.92	34.65	37.20	39.94
FS	24.75	25.72	20.93	44.83	17.43	15.40	13.92
WEF	77.14	74.37	77.57	96.83	88.29	91.44	88.83
JD	0.80	–	0.55	0.59	–	3.60	1.43
AE	22.06	25.63	21.88	2.58	11.71	4.96	9.73
mg#	0.72	0.74	0.83	0.35	0.82	0.76	0.84

NS: Nepheline syenite; I: Ijolite; S: Syenite; AG: Alkali gabbro.

9.22–10.09 wt%. The (FeO/FeO + MgO) ratio in biotite ranges between 0.39 and 0.52 and according to Czamanske and Wones (1973), such a low value of (FeO/FeO + MgO) reflects increasing fO_2 conditions during magmatic evolution. The aluminium saturation index (A.S.I) {i.e., $Al^{total}/Ca + Na + K$ } calculated from mineral chemical data shows an increasing trend (ranging from 1.0 to 1.4) (table 5) and indicates sufficient alumina activity in the crystallizing magma (Zen 1988). In the Eastonite–Siderophyllite–Annite–Phlogopite diagram (figure 7a; Deer *et al* 1979), the data points occupy the ‘biotite’ field. A plot of biotite compositions in $TiO_2 - FeO + MnO - MgO$ triangular diagram (Nachit *et al* 2005) (figure 7c)

suggests their secondary origin. This is consistent with petrographic observations as well.

4.5 Garnet

Representative compositions of garnet from syenite and melteigite of the Samchampi–Samteran complex have been furnished in table 6. The analyzed garnet compositions depict a prominent enrichment in CaO (ranging from 31.52 to 32.08 wt%) with lesser amounts of Al₂O₃ (ranging from 0.67 to 2.7 wt%) and Cr₂O₃ (ranging from 0.04 to 0.09 wt%). Most significantly, the Samchampi–Samteran garnets contain variable amounts of TiO₂, ranging from 3.62 to 12.88 wt%,

Figure 5. (a) Plot of investigated pyroxene compositions of Samchampi–Samteran complex in Q (Ca + Mg + Fe) – J(2Na) diagram (Morimoto *et al* 1989). (b) Plot of investigated pyroxene compositions of Samchampi–Samteran complex in Wo–En–Fs diagram (Morimoto *et al* 1989). (c) Plot of investigated pyroxene compositions of Samchampi–Samteran complex in WEF–En–Fs diagram (Morimoto *et al* 1989). (d) Clinopyroxene composition of Samchampi–Samteran complex in pyroxene quadrilateral (Morimoto *et al* 1988; Rock 1990). Variations shown as curved lines are (a) trend of pyroxenes from alkaline complexes (Dobosi 1987), (b) trend of pyroxene in mildly alkaline complexes (Dorais *et al* 1991). Fields are: (1) diopside, (2) ferroan diopside, (3) magnesian diopside, (4) hedenbergite, (5) magnesian-rich augite, (6) iron-rich augite, (7) subcalcic magnesian-rich augite, (8) subcalcic iron-rich augite, (9) calcian (magnesium-rich) pigeonite, (10) calcian (iron-rich) pigeonite, (11) magnesium-rich pigeonite, (12) iron-rich pigeonite, (13) clino-enstatite, (14) ferroan (clino) enstatite, (15) magnesian (clino) ferrosilite, and (16) clino-ferrosilite.

which reveals a unique compositional character. When the analyzed compositions of garnet are projected into the Spessartine+Pyrope-Ti-andradite–Grossular system, the compositional range corresponds to Ti-andradite (figure 8a) (Dingwell and Brearley 1985; Deer *et al* 1982). According to Deer *et al* (1992), Ti-rich andradites can be classified into melanite and schorlomite, depending on whether Fe^{3+} or Ti predominates in the octahedral site, placing the limit at approximately 15 wt% TiO_2 . Considering the classification parameters, the investigated Ti-andradite can be designated as melanite with a maximum 12.88 wt% TiO_2 (i.e., TiO_2 content less than 15%), $\text{Fe}^{3+} > \text{Ti}$, $\text{Al} < \text{Fe}^{3+}$ (Deer *et al* 1992; Dawson *et al* 1995; Gwalani *et al* 2000) in all analyzed samples.

4.6 Sphene

Representative electron probe analyses of sphene from syenite, melteigite, alkali pyroxenite and alkali gabbro have been given in table 7. The analyzed chemical compositions of sphene are broadly characterized by significant TiO_2 (ranging from 33.45 to 37.27 wt%) and CaO (ranging from 26.19 to 27.81 wt%) contents. The relative proportions of TiO_2 and CaO exhibit an overall uniform variation throughout the corresponding rock types.

4.7 Opaque minerals

Opaque minerals represent accessory phases in the constituent lithotypes of the present study

Table 3. *EPM analyses of feldspar.*

Sample	SAJ 11	SAJ 25	SAJ 3	SAJ 4B	SAJ 4A	SAJ 47					
Analysis	1	2	3	4	5	6	7	8	9	10*	11*
Rock type	AP	NS	NS	I	AG	S	S	S	S	S	S
SiO ₂	65.32	65.34	66.14	65.76	65.40	65.46	65.96	66.61	66.13	64.90	64.94
Al ₂ O ₃	18.88	18.55	18.08	18.87	18.54	18.54	19.23	19.30	19.77	23.28	23.16
FeO	0.08	0.29	0.91	0.16	0.45	0.19	0.01	0.01	0.02	0.03	0.10
MgO	0.01	0.01	0.01	—	0.02	—	—	—	—	—	—
CaO	—	—	—	0.06	—	—	0.08	0.09	0.42	3.74	3.86
Na ₂ O	1.19	1.86	1.92	0.18	0.27	0.48	1.24	2.98	3.10	9.02	9.31
K ₂ O	14.35	13.65	13.76	15.73	15.63	15.66	14.16	13.67	12.04	0.16	0.24
Total	99.83	99.69	100.82	100.76	100.11	100.34	100.67	102.67	101.48	101.13	101.61
O = 32											
Si	11.984	12.000	12.049	12.005	12.037	12.016	11.976	11.903	11.864	11.296	11.280
Al	4.079	4.012	3.879	4.057	3.975	4.008	4.112	4.062	4.177	4.772	4.737
Fe ₂	0.013	0.044	0.138	0.024	0.070	0.029	0.001	0.002	0.003	0.005	0.015
Mg	0.002	0.003	0.003	—	0.005	0.001	—	—	—	—	—
Ca	—	—	—	0.011	—	—	0.015	0.018	0.081	0.697	0.718
Na	0.424	0.661	0.678	0.063	0.096	0.171	0.437	1.034	1.078	3.044	3.136
K	3.359	3.198	3.198	3.663	3.670	3.667	3.280	3.116	2.756	0.036	0.053
Cations	19.861	19.918	19.945	19.823	19.853	19.892	19.821	20.135	19.959	19.850	19.939
X	16.063	16.012	15.928	16.062	16.012	16.024	16.088	15.965	16.041	16.068	16.017
Z	3.798	3.906	4.017	3.761	3.841	3.868	3.733	4.170	3.918	3.782	3.922
Ab	11.2	17.1	17.5	1.7	2.5	4.5	11.7	24.8	27.5	80.6	80.3
An	—	—	—	0.3	—	—	0.4	0.4	2.1	18.5	18.4
Or	88.8	82.9	82.5	98	97.5	95.5	87.9	74.8	70.4	1	1.4

AP: Alkali pyroxenite; NS: Nepheline syenite; I: Ijolite; AG: Alkali gabbro; S: Syenite.

*Analysis no. 1–9 represent the probe data of K-feldspar of different lithotypes whereas analysis no. 10 and 11 represent the probe data of plagioclase from syenite.

Figure 6. Plot of investigated feldspar compositions in Or–Ab–An triangular diagram.

Table 4. *EPM analyses of nepheline.*

Sample	SAJ 19	SAJ 19	SAJ 25
Analyses	1	2	3
Rock type	M	M	NS
SiO ₂	41.85	41.85	42.92
Al ₂ O ₃	34.87	34.78	33.60
FeO	0.65	0.66	0.72
MgO	0.02	—	—
CaO	0.04	0.03	—
Na ₂ O	15.44	15.68	15.95
K ₂ O	7.58	7.59	6.70
Total	100.45	100.59	99.91
Si	1.010	1.010	1.037
Al	0.992	0.989	0.957
Fe	0.013	0.013	0.015
Mg	0.001	—	—
Ca	0.001	0.001	—
Na	0.722	0.734	0.747
K	0.233	0.234	0.207
CatTot	2.972	2.980	2.962
X	61.571	61.715	64.988
Y	45.621	45.183	74.272
Na/(Na + K)	0.76	0.76	0.78

M: Melteigite; NS: Nepheline syenite.

Table 5. EPM analyses of biotite.

Sample	SAJ 11	SAJ 17	SAJ 25	SAJ 3	
Analysis	1	2	3	4	5
Rock type	AP	M	M	NS	I
SiO ₂	39.45	37.19	36.38	38.49	39.85
TiO ₂	1.35	2.93	1.90	2.57	2.33
Al ₂ O ₃	12.02	13.88	15.20	10.78	11.05
Cr ₂ O ₃	—	—	—	0.03	—
FeO	12.04	11.68	12.76	16.87	12.44
MnO	0.48	0.42	0.43	0.42	0.51
MgO	18.63	17.82	17.53	15.67	18.03
CaO	0.01	0.04	0.03	—	—
Na ₂ O	0.32	0.44	0.39	0.28	0.12
K ₂ O	9.56	9.22	9.32	9.36	10.09
Total	93.87	93.62	93.95	94.48	94.43
O = 24					
Si	5.947	5.633	5.484	5.923	6.042
Al ^{IV}	2.053	2.367	2.516	1.954	1.958
Al ^{VI}	0.081	0.109	0.182	—	0.015
Ti	0.153	0.334	0.216	0.297	0.266
Fe ²	1.518	1.479	1.609	2.171	1.577
Cr	—	—	—	0.004	—
Mn	0.061	0.054	0.055	0.055	0.066
Mg	4.187	4.024	3.939	3.595	4.075
Ca	0.002	0.006	0.004	0.001	—
Na	0.094	0.129	0.115	0.084	0.035
K	1.839	1.781	1.792	1.838	1.952
Cations	15.935	15.916	15.912	15.922	15.986
Fe–FeMg	0.27	0.27	0.29	0.38	0.28
Mg–FeMg	0.73	0.73	0.71	0.62	0.72
FeO/(FeO+	0.39	0.40	0.42	0.52	0.41
MgO)					
A.S.I.	1.1	1.3	1.4	1.0	1.0

AP: Alkali pyroxenite; M: Melteigite; NS: Nepheline syenite; I: Ijolite; A.S.I.: Alumina Saturation Index.

area. Electron probe micro analyses of opaque minerals from ijolite, melteigite and alkali pyroxenite have been presented in table 8. The FeO^(t) content of analyzed opaque minerals range from 81.95 to 88.72 wt% with relatively lesser amounts of TiO₂ (ranging from 3.46–5.68 wt%). The analyzed chemical compositions of opaque minerals correspond to magnetite.

It is to be noted that the mineral-chemical data for differentiation centres (related to Sylhet Traps) of northeastern India were practically absent since long. However, very recently, Melluso *et al* (2010) published a splendid account of mineral compositions of Sung Valley ultramafic–alkaline–carbonatite complex. In this view, a comparative assessment of mineralogical characters of Samchampi–Samteran alkaline complex (present study) and that of ultramafic–alkaline–carbonatite complex of Sung Valley, northeastern India will be

Figure 7. Plot of biotite compositions in eastonite–siderophyllite–phlogopite–annite diagram (Deer *et al* 1979, p. 212). Plot of biotite compositions in TiO₂–FeO*+MnO–MgO diagram (Nachit *et al* 2005).

worthwhile to present. The summary-table showing comparison of mineralogical characters between these two complexes has been given in table 9.

5. Geothermobarometry

The relevant mineral chemical data obtained for constituent phases can be successfully applied for geothermobarometric estimations. Several thermometric and barometric methods (proposed by several workers) have been considered in the present study on the basis of available mineralogical compositions.

5.1 Geothermometry

5.1.1 Pyroxene thermometry

The electron microprobe analyses of pyroxene compositions are available for syenite, alkali pyroxenite,

Table 6. *EPM analyses of garnet.*

Sample	SAJ 17		SAJ 4A		
Analysis	1	2	3	4	5
Rock type	M	S	S	S	S
SiO ₂	28.03	32.64	33.79	32.09	32.29
TiO ₂	12.88	3.62	4.06	7.10	6.66
Al ₂ O ₃	2.67	1.31	1.55	0.67	0.71
Cr ₂ O ₃	0.07	0.08	0.04	0.10	0.08
FeO	0.90	–	0.67	1.83	1.63
Fe ₂ O ₃	20.37	27.62	26.22	24.83	25.37
MnO	0.60	0.60	0.54	0.55	0.58
MgO	1.15	0.15	0.21	0.24	0.21
CaO	31.91	32.08	32.21	31.53	31.52
Na ₂ O	0.14	0.21	0.26	0.33	0.35
Total	98.71	98.31	99.55	99.27	99.40
O = 24					
TSi	4.788	5.601	5.706	5.477	5.503
TAI	0.536	0.264	0.294	0.134	0.142
Sum_T	5.325	5.865	6	5.611	5.645
Al ^{VI}	–	–	0.014	–	–
Fe ³	2.616	3.563	3.328	3.186	3.25
Ti	1.655	0.467	0.516	0.912	0.854
Cr	0.009	0.011	0.006	0.013	0.01
Sum_A	4	4	4	4	4
Fe ²	0.129	–	0.094	0.261	0.232
Mg	0.292	0.039	0.052	0.061	0.054
Mn	0.086	0.087	0.078	0.079	0.084
Ca	5.840	5.898	5.827	5.766	5.755
Na	0.048	0.070	0.085	0.111	0.116
Sum_B	6.396	6.094	6.136	6.278	6.241
Sum_cat	16	16	16	16	16
And	82.75	95.52	91.38	95.58	95.51
Gross	9.01	1.94	6.10	1.22	1.48
Pyrope	6.15	0.69	0.95	1.22	1.06
Spess	1.82	1.55	1.42	1.59	1.64
Uvaro	0.28	0.30	0.16	0.39	0.31
XCagnt	0.920	0.979	0.963	0.935	0.940
XFegnt	0.020	–	0.016	0.042	0.038
XMggnt	0.046	0.006	0.009	0.010	0.009
Fe_Mggnt	0.442	–	1.808	4.279	4.296

M: Melteigite; S: Syenite.

Figure 8. Compositional range of Samchampi–Samteran garnets (shaded area) in Spessartine + Pyrope – Ti-Andradite – Grossular system (Dingwell and Brearley 1985).

Table 7. *EPM analyses of sphene.*

Sample	SAJ 11	SAJ 19	SAJ 4B	SAJ 4A
Analysis	1	2	3	4
Rock type	AP	M	AG	S
SiO ₂	29.57	29.70	29.81	29.51
TiO ₂	34.85	33.45	37.27	35.06
Al ₂ O ₃	1.09	0.61	0.40	1.33
Cr ₂ O ₃	0.10	0.06	0.03	0.09
FeO	1.67	2.47	1.72	2.21
MnO	0.02	0.07	0.06	0.05
MgO	0.05	0.05	0.03	–
CaO	26.62	26.19	26.90	27.81
Na ₂ O	0.36	0.15	0.23	0.11
Total	94.34	92.74	96.45	96.17
O = 20				
Si	4.108	4.205	4.042	4.056
Al	0.178	0.102	0.215	0.064
Ti	3.642	3.562	3.612	3.814
Cr	0.010	0.007	0.010	0.003
Mg	0.010	0.010	–	0.007
Fe ²	0.194	0.292	0.253	0.195
Mn	0.002	0.008	0.006	0.007
Na	0.097	0.040	0.030	0.061
Ca	3.962	3.973	4.081	3.921
Sum_cats	12.203	12.199	12.249	12.128

AP: Alkali pyroxenite; M: Melteigite; AG: Alkali gabbro; S: Syenite.

Table 8. *EPM analyses of opaque oxide.*

Sample	SAJ 17	SAJ 11	SAJ 3
Analysis	1	2	3
Rock type	M	AP	I
SiO ₂	0.05	0.01	0.05
TiO ₂	5.68	4.92	3.46
Al ₂ O ₃	0.90	0.82	0.51
Cr ₂ O ₃	0.06	0.03	–
FeO ^(t)	81.95	83.83	88.72
MnO	1.84	2.17	0.40
MgO	0.66	0.67	0.03
CaO	–	0.01	–
NiO	0.05	0.07	0.02
ZnO	0.23	0.31	0.09
Total	100.32	98.62	99.41
O = 4			
Si	0.0013	0.0002	0.0021
Ti	0.1114	0.1425	0.1002
Al	0.0278	0.0371	0.0230
Cr	0.0013	0.0010	–
Fe ³⁺	1.7455	1.6764	1.7724
Fe ²⁺	0.0409	1.0228	1.0842
Mn	0.0406	0.0708	0.0132
Mg	0.0255	0.0382	0.0016
Ca	–	0.0005	0.0002
Ni	0.0011	0.0021	0.0006
Zn	0.0045	0.0088	0.0027
CatTot	2	3	3
X	27.56	15.54	56.85
Y	16.12	12.48	42.67

M: Melteigite; AP: Alkali pyroxenite; I: Ijolite.

Table 9. Summary-table showing a comparison between the mineralogical characters of Samchampi–Samteran (SS) alkaline complex and Sung Valley (SUV) ultramafic–alkaline–carbonatite complex.

Mineralogical characters in Samchampi–Samteran (SS) alkaline complex (present study)	Mineralogical characters in Sung Valley (SUV) ultramafic–alkaline–carbonatite complex (Melluso et al 2010)	Comments
Clinopyroxene		
<ul style="list-style-type: none"> • Clinopyroxene ($\text{Wo}_{40-48}\text{En}_{27-48}\text{Fs}_{15-40}$) occurs as essential mineral in ijolite, melteigite, alkali pyroxenite and alkali gabbro. Syenite and nepheline syenite contain clinopyroxene as major mafic phase. • Clinopyroxene compositions of Samchampi–Samteran intrusives range from diopside to aegirine augite. • Clinopyroxene from syenite, melteigite and alkali gabbro corresponds to diopside while in alkali pyroxenite, ijolite and nepheline syenite, clinopyroxene is aegirine augite. • Alkali pyroxenites have low Ti (TiO_2 from 0.16–0.21 wt%, 0.004–0.006 Ti apfu), low Al (Al_2O_3 from 0.7–0.9 wt%, 0.031–0.041 Al apfu) sodic clinopyroxene (Na_2O ranging from 2.66–4.72) with mg# ranging from 80–84. • In ijolite–melteigite, clinopyroxene varies from diopside (melteigite) to aegirine augite (ijolite) and is characterized by low Ti (TiO_2 from 0.09–0.68 wt%, 0.002–0.02 Ti apfu), low Al (Al_2O_3 from 0.46–2.58 wt%, 0.021–0.116 Al apfu) with mg# ranging from 68–83. Na_2O content shows a gradual increase from melteigite (Na_2O ranging from 1.3–2.1 wt%) to ijolite (3.06 wt% Na_2O). • In nepheline syenite, clinopyroxene is aegirine augite (Na_2O ranging from 3.13–3.52 wt%) with mg# ranging from 72–74. 	<ul style="list-style-type: none"> • Clinopyroxene occurs as essential mineral in uncompagrite, clinopyroxenite, ijolite and nepheline syenite. Peridotite contains clinopyroxene as relict phase. • Clinopyroxene compositions of Sung Valley intrusives range from diopside to aegirine. • Clinopyroxenites have low Ti (TiO_2 from 0.07–0.68 wt%, 0.002–0.02 Ti apfu), low Al (Al_2O_3 from 0.4–1.15 wt%, 0.02–0.05 Al apfu) clinopyroxene with mg# ranging from 62–87. • In ijolite, clinopyroxene ranges from diopside to increasingly sodic aegirine augite (Na_2O ranging from 1–3.24 wt%, 0.07–0.23 Na apfu), with relatively low Al_2O_3 (1.1 to 3.8 wt%, 0.05–0.17 Al apfu), generally low TiO_2 (0.14–1.8 wt%, 0.004–0.05 Ti apfu) and mg# ranging from 35 to 74. • In nepheline syenite, clinopyroxene varies from aegirine–augite to aegirine (Na_2O ranging from 4–13 wt%) with mg# ranging from 4 to 32. 	<ul style="list-style-type: none"> • Both SS and SUV complex manifest development of clinopyroxene in different intrusive lithotypes. In both the complexes, the clinopyroxenes have compositional spectrum ranging from ‘Q’ (diopside–augite) to ‘J’ (aegirine, aegirine–augite type (Morimoto et al 1989)). The trends of clinopyroxene variation is as per with almost similar variations noted in other ultramafic–mafic–alkaline–carbonatite complexes of the other parts of the world (Bindi et al 1999).
K-feldspar		
<ul style="list-style-type: none"> • K-feldspar (Or_{70-98}) occurs as essential mineral in syenite, alkali gabbro and nepheline syenite while ijolite–melteigite and alkali pyroxenite contain K-feldspar as accessory phase. • K-feldspar (Or_{70-98}) from syenite, ijolite, alkali pyroxenes, alkali gabbro and nepheline syenite corresponds to orthoclase. 	<ul style="list-style-type: none"> • K-feldspar is an essential constituent in nepheline syenite but also occurs in clinopyroxenite as an interstitial phase. • K-feldspar is compositionally potassic in nepheline syenite (Or_{70-96}) and clinopyroxenite (Or_{82-96}). 	<ul style="list-style-type: none"> • K-feldspar (occurring in relevant lithotypes) for both SS and SUV complex have comparable compositional range.

Garnet

- Garnet occurs as a major constituent in syenite and ijolite–melteigite rocks.
- In syenite, TiO₂ content of garnet ranges from 3.62–7.1 wt% and in melteigite, TiO₂ content of garnet reaches a value of 12.88 wt%. Thus, garnet shows a composition rich in andradite and schorlomite components and is designated as melanite.
- In syenite and melteigite garnet is calcic (CaO ranging from 31.52 to 32.21 wt%) and MgO content (0.15–0.24) systematically decreases with TiO₂.

Nepheline

- Nepheline occurs as essential mineral in ijolite, melteigite, alkali gabbro and nepheline syenite. Alkali pyroxenite contains nepheline as accessory phase.
- The Na/(Na + K) ratio of analysed nepheline in both melteigite and nepheline syenite is 0.76.

- Calcic garnet occurs in clinopyroxenite and ijolite.
- In ijolite, garnet has high TiO₂ contents reaching values upto 14–15 wt% indicating significant amounts of schorlomite, morimotoite and andradite components. Al contents are very low (Al₂O₃ ranging from 0.9 to 1.5 wt%) while MgO (0.2–1.1 wt%) content systematically decreases with TiO₂.
- In clinopyroxenite, garnet is richer in Al (4–9 wt% Al₂O₃) and has relatively lesser content of TiO₂ (1.45–8 wt%) indicating the presence of andradite and grossular components.
- Nepheline occurs as essential mineral in ijolite and nepheline syenite.
- The Na/(Na + K) ratio of nepheline in ijolite ranges from 0.78 to 0.85 while that in nepheline syenite ranges from 0.81–0.84.

- Characteristically the garnet in relevant lithotypes of both SS and SUV complex are Ti rich yielding varieties like melanite, schorlomite components involving complex substitution $Ti^{4+}Fe^{3+} \leftrightarrow Ti^{4+}Al^{3+}$ in appropriate crystal sites (Chakmouradian and McCammon 2005).

- Nepheline occurs as important mineral phase in both the SS and SUV complex. Compositional spectrum of nepheline in both of the complexes is identical.

alkali gabbro, ijolite–melteigite and nepheline syenite. Out of these, the analyzed pyroxene compositions corresponding to syenite, melteigite and alkali gabbro have been classified as ‘Quad’ pyroxenes (as mentioned earlier). Therefore, in order to determine the temperature, pyroxene compositions can be assessed in terms of pyroxene thermometry (Lindsley 1983), in order to determine temperature. The procedure involves simple recalculation of the analyzed pyroxene compositions in terms of several end-member molecules and subsequent plotting of those recalculated molecules in terms of experimentally determined pyroxene thermometer contours. The investigated pyroxene compositions when projected into Lindsley’s diagram (figure 9), reveal that the syenite represents a lower temperature of equilibration at ~400°C while, melteigite and alkali gabbro record a close range of temperature of equilibration ranging from ~450°–600°C.

5.1.2 Clinopyroxene–garnet thermometry

Geothermometric estimations have also been evaluated on the basis of coexisting clinopyroxene–garnet compositions for syenite and ijolite–melteigite rocks following the methods proposed by Mysen and Heier (1972); Raheim and Green (1974); Mori and Green (1978); Krogh (1988); Pattison and Newton (1989); Sengupta *et al* (1989) and Ai (1994). Temperatures calculated for syenite and ijolite–melteigite from different thermometric methods have been furnished in table 9. The average temperature deduced for syenite ranges from 569°–618°C (table 10). The ijolite–melteigite suite of rocks exhibits a relatively higher range of equilibration temperature ranging from 687° to 1373°C (table 10).

5.1.3 Two feldspar thermometry

Two feldspar thermometry with available electron microprobe data for syenite was estimated following the method of Haselton *et al* (1983). The calculated two feldspar thermometry yields an average equilibration temperature of 583°C for syenite (table 10).

5.2 Geobarometry

5.2.1 Pyroxene barometry

Ashchepkov (2009) put forward reliable barometric methods based on pyroxene compositions. In the present study, geobarometric estimates involve analyzed pyroxene compositions from syenite, ijolite–melteigite, alkali pyroxenite, alkali gabbro and nepheline syenite. The deduced values

Figure 9. Recalculated pyroxene compositions plotted in terms of Di-Hd-En-Fs diagram for thermometry (Lindsley 1983).

Table 10. Geothermometric data of different lithotypes.

Rock type	Thermometric method	Temperature (°C)	Average temperature (°C)
Melteigite-ijolite	Cpx-Garnet chemistry (Raheim and Green 1974)	1373.8	1373.8
	Cpx-Garnet chemistry (Sengupta <i>et al</i> 1989)	687.0	687.0
	Cpx-Garnet chemistry (Ai 1994)	942.2	942.2
Syenite	Cpx-Garnet chemistry (Raheim and Green 1974)	569.1	569.1
	Cpx-Garnet chemistry (Krogh 1988)	484.3	484.3
	Cpx-Garnet chemistry (Pattison and Newton 1989)	617.7	617.7
	Cpx-Garnet chemistry (Mysen and Heier 1972)	581.8	581.8
	Cpx-Garnet chemistry (Mori and Green 1978)	574.4	574.4
	Two feldspar thermometry (Haselton <i>et al</i> 1983)	580.6	583.3
		586.0	

(table 11) reveal a closely comparable pressure for ijolite-melteigite, alkali pyroxenite, alkali gabbro, and nepheline syenite (average pressure values ranging from 5.32–7.72 kb) corresponding to a depth of crystallization of ~16–23 km. Syenite exhibits a pressure of 11.81 kb (table 11) indicating a deeper level of intrusion at about 33 km (assuming 3 km/kb).

5.2.2 Clinopyroxene-plagioclase barometry

Barometric estimates involving coexisting clinopyroxene-plagioclase compositions have been adopted for syenite following the method proposed by Ellis and Green (1979). The calculated pressure of 11.61 kb corresponds to a depth of intrusion of ~33 km.

Table 11. Geobarometric data of different intrusives.

Rock type	Barometric method	P in kb	Avg. P in kb
Alkali pyroxenite	Cpx chemistry (Ashchepkov 2009)	7.72	7.72
Melteigite-ijolite	Cpx chemistry (Ashchepkov 2009)	8.1	6.68
		7.58	
		4.37	
Alkali gabbro	Cpx chemistry (Ashchepkov 2009)	4.93	5.32
		5.71	
		5.71	
Syenite	Cpx chemistry (Ashchepkov 2009)	11.81	11.81
		11.81	
		11.61	
Nepheline syenite	Cpx-Garnet chemistry (Ellis and Green 1979)	11.61	11.71
		11.61	
		11.61	
Nepheline syenite	Cpx chemistry (Ashchepkov 2009)	4.93	5.32
		5.71	
		5.71	

Table 12. Whole rock major oxide data (wt.%).

	AP1*	AP2**	AP3**	I1*	I2**	M1*	M2**	S*	NS1*	NS2**	C*
SiO ₂	44.09	44.07	46.26	43.63	38.50	45.20	38.09	53.66	52.48	57.07	5.48
TiO ₂	1.00	0.66	0.26	1.25	1.25	0.90	0.87	1.27	0.98	0.69	0.46
Al ₂ O ₃	14.90	9.27	6.52	13.45	11.84	3.20	7.83	9.12	16.80	14.43	0.50
Fe ₂ O ₃	10.89	3.66	5.93	5.38	3.83	5.80	2.36	10.06	3.65	2.35	3.92
FeO	0.70	3.58	3.36	2.75	6.28	5.91	2.00	3.27	3.67	1.14	2.41
MnO	0.12	0.29	0.82	0.11	0.31	0.38	0.27	0.05	0.11	0.02	0.20
MgO	4.48	5.33	7.31	8.04	10.36	14.80	6.71	3.47	4.11	0.01	5.63
CaO	20.27	16.30	17.61	11.33	9.45	16.58	18.17	13.02	6.07	0.10	46.32
Na ₂ O	1.93	6.50	5.25	4.35	4.67	1.62	5.87	2.03	4.48	9.25	0.13
K ₂ O	2.05	2.87	1.00	4.21	3.71	2.51	0.62	2.13	4.66	11.75	0.16
P ₂ O ₅	0.10	1.74	2.30	0.40	1.48	0.62	3.89	0.10	0.17	0.15	0.90
CO ₂	n.d	—	—	1.84	—	0.84	—	—	n.d	—	31.45
LOI	—	5.52	1.18	—	6.12	—	8.87	—	1.63	0.88	—
Total	100.53	99.79	97.80	96.74	97.80	98.36	95.55	98.18	98.81	97.84	97.56
CIPW norm											
Quartz	—	—	—	—	—	—	—	12.67	—	—	—
Plagioclase	25.94	—	—	4.74	0.39	—	—	26.66	37.46	—	0.31
Orthoclase	6.14	—	1.28	20.18	—	—	—	12.59	27.54	65.91	—
Nepheline	8.85	17.17	15.15	19.94	21.41	1.35	19.95	—	6.73	4.77	0.60
Leucite	4.68	13.30	3.63	3.69	17.19	11.63	2.87	—	—	2.76	—
Kalsilite	—	—	—	—	—	—	—	—	—	—	0.54
Diopside	24.07	36.77	51.51	28.97	24.18	45.38	41.20	18.64	13.54	—	—
Wollastonite	17.85	—	3.41	—	—	—	0.27	12.74	—	—	—
Olivine	—	1.12	—	4.62	15.15	16.72	—	—	4.37	0.78	10.44
Larnite	—	7.42	—	—	2.02	4.88	3.71	—	—	—	7.67
Acmite	—	10.59	14.50	—	—	9.89	6.83	—	—	6.80	—
Na ₂ SiO ₃	—	2.63	—	—	—	—	1.19	—	—	14.37	—
Ilmenite	1.74	1.25	0.49	2.37	2.37	1.71	1.65	2.41	1.86	1.31	0.87
Magnetite	—	—	1.33	5.60	5.55	3.45	—	7.02	5.29	—	5.68
Hematite	10.89	—	—	1.52	—	—	—	5.22	—	—	—
Apatite	0.23	4.03	5.33	0.93	3.43	1.44	9.01	0.23	0.39	0.35	2.09
Perovskite	0.15	—	—	—	—	—	—	—	—	—	—
Calcite	—	—	—	4.18	—	1.91	—	—	—	—	71.53
D.I.	45.60	30.50	20.10	48.60	39.00	13.00	22.80	51.90	71.70	73.40	1.50
A.I.	0.36	1.50	1.50	0.87	0.98	1.70	1.32	0.63	0.74	1.94	0.82

AP: Alkali pyroxenite; I: Ijolite; M: Melteigite; S: Syenite; NS: Nepheline syenite; and C: Carbonanite.

*Analyses taken from Nag *et al* (1999).

**Analyses taken from Kumar *et al* (1989).

6. Petrochemistry

Whole rock major oxide data for alkali pyroxenite, ijolite, melteigite, syenite, nepheline syenite and carbonatite from Samchampi–Samteran alkaline complex (after Kumar *et al* 1989; Nag *et al* 1999) and the corresponding CIPW norms have been furnished in table 12. The alkali pyroxenite (AP1, AP2 and AP3) and ijolite–melteigite (I1, I2, M1 and M2) rocks are characterized by alkaline normative minerals like nepheline, leucite and larnite. CIPW normative compositions suggest the alkaline nature of these rocks. The agpaitic indices [A.I. = (NaO + K₂O)/Al₂O₃] for two alkali pyroxenite samples (AP2 and AP3) are >1 suggesting

their agpaitic nature while one alkali pyroxenite sample (AP1) is miaskitic with A.I. = 0.36. The ijolite samples (I1 and I2) are miaskitic and the melteigite samples (M1 and M2) are agpaitic in nature. The miaskitic affinity of a nepheline syenite sample (NS1) reflects a close alkaline–carbonatite association (Srivastava and Sinha 2007). Major oxide variations of the Samchampi–Samteran rocks are plotted against differentiation index (D.I.) in Harker variation diagrams (figure 10). Differentiation Index (D.I.) has been calculated as normative Qtz + Or + Ab + Ne + Lc (after Thornton and Tuttle 1960). Figure 10 shows that SiO₂, Al₂O₃ and total alkalis (NaO + K₂O) gradually increase with rising D.I. while TiO₂, FeO^(t), CaO

Figure 10. D.I. vs. major oxides variation diagram for Samchampi-Santeran rocks.

Figure 11. Total alkali *vs.* silica diagram for Samchampi–Samteran rocks. Field boundary after Macdonald and Katsura (1964).

Figure 12. Total alkali *vs.* silica diagram for Samchampi–Samteran rocks. Field boundaries after Hyndaman (1985).

and MgO systematically fall with increasing D.I. The general trend of major oxide variations for the Samchampi–Samteran rocks is very much consistent with normal magmatic differentiation. But the variation of P_2O_5 with respect to D.I. in alkaline ultramafic (alkali pyroxenite) and alkaline mafic (ijolite–melteigite) rocks is distinctly anomalous. Phosphorous, being a high charge density (HCD) cation is normally concentrated in late stage differentiates, i.e., in more silicic rocks. However, for the Samchampi–Samteran complex, the alkaline ultramafic and alkaline mafic rocks are more enriched in P_2O_5 than their felsic counterparts (syenite, nepheline syenite) (figure 10). The geochemical

characters of the Samchampi–Samteran rocks are further illustrated in figures 11 and 12. In the total alkali *vs.* silica diagram (figure 11), the Samchampi–Samteran samples distinctly occupy the 'alkaline' field with a lone plot of syenite falling the 'subalkaline' field. Figure 12 depicts total alkali *vs.* silica variation diagram wherein two alkali pyroxenite samples plot in the Alkali basalt family and one sample falls in the Nephelinite family. The ijolite samples together with one melteigite sample correspond to the Nephelinite family while one melteigite sample belongs to the Alkali basalt family. Nepheline syenite occupies the fields of Alkali basalt family and Miaskitic syenite family while the syenite sample plots in the field of subalkaline rocks. Compositional plots of Samchampi–Samteran samples in the Petrogeny's Residua System (figure 13) reveal that only the syenite sample falls in the silica oversaturated field. Plots for alkali pyroxenite and ijolite fall in the nepheline field while melteigite and nepheline syenite samples show compositional occupancy in both nepheline and leucite fields. However, characteristically the samples falling within leucite field are devoid of normative and modal leucite. These observations suggest that the investigated rocks crystallized in a high P_{H_2O} regime where the stability field of leucite gradually contracted and ceased to exist under the influence of a water enriched milieu. Presence of amphibole in syenite and biotite in the alkaline felsic and alkaline mafic–ultramafic rocks of Samchampi–Samteran also supports the role of a hydrous environment in the formation of Samchampi–Samteran rocks. CaO *vs.* $(Na_2O + K_2O)$ variations in Samchampi–Samteran rocks depict a trend which corroborates the antipathetic relationship between CaO and total alkalis in a narrow dispersion zone characteristic of silica-undersaturated plutons (figure 14). Similar trend is observed for two other well-studied alkaline complexes of northeastern India, *viz.*, Sung Valley and Jasra (figure 14). Thus a geochemical association of the Samchampi–Samteran rocks with Sung Valley and Jasra alkaline complexes is documented.

7. Discussion

Lineament controlled emplacement comprising ultramafic–mafic–alkaline–carbonatite complexes are often associated with rift tectonics (Woolley 1989). In northeastern India, such lineament controlled differentiated complexes are relegated to an incubating mantle plume and concomitant extrusion of Bengal–Rajmahal–Sylhet volcanics (Evans 1964; Gupta and Sen 1988; Nandy 1980, 2001). The presently investigated Samchampi–Samteran complex represents an excellent development of

Figure 13. Compositional plots of Samchampi-Samteran rocks in Petrogeny's Residua System (after Hamilton and MacKenzie 1965).

Figure 14. CaO vs. (Na₂O+K₂O) diagram for Samchampi-Samteran rocks (after Ratnakar and Leelanandam 1989).

such flood-basalt related differentiation centre where plug-like body of syenite has been intruded by ijolite-melteigite suite of rocks with occasional presence of alkali pyroxenite and alkali gabbro inliers. The pulsating magmatic activity was further manifested in terms of development of vanadium bearing titaniferous magnetite ore bodies and later intrusions of carbonatite and nepheline syenite dykes.

In the following paragraphs, we discuss few important points which would be meaningful to constrain petrogenesis of Samchampi-Samteran alkaline complex.

7.1 Implications from mineral chemistry

Chemical compositions of coexisting phases have been used for thermobarometric estimations. Critical assessment of pyroxene thermometry data suggests an equilibration temperature from ~450°–600°C for melteigites and alkali gabbro and ~400°C for syenite. Other thermometric methods reveal a temperature of equilibration of ~700°–1373°C for ijolite-melteigite suite of rocks in contrast to relatively lower (~600°C) equilibration temperature for the syenites. These deduced temperatures for syenite speak in favour of subsolvus cooling. Barometric data based on pyroxene chemistry on the other hand critically deduce average pressure values from 5.32 to 7.72 kb for the ijolite-melteigite, alkali pyroxenite, alkali gabbro and nepheline syenite. The main syenite plug records an equilibration pressure of ~11 kb indicating a deeper level of intrusion. It appears that the syenite equilibrated at a relatively greater depth than other intrusive variants of the Samchampi-Samteran Complex.

7.2 Role of metasomatism

Petrographic observations reveal that two generations of clinopyroxene occur in ijolite-melteigite

Figure 15. Compositional plots of Samchampi–Samteran rocks in Greig diagram (Philpotts 1982).

rocks. The earlier formed clinopyroxene occur as inclusions in nepheline (figure 4b) while the late formed clinopyroxene grains containing nepheline inclusions (figure 4c) are more sodic and have developed due to metasomatism. Vermicular intergrowths of nepheline within K-feldspar indicate that nepheline has been replaced by K-feldspar as a result of metasomatic alterations. It has been observed that titanium bearing garnets enriched in andradite ($\text{Ca}_3\text{Fe}_2^{3+}\text{Si}_3\text{O}_{12}$), schorlomite ($\text{Ca}_3\text{Ti}_2[\text{Al} > \text{Fe}_2^{3+}]_2\text{SiO}_{12}$) or melanite ($\text{Ca}_3\text{Ti}_2[\text{Al} < \text{Fe}_2^{3+}]_2\text{SiO}_{12}$) molecules principally occur in a wide variety of alkaline igneous rocks and related types including syenites (Ramaswamy 1986), nepheline syenites (Gomes 1969), ijolite–melteigites (Larsen 1942), carbonatites (Howie and Woolley 1968; Huggins *et al* 1977; Ramaswamy 1986). Ti-rich garnets can form over a wide range of temperatures and pressures and particularly, in alkaline rocks, they appear to reflect complex late stage metasomatic reactions of earlier-formed mafic minerals with late-stage fluids (Dingwell and Brearley 1985; Gwalani *et al* 2000). This idea is consistent with petrographic study of the garnet bearing assemblages from the area, which indicate that Ti-rich garnets formed from clinopyroxene and biotite, perhaps driven by metasomatic alterations. These petrographic features distinctly point towards the effects of alkali metasomatism which influenced the evolution of the Samchampi–Samteran alkaline complex in a fluid-enriched milieu.

7.3 Role of liquid immiscibility

Anomalous enrichment of P_2O_5 in alkaline ultramafic (alkali pyroxenite) and alkaline mafic (ijolite–

melteigite, alkali gabbro) rocks from Samchampi–Samteran alkaline complex suggests differential dispersal of high charge density (HCD) cations like P^{5+} between felsic and mafic units. High charge density (HCD) cations like P^{5+} are incompatible with respect to the minerals formed during the early stage of fractional crystallization and are normally concentrated in late formed rocks. But, enrichment of P_2O_5 in mafic–ultramafic members of Samchampi–Samteran alkaline complex negates the idea of fractional crystallization and strongly favours liquid immiscibility as a dominant petrogenetic process for the formation of Samchampi–Samteran rocks (Philpotts 1982; Eby 1979; Subrahmanyam and Leelanandam 1989). Further, it is well documented that apatite is an effective concentrator of P (Nagasawa 1970) and occurrence of apatite in alkaline mafic–ultramafic rocks indicates significant apatite fractionation from a P_2O_5 rich melt. This apatite fractionation is favoured by a volatile/fluid enriched milieu. The process of liquid–liquid unmixing has been proposed as a suitable mechanism for producing contemporaneous liquids of felsic and mafic compositions in a variety of alkaline igneous complexes from India and other parts of the world (Markl 2001; Rajesh 2003; Halama *et al* 2005; Doroshkevich *et al* 2010). It has been documented by many researchers (Eby 1979; Philpotts 1982; Markl 2001; Rajesh 2003) that if liquid immiscibility is to produce magmatic bodies of contrasting compositions, then the parental magma has to first undergo fractional crystallization so that during immiscibility the conjugate liquids are free to split into two fractions and form felsic and mafic units. In the Greig diagram (figure 15) the Samchampi–Samteran samples plot close to the two liquid field suggesting that the parental magma (possibly charged with CO_2 , H_2O and P_2O_5) suffered pronounced liquid immiscibility. It has been suggested by Minarik (1998) that carbonate melt has a higher melt–solid interfacial energy than does the coexisting silicate melt. This behaviour prevents the carbonate melt from migrating independently from the silicate melt. Thus, for the Samchampi–Samteran alkaline complex, the parent melt must have immiscibly split into a silicate liquid fraction and a H_2O – CO_2 rich fraction. The immiscible H_2O – CO_2 rich liquid produced the carbonatite member of the complex. Field observations record lack of chilled facies and marked presence of a sharp contact between the alkaline felsic syenite member and alkaline mafic ijolite–melteigite member of the complex. Such field evidences serve as key factors supporting the role of liquid immiscibility for many alkaline-carbonatite complexes (Subrahmanyam and Leelanandam 1989).

Figure 16. (a) Projection of clinopyroxene compositions of different lithotypes from Samchampi-Samteran complex in TiO_2 - MnO - Na_2O triangular diagram (Nisbet and Pearce 1977). VAB = Volcanic Arc Basalts, OFB = Ocean Floor Basalts, WPT = Within Plate Tholeiite and WPA = Within Plate Alkalic basalt. (b) Plot of discriminant functions, F_1 ($F_1 = -0.012 \times \text{SiO}_2 - 0.0807 \times \text{TiO}_2 + 0.0026 \times \text{Al}_2\text{O}_3 - 0.0012 \times \text{FeO}^* - 0.0026 \times \text{MnO} + 0.0087 \times \text{MgO} - 0.0128 \times \text{CaO} - 0.0419 \times \text{Na}_2\text{O} + 0.0160 \times \text{Na}_2\text{O}$) and F_2 ($F_2 = -0.0469 \times \text{SiO}_2 - 0.0818 \times \text{TiO}_2 - 0.0212 \times \text{Al}_2\text{O}_3 - 0.0041 \times \text{FeO}^* - 0.1435 \times \text{MnO} - 0.0029 \times \text{MgO} + 0.0085 \times \text{CaO} + 0.0160 \times \text{Na}_2\text{O}$), for pyroxene analyses from Samchampi-Samteran complex (Nisbet and Pearce 1977). VAB = Volcanic Arc Basalts, OFB = Ocean Floor Basalts, WPT = Within Plate Tholeiite and WPA = Within Plate Alkalic basalt. (c) Plot of clinopyroxene compositions from Samchampi-Samteran complex in SiO_2 (wt%) vs. Al_2O_3 (wt%) diagram (Nisbet and Pearce 1977). OFB = Ocean-Floor Basalts and WPA = Within Plate Alkalic basalt. (d) Projection of clinopyroxene compositions of different lithotypes from Samchampi-Samteran complex in terms of En-Ac-Fs components. Clinopyroxene compositions from alkaline and tholeiitic rocks of Deccan volcanic province are also shown in the diagram (Rock et al 1994; Kumar 1996).

7.4 Evaluation of tectonic setting

In the present study, mineral chemical parameter obtained from electron probe micro-analyses have been considered as effective tool for fingerprinting the magma type and delineating the tectonic environment of the investigated Samchampi-Samteran ultramafic-mafic-alkaline-carbonatite complex. For evaluation of tectonic setting of parental magma-types, compositions of clinopyroxene were used. When the relevant compositions are projected into TiO_2 - Na_2O - MnO triangular diagram (Nisbet and Pearce 1977) (figure 16a),

the data-plots are distinctly concentrated in the field of Within Plate Alkalic Basalts (WPA), suggesting an intraplate, anorogenic setting and a Na_2O enriched alkaline character for the parent magma. The plot of clinopyroxene compositions in discriminant function diagram (F_1 vs. F_2) (Nisbet and Pearce 1977) (figure 16b) shows that the investigated clinopyroxene has a within plate alkaline affinity. Similar within plate alkaline affinity has also been envisaged in terms of SiO_2 vs. Al_2O_3 diagram (figure 16c) of clinopyroxene. Projection of clinopyroxene compositions in En-Ac-Fs diagram maintains close affinity for those

of alkaline rocks from Deccan Volcanic Province (figure 9d) (Rock *et al* 1994; Kumar 1996). Thus, tectonic discrimination diagrams involving clinopyroxene chemistry consistently point out a within plate alkaline affinity for the parental magma.

7.5 Regional implications

During the Late Jurassic–Early Cretaceous, NE India was marked by domal uparching of the Shillong Plateau accompanied by the development of E–W trending Brahmaputra and Dauki fault systems (Gupta and Sen 1988). The Dauki fault system broke the Shillong Plateau along its southern margin and acted as a fissure for the eruption of Sylhet Traps. A concurrent feature associated with the uparching of the crust probably led to the development of N–S and NE–SW trending lineaments and fracture zones (Gupta and Sen 1988). During the Upper Cretaceous, intrusive magmatic activities followed along these lineaments resulting in the emplacements of isolated bodies of ultramafic–mafic–alkaline–carbonatite complex. These complexes cover parts of the Shillong Plateau and Mikir Hills under a tensional regime, suggesting a deep-seated fault control and NE–SW uparching of the crust (Nandy 2001). Thus, both the phenomena of eruption of Sylhet Traps and the emplacement of differentiated alkaline complex may be related to crustal uparching and lithospheric thinning followed by fracturing and rifting. This can be attributed to the impact of an incubating mantle plume on the lithosphere. As a consequence to this effect, the crustal extension provided the passage for widespread extrusive igneous activity manifested in terms of Rajmahal–Sylhet volcanics in eastern and northeastern India, bearing the earliest signature of hotspot magmatism in the Indian Ocean (Datta and Mitra 1984).

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