

Early Cretaceous Sung Valley ultramafic-alkaline-carbonatite complex, Shillong Plateau, Northeastern India: petrological and genetic significance

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Summary

The Shillong Plateau of northeastern India hosts four Early Cretaceous (105–107 Ma) ultramafic-alkaline-carbonatite complexes (UACC), which have been associated with the Kerguelen plume igneous activity. Petrological and geochemical characteristics of one of these UACC, the Sung Valley, are presented. The Sung Valley UACC was emplaced in to the Proterozoic Shillong Group of rocks and consists of ultramafics (serpentinized peridotite, pyroxenite, and melilitolite), alkaline rocks (ijolite and nepheline syenite), and carbonatites. Serpentinized peridotite, pyroxenite, and ijolitic rocks form the major part of the complex, the others constitute less than 5% of the total volume. Ijolite and melilitolite intrude peridotite and pyroxenite, while nepheline syenite and carbonatite intrude the ultramafic rocks as well as ijolite. Mineralogically, the carbonatites are classified as calcite carbonatite with minor apatite, phlogopite, pyrochlore and ilmenite. The serpentinized peridotites are wehrlitic. Chemical compositions of the silicate rocks do not show a distinct co-genetic relationship amongst them, nor do they show any geochemical relationships with the carbonatites. No noticeable fractionation trend is observed on the chemical variation diagrams of these rocks. It is difficult to establish the genetic evolution of the Sung Valley UACC through fractional crystallization of nephelinitic magma or through immiscible liquids. On the basis of petrological and geochemical data and previously published isotopic results from these rocks, it is suggested that they have been derived from a primary carbonate magma generated by the low-degree melting of a metasomatized mantle peridotite.

Introduction

Ultramafic-alkaline-carbonatite complexes (UACC), though volumetrically insignificant, have attracted a great deal of attention from igneous petrologists because of the extremes in chemical composition which they display. They are characterised by high abundances of alkali metals and alkaline earth elements, unusual enrichments of light rare-earth elements (LREE), and high volatile contents. Another remarkable point is that low-viscosity carbonatite and alkaline melts can sample large volumes of mantle. This implies that such enriched melts characterise mantle composition and processes through the continental crust with limited crustal contamination (*Nelson et al.*, 1988; *Bell and Blenkinsop*, 1989). Several researchers have described petrological (*Le Bas*, 1987; *Wyllie et al.*, 1990), geochemical (*Nelson et al.*, 1988; *Simonetti and Bell*, 1994; *Harmer*, 1999; *Hoernle et al.*, 2002; *Ionov and Harmer*, 2002), stable isotopic (*Deines*, 1989; *Srivastava and Taylor*, 1996) and radiogenic isotopic (*Bell and Blenkinsop*, 1989; *Simonetti and Bell*, 1994; *Bell*, 1998) characteristics of carbonatites and associated silicate rocks, which clearly indicate their genesis from mantle derived melts. Carbonatite and associated alkaline magmatism has also been correlated with mantle plume activity (*Clague*, 1987; *Gerlach et al.*, 1988; *Veena et al.*, 1998; *Ray et al.*, 1999). The spatial and temporal association of many carbonatites and alkaline rocks with continental flood basalts (CFBs) is further evidence for plume-related activity (*Bell*, 2002).

In a special issue of the *Journal of Petrology*, devoted to carbonatites, *Bell et al.* (1998) formulated five key questions that they think outline the current outstanding problems in research on carbonatite and associated rocks. The present study addresses some of these questions, particularly with respect to the petrogenetic relationship among the silicate rocks (melilitite, nephelinite, ijolite, syenite, and phonolite) and spatially associated carbonatites. The ultramafic-alkaline-carbonatite complex exposed at Sung Valley and emplaced in the Shillong Plateau, has been selected for the present work because, although several workers have studied this complex, there is still no consensus on its origin. *Viladkar et al.* (1994) have suggested that the Sung Valley UACC is derived from carbonated nephelinite magma. *Veena et al.* (1998) and *Ray et al.* (2000) have suggested that these were derived from a parental magma generated by partial melting of sub-continental lithosphere, which was previously metasomatized by fluids derived from a mantle plume, but *Sen* (1999) has suggested that the Sung Valley UACC originated from melilitic magma. Most of these workers agreed, however, that at late-stage liquid immiscibility had played an important role. The present work is an attempt to review these observations on the basis of new geochemical data on the Sung Valley UACC and discuss possible petrogenetic relationship between carbonatites and associated silicate rocks.

Geological setting

Relationships between the ultramafic-alkaline-carbonatite complexes (UACC) and major tectonics, rifts or lineament structures are well established (*Woolley*, 1989; *Srivastava and Hall*, 1995). The Sung Valley UACC, emplaced within the Shillong Plateau, also appears to be linked to some of the major structural features of Northeastern India. The Shillong Plateau, roughly rectangular in shape, covering

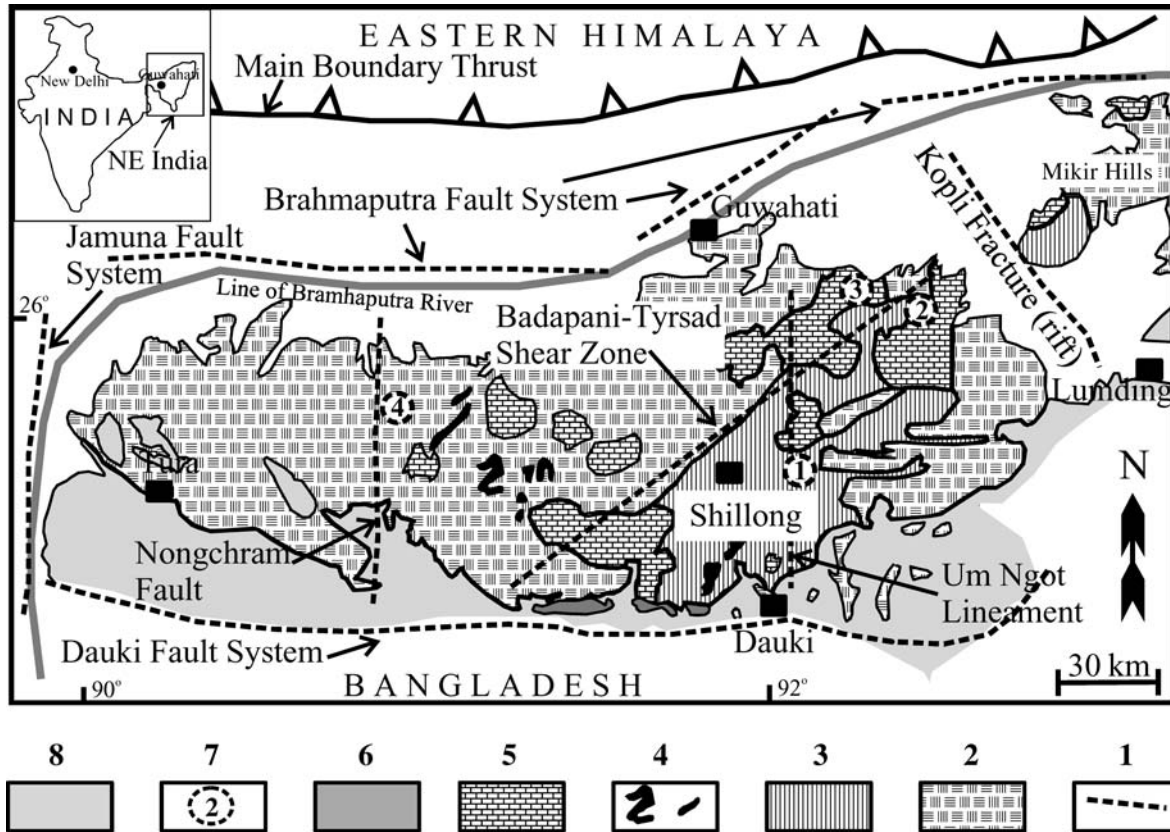


Fig. 1. Regional geological and tectonic framework of the Shillong Plateau (compiled from Evans, 1964; Desikachar, 1974; Mazumdar, 1976; Nandy, 1980; Acharyya et al., 1986; Gupta and Sen, 1988; Golani, 1991; Das Gupta and Biswas, 2000). 1. Major fault-systems, 2. Archaean gneissic complex, 3. Shillong Group rocks, 4. Mafic igneous rocks, 5. Porphyritic granites, 6. Sylhet traps, 7. Ultramafic-alkaline-carbonatite complexes [Circled numbers indicate different locations: (1) Sung Valley, (2) Jasra, (3) Samchampi, (4) Swangkre], 8. Cretaceous-Tertiary sediments. Blank portion represents alluvium and recent sediments

an area of about $4 \times 10^4 \text{ km}^2$, is considered to be an uplifted horst-like feature, bounded (see Fig. 1) by the E–W trending Dauki and Brahmaputra fault systems in the south and the north, respectively. The west and the east sides are bordered by the N–S Jamuna fault system and the NW–SE trending Kopali fracture zone (Evans, 1964; Desikachar, 1974; Nandy, 1980; Acharyya et al., 1986; Gupta and Sen, 1988). Other N–S trending structures that also traverse the Shillong Plateau are the Nongchram fault (Nambiar and Golani, 1985; Nambiar, 1988; Gupta and Sen, 1988; Golani, 1991) and Um Ngot lineaments (Gupta and Sen, 1988). Another important structure observed in the Shillong Plateau is the NE–SW trending Badapani-Tyrsad shear zone (Kumar et al., 1996). The N–S trending lineaments, which developed during the Late Jurassic-Early Cretaceous and the associated alkaline and carbonatite magmatism such as the Sung Valley UACC are genetically related to the Ninety-East Ridge in the Indian Ocean (Gupta and Sen, 1988).

The geology of the Shillong Plateau has been presented by several workers (Fig. 1; Desikachar, 1974; Mazumdar, 1976; Das Gupta and Biswas, 2000); major

constituents are Archaean gneisses and the Proterozoic orthoquartzites and phyllites of the Shillong Group. Several granite plutons intrude the gneissic basement, as well as the Shillong Group cover, with ages mainly around 700–450 Ma (Mazumdar, 1976; Ghose et al., 1994). Small bodies of metamorphosed mafic igneous rocks are also found in the Shillong Plateau. The Sylhet Traps, a part of the Rajmahal-Sylhet flood basalt province, are well exposed in the southern part. They and the ultramafic-alkaline-carbonatite complexes of the Plateau have an inferred association with the Kerguelen Plume (Storey et al., 1992; Kent et al., 1997, 2002; Veena et al., 1998; Ray et al., 1999, 2000). The Cretaceous-Tertiary sedimentary rocks occupy the southern fringe of the Plateau.

The Sung Valley UACC was first reported by Yusuf and Saraswat (1977) and several workers such as Chattopadhyaya and Hashmi (1984), Krishnamurthy (1985), Viladkar et al. (1994), Veena et al. (1998), Ray et al. (1999, 2000), and Sen (1999) have presented the geology and discussed the origin of the carbonatites and associated silicate rocks. The available age data on the Sung Valley complex, obtained by various methods on different materials (Table 1) range between 90 Ma

Table 1. Age data on the northeastern Indian ultramafic-alkaline-carbonatite complexes (UACC) and the Rajmahal-Sylhet flood basalts

Method	Material	Age (in Ma)	References
Sung Valley UACC			
Fission track	Apatite	90 ± 10	Chattopadhyay and Hashmi (1984)
K–Ar	Phlogopite from carbonatite	149 ± 5	Sarkar et al. (1996)
Pb–Pb	Carbonatite (WR)	134 ± 20	Veena et al. (1999)
Ar–Ar	Pyroxenite (WR) and phlogopite from carbonatite	107.2 ± 0.8	Ray et al. (1999)
Rb–Sr	Carbonatite (WR), pyroxenite (WR), and phlogopite from carbonatite	106 ± 11	Ray et al. (2000)
Swangkre UACC			
K–Ar	Lamprophyre	107 ± 3	Sarkar et al. (1996)
Samchampi UACC			
Fission track	Apatite	~105	Acharyya et al. (1986)
Jasra UACC			
U–Pb	Zircon and baddeleyite from differentiated gabbro	105.2 ± 0.5	Heaman et al. (2002)
Rajmahal-Sylhet Flood Basalts Province			
Ar–Ar	Basalts	105–117	Baksi et al. (1987); Baksi (1995); Kent et al. (1997, 2002)

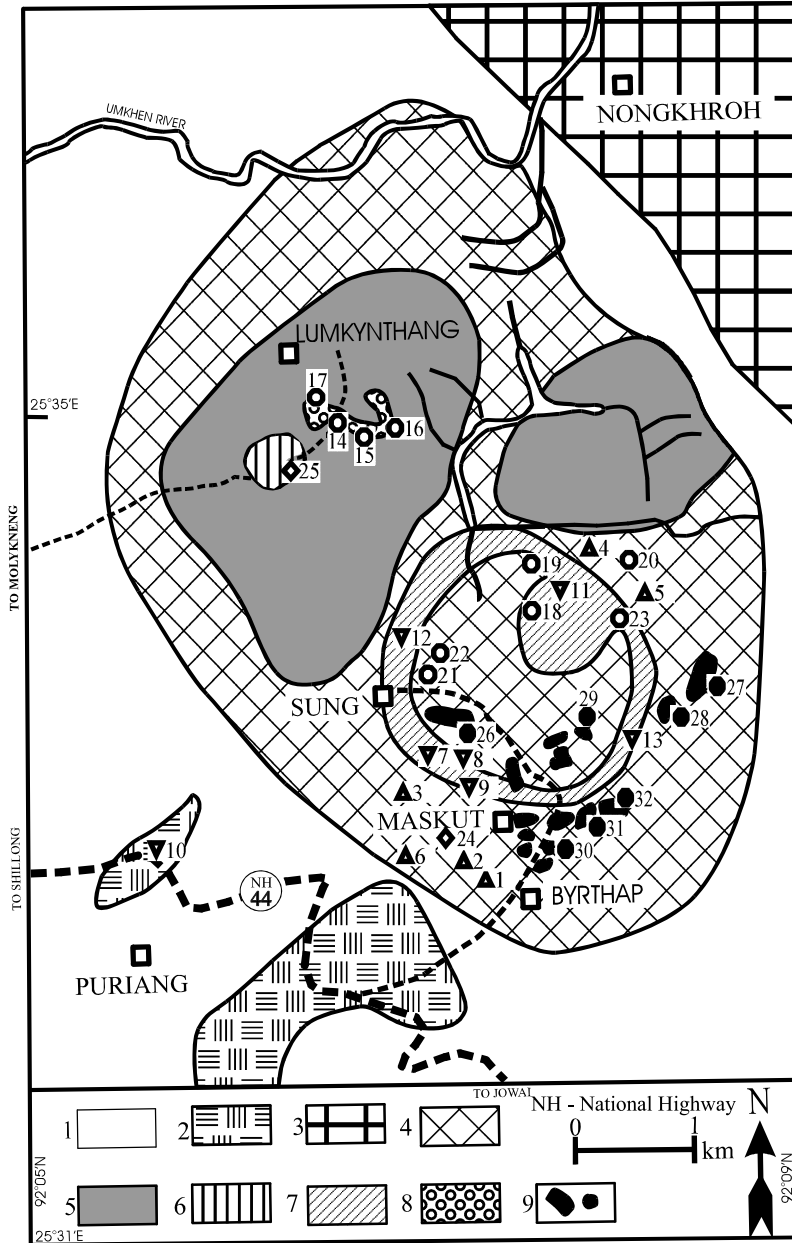


Fig. 2. Geological map of the Sung Valley ultramafic-alkaline-carbonatite complex (modified from Krishnamurthy, 1985; Viladkar et al., 1994; Sen, 1999). 1. Shillong Group rocks, 2. Amphibolite intrusives, 3. Porphyritic granite, 4. Pyroxenite, 5. Serpentinized peridotite, 6. Melilitolite, 7. Ijolite, 8. Nepheline syenite, and 9. Carbonatite. Locations of geochemically analysed samples are marked on the map. Symbols: open up-triangles (pyroxenites); open down-triangles (ijolites); open diamonds (melilitolites); open circles (nepheline syenites); filled circles (carbonatites). Nepheline syenite and melilitolites dykes exposed around the villages Sung and Maskut are very small and therefore not shown on the map

and 150 Ma. Considering these ages along with the ages of other Shillong Plateau UACC and Rajmahal-Sylhet flood basalts (Table 1) and their relation to the Kerguelen plume, the estimated emplacement age for the Sung Valley UACC is around 107 Ma.

The Sung Valley UACC consists of ultramafic rocks (pyroxenite, serpentinized peridotite, and melilitolite), alkaline rocks (ijolite and nepheline syenite) and carbonatite (Fig. 2). Pyroxenite, serpentinized peridotite and ijolites form the major part of the complex, whereas others constitute less than 5% of the exposed outcrop. Serpentinized peridotite occupies the central part of the complex; it is surrounded by pyroxenite. Serpentinized peridotite and pyroxenite are considered to be the oldest rocks of the complex; Ijolite, probably younger, forms a ring structure. Small dykes of melilitolite intrude the peridotite and pyroxenite. Nepheline syenite and carbonatite occur in dykes, veins, stocks, and ovoid bodies and probably intrude ultramafics as well as ijolites. Due to lacking contact relationships between minor intrusive phases in the field, it is difficult to establish age relationships, but *Krishnamurthy* (1985) has reported nepheline syenite/syenite dykes and veins that cut the pyroxenitic as well as the ijolitic rocks. Intrusive relationships suggest that carbonatite is the youngest member of the complex.

Petrography

Peridotite has been severely affected by extensive alteration due to post-magmatic hydrothermal activity. Only relicts of olivine and clinopyroxene may be seen in places. The pyroxenite samples are relatively fresh and are composed of clinopyroxene (cpx), dominated by diopside and show hypidiomorphic textures. In some thin sections a porphyritic texture is observed. Augite/aegirine-augite is present in all the pyroxenite samples. Most of the cpx are green to pale green in colour and have two perfect sets of cleavages at 87° and 93° (Fig. 3a). The aegirine-augite may be distinguished from the other cpx by lower extinction angles. Modal composition of cpx varies between 74% and 83%. Minor amounts of plagioclase (not more than 10%) are also present in these rocks. Other minor constituents are clino-enstatite, olivine, biotite, apatite, sphene, epidote-clinozoisite and opaques (ilmenite and rutile).

Ijolites consist of nepheline, aegirine-augite, and aegirine and vary widely in modal compositions (Figs. 3b, c). They are medium- to coarse-grained and show hypidiomorphic (Fig. 3b), poikilitic (Fig. 3c), and porphyritic textures. Fine- to medium-grained aegirine-augites are enclosed in nepheline (Fig. 3c). Diopside, apatite, sphene, epidote-clinozoisite, zircon, melanite, calcite and opaques are minor constituents. Nepheline syenites carry coarse-grained orthoclase, albite, perthite, nepheline, and aegirine. They vary between euhedral and anhedral representing panidiomorphic to allotriomorphic textures but hypidiomorphic textures are also common (Fig. 3d). Porphyritic (Fig. 3e), poikilitic (Fig. 3d), and sub-ophitic textures are also seen in few sections. Other minor constituents are sphene, zircon, calcite, and opaques. Melilitolites are mainly composed of melilite and diopside with minor amount of melanite and opaques. Carbonatites have calcite as the major constituent; they are mainly sövitic (coarse-grained, hypidiomorphic texture). Dolomite and siderite are minor. Other common accessories are apatite, phlogopite, (Fig. 3f), pyrochlore, zircon, and opaques.

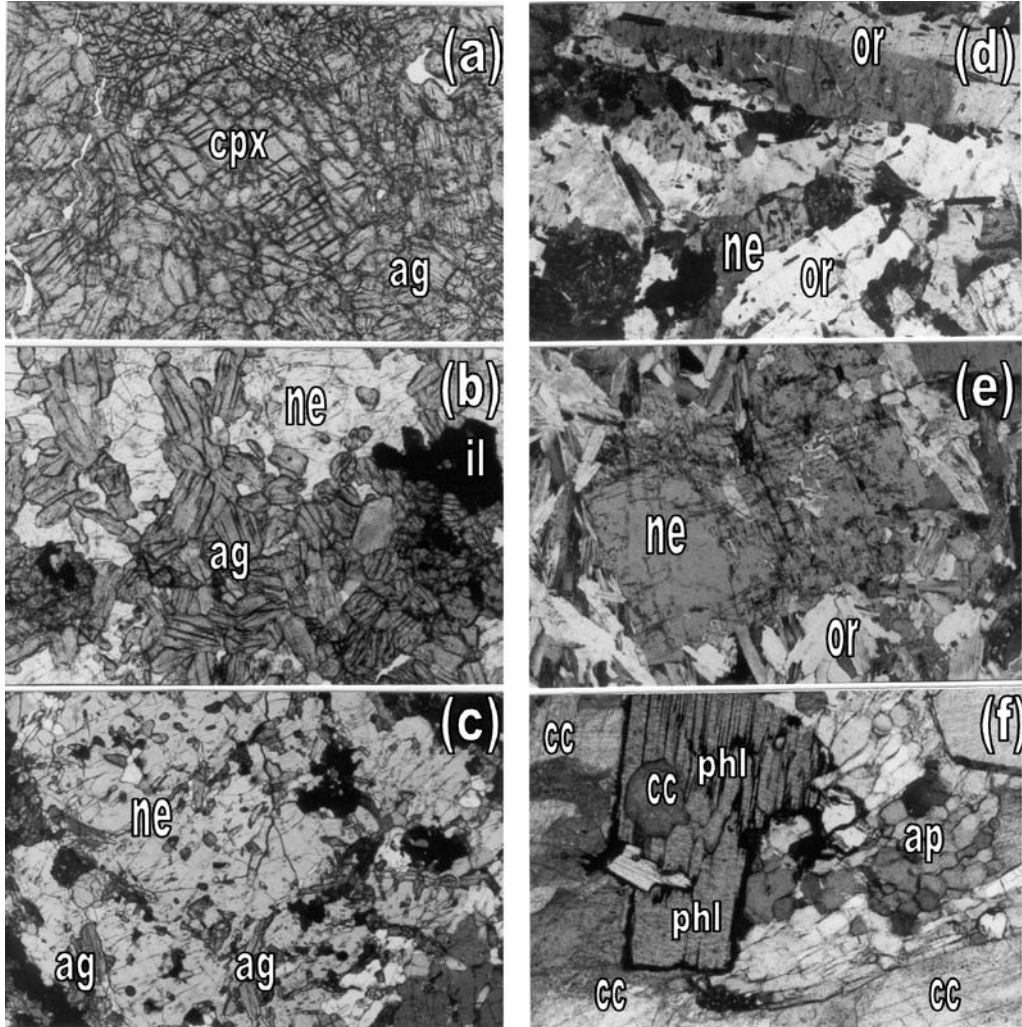


Fig. 3. Photomicrographs of Sung Valley UACC rocks. **a** Pyroxenite, **b** and **c** Ijolites, **d** and **e** Nepheline syenites, and **f** Carbonatites. For detail description, see text. Symbols: *cpx* clinopyroxene, *ag* aegirine, *ne* nepheline, *il* ilmenite, *or* orthoclase, *cc* calcite, *phl* phlogopite, and *ap* apatite. Scale: width of each photograph is 3.1 mm

IUGS recommendations (*Le Maitre*, 1989, 2002) have been followed for the classification of the samples studied. There are calcite carbonatite, apatite calcite carbonatite, and phlogopite calcite carbonatite. All the silicate rocks are also classified on the basis of their modal compositions. Ultramafic samples are classified as peridotite (mainly wehrlites) and clinopyroxenite, whereas melilitic rocks are mainly melilitolites to pyroxene melilitolites. According to *Dunworth* and *Bell* (1998) these melilitolites are classified as uncomphagrite as they contain <65% melilite (~45%) and >10% pyroxene (diopside ~45%). No IUGS mineralogical classification scheme is available for ijolite, although a rock that consists of pyroxene with 30% to 70% nepheline generally is classified as ijolite. Other alkaline rocks are classified as nepheline syenites. Some samples also have syenitic and monzonitic modal compositions.

Table 2. Comparison of the certified data (C) with the data obtained by the Activation Laboratories Ltd. (A) of used geostandards

		ICPMS analyses																					
		SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Ba	Sr	Zr	V	Cr	Nb	Rb	Ce	Nd	Sm	Eu	Lu	Th
MIRG1	C	39.09	3.77	8.46	17.93	13.55	14.71	0.74	0.18	0.08	61	266	108	526	97	12	149	88	38.0	7.5	1.55	0.40	11.9
	A	39.07	3.77	8.45	17.81	13.51	14.60	0.72	0.16	0.07	54	268	94	526	96	12	139	87	37.9	7.1	1.53	0.37	11.6
W2	C	52.44	1.06	15.35	10.74	6.37	10.87	2.14	0.63	0.13	182	194	94	262	93	7.9	20	24.0	14.0	3.25	1.10	0.33	0.53
	A	52.79	1.06	15.39	10.80	6.35	10.86	2.21	0.68	0.13	177	194	89	263	93	7.0	21	22.6	12.5	3.10	1.15	0.30	0.50
DNC1	C	47.04	0.48	18.30	9.93	10.05	11.27	1.87	0.23	0.85	114	145	42	148	285	3	4.5	10.6	4.9	1.38	0.59	0.32	0.2
	A	46.93	0.48	18.47	9.91	10.12	11.23	1.97	0.22	0.70	108	142	42	139	276	2	4.0	8.3	4.8	1.40	0.61	0.30	0.3
STM1	C	59.64	0.14	18.39	5.22	0.10	1.09	8.94	4.28	0.16	560	700	1210			268	118	259	79.0	12.6	3.60	0.60	31
	A	59.78	0.14	18.25	5.08	0.08	1.13	8.92	4.26	0.16	587	696	1210			246	114	247	78.4	11.7	3.59	0.62	30
SY3	C	59.62	0.15	11.75	6.49	2.67	8.26	4.12	4.23	0.54	450	302	320	50		148	206	2230	670	109	17.0	7.90	1003
	A	59.94	0.15	11.69	6.47	2.63	8.27	4.12	4.24	0.54	439	302	340	50		188	215	2200	722	122	19.4	8.65	1000

Table 3. Whole rock major (wt%), trace and rare-earth (ppm) elements analyses of samples from the Sung Valley ultramafic-alkaline-carbonatite complex, Meghalaya, Northeastern India

S. no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO ₂	53.81	53.88	52.02	51.63	51.58	48.30	44.78	41.69	38.75	42.05	42.94	44.33	39.85	56.99	54.90	58.16
TiO ₂	0.48	0.48	0.65	0.62	0.56	0.73	0.96	2.24	2.01	1.42	0.29	5.73	2.79	0.21	0.36	0.19
Al ₂ O ₃	2.79	2.01	2.24	3.07	3.19	6.29	15.23	15.58	8.66	7.72	19.91	7.98	13.55	20.64	20.45	20.44
Fe ₂ O ₃	7.75	8.17	10.44	11.81	8.62	8.27	9.48	10.99	12.64	11.98	6.05	8.54	13.38	3.79	5.28	1.93
MnO	0.13	0.14	0.18	0.19	0.12	0.11	0.19	0.19	0.27	0.18	0.15	0.21	0.32	0.07	0.09	0.05
MgO	11.91	12.15	11.12	9.54	12.20	10.76	5.90	3.80	5.95	9.93	4.15	7.34	2.29	0.32	0.41	0.31
CaO	19.67	20.25	20.10	17.96	19.65	19.25	13.10	13.21	2.50	18.33	11.06	19.45	14.74	1.08	1.50	0.89
Na ₂ O	1.94	1.84	2.27	3.32	2.33	3.37	7.67	4.87	4.40	1.73	7.31	3.60	6.01	11.54	11.56	9.18
K ₂ O	1.00	0.65	0.19	0.71	0.59	0.23	2.24	0.91	1.09	1.61	2.06	1.18	1.53	3.54	4.00	5.58
P ₂ O ₅	0.08	0.16	0.08	0.09	0.04	0.12	0.54	1.07	4.43	0.37	1.15	0.10	0.58	0.05	0.12	0.02
LOI	0.52	0.61	0.75	0.83	1.33	3.23	0.40	5.87	0.81	4.01	4.40	0.91	3.91	1.66	1.36	3.36
Total	100.07	100.35	100.05	99.77	100.21	100.65	100.49	100.42	99.50	99.34	99.46	99.36	98.95	99.90	100.04	100.12
Mg#	75.27	74.65	67.84	61.53	73.70	72.04	55.21	40.64	48.25	62.14	57.60	62.99	25.31	14.33	13.33	24.13
Cr	110	123				204		387		165		30				
Ni	150	120			130	104		109	70	99	25	64				
Sc	50	39	36	24	39	31	21	2	1	38	2	7	2			
V	96	114	183	182	98	81	225	395	414	237	161	436	620	33	57	16
Rb	35		4		23	15			18	52	43	19			76	
Ba	138	143	70	224	91	50	10	55	11	266	568	35	12	244	505	366
Sr	191	250	257	280	308	395	362	1205	498	559	1229	298	537	424	385	419
Ga	5		5		5	6		10	18	12	20	17			24	
Ta	0.40		1.30		0.30	2.30			6.60	1.40	0.70	28.00			1.30	
Nb	7		9		7	8		1	65	25	18	943			17.0	
Hf	1.80		2.60		2.00	2.50		1.10	2.30	2.80	1.20	31.80			5.80	
Zr	53	54	91	108	67	76	117	453	638	105	213	1291	495	143	181	365

(continued)

Table 3 (continued)

S. no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Y	8	9	7	7	6	9	21	45	76	16	16	123	133	5	16	9
Th	2.10	1.60	1.60	3.40	3.60	3.40	3.60	4.30	4.30	2.90	5.70	18.80	6.50		6.50	
U	0.70	0.30	0.30	1.00	0.60	1.00	0.60	1.20	0.50	0.50	0.50	6.70	0.80		0.80	
La	8.20	5.60	5.60	7.00	9.00	7.00	9.00	5.40	89.50	23.50	43.30	126.00	25.40		25.40	
Ce	17.60	12.70	12.70	13.60	18.10	13.60	18.10	11.70	188.00	44.00	83.90	321.00	42.40		42.40	
Pr	2.14	2.00	2.00	1.60	2.18	1.60	2.18	1.55	26.40	5.33	9.92	43.80	4.51		4.51	
Nd	8.10	8.20	8.20	6.10	8.60	6.10	8.60	6.40	106.00	20.90	36.40	175.00	15.10		15.10	
Sm	1.80	1.90	1.90	1.30	1.80	1.30	1.80	1.20	22.40	4.00	5.80	33.70	2.80		2.80	
Eu	0.43	0.53	0.53	0.35	0.50	0.35	0.50	0.40	7.50	1.31	1.71	10.90	0.88		0.88	
Gd	1.70	1.90	1.90	1.30	1.80	1.30	1.80	0.10	22.40	3.60	4.50	30.80	2.70		2.70	
Tb	0.30	0.30	0.30	0.20	0.30	0.20	0.30	0.10	3.50	0.60	0.60	4.90	0.50		0.50	
Dy	1.70	1.80	1.80	1.40	1.70	1.40	1.70	0.60	18.10	3.10	3.00	26.34	3.10		3.10	
Ho	0.30	0.30	0.30	0.30	0.40	0.30	0.40	0.10	3.20	0.60	0.50	4.90	0.60		0.60	
Er	1.00	1.00	1.00	0.90	1.00	0.90	1.00	0.30	8.10	1.50	1.40	13.10	2.00		2.00	
Tm	0.19	0.19	0.19	0.16	0.16	0.16	0.16	0.20	6.40	1.20	1.40	10.50	0.35		0.35	
Yb	1.40	1.40	1.40	1.10	1.10	1.10	1.10	0.59	0.95	0.17	0.24	1.40	2.50		2.50	
Lu	0.24	0.27	0.27	0.19	0.17	0.19	0.17						0.43		0.43	
S. no.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
SiO ₂	52.00	51.26	63.61	54.81	54.18	53.87	52.78	41.26	44.19	0.49	0.63	0.50	0.42	0.44	0.44	0.30
TiO ₂	0.64	0.81	0.09	0.33	0.79	0.79	0.63	1.89	0.84	0.05	0.07	0.61	0.05	0.07	0.03	0.03
Al ₂ O ₃	18.69	15.01	16.36	19.47	19.19	19.09	19.32	8.57	4.37	0.16	0.24	0.23	0.17	0.19	0.14	0.21
Fe ₂ O ₃	5.14	7.38	3.53	4.63	6.68	6.93	5.73	15.06	8.34	1.65	0.87	5.50	0.62	1.87	1.65	3.41
MnO	0.14	0.12	0.04	0.13	0.10	0.10	0.13	0.22	0.06	0.12	0.19	0.23	0.22	0.19	0.14	0.15
MgO	0.84	0.92	0.59	0.25	0.54	0.55	0.71	8.92	11.91	2.05	2.70	2.47	2.93	2.44	2.86	3.03
CaO	3.23	6.35	1.38	1.86	2.67	2.62	3.24	23.01	28.00	51.91	51.06	49.12	51.13	51.18	51.13	50.45
Na ₂ O	11.71	6.87	7.60	7.81	6.54	6.54	8.17	0.40	1.40		0.05	0.03				0.03
K ₂ O	3.95	6.46	5.08	7.47	7.10	7.18	6.61	0.03	0.11	0.11	0.18	0.15	0.18	0.05	0.05	0.05

P ₂ O ₅	0.45	0.53	0.21	0.05	0.01	0.01	0.03	0.54	0.01	1.95	4.00	1.91	0.69	0.08	1.25	5.31
LOI	3.39	3.52	0.32	1.83	1.35	1.35	1.62	0.59	0.53	40.90	38.51	37.84	42.45	41.22	40.93	35.55
Total	100.18	99.23	98.81	98.63	99.34	99.03	98.96	100.48	99.74	99.39	98.51	98.61	98.87	97.75	98.60	98.47
Mg#	24.45	19.80	24.87	9.66	13.45	13.58	19.70	53.98	73.88	71.10	86.01	47.07	90.35	72.10	77.44	63.76
Cr	22						110	387								
Ni							107	109				28	39			
Sc			4	1												
V	76	327	80	81	197	200	235	223	50	13	16	19	17	18	15	12
Rb	104		113	201	83	82	153			39	35	179	22	16	28	55
Ba	726	1164	183	1403	1467	1457	1680	38	13	124	280	230	256	239	158	97
Sr	526	619	91	308	680	672	569	365	665	3864	4691	4515	5048	4682	4188	3629
Ga	23		21	5	24	23	31	17	10		3	3	2			
Ta	2.10		0.20	0.30	4.00	4.10	3.30	2.70			1.00	20.30	1.20			
Nb	38.0		5.0	7.0	107.0	105.0	105.0	34.0	1.00		12.0	317.0	14.0			
Hf	5.40		0.80	2.00	4.20	4.30	9.20	3.00	1.10		0.30	0.50	0.20			
Zr	264	455	46	67	182	195	463	108	35	29	11	22	12	20	92	18
Y	19	10	5	6	5	7	9	20		54	58	55	58	58	58	37
Th	5.70		2.00	3.40	1.30	1.30	0.90	4.50			2.10	97.50	2.30			
U	0.70		0.30	1.00	0.20	0.30	0.20	0.70			0.30	0.50	1.00			
La	21.30		8.00	7.00	8.50	8.80	9.70	37.50	5.40		179.0	151.0	153.0			
Ce	38.30		14.60	13.60	26.10	29.20	29.00	68.30	11.70		393.0	331.0	328.0			
Pr	4.20		1.55	1.60	4.18	4.36	4.50	8.61	1.55		49.80	41.80	40.70			
Nd	15.40		5.30	6.10	16.10	16.80	16.30	31.90	6.40		196.0	163.0	157.0			
Sm	2.80		0.80	1.30	2.80	2.90	3.00	5.40	1.20		32.80	27.20	26.30			
Eu	0.91		0.20	0.35	0.79	0.81	0.86	1.99	0.40		10.20	8.50	8.38			
Gd	2.60		0.70	1.30	2.10	2.20	2.50	5.40	1.00		25.20	21.70	20.28			
Tb	0.50		0.10	0.20	0.30	0.30	0.40	0.80	0.10		3.30	2.90	2.80			
Dy	3.00		0.70	1.40	1.50	1.60	1.90	4.40	0.60		14.30	12.60	13.00			
Ho	0.60		0.10	0.30	0.30	0.30	0.30	0.80	0.10		2.20	2.00	2.10			
Er	2.00		0.40	0.90	0.70	0.70	1.00	2.10	0.30		5.40	4.80	5.30			
Tm	0.32		0.70	0.16	0.10	0.10	0.15	0.26			0.51	0.48	0.58			
Yb	2.10		0.50	1.10	0.90	0.90	1.40	1.60	0.20		3.40	3.10	3.60			
Lu	0.32		0.80	0.19	0.17	0.17	0.29	0.23			0.40	0.38	0.45			

Sample numbers 1–6 Pyroxenites; 7–13 Ijolites; 14–23 Nepheline syenites; 24–25 Melilitolites (uncompagrite); 26–32 Carbonatites

Analytical techniques

Approximately one hundred whole rock samples from different units of the Sung Valley UACC were studied petrographically; of these, 32 samples were selected for whole rock chemical analyses. As most of the peridotite samples are serpentinized they were not analysed. Out of these 32 samples 21 samples were analysed for complete trace and rare-earth element compositions. All analyses were performed at the Activation Laboratories Ltd., Ancaster, Ontario, Canada. ICP (Thermo-JarretAsh ENVIRO II) was used to analyse major elements, whereas ICPMS (Perkin Elmer Sciex ELAN 6000) was used to determine trace and rare-earth element concentrations. Several standards were run to check accuracy and precision (see Table 2 for details). Table 3 presents all of the analysed chemical data from the Sung Valley UACC. Locations of all the analysed samples are marked on the geological map (Fig. 2).

Geochemistry

Most of the rocks studied are already classified on the basis of their mineralogical compositions. To confirm mineralogical observations IUGS chemical classifications are also used. All analysed silicate samples (ultramafic and alkaline rocks) are plotted on the total-alkali silica (TAS) diagram (Fig. 4a; *Le Maitre, 1989*).

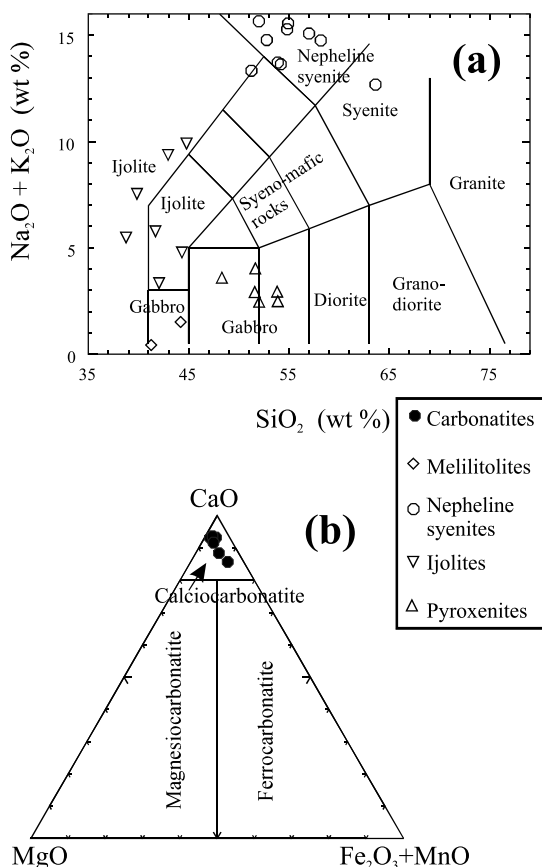


Fig. 4. **a** Total-alkali silica (TAS) diagram (after *Le Maitre, 1989*). **b** CaO–MgO–Fe₂O₃ + MnO triangular diagram for carbonatites (after *Woolley and Kempe, 1989*)

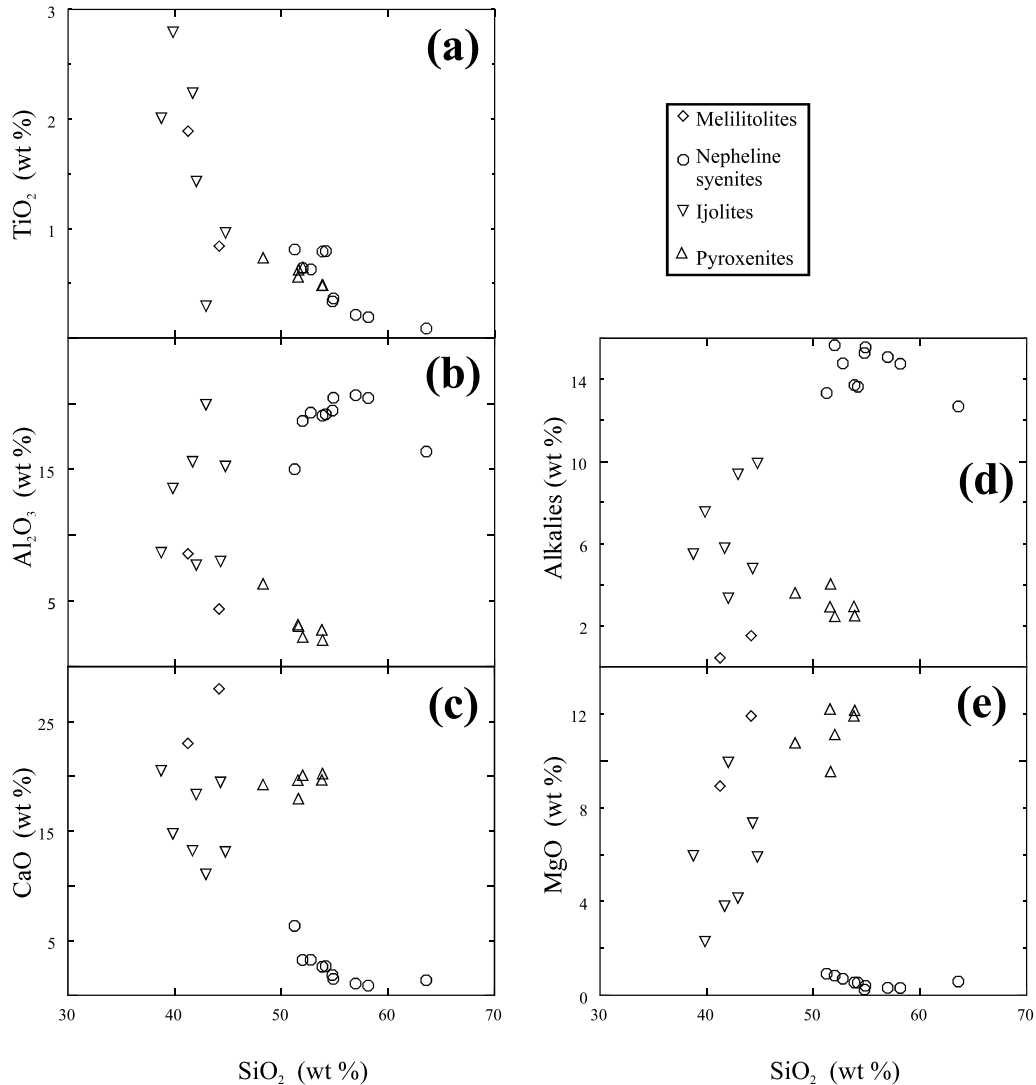


Fig. 5. Harker variation diagram for the silicate rocks

Chemical compositions clearly reflect the observed mineralogical compositions of these rocks. Carbonatite samples correspond to calciocarbonatite on the chemical classification diagram (Fig. 4b; *Woolley and Kempe, 1989*).

On Harker variation diagrams, TiO₂, Al₂O₃, alkalies, CaO and MgO are plotted against SiO₂ for silicate rocks (Fig. 5). There is no evidence from this data for a co-genetic relationship between these rock types. Only the SiO₂–TiO₂ plot shows an inverse relationship amongst silicate rocks; TiO₂ decreases with increasing SiO₂ from ijolite to nepheline syenite through pyroxenites. Melilitolite and ijolite samples show similar geochemical characteristics. Nepheline syenite samples clearly plot separately from other silicate rocks. Decrease in CaO, MgO, and alkalies, and increase in Al₂O₃ with increasing silica is observed in nepheline syenite samples. Other silicate rocks do not show discernible trends. In other Harker-type variation

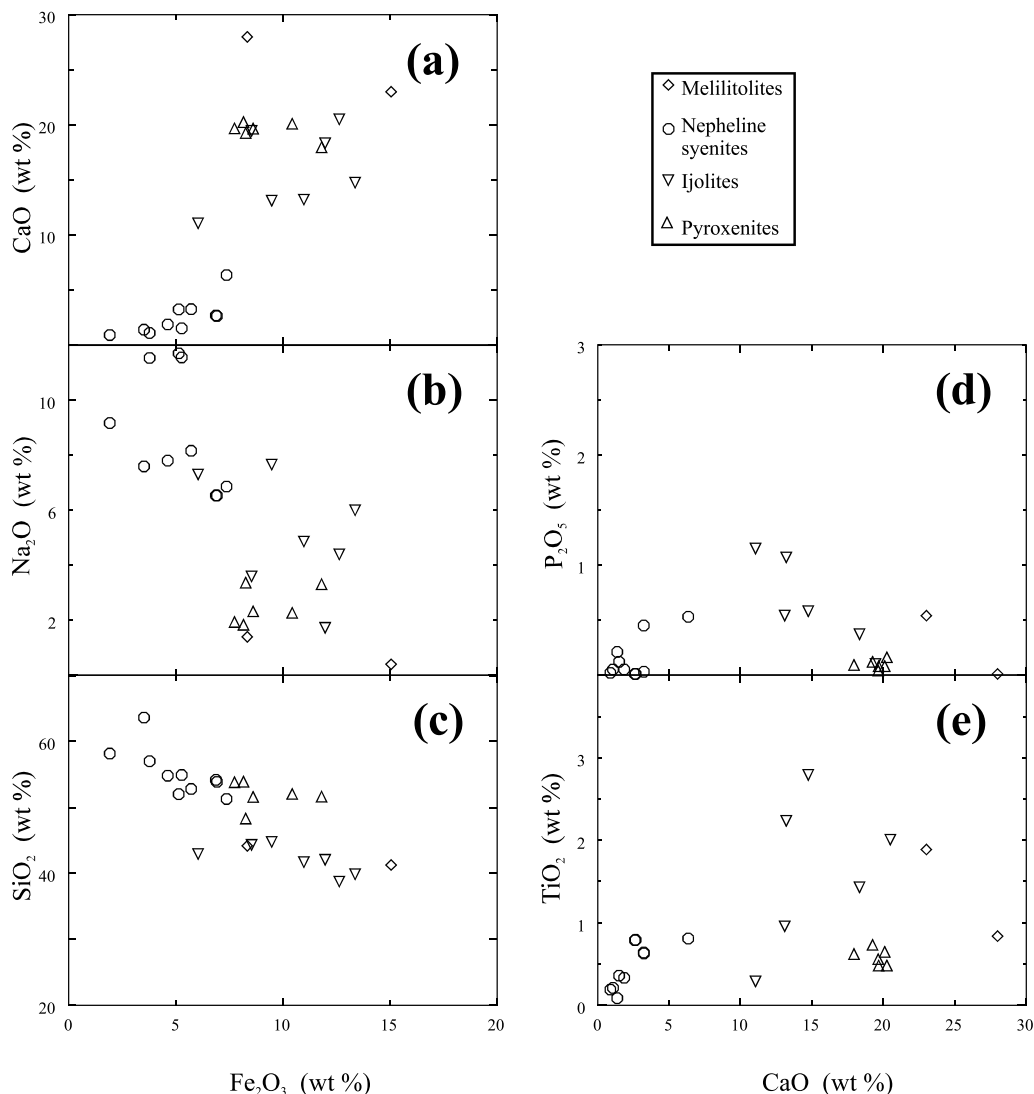


Fig. 6. Harker-type variation diagram for the silicate rocks

diagrams; Fe₂O₃ vs CaO, Na₂O and SiO₂ (Fig. 6a to 6c) and CaO vs P₂O₅ and TiO₂ (Fig. 6d and 6e), again these silicate rocks do not show any definite co-genetic relationship. With increase in Fe contents, these silicate rocks show a decrease in silica and Na values and increase in Ca contents. The nepheline syenite samples have the highest values of silica and Na and lowest values of Ca. The TiO₂ and P₂O₅ concentrations are low in nepheline syenite and pyroxenite, whereas ijolite samples show a wide variation in P₂O₅ (0.10 to 4.43) and TiO₂ (0.29 to 5.73). Nepheline syenite samples plot separately as a cluster distinct from pyroxenite and ijolite samples (Fig. 6d and 6e).

Figure 7 presents primordial mantle normalized multi-element spidergrams for the Sung Valley silicate rocks. All plotted elements show enriched values in comparison to primordial mantle. A wide compositional range is observed in the ijolite

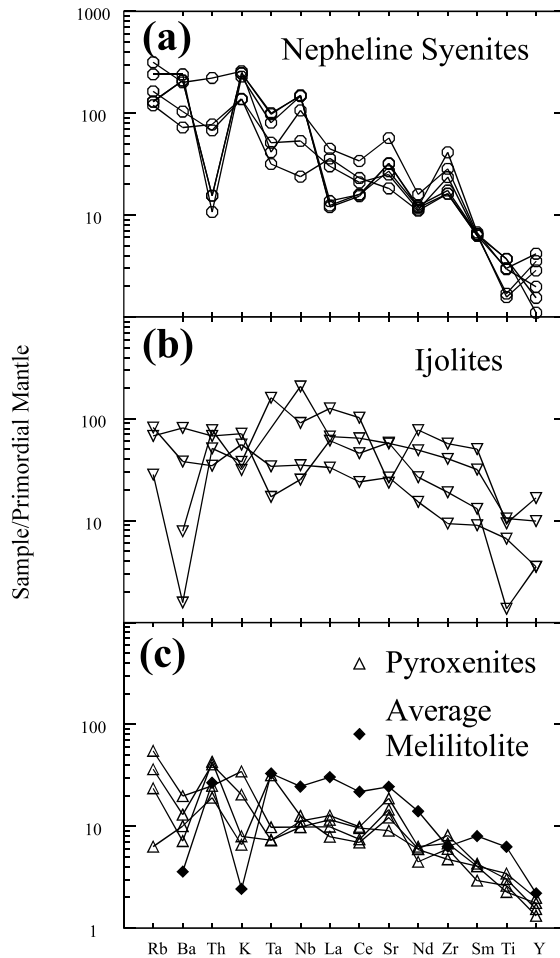


Fig. 7. Primordial mantle normalized multi-elements spidergrams. Normalized values are after *McDonough et al. (1992)*

samples (Fig. 7b) in comparison with pyroxenites (Fig. 7c) and nepheline syenites (Fig. 7a). There is little similarity in the multi-element patterns and hence it is difficult to establish any relationship between these different silicate rocks. The average chemical composition of melilitolite is also plotted with the pyroxenite samples (Fig. 7c); again this pattern does not match those of other silicate rocks. These observations are further corroborated by the rare-earth element patterns (Fig. 8). Comparatively, chondrite normalized values of LREE are highest in the ijolites (sample/chondrite >100; Fig. 8b) and lowest in the pyroxenites (sample/chondrite <40; Fig. 8c). The average REE pattern of melilitolite (Fig. 8c) is almost identical to ijolite samples. Nepheline syenite samples show different REE patterns (Fig. 8a), few samples show more depletion in La and Ce than the other samples. Overall, nepheline syenite samples show 'U' shaped REE patterns, middle REEs show lower concentration than LREE and HREE. On the other hand, ijolite samples show wide range of REE concentration and have inclined patterns. Variation of REE in pyroxenite samples is limited and shows 'U' shaped patterns but have lower LREE concentration than the nepheline syenite samples. *Dunworth and Bell (2001)* discussed a genetic relationship between pyroxenite and melilitolite on the basis of Zr-Hf-HREE concentration and suggested that enrichment of these

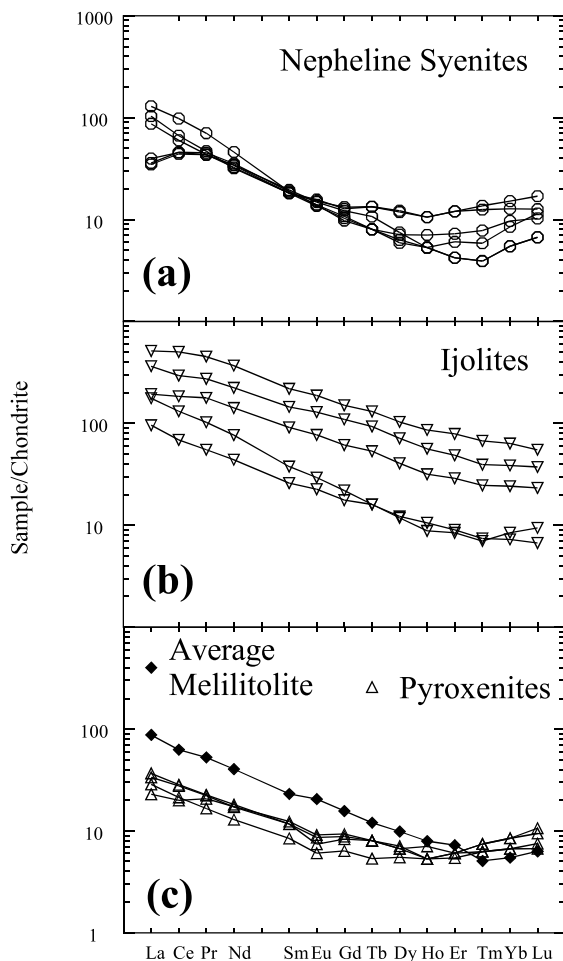


Fig. 8. Chondrite normalized rare-earth patterns. Chondrite values are after *Evenson et al. (1978)*

elements in pyroxenite rocks of the Tury massif complex is due to pyroxene accumulation, whereas the depletion of these elements in the melilitolite samples is because of the presence of melilite and perovskite. A similar interpretation could be made for the Sung Valley samples (Figs. 7c and 8c). It is difficult to establish a genetic relationship between the silicate rocks because pyroxenes crystallizing from an alkaline silicate melt at crustal pressures are likely to show well-matched Zr-HREE (*Dunworth et al., 2001*) patterns but present silicate rocks show wide variations.

Multi-element and rare-earth element patterns of associated carbonatites are presented (Fig. 9). Two different multi-element patterns, normalized to average calciocarbonatites (Fig. 9a) and primordial mantle (Fig. 9b) are plotted. In Fig. 9a, the concentration of all elements, except Sc, of the Sung Valley carbonatites show lower values than the average calciocarbonatites, established by *Woolley and Kempe (1989)*, although most of these elements fall within the compositional range of magmatic carbonatites. Sample 28 shows higher concentration of Th and Ti than the average calciocarbonatites, probably because it contains appreciable amount of pyrochlore and titanite. On the other hand, in Fig. 9b, all elements, except Zr and

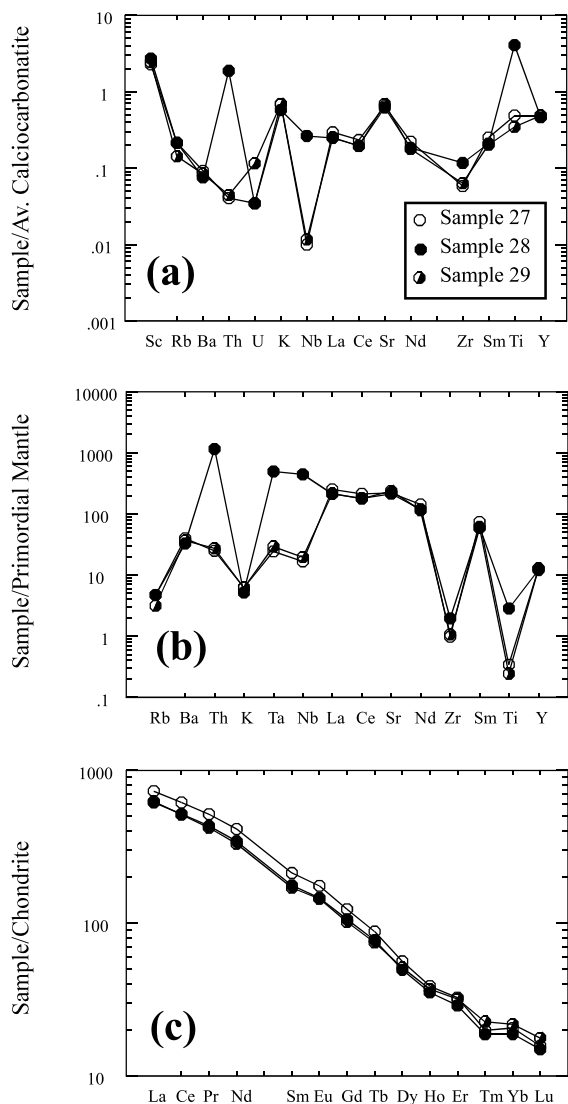


Fig. 9. Geochemical variations in carbonatite rocks. **a** Woolley and Kempe's (1989) average calciocarbonatite normalized multi-elements spidergrams. **b** Primordial mantle normalized multi-elements spidergrams. **c** Chondrite normalized rare-earth patterns

Ti, show higher concentrations than the primordial mantle, although Zr values are almost identical to the primordial mantle value. The chondrite-normalized rare-earth element patterns of these carbonatites (Fig. 9c) are typical, with steep inclined profiles showing very high LREE concentration, and comparable to other well-known carbonatites (Cullers and Graf, 1984; Woolley and Kempe, 1989; Woolley et al., 1991; Srivastava, 1997; Harmer, 1999).

From the geochemical characteristics of the Sung Valley silicate and carbonate rocks, presented above, it can be seen that the primordial mantle normalized multi-element and the chondrite normalized rare-earth element patterns of the carbonatite samples (Fig. 9) are quite different from those of the associated silicate rocks (Figs. 7 and 8), so it is difficult to establish a genetic relationship between these rocks. On the basis of the data presented, different models for the genesis of the ultramafic-alkaline-carbonatite complexes will now be discussed.

Discussion

There is a number of reviews on the genesis of the carbonatites *Le Bas* (1981, 1987, 1989), *Gittins* (1989), *Bailey* (1995), and *Bell et al.* (1998). Three genetic models have been proposed:

1. Direct melting of carbonated mantle,
2. Fractional crystallization of carbonated nephelinite, and
3. Derivation from an immiscible liquid that separated from nephelinitic/phonolitic magma.

In the fractional crystallization and liquid immiscibility models, carbonatites may be correlated, genetically, with the associated silicate rocks but the direct melting model (1) implies no such relationship between these rocks. It is important to note that models (2) and (3) postulate a secondary origin for carbonatite magma. Here it is also important to point out that the basic experimental results of liquid immiscibility studies have been questioned (*Twyman and Gittins*, 1987; *Gittins*, 1989; *Lee et al.*, 1994). According to these workers the experiments fail to explain whether (i) carbonatite liquid is generated from a homogeneous silicate melt, (ii) both, carbonate and silicate, liquids are immiscible but no mechanism has been presented to explain why carbonatite intrusions are younger than the associated silicate rocks in most of UACC, (iii) why Nb, REE, P and Sr contents are high in carbonatites but not in the associated silicate rocks. *MacDonald et al.* (1993) have suggested that immiscibility processes mainly works in the alkalic system.

The geochemical compositions of the different rock units from the Sung Valley UACC do not show a co-genetic relationship. In most of the geochemical diagrams presented (Figs. 5 and 6), nepheline syenite samples plot separately from the other silicate rocks and show different crystallization behaviour. This indicates that nepheline syenites are produced by the removal of significant amounts of Ti–P mineral phases and not by the olivine-pyroxene fractionation. This is also supported by field evidence. The nepheline syenite dykes and veins intrude the ijolites suggesting that they are derived from two discrete melts. Multi-element and rare-earth element patterns are also significantly different in ijolite and nepheline syenite samples. Thus, field evidence and geochemical data do not support fractionation of ijolite to form nepheline syenite. Figure 10 is prepared for further discussion on this topic. From this diagram the following conclusions may be drawn:

1. A considerable gap is noticed between nepheline syenite and other silicate rocks. This gap is prominent in Mg#–Nd plot (Fig. 10b). If these silicate rocks are derived from any of the two models (2 and 3), it should show consistent fractionation trends. Carbonatite samples also plot separately.
2. If we consider the possibility of fractionation of carbonated nephelinitic magma, crystallization trends should start from pyroxenite and end at carbonatite through melilitolite, ijolite, and nepheline syenite, but this is not observed in any plot. The nepheline syenites have lowest Mg#, CaO, Sr, and Nd and such values are highest in the carbonatites rejecting fractionation model.

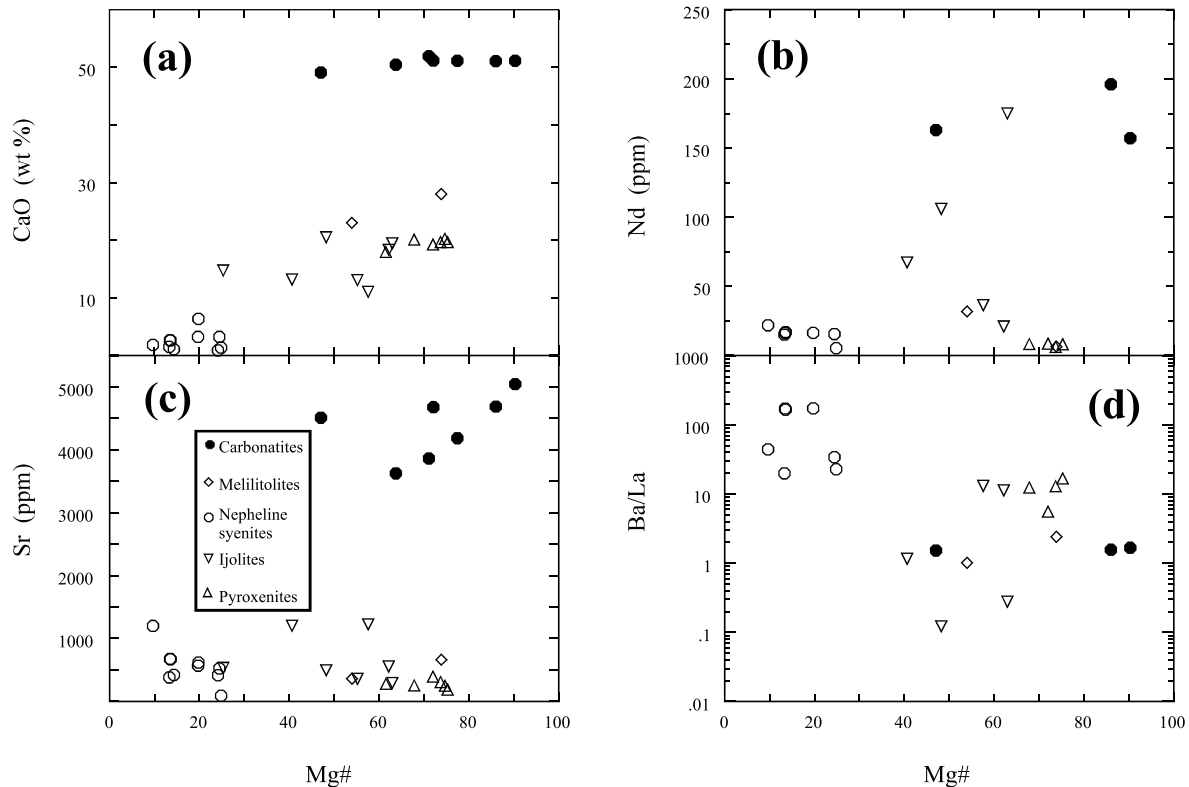


Fig. 10. Relationship between Mg# and CaO, Nd, Sr, and Ba/La in different rock units of the Sung valley UACC

3. If we consider immiscible silicate and carbonate liquids for the crystallization of these rocks, the Ba/La ratios must be higher in the carbonatite rocks in comparison to associated silicate rocks (*Hamilton et al., 1989*), but this is not the case; most of the silicate members have higher Ba/La ratio than carbonatite samples (Fig. 10d).

Despite the fact that most of the previous workers have supported the liquid immiscibility model for the Sung Valley UACC (*Viladkar et al., 1994; Veena et al., 1998; Sen, 1999; Ray et al., 2000*), little attention has been given to establish the relationship between the carbonate and silicate end members. Another point, which argues against the immiscible model, is that no immiscible droplets of carbonate liquid in the associated silicate rocks and vice-versa have been reported. But before rejecting the liquid immiscibility model, it is essential to have radiogenic isotope data, particularly Nd, Sr and Pb isotopic data, for both rock types; these are still lacking. Such data are available only for the carbonate fraction (*Veena et al., 1998; Ray et al., 2000*) but not for the silicate fraction, except one Sr isotope data for a pyroxenite sample (*Ray et al., 2000*).

Gittins (1989) favours direct melting of a carbonated mantle (model 1) for the origin of carbonatite magma. Fluorine-rich fluids, which can enrich the magma with Nb, P, REE, SR, etc., may metasomatize the carbonated mantle. *Gittins (1989)*

further stated that this melt might dissolve an adequate amount of olivine and pyroxene to provide Al, Fe, and Si necessary for crystallization of silicate minerals. Later, workers such as *Wallace and Green* (1988), *Thibault et al.* (1992), *Dalton and Wood* (1993), and *Sweeney* (1994) have performed experiments on the carbonated peridotite and established that carbonate melts may be generated at pressures greater than ~ 25 kbar. These experiments also explain that this melt contains appreciable amount of alkalis (up to 7%). Due to low viscosity, this melt can move upward and interact with peridotite to form metasomatic clino-pyroxene and olivine. This process would progressively metasomatize the lherzolite to alkaline wehrlite and release CO₂ fluids.

Conclusions

Field and geochemical data of different rock units of the Early Cretaceous Sung Valley ultramafic-alkaline-carbonatite complex of North-eastern India do not show co-genetic relationships. These observations rule out the possibilities of liquid immiscibility or fractional crystallization models for the genesis of carbonatite and associated silicate rocks. The petrological and geochemical characteristics of the Sung Valley UACC suggest that they are derived from a primary carbonate magma generated by low-degree partial melting of a metasomatized mantle peridotite at pressures greater than ~ 25 kbar. This melt contained appreciable amounts of alkalis and dissolved an adequate amount of olivine and pyroxene to provide Al, Fe, and Si necessary for the crystallization of the silicate minerals.

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