Petrogenesis of an early Cretaceous potassic lamprophyre dyke from Rongjeng, East Garo Hills, Shillong plateau, north-eastern India

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An early Cretaceous potassic lamprophyre dyke, exposed near Rongjeng, East Garo Hills, Shillong plateau, north-eastern India, is a highly porphyritic rock with large phenocrysts of clinopyroxene, phlogopite, amphibole and olivine. Reversely zoned phlogopite and clinopyroxene grains indicate that some degree of interaction between magma batches of variable composition took place somewhere during the crystallization of the lamprophyre. Mineral compositions indicate its derivation from an alkaline magma comparable with those that filled the nearby Jasra potassic intrusion. Moreover, the geochemistry of the Rongjeng lamprophyre is distinctly different from that of the Damodar Valley lamproites, the Sung Valley carbonatitic-ijolitic intrusion, and the Antarctic ultramafic lamprophyres. The contrasting geochemical affinity is suggestive of heterogenous lithospheric mantle sources, rather than input of plume-related magmatism.

Keywords: Geochemistry, lithospheric alkaline magmatism, mantle heterogeneity, petrogenesis, potassic lamprophyre.

LAMPROPHYRE is an alkaline rock that normally contains high alkalis at a given percentage of SiO_2, together with one or more of normative nepheline, leucite or acmite, modal foids, and Na–K–Ti-rich amphiboles, micas or pyroxenes[1]. They usually occur as dykes throughout all geologic eras. Many[2,3] have strictly forbidden the terms like 'lamprophyric rocks', or 'lamprophyre clan' and defined lamprophyre as a porphyritic igneous rock with mafic index between 35 and 90 and contain phenocrysts of biotite/phlogopite, amphibole, clinopyroxene and olivine. Feldspars and/or feldspathoids, if present, are restricted to the groundmass. Calcite and zeolite may be secondary phases. Although lamprophyres are volumetrically insignificant components of continental magmatism, their systematic studies may provide significant information to our understanding of deep melting events during the initial stages of continental rift development[4,5] or inference a mantle-plume connection[6,7].

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The Indian shield comprises a number of lamprophyric occurrences ranging their ages from Precambrian to Cretaceous and varies in compositions from calc-alkaline to ultramafic[8–11]. Alkaline and mafic dykes of different compositions are reported from the Shillong plateau, north-eastern India[12], however, concentration of these dykes is more in East Garo Hills, particularly around Swangkre, Rongjeng, Nongchram, Rongmil and Darugiri areas[12–17]. Most of these mafic dykes are Proterozoic in age[12], whereas alkaline and carbonatite dykes, mostly exposed around Swangkre, Rongjeng and Nongchram, are emplaced during early Cretaceous[15,16]. Nambiar[15,16] has presented some petrological and major element oxides data on alkaline dykes of this region, however, no other work is available on these rocks. Here we present a detailed account on mineral chemistry and whole-rock geochemistry which includes major, trace and rare-earth element concentrations on an early Cretaceous potassic lamprophyre dyke exposed near Rongjeng, East Garo Hills, Shillong plateau, north-eastern India to understand the petrogenesis and possible role of a mantle plume.

Geological setting

The most spectacular geological feature in north-eastern Indian shield is Shillong plateau which is an uplifted horst-like feature, bounded on all sides by several fault systems such as Dauki, Brahmaputra, Jamuna and Kopili[18–22] (Figure 1). There are some other deep faults which traverse the Shillong plateau; this includes the N–S trending Nongchram fault and Um Ngot lineaments and NE–SW trending Badapani–Tyrsad shear zone[14,16,22,23] (Figure 1). It is believed that most of these deep faults/lineaments are developed during the late Jurassic–early Cretaceous and spatially and temporally associated with the early Cretaceous mafic–ultramafic–alkaline igneous magmatism[22]. The Shillong plateau is mainly formed by (i) Archaean gneisses, (ii) Proterozoic mafic dykes, (iii) Shillong Group of rocks (Proterozoic orthoquartzites and phyllites), (iv) a number of 700–450 Ma granite plutons that intrude the gneissic basement as well as the Shillong Group cover, (v) the Sylhet Traps, a part

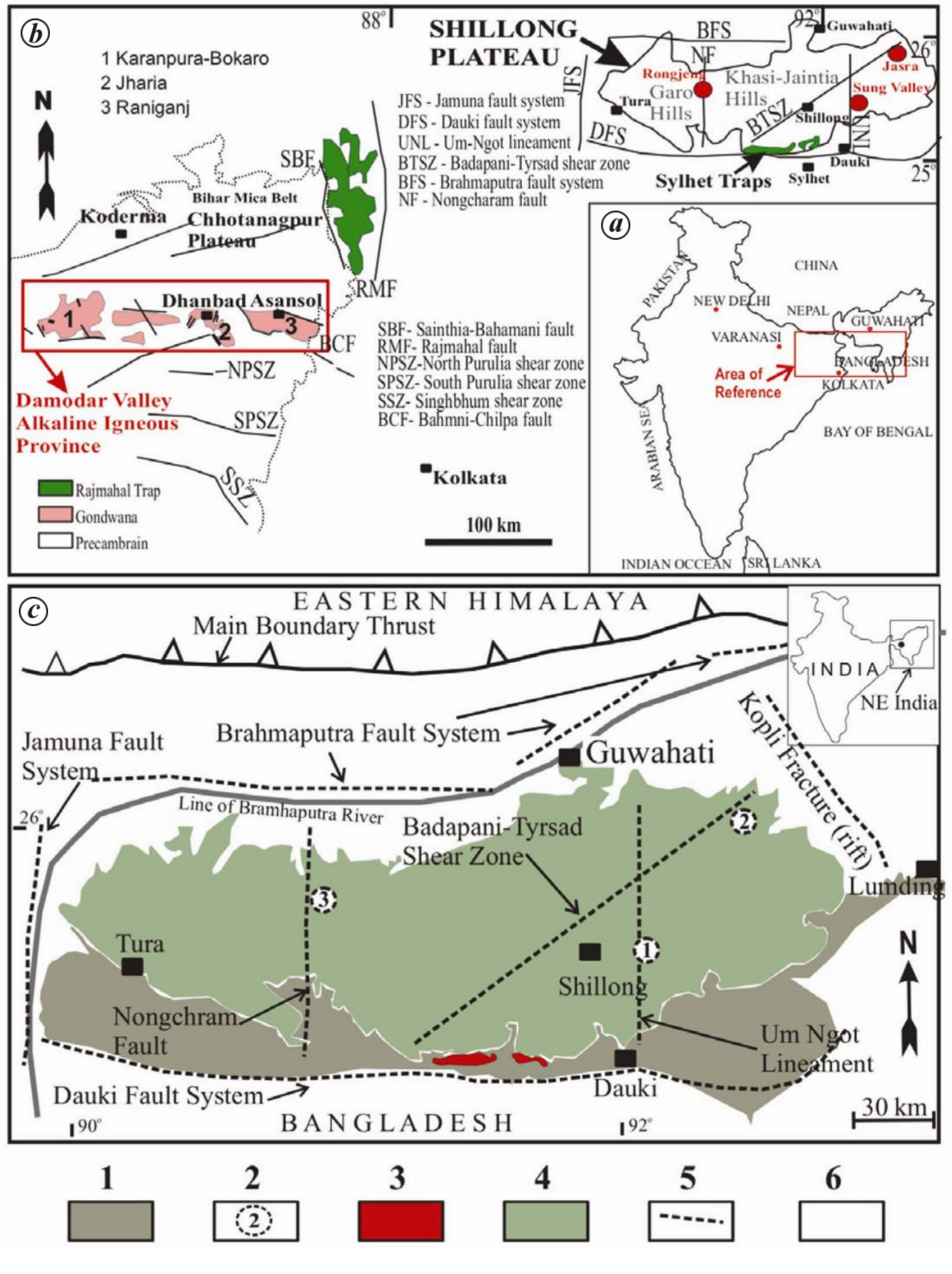

Figure 1. ***a***, Map of India showing area of present study. ***b***, Geological sketch map of northeastern India showing the locations of Cretaceous magmatic activity in the Damodar Valley, Rajmahal and Sylhet Traps and on the Shillong Plateau[38]. ***c***, Regional geological and tectonic set-up of the Shillong Plateau[18]. 1, Cretaceous–Tertiary sediments; 2, Ultramafic-alkaline-carbonatite complexes [(1) Sung Valley; (2) Jasra; (3) Rongjeng–Swangkre]; 3, Sylhet basalts; 4, Archaean–gneissic complex, Shillong Group rocks, mafic igneous rocks, and Proterozoic granites; 5, Major fault-systems, and 6, Alluvium and recent sediments.

of the early Cretaceous Rajmahal–Sylhet flood basalt province, and (vi) the early Cretaceous ultramafic–alkaline–carbonatite complexes[18,20,23–26] (Figure 1). It is suggested that early Cretaceous magmatism recorded in the Shillong plateau has definite association with the Kerguelen plume[27–31].

A number of early Cretaceous dykes are reported to be emplaced within the Archaean gneissic complex of the Shillong plateau, which includes hornblende and biotite gneisses, porphyritic granitoids and pink granites[15,16]. Although Nambiar[15,16] reported dykes of different compositions such as basalt/dolerite, nepheline syenite, lamprophyre, ijolite and carbonatite; basalt/dolerite and feldspathic dykes dominate, other lithotypes are rare. Most of these dykes trend N–S and were emplaced parallel to the Nongcharam deep fault[15,16] (Figure 2). The potassic lamprophyre dyke under study (25°38′19″E : 90°48′31″N) is exposed around Rongjeng area and is an integral part of the Swangkre dyke swarm[15–17] (Figure 2). It is a small dyke (width varies between 50 cm to 100 cm), trends N–S, and has been emplaced at 107 ± 3 Ma (ref. 32). It is a highly porphyritic rock (Figure 3), with large phenocrysts of clinopyroxene and phlogopite (up to 5 mm in size), with lower amounts of amphibole, olivine and oxides (in order of abundance), with microlites of clinopyroxene, phlogopite, apatite and alkali feldspar. Carbonates, analcime, other zeolites and rutile are secondary minerals. Very frequent and highly distinctive is the presence of reversely zoned phlogopite and clinopyroxene, with cores of Fe-rich, green clinopyroxene and Fe-rich, dark brown phlogopite and distinctly more magnesian (colourless) rims.

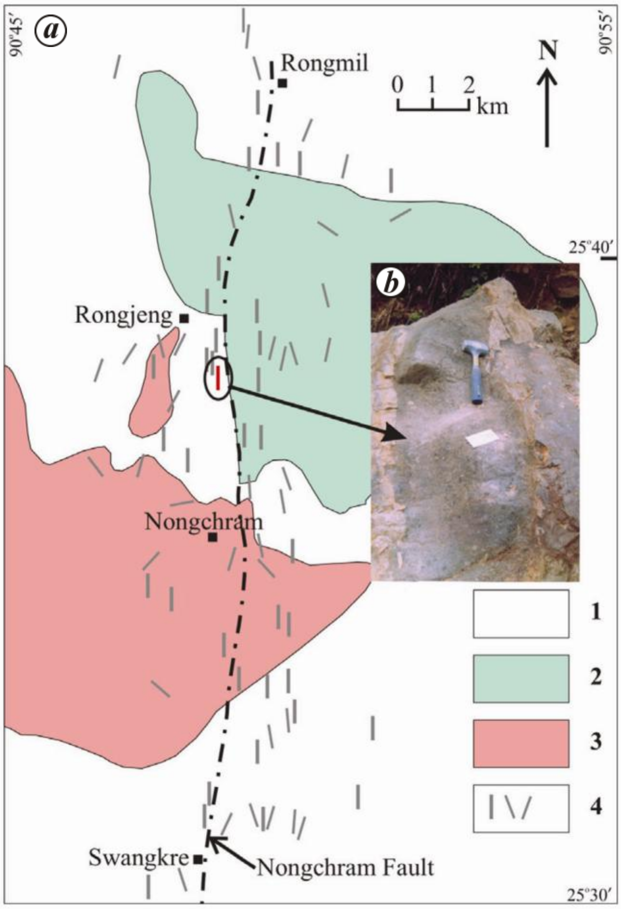

Figure 2. *a*, Simplified geological map of Swangkre-Rongjeng area[15–17]. (1) Migmatitic gneisses, (2) Porphyritic granite, (3) Pink granite, (4) Dykes of different petrological compositions. Location of studied potassic lamprophyre dyke is encircled. Width and length of dykes are not to scale. *b*, Field photograph of potassic lamprophyre dyke exposed near Rongjeng.

Mineral compositions

Mineral analyses, obtained with energy dispersive spectrometry (EDS), have been performed at CISAG, University of Napoli Federico II, utilizing an Oxford Instruments Microanalysis Unit, equipped with an INCA X-act detector and a JEOL JSM-5310 microscope operating at 15 kV primary beam voltage, 50–100 mA filament current, and 50 s net acquisition time. Measurements were done with an INCA X-stream pulse processor. The following standards were used for calibration: diopside (Mg), wollastonite (Ca), anorthoclase (Al, Si), albite (Na), rutile (Ti), almandine (Fe), Cr_2O_3 (Cr), rhodonite (Mn), orthoclase (K), apatite (P), fluorite (F), barite (Ba), strontianite (Sr), Smithsonian orthophosphates (REE, Y), pure niobium (Nb), pure vanadium (V), zircon (Zr, Hf), Corning glass (Th and U), sphalerite (S) and sodium chloride (Cl). Table 1 presents representative mineral analyses of different mineral phases; complete analyses (see Supplementary Information Tables S1–S4, online) are available as supplementary material on journal's website.

Olivine

The rare olivine phenocrysts have a composition ranging from Fo_{85} to Fo_{81}, are low in CaO (CaO from 0.2 to 0.6 wt%) and do not host chromite crystals. Their compositions indicate crystallization from a slightly evolved melt composition, having Mg# from 85 to 81; according to the olivine–liquid Fe–Mg partitioning[33] (see Supplementary Information, Table S1, online). These values are close to the bulk rock composition of SW02/9, having an Mg# = 67, suggesting near equilibrium.

Clinopyroxene

Two generations of clinopyroxene are observed among phenocrysts and/or cores (see Supplementary Information, Table S2, online; Figure 4). Diopside (Mg# = 70–82) has the marked enrichment in TiO_2 and Al_2O_3 (up to 4 and 9 wt% respectively) with decreasing Mg#, typical of pyroxene crystallizing in within-plate alkaline magmas. Fe-rich clinopyroxene (Mg# 20–70) tends to be rich in Na (up to 5 wt%) and low in TiO_2 and Al_2O_3. This pyroxene also occurs as green cores, likely crystallized in more evolved magma batches.

Phlogopite

Brown mica has also two generations of phenocrysts (see Supplementary Information Table S3, online; Figure 5). Phlogopite has high Mg# (76–83) and TiO_2 up to 5 wt%, whereas Fe-rich varieties (Mg# 33–57) have variable TiO_2 (4.3–5.4 wt%). BaO reaches values as high as

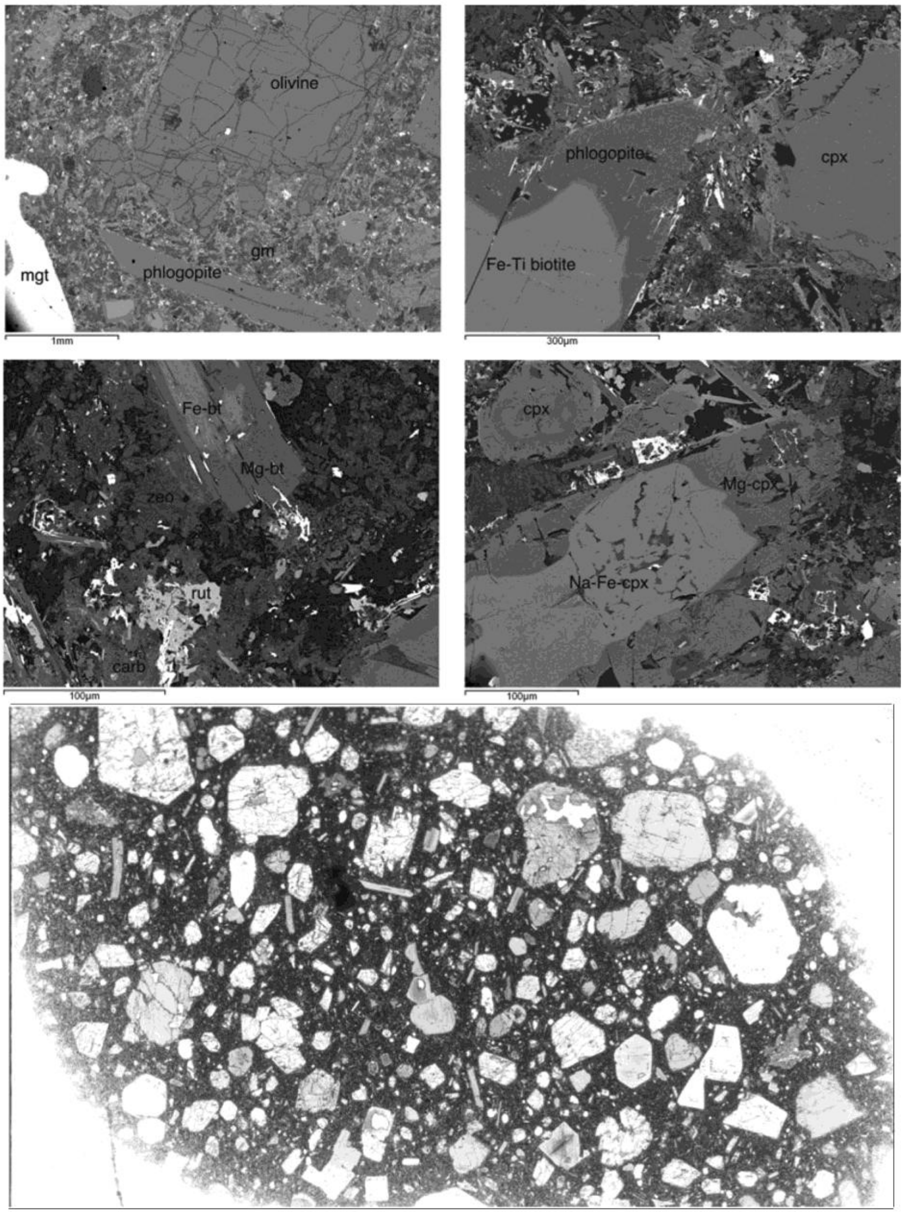

Figure 3. Back-scattered electron and microscope images of peculiar petrographic features of the Rongjeng potassic lamprophyre sample showing porphyritic texture. Phenocrysts of biotite-phlogopite, clinopyroxene and olivine are visible. Fine-grained groundmass is composed of feldspathic minerals, feldspars and biotite. The bottom photograph is polished slab of the studied sample (the long side is about 2.5 cm).

1.3 wt%. The mica compositions are similar to those of the Jasra micas, and very different from those of the Damodar Valley lamproites or those of the Sung Valley carbonatite–ijolite complex (Figure 5), thus suggesting a range of different parental magmas.

Amphibole

Amphibole is quite rare as phenocryst, and has pargasitic chemistry (Supplementary Information, Table S4, online; Figure 6), with Mg# from 64 to 71 and TiO_2 reach values as high as 4.9 wt%. The Jasra amphiboles are mostly kaersutites, hence having slightly more TiO_2 (up to 6.3 wt%).

Other minerals

Rare Ti-magnetite has been found (TiO_2 10.7–11.2 wt%; ulvöspinel content) and rutile/leucoxene. Pyrite, pyrrhotite and blende are sporadically found in the groundmass. Alkali feldspar has a quite uniform composition ($Or_{87–89}$ $Ab_{11–12}$ $An_{0–1}$) and tends to be altered to zeolites. Apatite is rare and has F and SO_3. Barite is also sporadically found. Secondary carbonates are sometimes rich in Fe.

Table 1. Representative chemical compositions of different mineral phases in Rongjeng potassic lamprophyre (SW02/9)

	Olivines		Clinopyroxes						Micas							Amphiboles					
			cpx core	cpx rim	cpx core	cpx rim	cpx	cpx	phlog mtl	phlog mic	phlog core	phlog rim	phlog gm	phlog	phlog	bt	bt	amph core	amph rim	amph	amph
SiO_2	40.49	39.86	48.51	48.71	50.93	43.72	43.94	50.04	36.88	37.15	37.92	37.83	37.26	37.48	37.06	36.47	37.70	40.91	41.33	41.68	39.83
TiO_2			1.84	1.53	1.16	3.64	3.46	1.68	4.56	4.22	4.95	4.28	4.26	4.75	4.79	3.71	3.57	3.37	3.56	3.49	3.94
Al_2O_3			6.59	6.68	3.22	8.80	7.70	6.07	16.23	15.93	16.07	15.35	9.21	13.67	15.86	15.83	15.09	13.16	13.35	13.30	13.31
FeO	13.61	16.34	5.51	5.03	10.90	7.67	7.18	8.30	7.20	8.37	6.66	9.19	24.94	12.04	6.59	7.60	10.18	11.00	10.25	10.03	10.16
MnO	0.07	0.29	0.09	0.09	0.27	0.00	0.13	0.00	0.13	0.10		0.20	0.62	0.32	0.24	0.04	0.02	0.11	0.11	0.07	0.44
MgO	44.70	43.46	12.88	12.99	10.44	11.04	11.66	12.24	18.62	19.06	18.77	18.16	9.86	16.49	18.64	19.46	18.32	12.95	13.27	13.48	13.43
CaO	0.25	0.21	23.25	22.94	21.59	24.01	23.70	22.31	0.11	0.35	0.04	0.02	0.14	0.14	0.15	0.08	0.12	11.84	11.37	11.51	11.44
Na_2O			0.70	0.93	1.78	0.60	0.73	1.22	0.74	0.66	0.75	0.73	0.26	0.43	0.58	0.58	0.67	2.29	2.50	2.35	2.58
K_2O									9.63	9.49	10.18	10.08	9.80	10.21	9.84	9.01	9.24	2.23	2.12	2.14	2.10
BaO									0.59	1.18	0.61	0.47	0.78	0.52	0.49	1.17	0.96				
SrO																		0.08		0.14	0.41
Cr_2O_3			0.06	0.25	0.06	0.11	0.09	0.11		0.05	0.42				0.30						
V_2O_5																					
F									0.06	0.24	0.29		0.16	0.10	0.09						
Cl									0.02		0.08	0.02	0.08								0.05
H_2O*									4.07	4.03	4.02	4.12	3.73	4.00	4.06	4.05	4.10				
O=F,Cl									0.03	0.10	0.14	0.01	0.08	0.04	0.04	0.00	0.00	0.00	0.00	0.01	0.00
Total	99.11	100.16	99.43	99.14	100.34	99.60	98.59	101.98	98.8	100.7	100.6	100.4	101.0	100.1	98.6	98.0	100.0	99.98	99.90	100.28	99.74
Mg#	85	82	80	82	63	72	74	72	82	80	83	78	41	71	83	82	76	68	70	71	71

Geochemistry

Whole rock major, trace and rare-earth element analysis of the lamprophyre was performed at the Activation Laboratories Ltd, Ancaster, Ontario, Canada. ICP-OES (Model: Thermo-JarretAsh ENVIRO II) was used to analyse major elements, whereas ICP-MS (Model: Perkin Elmer Sciex ELAN 6000) was used to determine trace and rare-earth element concentrations. The precision is <5% for all analysed elements when reported at 100 × detection limit. Several standards, such as SY-3, W-2, DNC-1, BIR-1 and STM-1, were run along with the analysed UML sample to check accuracy and precision. Geochemical data is presented in Table 2. Mg number (Mg#) is calculated using the SINCLAS Computer Program[34].

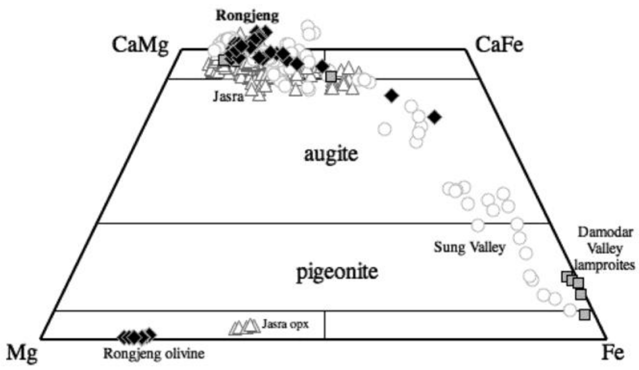

Figure 4. Pyroxene compositions in the Rongjeng potassic lamprophyre plotted on a standard Ca–Mg–(Fe + Mn) ternary diagram (in at%).

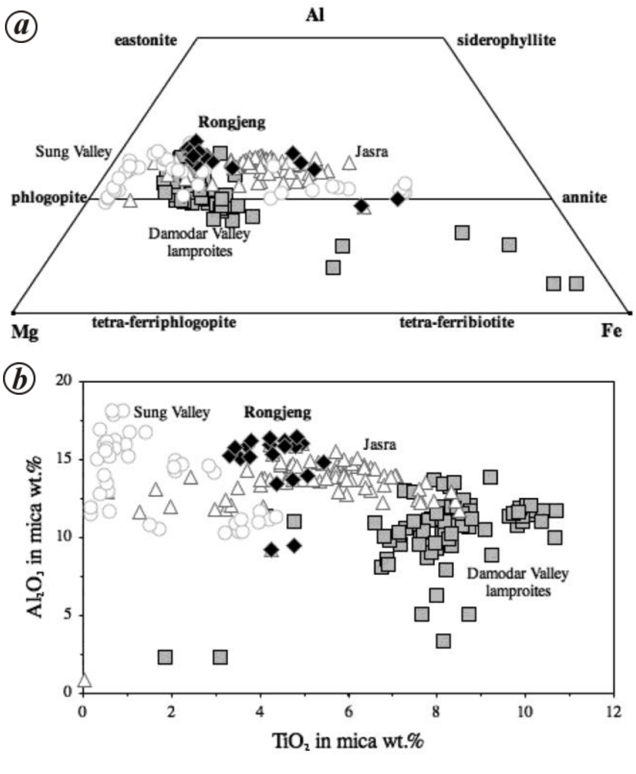

Figure 5. Classification of micas in the Rongjeng potassic lamprophyre. TiO_2 versus Al_2O_3 variation in micas in the Rongjeng potassic lamprophyre.

Chemical composition of the studied potassic lamprophyre sample shows low-silica, high-magnesium and moderate-alkalis composition. The weight loss on ignition (LOI) is high; due to the carbonate phases. High Mg# indicates its derivation from a mantle-derived melt. On TAS plot[3] (Figure 7 *a*), the potassic lamprophyre sample shows basanite composition. The SINCLAS Computer Program[34] classifies it as melanephelinite type basanite, which also indicates its melanocratic alkaline nature. Although Rock[35,36] distinguished 'alkaline' from 'ultramafic' lamprophyres, it is difficult to differentiate them; both have several overlapping mineralogical and geochemical characteristics. Their overlapping geochemical nature is well observed on Al_2O_3–CaO–MgO plot[1] (Figure 7 *b*). Nevertheless, it is also true that both lamprophyre types suffered broadly similar petrogenetic histories[37].

The Rongjeng dyke has low Cr and Ni concentrations (130 and 100 ppm respectively), indicating that it experienced some degree of fractional crystallization from more primitive compositions. Nonetheless, the high Ba, Sr Nb and Zr concentrations are typical of alkaline-within-plate alkaline magmas. The rare earth element chondrite normalized pattern is steep ($La/Yb_N = 22$), and has no negative Eu anomalies, indicating no previous feldspar removal. The mantle normalized incompatible element pattern of the Rongjeng lamprophyre is typical of potassic within-plate mafic rocks. It has a peak at Ba, no K, Nb, Ta and Ti troughs and a substantially smooth pattern towards the least incompatible elements.

Discussion

From the petrography, mineral chemistry and geochemistry, presented above, it can be established that the

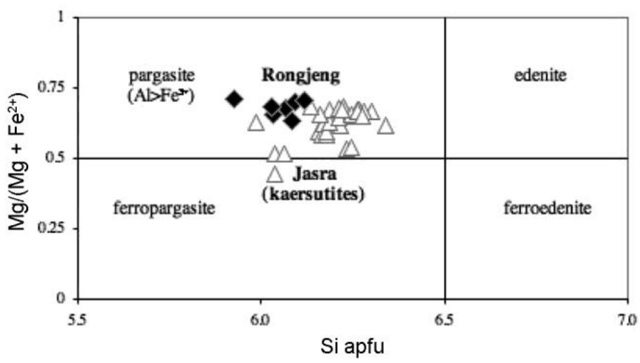

Figure 6. Amphibole compositions in the Rongjeng potassic lamprophyre.

Table 2. Whole rock major, trace and rare-earth element and CIPW normative compositions of potassic lamprophyre (SW02/9) from the Rongjeng, Shillong Plateau NE India

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Mg#	
Major oxides (wt%)	37.42	2.41	10.28	11.15	0.15	10.17	12.76	2.76	2.00	0.63	9.12	98.85	68.07	
	V	Cr	Ni	Ga	Rb	Sr	Ba	Y	Zr	Hf	Nb	Ta	Th	U
Trace elements (ppm)	260	128	102	14	72	744	968	20	192	4.5	47	2.6	4.8	1.0
	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Rare-earth elements (ppm)	45.00	88.20	9.63	36.20	6.60	2.01	6.00	0.80	3.90	0.70	1.80	0.24	1.50	0.21

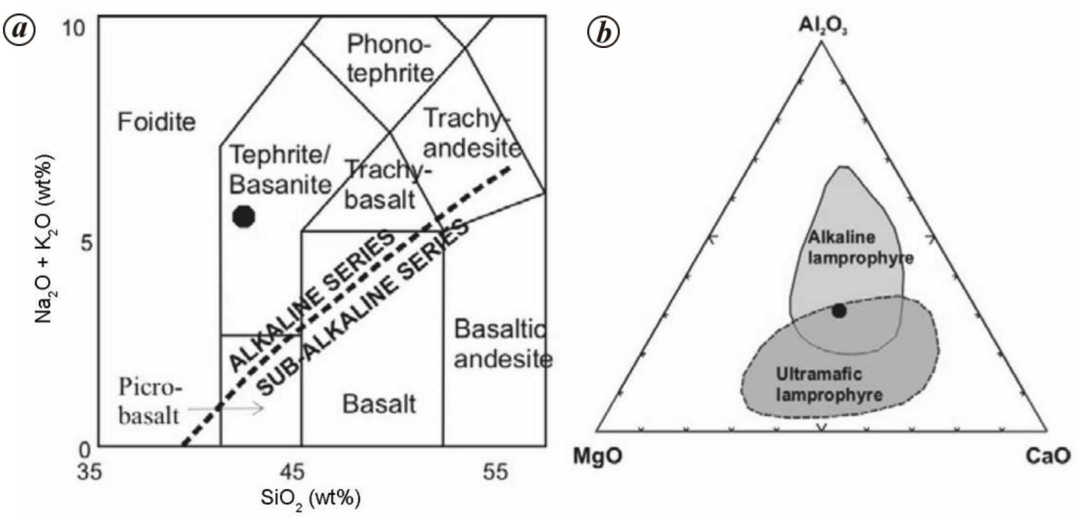

Figure 7. ***a***, Total-alkali and silica diagram[3]. Dotted line separates sub-alkaline rocks from alkaline rocks[42]. ***b***, Al_2O_3–CaO–MgO (wt%) ternary plot for distinguishing alkaline and ultramafic lamprophyres[1].

studied sample has potassic affinity. It mainly contains phenocrysts of clinopyroxene and phlogopite, and minor amounts of amphibole, olivine and oxides are also present in a fine-grained groundmass. Its alkaline nature is also reflected from the geochemical characteristics. The mineral compositions of the lamprophyre are typical of those crystallizing in alkaline magmas and substantially similar to those found in the nearby alkaline intrusions of the Shillong Plateau. The reversely zoned phases indicate that some degree of interaction between magma batches of variable composition took place somewhere during the crystallization of the lamprophyre (Figure 3).

The chemical composition of the main mineral phases of the Rongjeng lamprophyre is close to the range observed in the mafic samples of the nearby Jasra potassic intrusion, thought to be filled by magmas of potassic affinity[38], and distinctly different from that observed in the clinopyroxene, mica and amphibole of the Damodar Valley lamproites[39] and authors' unpublished data. The Rongjeng minerals are also chemically different from those observed in the Sung Valley carbonatitic–ijolitic intrusion[40].

The Primitive mantle normalized multi-element spidergrams of the Damodar Valley lamprophyres, eastern India Sylhet Traps and ultramafic lamprophyres from the Beaver Lake, Antarctica are also compared with the studied Rongjeng potassic lamprophre (Figure 8). It is observed that the sources of the nearby tholeiitic basalts of Sylhet and Rongjeng–Swangkre tholeiites must be chemically different, as pointed out by the distinct patterns and absolute abundances. The same can be noted for the contrasting geochemical patterns of the ultramafic lamprophyres in Antarctica, which were almost contemporaneously emplaced on the conjugate margin, and of the ultrapotassic rocks of the Damodar Valley, which also show negative Nb, Ta and Ti troughs resembling a crustally derived enrichment event in the mantle. The geochemical characteristics of the Rongjeng potassic lamprophyre are shared with other K-rich within plate basaltic-basanitic dyke suites, such as that in the Late Cretaceous magmatism of southeastern Brazil of the African Rift, among other examples[41].

A simple mixing model between average compositions of depleted mantle melts (MORB) and melts derived from enriched sources (OIB) is presented in Figure 9. This simplistic model can be fruitful for the petrogenesis of the Sylhet traps and of the Rongjeng tholeiites, apart from likely effects of crustal contamination. Looking at the petrogenesis of the Rongjeng dyke to a regional scale, we note that the extreme trace element enrichment of the

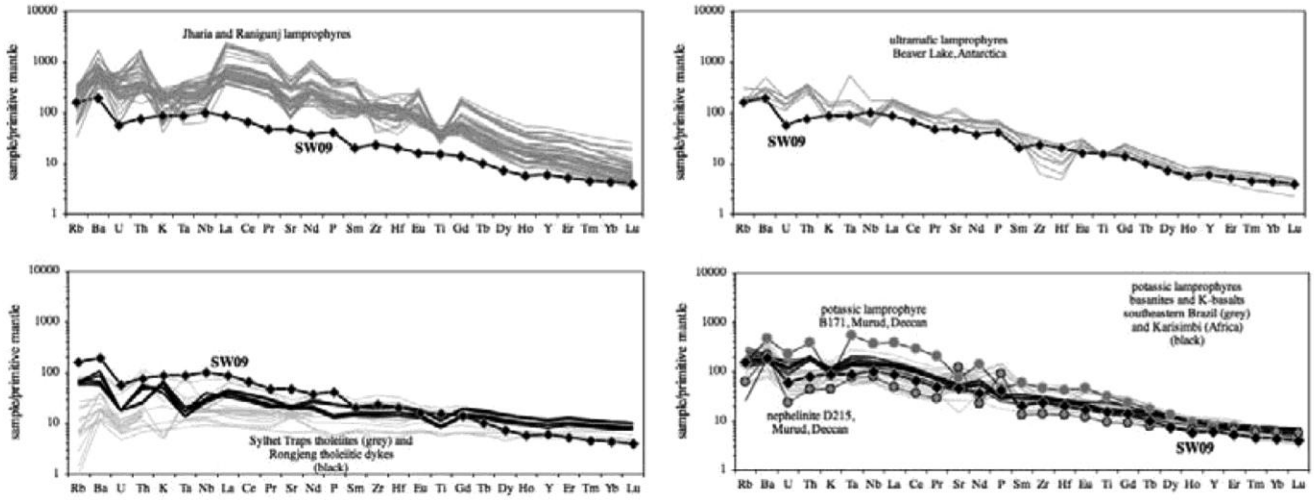

Figure 8. Primitive mantle normalized diagrams for mafic-ultramafic rocks and the studied Rongjeng potassic dyke (Data source (refs 17, 39, 41, 43–47)). The normalization values from Lyubetskaya and Korenaga[48].

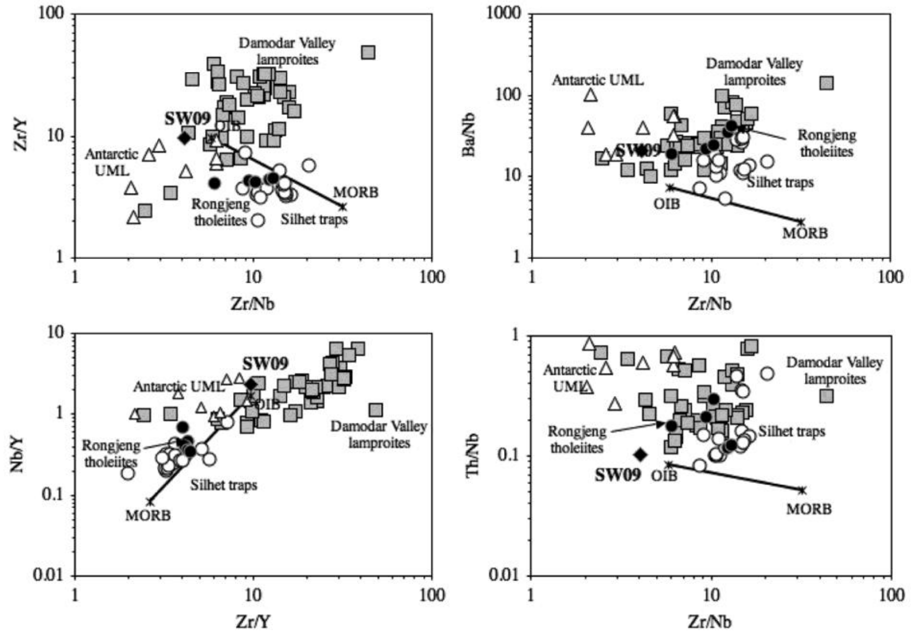

Figure 9. Incompatible element ratios of the Rongjeng potassic lamprophyre and other Cretaceous rocks from India, and Antarctica. The data are the same as in Figure 8. Trace element data for MORB and OIB are taken from Sun and McDonough[49].

Rongjeng dykes, the ultrapotassic rocks and the Antarctic ultramafic lamprophyres and their contrasting geochemical patterns cannot be due to input of plume-related magmatism of unknown composition, but, rather, to distinctive heterogeneity of the mantle source, which are typical of lithospheric alkaline magmatism.

Conclusions

Petrography, mineral chemistry and whole-rock geochemistry of an early Cretaceous, highly porphyritic lamprophyre sample from a dyke exposed near Rongjeng, East Garo Hills, Shillong plateau clearly suggest its potassic affinity. These features are typical of those crystallizing in hydrous alkaline magmas. Mineral chemistry of micas, pyroxenes and amphiboles is well comparable with the nearby Jasra potassic intrusion, and distinctly different from the Damodar Valley lamproites and the Sung Valley carbonatitic-ijolitic intrusion. The geochemical characteristics of the Rongjeng lamprophyre are very close to other K-rich within plate basaltic-basanitic dyke suites (Figure 8). A simple mixing model between average compositions of depleted mantle melts (MORB) and melts derived from enriched sources (OIB) applied to the studied Rongjeng lamprophyre sample together with the Sylhet traps, the Rongjeng tholeiites, the ultrapotassic rocks, and the Antarctic ultramafic lamprophyres is suggestive of distinctive heterogeneity of the mantle source rather than input of plume-related magmatism; a typical situation of lithospheric alkaline magmatism.

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