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Petrological and Geochemical Characteristics of a Shoshonitic Lamprophyre, Sivarampet, Wajrakarur Kimberlite Field, Southern India

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Abstract: *Field geological, petrographic and geochemical characteristics of a lamprophyre intrusion, presumably of pug-type, at Sivarampet (SPL), occurring within the Wajrakarur kimberlite field (WKF) to the west of Cuddapah basin, are presented and discussed. The lamprophyre intrusion occurs as brecciated outcrop with angular country rock granitoid clasts and also it forms stringers/veinlets within the granitic country rock. The melanocratic rock displays panidiomorphic/porphyritic texture, typical of lamprophyres, comprising clinopyroxene, biotite, phlogopite set in a groundmass of feldspar, magnetite and spinel. Plagioclase is dominant feldspar. The K_2O/Na_2O ratio ranges from 1.55 to 1.89 wt %, making it distinctly potassic and brings out its shoshonitic behaviour. The fractionated chondrite normalised patterns of REE (with average $(La/Yb)_N$= 21.01 ppm) implies involvement of an enriched mantle source while depleted values of Nb, Hf, Th and U concentrations indicate prevalence of subducted component in the mantle source. The concentrations of Rb, Sr and Ba indicate presence of phlogopite in the source. Based on the mineral assemblages, the SPL can be classified as calc-alkaline variety; however, its geochemistry shows characteristics of both alkaline and calc-alkaline varieties. The moderate Mg# (52 to 55.6) and low concentration of Ni (95.61 to 112.4 ppm) in the bulk rock indicate a low degree of partial melting of magmatic fluid from enriched asthenospheric mantle which underwent fractionation of olivine and pyroxene, subsequently producing lamprophyre magma. Recent discovery of diamonds in shoshonitic lamprophyres of Canada, appeals further investigations on diamondiferous nature of similar rock types of the WKF.*

Keywords- *Petrography, Geochemistry, Petrogenesis, Plug-type intrusion, Sivarampet lamprophyre, Shoshonitic lamprphyre, EDC, southern India*

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I. Introduction

The term “Lamprophyre” was coined by von Gumbel in the year 1874 for a group of dark complexioned rocks which occur as minor intrusions containing brown mica and hornblende phenocrysts but lacking feldspar phenocrysts. Subsequently the term was used by Rosenbusch (1877) to encompass a wide variety of hypabyssal rocks such as minette, kersantite, camptonite and vogesite which contain ferromagnesian phenocrysts. Eventually, spessartite, monchiquite and alnoite were also added to the group. Rock (1991) has used ‘lamprophyre’ synonymously with ‘*lamprophyre clan*’, a term that has collectively included lamprophyres, lamproites and kimberlites. Thus lamprophyre is a special type of melanocratic hypabyssal igneous rock of inordinate petrological and tectonomagmatic significance like kimberlite and lamproites. Lamprophyres are characterised by microporphyritic textures with mafic phenocrysts which are usually phlogopite, amphibole, clinopyroxene, olivine, and also occasionally melilite set in a groundmass composed of the same minerals as well as feldspars and feldspathoids (Wimmenauer, 1973; Rock, 1977; 1991). Abundant carbonate minerals, apatite and zeolites are also constituents of lamprophyres.

Rock (1991), Le Maitre (1989) and Streckeisen (1979) classified lamprophyres into five main categories namely (1) calc-alkaline lamprophyre (CAL), (2) alkaline lamprophyre (AL), (3) ultramafic lamprophyre (UML), (4) lamproitic lamprophyre (LL) and (5) kimberlitic lamprophyre (KL). The CALs, specifically spessartites and vogesites, possess same mineralogy as andesites, diorites, absorkites and shoshonites, i.e. plagioclase-hornblende-feldspar± clinopyroxene± biotite. Nevertheless, the characteristics given below can be used to distinguish lamprophyres (Rock, 1991):

a) castellated, globular and panidiomorphic textures;
b) lack of orthopyroxene bur enrichment of olivine;

c) amphibole, clinopyroxene and mica which are far more Mg-rich;
d) presence of alkali-rich pyriboles, Zn-rich spinels, primary carbonates and sulphates and
e) higher Mg-nubmber (Mg#), K_2O, Ba, Rb, Sr, V, Ni and LREE/HREE

In general, alkaline igneous rocks such as carbonatites, kimberlites, lamprophyres of Precambrian age are rare and have been reported sporadically in few geological terrains only when compared to their occurrence in the Phanerozoic (Blihsert- Tot et al., 1996). Blihsert-Toft et al. (1996) advocated few possible reasons for their rare occurrence as given below.

• either lamprophyres and related rock types derive from very small volumes of melt and/or did not persist through time.
• or thermodynamic conditions for the generation of such melts were unsuitable
• or lower CO_2 contents in the melting regions did not support the formation of silica-undersaturated magmas
• or the absence of metasomatized lower lithosphere prohibited the formation of rift-type magmas in general.

The calc-alkaline types are characteristically found in convergent tectonic environments, whereas alkaline and ultramafic types are associated with extensional and divergent tectonic environment and in anorogenic settings. It is observed that the ultramafic and other lamprophyres are often found as dykes or plugs (Rock 1991).

In recent years, considerable research is being carried out by various workers on alkaline rocks in general and lamprophyres in particular. As per current definition, alkaline lamprophyres are hydrous equivalents basalts from the divergent margins (rift zones) as well as continental intra-plate (plume related) environments (Chen and Zhai, 2003. Orejana et al., 2008; Chalapathi Rao et al., 2012; Stoppa et al., 2014; Lu et al., 2015) whilst calc-alkaline lamprophyres are predominantly associated with the convergent settings (Hoch et al., 2001; O'Leary et al., 2009; Garza et al., 2013; Karsli et al., 2014; Ma et al., 2014). The shoshonitic lamprophyres are equivalents of calc-alkaline lamprophyres and are frequently considered as deeper mantle derivatives depicting mantle enrichment processes and having mixed affinities to both alkaline and calc-alkaline lamprophyres (e.g., Rock 1987, 1991).

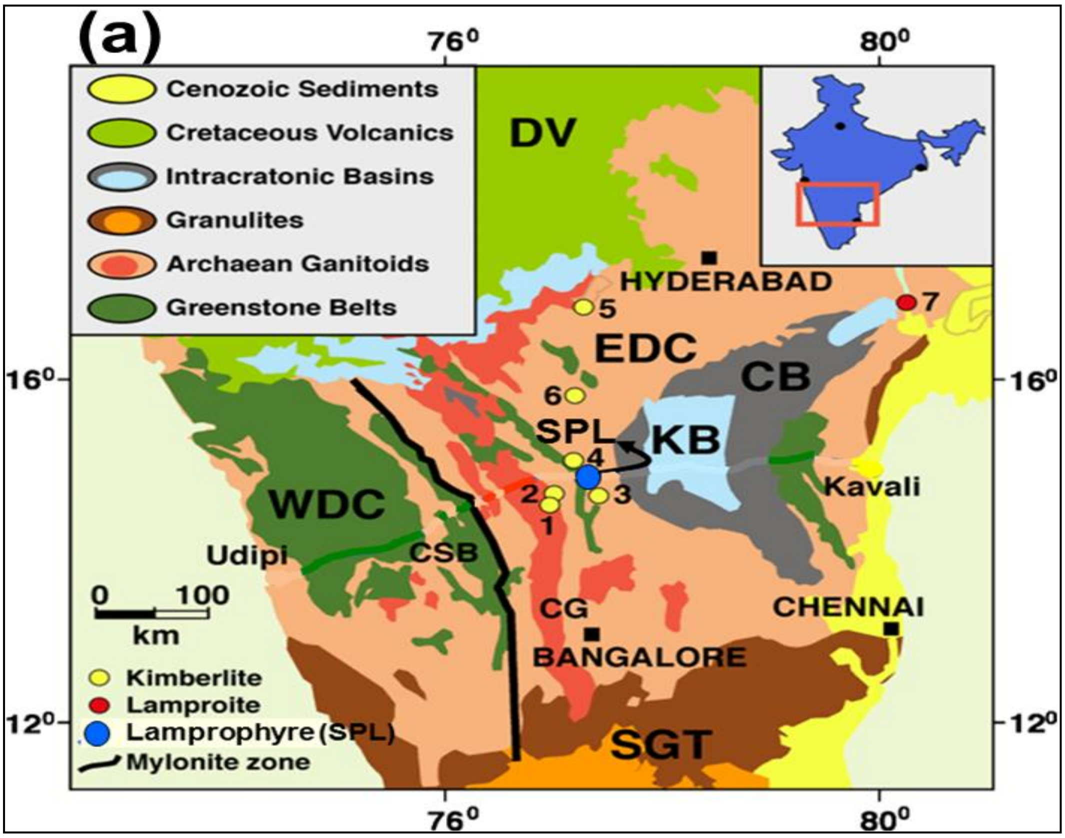
The peninsular India has perceived emplacement of many kimberlite, lamproite and lamprophyre intrusions, especially in various cratons viz., Eastern Dharwar Craton (EDC), Aravalli-Bundelkhand and Bastar-Bhandara Craton (Nambiar, 2007, Chalapathi Rao, 2008). In the EDC, a famous occurrence of lamprophyres is recorded as Prakasam Alkaline Province (PAP) in Prakasam district of Andhra Pradesh (Leelanandam, 1980, 1989; Leelanandam and Srinivasan, 1986) and more than 100 lamprophyre dykes have been recorded from the Elchuru Pluton of Cuddapah Intrusive Province (CIP) (Madhavan et al., 1995). The EDC alone hosts the maximum number and variety of lapmrophyres (*sensu lato*) (Madhavan et al., 1998). Majority of Indian lamprophyres possess a geological age ranging from Meso-proterozoic (Madhavan *et al.*, 1998) to Tertiary (Nambiar, 2007). However, Sugavanam et al. (1994) reported metalamprophyre belonging to Archaean age from Nuggihalli schist belt (NSB) of Karnataka. Of late, four lamprophyre dykes have been reported from Kalwakurty of Telangana within the EDC (Meshram and Rao, 2009).

Many researchers postulated the co-genetic, co-spatial and co-eval association of kimberlites, lamproites, carbonatites and lamprophyres (e.g. Secher & Larsen 1980, Blihsert- Tot et al., 1996, Tappe, 2005). At a distance of 1.8 Km towards west of Udiripikonda village, Anantapur district, yet another shoshonitic lamprophyre (UKL) dyke, occurring in juxtaposition to an E-W trending dolerite dyke, about 2.5 km south of SPL was reported by the Geological Survey of india (GSI) in 1998 by Ravi et al. (Pandey et al., 2017). Furthermore, occurrence of several kimberlites in this area is well-known. Even though alkaline silicate rocks (e.g. melilitolites, ijolite, phonolite, syenite, lamprophyres, kimberlites, ultramafic-mafic rocks, carbonatites etc.) are commonly associated with each other (Bell 1998; Bell et al. 1998; Woolley 2003; Tappe et al. 2011. Chalapathi Rao et al., 2014), many workers have apprehended and have questioned the petrogenetic relationship between these rocks (Harmer 1999; Gittins and Harmer 2003; Srivastava et al. 2005). Despite varied opinions, lamprophyres offer a wide scope to understand the geochemical characteristics of the sub-continental lithosphere in the areas of their occurrence. Similar to the UKL, the lamprophyre occurrence at Sivarampet also offers a rare opportunity to study the petrogenetic relationship if at all exists, between lamprophyres and kimberlites. The widely accepted concept for the genetic relationship of these rocks is suturing of the eastern and western domains of the Dharwar Craton by Neo-Archaean convergence and subduction (Jayananda et al., 2013). In records of the GSI, there was a mention of a lamprophyre in north of Sivarampet by Rao and Jayaraman (1981) (cf. Reddy, 2003). Though the exact geographic location of the lamprophyre occurrence was not traced in the consulted literature; the authors have located an outcrop while carrying out systematic geological field traverses in parts of Wajrakarur Kimberlite Field (WKF) and presume that the lamprophyre presented herein is the same as the occurrence mentioned by the GSI. The aim of this paper is to present first-hand information on field geological, petrological and geochemical characteristics of lamprophyre occurrence at Sivarampet (SPL). From this study, it is observed that the SPL possesses mineralogical, petrographic and geochemical characteristics similar to lamprophyres mentioned by previous workers (e.g. Rock, 1991; Blihsert-Tot et al., 1996, Madhavan et al., 1998, Pandey et al., 2017).

II. Geological Setting

The Dharwar craton is a granite-greenstone terrain of Archaean age intruded by numerous mafic dyke swarms of Proterozoic age with sedimentary depositional regimes such as Cuddapah, Kurnool, Bhīma and Kaladgi basins (Ramakrishnan and Vaidyanathan, 2008). The Archaean granitic rocks belong to the trondhjemite- tonalite- granodiorite (TTG) suites which are collectively termed as the 'Peninsular Gneisses'. The Dharwar craton is divided into two main domains viz., the eastern Dharwar craton (EDC) and the western Dharwar craton (WDC) distinctly divided by the Chitradurga Shear Zone located at the eastern extremity of Chitradurga schist belt which includes a linearly trending Closepet granite intrusion (Friend and Nutman, 1991) (Fig. 1a). The outcrop is easily accessible from Anantapur- Bellary highway, at about 1.5 km north of Sivarampet village on the way to Marutla colony/village (Fig.1b).

As per geophysical interpretations, it was understood that the crustal column and lithospheric keel are thinner beneath the EDC compared to the WDC. The EDC is emplaced with numerous alkaline rock intrusions derived from the deep mantle, such as kimberlites, lamproites and lamprophyre. Most of these occurrences are prominently reported from the western, northern and northwestern peripheries of the Cuddapah basin (Chalapathi Rao, 2008, Meshram et al., 2015; Pandey et al., 2017) which represent an extensive alkaline magmatic event spanning from 1.38 to 1.1 Ga (Osborne et al., 2011; Chalapathi Rao, 2013). Among all kimberlite fields in the EDC, the WKF occupies largest geographical area and hosts a plethora of more than 45 kimberlites and lamproites (Shaikh et al., 2016). Majority of the kimberlites and related rocks of the WKF occur at the intersection of either NW-SE or NE-SW trends (Fareeduddin and Mitchell, 2009) and morphostructurally occur in the peripheries of domal structures such as Marutla, Katrimala, Cherlopalli domes (Phani, 2015). The SPL occurs within granitoid country in the western peripheries of Marutla dome. During field studies it was observed that mafic dykes, trending more or less E-W to ENE-WSW, occur cutting across the Marutla dome. The SPL occurs within the WKF, in the close purlieu of UKL, kimberlite pipes- 5, 13 and 16 situated at Udiripikonda, Muligiripalli, Tummatapalli discovered by the GSI and Pennahobilam (Phani and Raju, 2017) respectively. In the study area, at several locations, abrupt enrichment of potash feldspar locally within the granite has been observed. Occurrence of intricate mafic enclaves within the PGC rocks giving rise to agmatites is also not an uncommon feature.



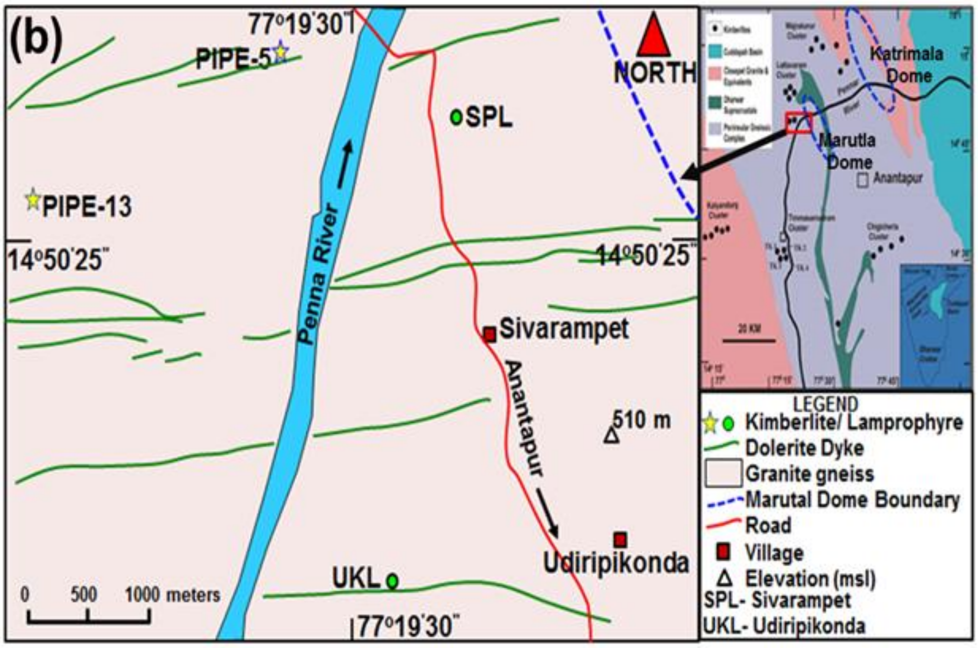


Figure 1. (a) Regional geological milieu of the eastern Dharwar craton (Griffin and O'Reilly, 2004). WDC-Western Dharwar Craton, EDC-Eastern Dharwar Craton, SGT, Southern Granulite Terrain, EGGT-Eastern Ghats Granulite Terrain, CB-Cuddapah Basin, KB-Kurnool sub-Basin, DV-Deccan Volcanics, GG-Godavari Graben, CSB-Chitradurga Schist Belt and CG-Closepet Granite. Kimberlite/Lamproite clusters: 1-Kalyandurg, 2-Brahmanapally, 3-Chigicherla, 4-Wajrakarur, 5-Mahabub Nagar, 6-Raichur and 7-Ramannapeta. SPL- Sivarampet Lamprophyre. (b) Location of Sivarampet lamprophyre (SPL) with respect to kimberlite pipes-5, 13 and Udiripikonda lamprophyre (UKL). Pennahobilam pipe (P16), situated in the northern part of the study area, is not shown in the map. Generalised geology, modified after Naqvi (2005) and regional geological map of WKF after Nayak and Kudari (1999).

In general the country is made up of granites and gneisses intruded by dolerite dykes. Geomorphologically, the terrain is rugged forming pediplain-pediment-inselberg complex. The SPL occurs as a small intrusion in a mound composed of coarse-grained granite of Peninsular Gneissic Complex (PGC) (Fig.2a). Based on several closely spaced systematic traverses carried over 2 Sq.Km. encircling the outcrop, it is observed that the occurrence has no linear extensions but it is confined to small area of approximately 15x 15 meters and hence it is presumed to be a plug type intrusion. The SPL contains angular granitic clasts, which were entrained during the emplacement of lamprophyre, giving rise to brecciated appearance. The weathered/mottled surface is greenish brown and the fresh surface is dark greenish (Fig. 2b, c and d). The rock surface exhibits typical weathered surface characteristic of a lamprophyre. At many places in the outcrop, the surface has undergone weathering giving rise to pitted surfaces due to removal of softer minerals. (Fig. 2e). The lamprophyre intrusion forms few dykelets (width 10-15 cm) and stringers within granitic country rock (Fig.2f). The granitic rock hosting the lamprophyre intrusion differs from that of the country rock in possessing deeply reddened feldspar while the grey granite prevails ubiquitously in the surroundings (Fig.2g and h).

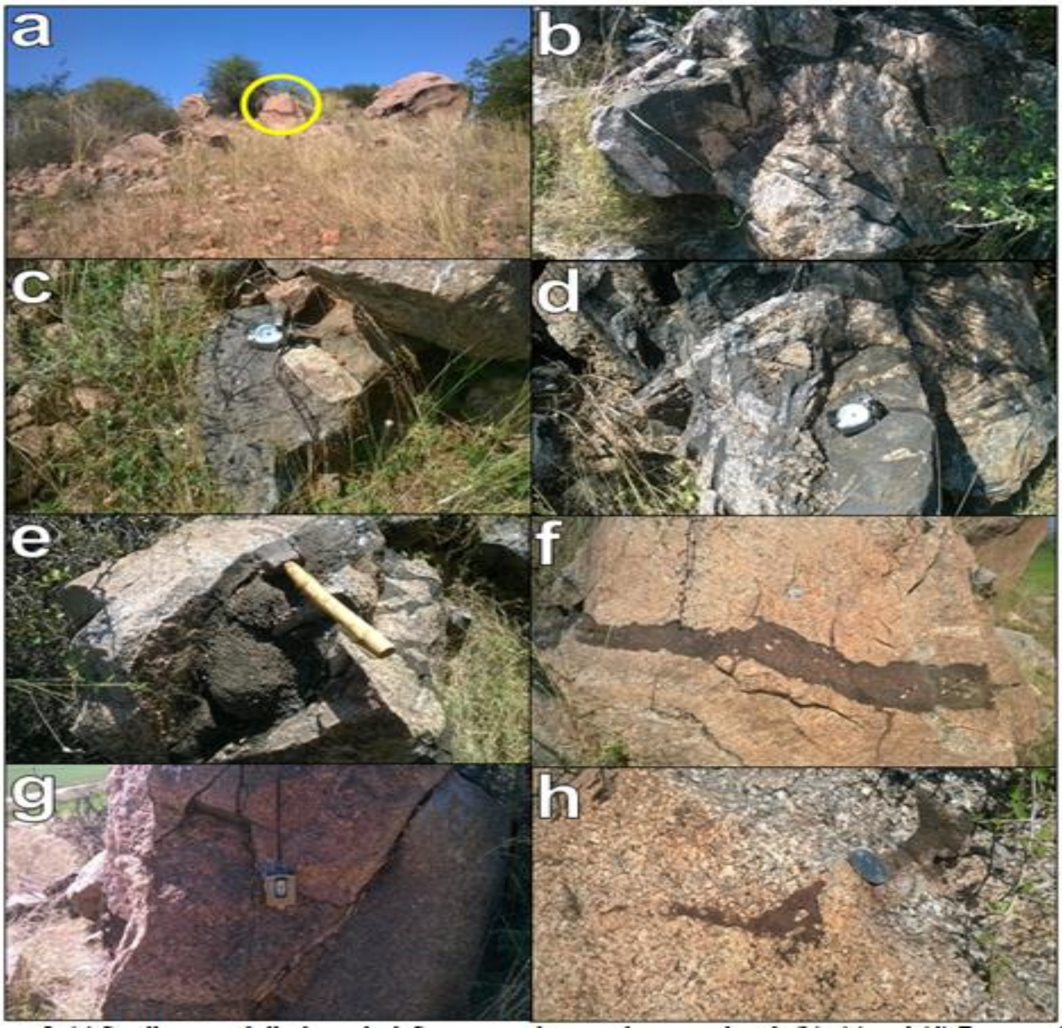


Figure 2. (a) Small granitic hillock in which Sivarampet lamprophyre emplaced. (b), (c) and (d) Brecciated appearance of granitoid due to lamprophyre emplacement. Note angular granitic clasts varied size (e) Typical weathering surface of lamprophyre. (f) Lamprophyre dykelet and stringers shown in yellow encircled portion of (a). Note minute crustal granitoid angular fragments. (g) Reddened feldspars in the granite host rock and (h) Coarse grained texture in grey granite at the close proximity of the lamprophyre plug.

III. Analytical Methodology

Six fresh samples of lamprophyre were collected and analysed for petrography and geochemistry. Several thin-sections were made at Gita Laboratories, Kolkota and studied under petrological research microscope (Leica DM750P) at Department of Geology, University College of Science (Saifabad), Osmania University, Hyderabad. The samples contain undiscernible minute fragments of crustal granitoid. After removing the visible crustal fragments in the samples, the major, trace and rare earth element concentrations were determined, using standard digestion techniques at Shiva Analyticals (India) Pvt. Limited, Bangalore, deploying XRF and ICPMS and ICPOES. Analyses of standards and repeat sample analyses were also made to demonstrate accuracy and precision for both major and trace and REE analyses.

IV. Petrography

Megascopically, the SPL is melanocratic rock predominantly comprising mafic minerals like biotite, phlogopite, pyroxene, amphibole with rare feldspar. In general, the rock exhibits inequigranular, holocrystalline panidiomorphic texture in hand specimens. The common opaque minerals are mostly ilmenite, magnetite. The rock contains inseparable fragments of crustal xenoliths of granitic composition. Phlogopite is the most characteristic ferromagnesian mineral in potassic-ultrapotassic intrusives like kimberlite, lamproite and rarely in lamprophyres (minnettes) (Chalapathi Rao and Madhavan, 1996). It occurs as megacrystal or macrocrystal and microcrystal- groundmass constituent in kimberlite and lamproite whereas in the lamprophyres it is restricted to microphenocryst phase (Rock, 1990).

Under the microscope, the SPL shows porphyritic texture, with phenocrysts of euhedral clinopyroxene (augite) (Fig.3a). The groundmass is made up plagioclase, tiny pyroxenes with a turbid appearance. Numerous grains of phlogopite are seen (Fig. 3b). Both biotite and phlogopite microphenocrysts are found to be ubiquitous. Garland of biotite bordered with perovskite are not so uncommon (Fig.3c). The pyroxene grains exhibit brush-like structures surrounded by closely-knit fabric of biotite and clinopyroxenes (Fig. 3d). The biotite flakes are numerous and ubiquitously distributed all over the rock (Fig. 3e and f). Serpentinised olivine pseudomorphs and biotite enclosed in a highly altered and turbid looking groundmass comprising plagioclase, euhedral clinopyroxene (augite) and biotite (Fig.3g and h). The phenocrysts are highly altered to serpentine and calcite with the development of acicular amphiboles.

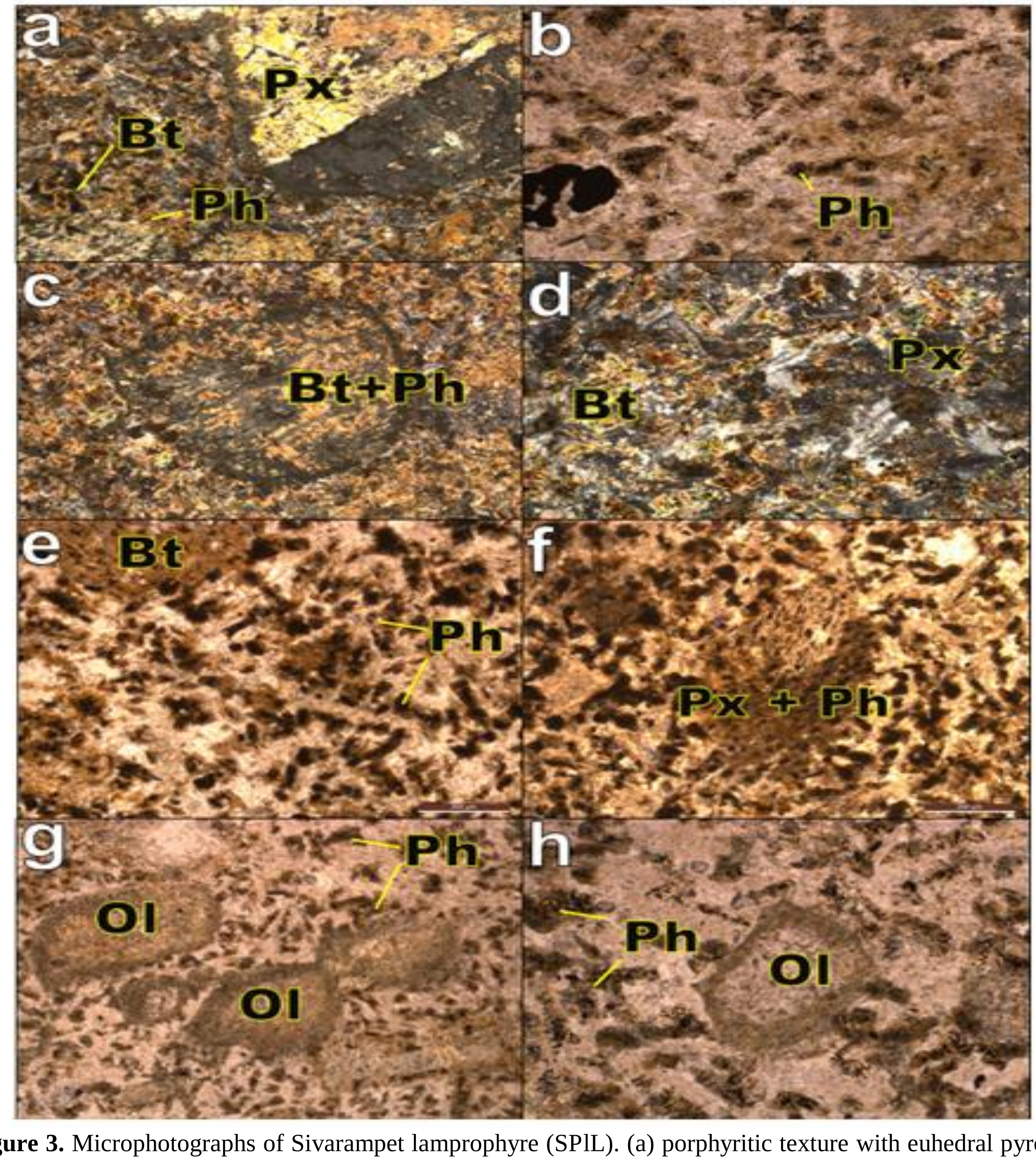


Figure 3. Microphotographs of Sivarampet lamprophyre (SPlL). (a) porphyritic texture with euhedral pyroxene microphenocrysts. (b) Profuse population of phlogopite microphenocrysts within a fine-grained groundmass. (c) Garland of biotite as microphenocrysts as well as groundmass bordered by perovskite corona. Note enrichment of phlogopite. (d) Euhedral pyroxene and biotite grains giving rise to panidiomorphic texture typical of lamprophyres. (e) Biotite microphenocrysts (f) Pyroxene and phlogopite grains forming globular texture. (g) and (h) Resorbed olivine grains engulfed by phlogopite microphenocrysts. Abbreviations: Bt- biotite, Ol- olivine and Px- pyroxene, Ph- phlogopite.

V. Geochemistry

The major elements concentrations of the SPL are listed in Table 1. The trace and rare earth element (REE) concentrations are shown in Table 2. Geochemically, the SPL samples show a remarkable ultrabasic (SiO_2 <46 wt %) and highly potassic (2.89-3.61 wt %). The Al_2O_3 and TiO_2 range from 11.7 to 12.81wt% and 1.5 to 1.78 wt% respectively. The CaO content ranges from 5.4 to 6.21 wt %. The major oxide concentrations show a good correlation with respect to MgO enunciating the involvement of fractionation. The Mg# (Mg/Mg+Fe^{2+}) X 100) in rock ranges from 52 to 55.6 whilst that in silicate minerals ranges from 76.3 to 82. The SPL possesses K_2O>Na_2O and exhibits calc-alkaline nature. As a whole, the major element concentrations of the SPL are comparable with those shown by averages of world-wide alkaline lamprophyres (Rock, 1987, 1991). The CIPW normative calculations show modal quartz (0.03to 4.23 wt %) which might be due to generation of lamprophyric magma at a higher pressure (Hirose and Kushiro, 1993) and relatively slightly shallower depths than those of kimberlites and lamproites (Paul, 1991). The higher concentration of SiO_2 in normative wt % is possibly due to crustal contamination by granitoid rocks. Further, quartz in basic magmas represents an anomalous residual phase because its experimentally determined diffusion rate in basic melts is higher than that for most other minerals (Edwards and Russell, 1996). Several granitic xenocrysts are present in the SPL outcrop, which offer important information about the continental crust beneath the region and about the physical conditions of the ascending lamprophyric magma.

Table 1. Major element concentrations in the Sivarampet lamprophyre along with published data used for comparison (Bayyaram- Meshram et al., 2015; Polayapalli- Subrahmanyam et al., 1987 ; Madhavan et al., 1998)

Sample#	SVP01	SVP02	SVP03	SVP04	SVP05	SVP06	Bayyaram	Bayyaram	Bayyaram	Polayapalli	Purimetla
					MAJOR ELEMENT ANALYSIS						
SiO_2	45.2	44.64	44.34	44.77	45.65	44.78	40.68	40.96	40.82	53.21	46.91
TiO_2	1.62	1.7	1.5	1.61	1.78	1.76	1.57	1.67	1.62	1.53	2.24
Al_2O_3	12.79	11.7	13.2	12.81	11.87	11.87	11.83	12.24	12.035	11.92	13.8
Fe_2O_3	9.1	8.67	10.02	9.21	9.12	10.01	12.48	11.18	11.83	4.42	4.91
FeO	8.19	7.89	7.77	8.19	7.81	8.21				3.88	7.44
MnO	0.18	0.21	0.17	0.19	0.21	0.19	0.36	0.34	0.35	0.3	0.23
MgO	5.3	4.8	5.45	5.32	5.32	5.35	7.97	7.69	7.83	7.11	8.06
CaO	5.93	5.4	6.01	5.94	6.03	6.21	10.58	10.85	10.715	5.99	7.23
Na_2O	1.89	1.9	1.76	1.92	1.87	1.81	0.74	0.82	0.78	3.96	3.22
K_2O	3.58	3.4	3.2	3.61	2.89	3.38	5.65	5.74	5.695	5.28	3.34
P_2O_5	0.45	0.3	0.43	0.46	0.55	0.52	1.21	1.38	1.295	1.02	0.71
LOI	5.37	4.87	5.25	5.63	6.01	5.02	4.98	5.67	5.325		
Total	99.60871	95.48	99.1	99.65101	99.11	99.11	98.05	98.54	98.295	98.62	98.09

Table 2. Trace and Rare Earth element data of Sivarampet lamprophyre and published data for comparison as in Table 1.

Sample#	SVP01	SVP02	SVP03	SVP04	SVP05	SVP06	Bayyaram	Bayyaram	Bayyaram	Polayapalli	Purimetla
					TRACE ELEMENT ANALYSIS						
Sc	15.82	13.2	14.45	14.82	16.12	16.24	27.6	25	26.3	20	18.08
V	120.99	124.5	132	119.83	125.4	131.67	175	187.8	181.4	155	163
Cr	400	412	523	380	423	480	1015	890	952.5	174	252
Co	33.64	31.23	32.23	32.64	35.23	32.67	26	32	29	41	55.35

Ni	99.61	101.2	112.4	95.61	103.24	104.34	195	206	200.5	119.41	172.47
Cu	38.85	41	43	39.8497	41.23	42.67	36	16	26	54	40
Zn	78.95	81	81.2	79.95	81.23	81.23	0.5	0.5	0.5	192	167
Ga	18.12	17.5	19.01	17.21	17.68	19.32	13	8.9	10.95	21.55	22.57
Rb	108.24	111.2	113.45	107.24	111.4	115.45	132.8	137.5	135.15	296	79.24
Sr	629.25	632.3	635.4	628.25	721	643.32	618	677	647.5	942	918
Y	22.33	24.5	25.3	22.332	23.22	25.34	47	27	37	37.48	27.49
Zr	212.99	223.45	218.45	212.99	218.66	218.34	744	752	748	922	287.4
Nb	38.5	36.78	37.8	38.5	40.03	42.67	24	27	25.5	64	113
Ba	1100	1150	1050	1100	1210	1270	1983	2213	2098	4854	1459
Hf	4.08	4.12	3.89	4.08	4.23	4.23	10.7	11.65	11.175	21.51	5.99
Ta	2.12	2.32	2.34	2.12	2.23	2.23	1.12	1.2	1.16	4.53	8.62
Pb	8.27	7.9	8.1	8.27	8.34	8.34	5	5.9	5.45	24.38	8.94
Th	4.66	4.78	4.67	4.66	5.1	5.12	67	75	71	137.42	10.37
U	0.68	0.75	0.72	0.68	0.78	0.83	7.43	7.96	7.695	15.46	1.58
RARE EARTH ELEMENT ANALYSIS											
La	54.78	64	61	53.25	53.35	57.8	221.86	195.09	208.48	281	79
Ce	128.86	132	134	142	131.25	142.68	405.94	371.93	388.94	548	144.12
Pr	13.68	14.2	12.89	13.6	14.32	14.12	49.87	44.76	47.32	57	14.82
Nd	50.89	52.45	51.34	51.78	51.65	53.34	164.83	150.28	157.56	225	62
Sm	8.63	9.21	8.9	8.89	9.32	8.91	23.3	21.32	22.31	25.21	9.11
Eu	2.24	2.34	2.5	2.28	2.35	2.25	5.09	4.47	4.78	5.61	2.65
Gd	7.53	8.23	7.8	8.12	8.15	8.25	16.93	14.28	15.61	19.27	7.89
Dy	4.69	5.20	4.8	4.76	5.21	5.27	10.97	7.63	9.3	8.11	5.42
Er	2.43	3.01	2.87	3.03	2.78	3.12	4.85	2.92	3.89	2.93	2.22
Yb	1.88	1.98	1.77	2.02	2.02	2.13	3.35	2.30	2.83	2.1	1.68
Tb	0.98	1.02	1.02	0.97	1.23	1.21	2.26	1.83	2.05	1.77	1.04
Ho	0.92	1.22	1.01	0.94	1.67	1.05	1.97	1.24	1.61	0.93	0.83
Tm	0.27	0.31	0.25	0.32	0.36	0.32	0.65	0.43	0.54	0.38	0.32
Lu	0.26	0.25	0.26	0.27	0.29	0.28	0.49	0.34	0.42	0.28	0.24
Σ REE	278.06	295.42	290.41	292.23	283.95	300.73	912.36	818.82	865.59	1177.59	331.34

The trace element Ni has low abundance and ranges from 95.61 to 112.4 ppm whereas the concentration of Cr is high (380- 523 ppm). The LILE (large ion lithophile elements) are substantially higher in the SPL when compared to those in Bayyaram, Polayapalli and Purimetla. Barium concentration ranges from 1050 to 1270 ppm whereas Sr ranges from 628.25 to 721 ppm. Such a high concentration of the LILE along with elevated Ba/Nb (27.78 to 31.27 ppm) and Ba/La (17.21 to 22.68 ppm) indicate an enriched mantle source for the SPL (Ryan et al., 1996; Kepezhinskas et al., 2016). However, the source of Ba could also be derived from fluid. Furthermore, the enrichments of Nb and Ta relative to Hf, coupled with small depletion in HRE elements in the SPL samples when compared to lamprophyres of Bayyaram, can probably be explained by enrichment of the upper mantle source (Pearce, 1983).

The geochemical data has been plotted in various ternary and binary diagrams to elucidate the geochemical character of the SPL. The ternary plots between MgO-Al_2O_3-CaO and CaO-TiO_2-SiO_2/10 (Rock, 1987) expound that the SPL is alkaline in nature similar to lamprophyres of other regions (Bayyaram, Polayapalli and Purimetla) considered in this study (Fig. 4a and b).

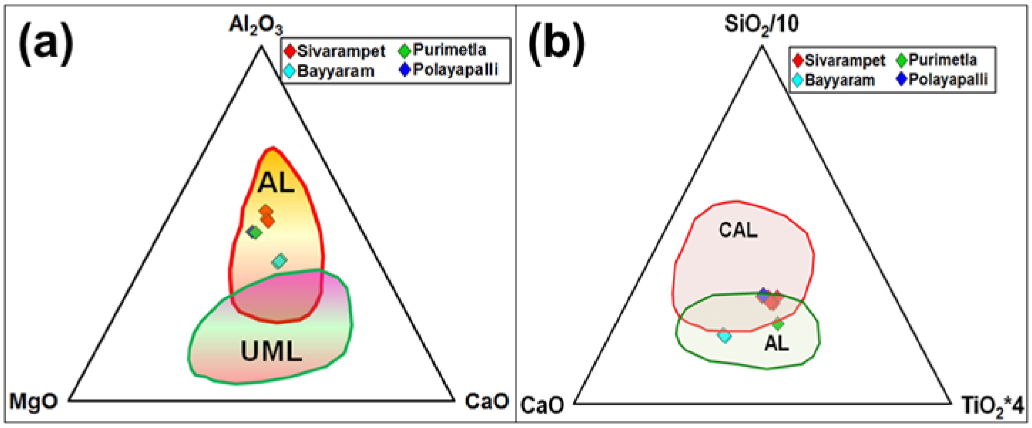


Figure 4. Ternary diagrams showing alkaline nature of Sivarampet lamprophyre samples in comparison with lamprophyes of Bayyaram, Polayapalli and Purimetla (Table 1).

The ternary diagram between Fe_2O_3, Al_2O_3 and MgO (Cornelissen and Verwoerd, 1975 and Kornprobst, 1984), the SPL samples plot in the lamprophyre field whereas the lamprophyres of Purimetla and Polayapalli plot in overlapping field of lamproites and lamprophyres (Fig 5a). In the ternary diagram between MgO-K_2O-Al_2O_3 (Bergman, 1987), the SPL samples are positioned in lamprophyre field whereas lamprophyres of Bayyaram and Polayapalli plot in the overlapping fields of lamproites and lamprophyres (Fig.5b). In the binary diagram of SiO_2 versus (Na_2O+K_2O) (Rock, 1987), the SPL samples plot in ultramafic to alkaline lamprophyre fields (Fig.5c). Further, in the binary plot of Al_2O_3 and CaO (Foley et al., 1987), the SPL samples plot in the marginal zone of lamproites and lamprophyre. However, samples of Bayyaram and Purimetla plot in lamprophyre field whereas the Polayapalli sample plots in the lamproite field (Fig.5d). In this plot, it is noticed that lamprophyres of Bayyaram, Polayapalli and Purimetla are stationed mostly in the alkaline field (Fig.5d).

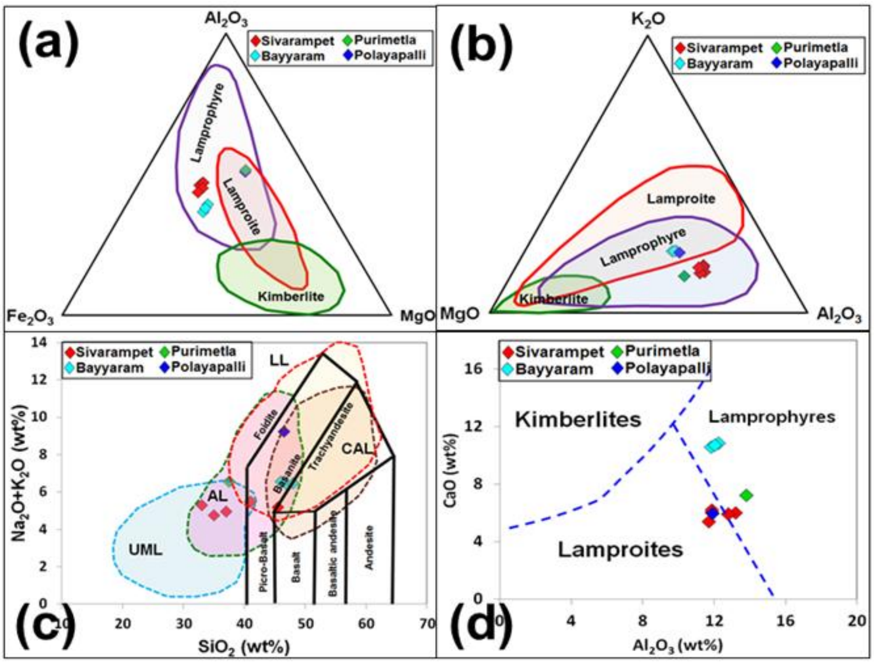


Figure 5. Plots showing geochemical character of Sivarampet lamprophyre based on major element components. (a) and (b) Ternary plot showing Sivarampet samples in lamprophyre field (c) Binary diagram between SiO_2 and Total Alkali (Na_2O+K_2O) showing alkaline character and (d) Binary diagram displaying Sivarampet lamprophyre in the marginal zone of lamproite and lamprophyres. Comparative data from sources as in Table 1.

In the binary diagram of MgO versus SiO_2 (Lefebvre et al., 2005), the SPL samples plot in the calc-alkaline lamprophyre field, similar to lamprophyres of Purimetla, Polayapalli whereas the Bayyaram lamprophyres plot in the alkaline field (Fig. 6a). The bivariate diagram of SiO_2 versus K_2O (Peccerillo and Taylor, 1976) indicates that the SPL samples plot in the high calc-alkaline series field along with Purimetla lamprophyre. However, one sample plots in the shoshonite field similar to Bayyaram and Polayapalli lamprophyres (Fig. 6b). The bivariate diagram between MgO and K_2O (Peccerillo and Taylor, 1976) clearly shows that the SPL samples plot in the high-potassium field whereas the Bayyaram lamprophyre plots in the marginal zone of high-potassium and ultra-high potassium regions (Fig. 6c). In the bivariate diagram of Na_2O versus K_2O (Turner et al., 1996), the SPL samples plot in the field of shoshonite similar to lamprophyres of Polayapalli and Purimetla. The Bayyaram lamprophyres plot in the ultrapotassic field (Fig. 6d). The shoshonitic lamprophyres have attracted researchers with the discovery of volcaniclastic shoshonitic lamprophyre breccias in Wawa, Ontario, Canada which are reported to be diamondiferous (Buckle, 2002, Ayer et al., 2003, Vallancourt et al., 2003, Lefebvre, 2005). The SPL being emplaced in close proximity to kimberlite/lamproite pipes in its occurrence offers a scope for further investigations to ascertain its diamondiferous nature.

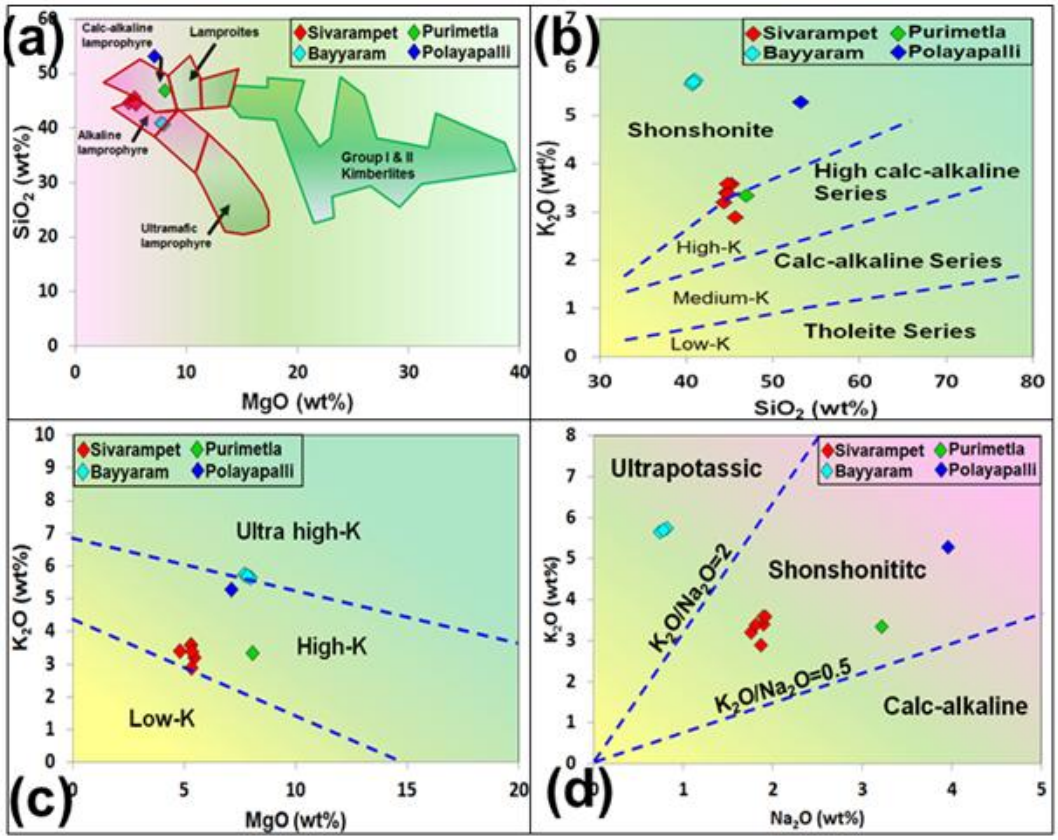


Figure 6. Binary plots showing geochemical character of Sivarampet lamprophyres. (a) MgO- SiO_2 diagram showing alkaline character. (b) SiO_2-K_2O diagram with Sivarampet samples in high calc-alkaline to shoshonite fields. (c) MgO- K_2O plot showing high potassic nature and (d) Na_2O- K_2O plot showing shoshonitic affinity of Sivarampet lamprophyres (read Shonshonitic in figure as Shoshonitic). Comparative data from sources as in Table 1.

Using the binary plot between Al_2O_3 and TiO_2 (Thorpe, 1987; Muller et al., 1992), it can be stated that the SPL along with lamprophyres of Bayyaram, Purimetla and Polayapalli must have emplaced in the transition zone of 'within plate' and 'arc-related' tectonic environments (Fig 7a). The inferences drawn from the binary diagram between K_2O and TiO_2 (Thorpe, 1987; Muller et al., 1992) also support this aspect (Fig.7b). The binary diagram involving ratios of Ba/Rb and Rb/Sr (Furman and Graham, 1999) depict involvement of phlogopite mineral phase in the mantle source for SPL samples similar to Bayyaram, Polayapalli and Purimetla (Fig.7c). In the binary diagram of La/Nb and Ba/Nb ratios (Kepezhinskas et al., 2016), the SPL samples straddle towards subduction enrichment (Fig.7d)

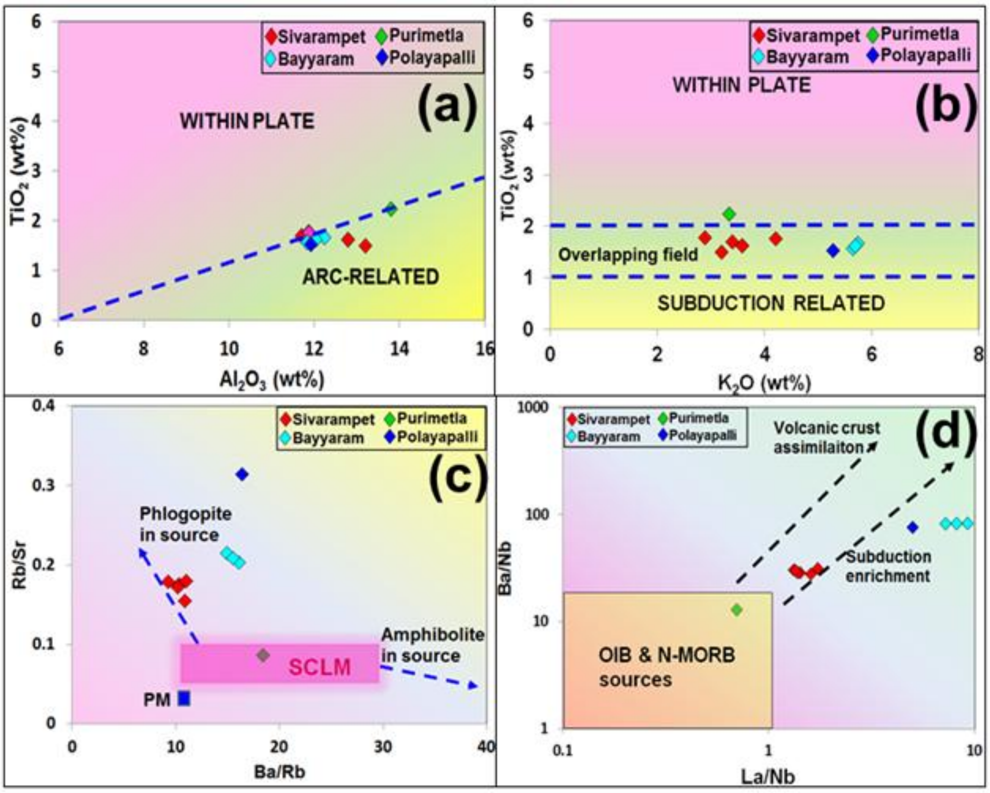


Figure 7. Binary diagrams depicting tectonic setting of Sivarampet lamprophyre. (a) Al_2O_3-TiO_2 plot showing arc-related and character of SPL samples. (b) K_2O-TiO_2 plot showing the SPL samples positioned in the overlapping field of subduction-within plate settings. (c) Variations in the ratios of Ba/Rb and Rb/Sr showing presence of phlogopite in the SPL samples and (d) Diagram of La/Nb and Ba/Nb ratios showing affinity of subduction enrichment for the SPL samples. Comparative data from sources as in Table 1 and 2.

The SPL samples show coherent chondrite normalised REE patterns with light rare earth elements (LREE) being 200 times enriched than the chondritic values (Fig. 8a). The steeper REE patterns with high LREE content and relatively low HREE content suggest low degree of partial melting. The low concentration of HREE than those of Bayyaram lamprophyre and similar to Polayapalli and Purimetla lamprophyres suggests control of strong garnet as a residue (le Roex et al., 2003). The Polayapalli lamprophyre is reported to display unusually higher concentrations of REE. The lack of Eu anomaly rules out plagioclase fractionation in the SPL samples. In the primitive mantle normalised multi-element diagram (Fig.8b), the SPL samples show a noticeable enrichment in the concentrations of Rb, Sr, Ce and Ba (LILE) but lower concentrations of U and Th. The concentrations of HFSE (high field strength elements) group comprising elements like Nb, Hf, Th and U have low concentrations. The presence of HFSE anomalies is postulated to be indicators of arc-related magmatism or subduction modified lithospheric mantle (Wilson, 1989; Pearce, 2008). In case of SPL, the HFSE anomalies are not observed. Further, high Nb/U (49.04 to 56.61 ppm) and Nb/Ta (15.85 to 19.13 ppm) ratios also reflect an enriched mantle reservoir (Hofmann et al., 1986; Sun and McDonough, 1989; Stolz et al., 1996). In the binary diagram of Nb and Nb/U ratio, the SPL samples decipher an OIB affinity (Fig.8c). The moderate HFSE/LREE ratio (e.g., Nb/La ratio of 0.57 to 0.74 ppm) in SPL samples, support an asthenospheric input in the lithospheric mantle source. This is also displayed in the binary plot of La/Yb and Nb/La ratios (Smith et al., 1999), wherein the SPL samples plot in lithospheric-asthenospheric region (Fig.8d).

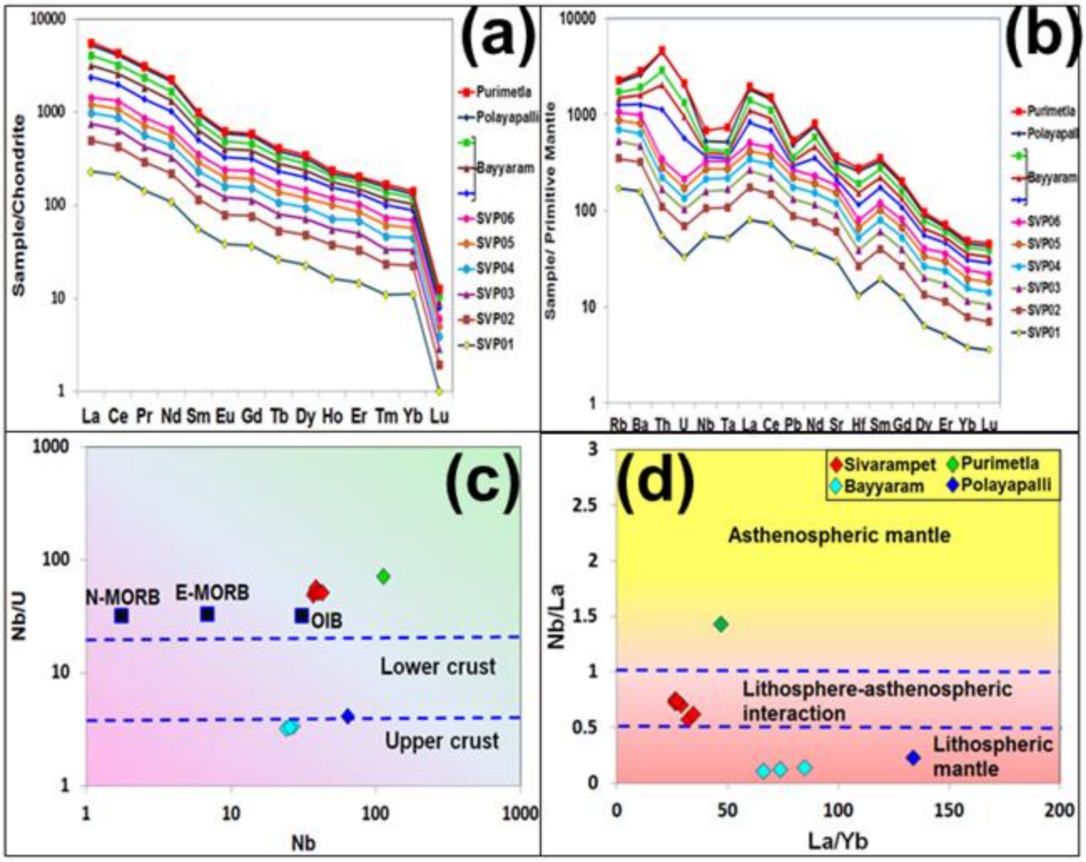


Figure 8. REE and trace element patterns in Sivarampet lamprophyre samples. (a) Chondrite normalised patterns (Sun and McDonough, 1989). (b) Primitive mantle normalised trace element patterns (Sun and McDonough, 1989). (c) Binary diagram between Nb and Nb/U displaying OIB affinity of SPL samples and (d) Binary diagram of La/Yb and Nb/La ratios showing SPL samples placed in lithosphere- asthenosphere interaction zone. Comparative data from sources as in Table 2.

Geochemically, lamprophyres are considered to be the products of melting of metasomatized mantle above ancient subduction zones as established by their high amount of compatible major and trace element concentrations (e.g., MgO, Cr, Ni, Mg#) as well as incompatible trace elements (e.g., Cs, Rb and Li). Their high volatile content has often been considered as significant in ore formation process caused or contributed by magmatic fluids (Rock 1991). It is believed that the alkaline lamprophyre (AL) and ultramafic lamprophyre (UML) magmas are originated within the upper mantle (Rock, 1991; Delor and Rock, 1991). However, recent research works have demonstrated that origin of lamprophyre involves more than one process such as contamination of ultrabasic magma with the crustal material (McDonald et al., 1985), extreme enrichment of volatiles like CO_2 and H_2O in basic magma (Currie and Williams, 1993) and low-degree partial melting of metasomatised sub-continental lithospheric mantle (Rock,1991). Presence of enriched phlogopite and biotite in the SPL samples is consistent with this aspect. However, the magmatic differentiation is widely accepted to be the hallmark of lamprophyre magmatism. A majority of EDC lamprophyres are considered to be originated from primitive melts undergoing fractionation of olivine±clinopyroxene±phlogopite±apatite mineral phases (Madhavan et al., 1998). On the other hand, the Indian Precambrian lamprophyres in the Cuddapah Intrusive Province (CIP) of EDC are delineated to be parental melts of the alkaline complexes (Ratnakar and Leelanandam, 1989; Madhavan et al., 1998).

The deplepted Ni content and moderate Mg# values in the SPL samples are suggestive of considerable crystal fractionation in the mantle derived melt and is not considered to be the character of primary magma (Green, 1971; Sato, 1977; Wallace and Carmichael, 1989). The low average concentration of Ni (102 ppm) and moderate Mg# in the SPL rock (<65) denote a predominance of fractionation and low degree of partial melting thus generating lamprophyric melt from enriched asthenospheric mantle which subsequently might have underwent fractionation.

VI. Conclusion

Based on the present investigations on Sivarampet lamprophyre, following points can be summarised. The Sivarampet lamprophyre occurring as an isolated intrusion, with no linear surficial extension of the outcrop, or in the form of a plug, to the west of Cuddapah basin and close to Marutla domal structure petrographically exhibits porphyritic and panidiomorphic texture typical of lamprophyres with mineral assemblages of phlogopite, biotite, perovskite, pyroxene and olivine. Major oxide geochemistry reveals mixed alkaline to calc-alkaline character in general and shoshonitic in particular; while trace element geochemistry suggests enriched heterogeneous mantle source due to interaction between subduction modified lithosphere and asthenosphere. The higher amount of normative quartz is attributed to contamination by crustal granitoid rocks in the SPL. The SPL plug occurs co-spatial with the kimberlite pipes (5, 13 and 16) which are presumed to be derived from shallower depths, based on their non-diamondiferous nature, indicates a probable shallower depth of origin from an enriched asthenospheric mantle which was modified by asthenospheric upwelling while the corresponding kimberlites of the area were generated from a depleted mantle sources during small-scale lithospheric extension in the Mesoproterozoic era. This manifests a wide heterogeneity of mantle composition beneath this part of the eastern Dharwar craton. Nevertheless, the discovery of diamonds in shoshonitic lamprophyres in Canada and occurrence of SPL in close proximity of kimberlite/lamproite pipes enhances scope for further investigations on possibility of diamond incidence in shoshonitic lamprophyres of the WKF.

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