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Lamprophyres from the Indian shield: A review of their occurrence, petrology, tectonomagmatic significance and relationship with the Kimberlites and related rocks

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Lamprophyres are some of the oldest recognized alkaline rocks and have been studied for almost the last 150 years. Known for hosting economic minerals such as gold, diamond and base metals, they are also significant in our understanding of the deep-mantle processes (viz., mantle metasomatism and mantle-plume-lithosphere interactions) as well as large-scale geodynamic processes (viz., subduction-tectonics, supercontinent amalgamation and break-up). The Indian shield is a collage of distinct cratonic blocks margined by the mobile belts and manifested by large igneous provinces (LIPs) such as the Deccan. A plethora of lamprophyres, varying in age from the Archaean to the Eocene, with diverse mineralogical and geochemical compositions, are recorded from the Indian shield and played a key role in clarifying the tectonic processes, especially during the Paleo- and Mesoproterozoic and the Late Cretaceous. A comprehensive review of the occurrence, petrology, geochemistry and origin of the Indian lamprophyres is provided here highlighting their tectonomagmatic significance. The relationship of the lamprophyres to the Kimberlite clan rocks (KCRs), focusing on the Indian examples, is also critically examined.

Introduction

Lamprophyre (derived from Greek word *lampros porphyrous* meaning 'glistening porphyry') is basically a field term introduced by Von Gümbel in 1874 representing its diagnostic character. Lamprophyres, for long, have been misinterpreted and confused with porphyritic varieties of igneous rocks (viz., basalts and andesites) and were considered to be 'impossible to classify' igneous rocks and treated as 'obscure petrological curiosities'. The most remarkable and

distinguishing works in the field of lamprophyres were carried out by late N.M.S. Rock. In a series of papers (summarized in Rock, 1991), he focused the petrological attention towards this very significant rock-type, which was considered until then to be enigmatic. Lamprophyres are currently defined as the mantle-derived mafic-ultramafic volatile-rich alkaline igneous rocks characterized by porphyritic-panidiomorphic texture with phenocrysts of hydrous mafic silicates such as amphibole and mica with feldspars, where recognizable, are always restricted to the groundmass (Rock, 1991).

Although these rocks are volumetrically insignificant (<1%), they have profound implications for understanding enrichment and depletion processes in the sub-continental lithospheric mantle (SCLM, e.g., Guo et al., 2004; Krmíček et al., 2011, 2016; Abdelfadil et al., 2013) and large scale-geodynamic processes (e.g., Tappe et al., 2006; Ulrych et al., 2014; Pandey et al., 2017a). Lamprophyres, together with other deep mantle-derived rocks such as kimberlites, lamproites and alkali basalt, are essentially restricted to the continental plates and their geochemistry provide invaluable clues with regard to probing the nature and evolution of the underlying mantle domains. Owing to very high contents of incompatible trace elements in primary lamprophyre magma, the assimilation of continental crust is insignificant in controlling the abundance of these elements and therefore, these rocks retain geochemical memories of mantle source regions. Some of the lamprophyres are known to be diamondiferous and some are also associated with the mesothermal gold-copper deposits (Wyman et al., 2006; Muller and Groves, 2019) and hence of economic significance. The mantle- and crustal-xenoliths and xenocrysts often entrained in lamprophyre magmas also constitute direct samples to understand the nature of the earth's continental plates (Dostal et al., 2005; Orejana et al., 2006).

International Union of Geological Sciences (IUGS) has recommended classification of the lamprophyres into three broad categories: (i) alkaline lamprophyres, which are considered as the hydrous equivalents of basalts from the divergent margins (e.g., Orejana et al., 2008; Batki et al., 2014; Stoppa et al., 2014), (ii) calc-alkaline lamprophyres, which are essentially associated with convergent settings and hence carry 'crustal' geochemical signature (e.g., Luhr et al., 1989; Owen, 2008; Garza et al., 2013; Pandey et al., 2017a, 2018b), and (iii) ultramafic lamprophyres, which are associated

with the regions of lithospheric extension, continental rifting and continental break-up (e.g., Delor and Rock, 1991; Andronikov and Foley, 2001; Foley et al., 2002; Tappe et al., 2004, 2006; Nasir, 2016; Pandey et al., 2018a).

In the Indian shield, lamprophyres have been reported from various cratons, mobile belts and large igneous provinces viz., the Eastern Dharwar Craton (EDC), the Mahakoshal supracrustal belt and the Sidhi alkaline complex in the Central Indian Tectonic Zone, the Gondwana coalfield and the Deccan large igneous province. In this paper, we review the lamprophyre magmatism from the Indian shield in space and time in terms of their occurrences, nature of the mantle source regions and geodynamic setting. We also venture to critically examine their relationships with the co-spatial and co-eval kimberlite clan rocks (KCRs).

Distribution of lamprophyres in India

The occurrences of lamprophyres from the Indian shield (Fig. 1) along with their available emplacement ages have been compiled in

Figure 1. A generalized geological map of the peninsular India (Naqvi, 2005) showing locations of the lamprophyres reported from the Indian Shield.

Table 1. Some representative field photographs, photomicrographs depicting mineralogy and textures of Indian lamprophyres are also provided in Fig. 2. Broadly, the lamprophyre occurrences can be divided into the following four groups (see also Paul, 1991):

Group 1: Occurrences in the Archaean and Paleo-Mesoproterozoic schist belts e.g., Nuggihalli (Western Dharwar craton), Kadiri (Eastern Dharwar craton), and Jungel valley, Mahakoshal belt (Central Indian tectonic zone).

Group 2: In the Precambrian granite-gneissic terrain as isolated dykes or as clusters e.g., Udiripikonda, Korakkodu, (Eastern Dharwar craton), Sidhi (Central Indian Tectonic zone).

Group 3: Associated with the Meso-Neoproterozoic alkaline

complexes e.g., Elchuru, Purimetala (Prakasam Alkaline Province), Pikkili (Southern Granulite Terrain).

Group 4: Associated spatially and temporally with the Early- and Late Cretaceous large igneous provinces viz., the lamprophyres from the Deccan Traps and the Gondwana coalfield (Rajmahal Traps).

Overall, the Eastern Dharwar Craton (EDC) hosts the maximum number of lamprophyre dykes all around the Paleo-Mesoproterozoic Cuddapah Basin. All these lamprophyres are of Mesoproterozoic in age. The Western Dharwar Craton (WDC) is known to be barren in terms of alkaline magmatism, unlike its eastern counterpart. However, Sugavanam et al. (1994) have reported the occurrence of Archean meta-lamprophyres from the Nuggihalli greenstone belt. The Southern Granulite Belt hosts numerous Neoproterozoic lamprophyres that are co-eval with the shonkinites, syenites and carbonatites and associated with the alkaline complexes. Recently, Meshram et al. (2018) have reported calc-alkaline lamprophyres from the Thanewana area, the western part of the Bastar Craton. A number of presumably Meso- to Neoproterozoic lamprophyres are also hosted in the Aravalli-Bundelkhand and Singhbhum Craton, which have been comparatively far less studied and their petrogenetic and geodynamic significance remains unexplored. Various lamprophyre dykes of Paleoproterozoic and Late Cretaceous have also been reported from the Mahakoshal supracrustal belt and Sidhi alkaline complex, in the Central India Tectonic Zone. The youngest of the lamprophyres in the Indian shield are those associated spatially with the Deccan Large Igneous Province. The Deccan lamprophyres range in age from Early to Late Cretaceous and predate, synchronous with as well as postdate the Cretaceous main flood basalt eruption (~65 Ma.). In the following sections, we review the mineralogical and geochemical characters of important lamprophyre clusters of the Indian shield along with their tectonic implications.

Eastern Dharwar Craton lamprophyres

The lamprophyres in the Eastern Dharwar Craton (EDC) are exposed in two-broad domains: (i) the Prakasam Alkaline Province (PAP) towards the east of the Cuddapah Basin at the junction of the EDC and Eastern Ghats Mobile Belt (EGMB), and (ii) towards the western margin of the Cuddapah Basin within the Eastern Dharwar Craton (Fig. 1).

The PAP lamprophyres constitute those exposed at Elchuru, Settopalle, Kommalapadu, Purimetla, Pasupugallu, Kellampalle, and Ravipadu, and have intruded a variety of host rocks including nepheline- and quartz-syenites, gabbro and granites (Madhavan et al., 1998 and references therein). These lamprophyres are meso- to melanocratic and constitute phenocrysts of clinopyroxene and olivine with biotite, plagioclase and orthoclase confined to the groundmass, classifying them as alkaline lamprophyres in general and camptonites in particular (Madhavan et al., 1998 and references therein). The Kellampalle lamprophyre, which is a plug-like body covering an area of about five square meters unlike other dyke exposures, has phenocrysts of amphibole and classified as sannaite variety (Ratnakar et al., 1992, 1996). An interesting feature of the lamprophyres exposed at Settopalle, Purimetla and Kellampalle is the presence of ocellar structure that constitute of minerals like analcite, cancrinite and nepheline, which are otherwise absent in the host rock (Leelanandam and Ratnakar, 1980; Leelanandam and Srinivasan, 1986; Ratnakar et al., 1992). Clinopyroxene is ubiquitous in these lamprophyres and compositionally a salite (Madhavan et al., 1998). These

Table 1. Distribution and age of lamprophyres from the Indian shield (updated after Chalapathi Rao, 2008).

	Locality	Lamprophyre type	Age	Important References
Eastern Dharwar craton (EDC)				
1	Elchuru	minette, sannaite, tjosite, damkjernite	1242±33 Ma; 1321 Ma	Subba Rao et al. (1989); Madhavan et al. (1992); Upadhyay et al. (2007);
2	Purimetla	sannaite, camptonite	Mesoproterozoic	Leelanandam and Ratnakar (1980)
3	Settupalle	camptonite	Mesoproterozoic	Leelanandam and Srinivasan (1986)
4	Pasupugallu	camptonite	Mesoproterozoic	Madhavan et al. (1998)
5	Kommalapadu	camptonite	Mesoproterozoic	Madhavan et al. (1998)
6	Kellampalle	sannaite	Mesoproterozoic	Ratnakar et al. (1996)
7	Ravipadu	camptonite	Mesoproterozoic	Ratnakar et al. (1995)
8	Yachenahalli	spessartite, vogesite	Mesoproterozoic	Raghunatha Rao (1939)
9	Polayapalle	minette	Mesoproterozoic	Subrahmanyam et al. (1987)
10	Garla-Khammam	minette	Mesoproterozoic	Appavadhanulu (1971)
11	Kushalnagar	camptonite	Mesoproterozoic	Rock and Paul (1989)
12	Bayyaram	camptonite	Mesoproterozoic	Meshram et al. (2015)
13	Kadiri	spessartite	Mesoproterozoic	Pandey et al. (2018a)
14	Mudigubba	spessartite	1169 Ma	Pandey et al. (2017a); unpublished data
15	Udiripikonda	kersanite	Mesoproterozoic	Pandey et al. (2017b)
16	Korakkodu	kersanite	Mesoproterozoic	Raghuvanshi et al. (2019)
17	Harohalli	spessartite, vogesite	Neoproterozoic	Lanjewar and Randive (2017); Devaraju et al.(1995)
Western Dharwar craton (WDC)				
1	Kempinkote, Nuggihalli Schist belt	meta-lamprophyre	Archaean	Sugavanam et al. (1994)
Southern Granulite Terrain (SGT)				
1	Pikkili	camptonite	700-800 Ma	Navaneethakrishnan and Chandrasekharan (1994)
2	Tiruppattur	vogesite	700-800 Ma	Saravanan and Ramasamy (1995); Rock and Paul (1989)
Bastar craton (BC)				
1	Thanewasna	minette	Mesoproterozoic	Meshram et al. (2018)
Aravalli-Bundelkhand craton				
1	Pipela	meta-lamprophyre	1.5-0.85 Ga	Fareeduddin et al. (1995); Kirmani and Fareeduddin (2000)
2	Kishangarh	camptonite	Precambrian	Rock and Paul (1989)
Singhbhum-Eastern India craton and Meghalaya				
1	Singhbhum	spessartite	Precambrian	Sinha et al. (1973); Saha et al. (1973)
2	Simdega		Precambrian	Singh et al. (2004)
3.	East Garo Hills and West Khasi Hills, Meghalaya	camptonite, monchiquite	107 Ma	Nambiar (1988, 2007)
Central Indian Tectonic Zone, Mahakoshal Supracrustals				
1	Jungel	Meta-lamprophyre	1.6 Ga	Nair et al. (1995); Srivastava and Chalapathi Rao (2007)
2	Chitrangi	aillikite	1.6 Ga	Srivastava (2013)
3	Sidhi	minette	97 Ma	Paul and Potts (1981); Paul and Sarkar (1984)
Damodar valley (Rajmahal Traps)				
1.	Gondwana coal fields (Jharia, Raniganj, Bokaro etc)	aillikite-orangeite-kimberlite transitional type	117 Ma	Sarkar et al. (1980); Kent et al (1998); Chalapathi Rao et al (2014)
Kutch and the Deccan Traps				
1	Murud Janjira	camptonite, monchiquite	64.9 ± 0.8 Ma	Deshpande and Chakranarayan (1973); Sahu et al (2003); Desai and Viegas (2010)
2	Chhota Udepur, Seraphalia, Piliwat, Panwad, Moradungri, Jitnagar, Kanthari, Heran, Hamirpur, Dongargaon	kersanite, sannaite, vogesite, alnoite, damtjernite, camptonite	65 to 55± 2 Ma	Gwalani et al (1993); Chawade (1996); Srikarni and Sanjay Das (2005); Chalapathi Rao et al. (2012); Randive et al (2012); unpublished data; Pandey et al. (2019)
3	Palanpur	damtjernite	124 Ma	Karmallkar et al(2014); Pandey et al.(2017)
4	Parol, Bassein district; Trombay island, Bombay	camptonite	Late Cretaceous	Sukeshwala and Sethna (1962)
5	Phenai Mata	camptonite	Late Cretaceous	Sadashivaiah and Durgadmath (1976)
6	Chaktalao	camptonite, kersanite	Late Cretaceous	Chawade (1996); Hari (1998)
7	Mount Girnar	monchiquite, camptonite, vogesitespessartite	69.1 ± 1.17 Ma to 56.2 Ma	Evans (1901); Subba Rao (1971); Paul et al. (1977); Rathore et al (1996)
8	Mundwara	minette, camptonite, vogesite	68.53 ± 0.16 Ma to 80-110 Ma	Basu et al. (1993); Yadava and Karkare (1975); Pande et al. (2016)
9.	Nir-Wandh	sannaite, camptonite	67 Ma	Jaitly et al (1980); Paul et al. (2008); Ray et al (2014)

Figure 2. Field photographs and photomicrographs of some Indian lamprophyres. (A) A lamprophyre dyke in the Gondwana coal fields (Chhoti Nadi) exposed in a river cutting; (B) A shoshonitic lamprophyre dyke intruding the country rock granite in the Wajrakarur kimberlite field at Udiripikonda in the Eastern Dharwar Craton; (C) A cross-cutting lamprophyre in a syenite at Moradongari in the Chhotaudepur sub-alkaline province in the Deccan LIP. The syenite itself intrudes the Deccan Traps; (D) A calc-alkaline lamprophyre from Mudigubba, Eastern Dharwar Craton. Big amphibole phenocrysts impart a porphyritic texture on a megascopic scale; (E) The Chhotaudepur lamprophyre in the Deccan LIP displaying particularly large amphibole phenocrysts; (F) A composite dyke of lamprophyre and nepheline syenite in the Girnar alkaline complex, Deccan LIP. (G) Phlogopite-rich lamprophyric dyke in the Gondwana coal fields (Raniganj) PPL; (H) Abundance of amphibole and clinopyroxene phenocrysts in the Mudigubba lamprophyre, Eastern Dharwar Craton (XPL); (I) A clinopyroxene phenocryst showing corroded margin in the Udiripikonda shoshonitic lamprophyre, Eastern Dharwar Craton (PPL); (J) Bimodal distribution of olivine and clinopyroxene phenocrysts in the Seraphalia lamprophyre, Deccan LIP (PPL); (K) Zoned amphibole and biotite phenocrysts in the Dongargaon lamprophyre, Deccan LIP (PPL); (L) Phenocryst of clinopyroxene from the Purimetla area Prakasam alkaline province (XPL); (M) Zoned phlogopite phenocryst from the Sidhi lamprophyres of CITZ showing reverse pleochroism (PPL). (N) Zoned euhedral phenocryst of clinopyroxene from the Udiripikonda shoshonitic lamprophyre, Eastern Dharwar Craton (in XPL); (O) Clusters of amphibole phenocrysts from Mudigubba lamprophyre showing panidiomorphic- porphyritic- glomerophytic texture (in PPL). Abbreviations: Am= amphibole; Cpx= clinopyroxene; Ol= olivine; Bt= biotite; Ph= phlogopite; LL= lamprophyre; Sy= syenite; PPL = plane polarised light; XPL= crossed polarised light.

clinopyroxenes are characterized by depletion in TiO_2 akin to that of orogenic alkaline magmatic rocks (Fig. 3). Biotite is another common mineral with Al_2O_3 content much higher than that in the lamproites, similar to those exhibited by the alkaline (AL) and calc-alkaline lamprophyres (CAL) (Fig. 4). A conspicuous feature of the olivines from the Kommalapadu lamprophyres is that they are exceptionally fayalitic (Fo_{28}) unlike global lamprophyres (Madhavan et al., 1998). The bulk-rock total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) of the PAP lamprophyres

varies between 4.1 and 9.26 (Madhavan et al., 1998; Vijaya Kumar and Rathna, 2008) and the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ranging between 0.5 and 2, and highlights their affinity with the shoshonitic volcanics (Fig. 6a). Shoshonitic lamprophyres are those with mixed affinities to the calc-alkaline (orogenic) and alkaline (anorogenic) lamprophyres, which are well exhibited for these lamprophyres on a SiO_2 vs. K_2O diagram (Fig. 6b). This observation is further corroborated by their deficiency in silica content alike the alkaline lamprophyres yet displaying potassic

Figure 3. Ti (a.p.f.u) vs Ca (a.p.f.u) plot (after Sun and Bertrud, 1991) of clinopyroxenes from Indian lamprophyres. Data Sources: Prakasam Alkaline Province (Madhavan et al., 1998; Madhavan et al., 1992; Upadhyay et al., 2006; Vijaya Kumar and Rathna, 2008); Deccan LIP (Hari et al., 1998; Chalapathi Rao et al., 2012; Melluso et al., 2012; Dessai and Vegas, 2010; Pandey et al., 2017c); Mahakoshal (Srivastava and Chalapathi Rao, 2007; Srivastava, 2013) Gondwana Coalfield (Srivastava et al., 2009; Chalapathi Rao et al., 2014); Eastern Dharwar Craton (Meshram et al., 2015, Pandey et al., 2018b, Pandey et al., 2017a, b; Lanjewar and Randive, 2017).

Figure 4. Mg# vs Al_2O_3 (wt %) variation diagram (after Rock, 1986) classifying the mica based on $\text{Mg}/\text{Fe}^{(II)}$ ratio and lamprophyres into CAL (calc-alkaline), AL (alkaline), UML (ultramafic). Data sources are same as in Fig. 3.

nature portrayed by the calc-alkaline lamprophyres (Rock, 1991). According to Madhavan et al. (1998), these lamprophyres correspond to a mixed affinity to the CAL and AL in terms of trace element concentrations with their V, Cr, and Hf contents being similar to the average CAL and Co, Ga and REE abundances are indistinguishable from that of the average AL. A restricted range in the major oxide composition variation for these lamprophyres suggests they are likely to be a part of a single magmatic episode.

Subba Rao et al. (1989) have reported Rb-Sr isochron age of the

Figure 5. TiO_2 (wt %) vs SiO_2 (wt %) plot comparing amphibole chemistry of the Indian lamprophyres with the worldwide calc-alkaline and ultramafic lamprophyres (after Rock, 1991). Data sources are same as in Fig. 3.

lamprophyres and other associated rocks from Elchuru to be 1242 ± 33 Ma. The chondrite-normalized rare earth elements pattern is very steep because of highly fractionated light and heavy rare earth elements (LREE and HREE, respectively). A negative trough for potassium on the chondrite-normalized multielement diagram is common in all these lamprophyres, which along with depletion in Sr content for the Polayapalle lamprophyre correspond to the presence of phlogopite in their mantle source regions (see Madhavan et al., 1998). Although, Madhavan et al. (op. cit.) have advocated a primary nature of these lamprophyres based on Mg#, Ni and Cr contents, they have highly variable Nb/U and Ce/Pb ratios offsetting from the mantle array defined by the MORBs and OIBs (Fig. 7). However, they are characterized by higher Th/Yb and Nb/Yb ratios similar to those of the OIBs (Fig. 8). It is clear from these trace element ratios, that these shoshonitic lamprophyres show dual geochemical traits of orogenic as well as anorogenic alkaline volcanics. Such a mixed character can be explained by two-stage metasomatism, wherein the early stage is characterized by a subduction-accretion related metasomatism of the mantle edge, followed by the SCLM metasomatism by asthenospheric melts/fluids. This model is also invoked to explain the genesis of shoshonitic lamprophyres from the EDC, which also show mixed orogenic-anorogenic characters (Pandey et al., 2017b).

The lamprophyres towards the western margin of the Cuddapah Basin are exposed at (i) the Mudigubba, (ii) in the Wajrakarur kimberlite field, and (iii) the Kadiri schist belt (Fig. 1; Pandey et al., 2017a, b, 2018b; Khan et al., 2018). These lamprophyres can be compositionally grouped into two groups: (i) calc-alkaline lamprophyres (CALs) at Mudigubba and Kadiri, and (ii) shoshonitic lamprophyres, which are co-eval and co-spatial with the kimberlites from the Wajrakarur kimberlite field as at Udiripikonda, Sivarampet and Korakkodu. These calc-alkaline lamprophyres are characterized by the presence of amphibole phenocrysts, which are essentially classified as magnesio-hornblende. These amphiboles are depleted in the TiO_2 content that is consistent with their calc-alkaline nature (Fig. 5). Some of these amphiboles are rich in silica and are classified as actinolite, which are rarely found in the igneous rocks and are characteristics of the low-grade metamorphic rocks. Pandey et al. (2017a) explained them to be a result of auto-metamorphism given

the fact that lamprophyres are hydrous melts and capable of altering the composition of their mafic phenocrysts. Pyroxenes are confined only to the Mudigubba CALs and are absent in the Kadiri CALs. The pyroxenes can be essentially classified as diopside. Mica is absent in the CALs exposed at Mudigubba but form an important constituent in the Kadiri lamprophyres supplementing their bulk-rock K_2O content (Pandey et al., 2018b). These micas are classified as biotite and are compositionally comparable to those observed from CALs worldwide (Fig. 4).

Based on the bulk-rock K_2O and Na_2O abundances also, these rocks are classified as calc-alkaline variety (Fig. 6). An important geochemical trait exhibited by these lamprophyres is the conspicuous negative anomalies at Nb, Ta, Zr, Hf and Ti on primitive mantle normalized multi-element diagram, which are considered to be

Figure 6. (A) Na_2O (wt%) vs. K_2O (wt%) and (B) SiO_2 (wt%) vs. K_2O (wt%) (after Rock, 1987) plots classifying the lamprophyres from the Indian shield. Data sources: Prakasam Alkaline Province (Subrahmanyam et al., 1987; Madhavan et al., 1992, 1998; Ratnakar et al., 1996; Vijaya Kumar and Rathna, 2008), Mahakoshal (Srivastava and Chalapathi Rao, 2007; Srivastava, 2013), Eastern Dharwar Craton (Meshram et al., 2015; Lanjewar and Randive, 2017; Pandey et al., 2017a, b, 2018b), Deccan LIP (Dessai and Vegas, 2010; Chalapathi Rao et al., 2012; Pandey et al., 2017c), and Gondwana coalfield (Srivastava et al., 2009; Chalapathi Rao et al., 2014).

characters of subduction-related mafic magmas (Pandey et al., 2017a, 2018b). Crustal materials are characterized by elevated U and Pb content, hence, trace element ratios such as Nb/U and Ce/Pb are considered as important indicators of crustal contamination. A reducing value of Nb/U and Ce/Pb of the mantle zones suggest them to be metasomatized by the subduction-related fluids. The clear cut evidence of subduction is again exhibited on the suppressed Nb/U and Ce/Pb, and elevated Th/Yb ratios in these calc-alkaline lamprophyres (Fig. 7, 8). Pandey et al. (2017a, 2018b) have suggested the presence of a subduction modified mantle wedge in the SCLM beneath EDC, probably, as a result of Neoproterozoic accretion related

Figure 7. Nb/U vs. Ce/Pb variation plot with mantle array defined by MORBs and OIBs from Hofmann et al. (1986) and average OIB data from Sun and McDonough (1989). Data sources are same as in Fig. 6.

Figure 8. Nb/Yb vs. Th/Yb trace element ratio diagram (after Pearce, 2008) showing mantle array defined by MORBs and OIBs. Lamprophyres from the Mahakoshal belt show affinity to the OIBs and within-plate enriched mantle source is represented by the lamprophyres from the Prakasam Alkaline Province, the Deccan LIP and the Gondwana coalfield. Data sources are same as in Fig. 6.

growth of the Dharwar Craton (Jayananda et al., 2018 and references therein).

Chemically distinct from these rocks are the shoshonitic lamprophyres exposed at Udiripikonda, Sivarampeta and Korakkodu in the Wajrakarur kimberlite field of the EDC. These rocks host olivine and oscillatory zoned pyroxene phenocrysts silica-undersaturated (Pandey et al., 2017b; Khan et al., 2018). These pyroxenes show variable Ti content leading to their transitional or mixed orogenic-anorogenic geochemical behaviour, which is also reflected by their bulk-rock geochemistry, alike the lamprophyres from Prakasam Alkaline Province (Fig. 3). An interesting finding is the presence of sagenitic texture in mica grains as a result of exsolution of 5–10 μm titanite needles, which is found in shoshonitic lamprophyres from other parts of the globe as well (Raghuvanshi et al., 2019). The elevated K_2O content as compared to other lamprophyres from the EDC is due to the abundance of biotite. In the SiO_2 vs. MgO and Al_2O_3 vs. TiO_2 variation plots (not shown), these rocks show a mixed affinity to the global alkaline and calc-alkaline lamprophyres. The SIMS zircon U–Pb isotopic data gave an emplacement age 2511 ± 6.6 Ma for the samples from the Udiripikonda lamprophyre, which has been interpreted to be due to crustal derivation of zircons in lamprophyre dyke as the host granites in EDC have an age of ~ 2.51 Ga (Khan et al., 2018). Pandey et al. (2017b) have suggested that this dyke, emplaced in the vicinity of ~ 1100 Ma kimberlites without any cross-cutting relationship between two, and therefore should be co-eval, which is also further apparent from whole-rock Rb–Sr isochron age of 0.96 Ga. Certain trace element ratios such as Th/Yb, Nb/Yb, Mo/Pr, Ce/Pb and Nb/U along with abundant TiO_2 content in these shoshonitic lamprophyres from Wajrakarur kimberlite field show their affinity to the ocean island basalts (OIBs) (Fig. 7, 8); however, the radiogenic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios along with un-radiogenic initial ϵNd highlight the role of an old (Neoproterozoic ~ 2.6 Ga) Nd model ages) enriched sub-continental lithospheric mantle (SCLM) in their genesis, unlike the OIBs, which are essentially derived from an asthenospheric mantle (Fig. 9). This character has been explained to be a result of metasomatism of the lower reaches of SCLM by the metasomatic fluids percolating from the sub-lithospheric depths (Pandey et al., 2017b; Khan et al., 2018). Based on the elevated Zr/Hf ratios and

silica under-saturated nature of these rocks, Raghuvanshi et al. (2019) have proposed carbonatite metasomatism overprint on the SCLM, which had already gone a previous episode of subduction-related metasomatism, probably, during Neoproterozoic accretion related-growth of the EDC as reflected by their Neoproterozoic depleted mantle Nd model ages. A previous silicate related metasomatic activity is not only apparent from the enriched isotopic character, but also from moderate Nb/La and elevated Ba/Th ratios. Giri et al. (2019) have identified three different domains of lamprophyres in the EDC based on contribution of different mantle reservoir sources: Domain I - which includes SCLM (sub-continental lithospheric mantle) source metasomatized by subduction components (Kadiri lamprophyre); Domain II, which includes a mixed source with involvement of both SCLM and asthenosphere (Udiripikonda and Korakkodu lamprophyre); and Domain III that includes plume originated lamprophyres (Ankaraopalli lamprophyre).

Central Indian lamprophyres

The lamprophyres in Central India are exposed mainly in the Jungel valley, the Chitrangi region, and the Sidhi region of Mahakoshal supracrustal belt (MSB), which is a part of Central India Tectonic Zone (CITZ) (Fig. 1). CITZ which is one of the ENE–WSW trending major crustal features in the peninsular India fenced by Son–Narmada North Fault (SNNF) and Son–Narmada South Fault (SNSF) in the north and south, respectively (see Roy and Bandyopadhyay, 1988). The ENE–WSW trending MSB extend for 500 km and comprises granitic plugs, syenites, alkaline intrusive along with pyroclastic metavolcanics and chemical precipitates, which reflects a greenstone association of typical rift setting (Srivastava, 2013; Srivastava and Chalapathi Rao, 2007). Granite–granodiorite, syenites, dolerites and gold-bearing quartz–carbonate veins constitute the youngest lithologies of the supracrustal belt, whereas lamprophyres here constitute youngest magmatic event and yielded an age of 1610 Ma (Nair et al., 1995). These lamprophyres show sharp contacts with the supracrustals and were emplaced prior to regional deformation in MSB.

The Jungel valley Paleoproterozoic lamprophyres intrude the MSB, located 280 km east of the Mesoproterozoic diamondiferous Majhgawan pipe, and are exposed as dykes, plugs and lava flows. These lamprophyres show inequigranular, porphyritic and glomeroporphyritic texture, where original mineralogy of the phenocrysts of olivine, pyroxene, mica and amphibole (10–20% by volume) is completely altered and only their relicts are present (Srivastava and Chalapathi Rao, 2007). Large panidiomorphic phenocrysts are suggestive of crystallization from a water-rich magma, whereas multiple generations of phenocrysts (olivine, clinopyroxenes, mica and amphibole) suggest repeated degassing and recharge of magma (Currie and Williams, 1993). Alumina vs. Mg# plot suggests that they contain phlogopite as the dominant mica (Fig. 4). Mineral chemistry studies by Vinod Kumar (1995) reveal that three types of amphiboles are present viz., hornblende, oxy-hornblende (lamprobolite) along with the rare presence of alkali-amphibole (kaersutite and kataphorite), which suggest alkaline nature of lamprophyric rocks (see Rock, 1991). Feldspar constitute 0.35–23.75% of the groundmass (>90% of the rock) of the Jungel valley lamprophyres, in which plagioclase is dominant than orthoclase. A notable feature of the feldspars is their partially altered and rugged boundaries, which represent evidence of metamorphic

Figure 9. $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}}$ vs. $\epsilon\text{Nd}_{\text{initial}}$ variation in the lamprophyres from the Eastern Dharwar Craton (solid circles) and Gondwana coalfield (cross) showing their derivation from an old sub-continental lithospheric mantle and an enriched mantle related to mantle plume, respectively.

recrystallization. Few lamprophyres show the presence of rounded or elliptical ocelli (up to 5 mm size). They are mostly undersaturated, ultrabasic, and sodic in nature ($\text{Na}_2\text{O} > \text{K}_2\text{O}$), with only a few of them which are potassic (see Srivastava and Chalapathi Rao op. cit; Fig. 6A). They are mainly alkaline with some plugs of calc-alkaline nature (Fig. 6B). On the basis of petrography and bulk-rock geochemistry, these rocks have been classified as alkaline lamprophyre in general and camptonites in particular. In the primitive-mantle normalized multi-element diagram, (i) all elements show an enrichment over the primordial mantle, (ii) trends of all HFSE are similar and (iii) but LILE show a wide variation. Enrichment in LREE over HREE which suggest a strong fractionation and resemble those of mildly undersaturated alkaline basalt; whereas parallel chondrite normalized REE patterns imply derivation from a similar mantle source. Fractional crystallization has a strong influence on their magma evolution. The Jungel lamprophyres have been interpreted to exhibit primitive as well as evolved nature of magma. A high concentration of LREE and relatively high concentration of compatible elements {Ni (up to 729 ppm) and Cr (up to 1280 ppm)} suggest that magma was produced by a small degree of partial melting of peridotite in garnet stability and derived from shallower depths than the diamondiferous Majhgawan pipe (Srivastava and Chalapathi Rao, 2007).

The Chitrangi lamprophyres intrude MSB and are situated in the eastern part of the MSB, exposed as dykes and plugs and are found to be associated with the carbonatites. These lamprophyres are melanocratic and constitute of pseudomorphs of olivine replaced by calcite, amphibole, mica and pyroxenes. A noteworthy feature of these lamprophyres is the presence of melanite garnet and rounded to elliptical carbonate ocelli (Srivastava, 2013). On the basis of petrography and bulk-rock geochemistry, these rocks have been classified as ultramafic lamprophyres in general and aillikites in particular. High Mg#, Ni and Cr content along with low HREE concentration corroborate their primary nature. The Chitrangi lamprophyres are found associated with the carbonatites, but exclude any genetic relationship with the latter. Rubidium, Ba, K and Sr of the Chitrangi lamprophyres display a wide range of variation and thus reflects subtle post-magmatic alteration. Both the Jungel valley and Chitrangi lamprophyres have ocelli present in them thereby suggesting the role of late-stage liquid immiscibility. Trace element ratios Th/Yb vs Nb/Yb of the Jungel and Chitrangi lamprophyre shows similarity with the mantle array and within plate characteristics (Fig. 8). It has been inferred that the Chitrangi lamprophyres were emplaced during the early stages of rifting in MSB due to lithospheric relaxation caused, very likely, by mantle plume activity (Srivastava, 2013).

The Sidhi Gneissic complex (SGC) is a 2.5 Ga old tectonic block, which is situated at the northern margin of the CITZ. The SGC is an inlier of granite-gneiss-migmatite, surrounded by MSB in the north and by the Vindhyan basin in the south (Roy and Bandhyopadhyaya, 1988). A number of lamprophyres, lamproite and ultramafic dykes have been reported from the Sidhi region (see Bhattacharya et al., 2014; Satyanarayanan et al., 2017, Giri et al., 2018 and references therein). Previously, Paul and Potts (1981) and Paul and Sarkar (1984) reported lamprophyres with mica as dominant phenocryst along with olivine and classified them as olivine-minette. Giri et al. (2018) reported the occurrence of a lamprophyre from south-west of Banjari area near Sidhi town. This NW-SE trending lamprophyric dyke occurs as small body and intrudes the Sidhi alkaline complex. This lamprophyre is meso-melanocratic and constitutes mica-dominated phenocrysts and a groundmass comprise feldspar, titanomagnetite,

apatite, secondary carbonates and opaques (pyrite and chalcopyrite). A notable feature of this lamprophyre is the occurrence of cobaltopyrite, which contains an appreciable amount of cobalt up to (5.61 wt%) and minor content of nickel (up to 0.70 wt%).

Gondwana coalfield lamprophyres

The Eastern Indian shield comprises the Singhbhum craton, Singhbhum mobile belt, Chotanagpur gneissic terrain (CGT) and the Shillong plateau. Gondwana coalfield such as the Bokaro, the Daltonganj, the Jharia and the Karanpura are situated in the east-west trending Damodar valley located in the CGT at the northernmost margin of Singhbhum craton. Interestingly, Damodar valley is the only known geological domain in the Indian shield which host both Early Cretaceous (Rajmahal Traps) and Late Cretaceous (Deccan Traps) volcanic igneous activity. Hundreds of lamprophyres intrude the coalfield and often burn the coal leading to ash locally known as *Jhama*. Kent et al. (1998) reported Ar-Ar age of 117 Ma for some of these dykes which are almost synchronous with the nearby Rajmahal basalts and linked them to the Kerguelen mantle plume. The Gondwana lamprophyres have been variably described by various workers viz., kimberlites (Kent et al., 1998; Kumar et al., 2003); lamprophyres *sensu stricto* (Paul and Potts, 1981; Rock et al., 1992), as well as lamproites (Jia et al., 2003).

The Gondwana lamprophyres from the Jharia and Raniganj coalfields are shown to have petrological and geochemical similarity to cratonic magmas (kimberlites and lamproites) as well as rift-related magmas (aillikites) (Srivastava et al., 2009; Chalapathi Rao et al., 2014). Petrographic study reveals they constitute of phenocrysts of pseudomorphs of olivine, amphibole and mica along with groundmass of feldspar, primary carbonates and opaque minerals. Mineral chemistry studies reveal mica to be mainly phlogopite (Fig. 4) and exhibits a wide variation in its composition in terms of TiO_2 , Al_2O_3 and FeO_T contents. On the other hand, the amphiboles are primary as well as the secondary type (Fig. 5). High modal abundances of the mica, apatite, and carbonate reflect high-volatile content of their parent magma. Major rock geochemistry suggests them to be silica-undersaturated, ultrapotassic and ultramafic (Fig. 6A and B). Transition elemental abundances are variable with a high Mg# (59.15-71.56), Ni (20-690 ppm), and Cr (220-1200 ppm) and a positive correlation between LILE and HFSE represents their uncontaminated and primary nature. Cerium and Nb contents are many folds higher than that of MORB or OIB, even continental lithospheric mantle and nullify their direct derivation from the asthenosphere. Incompatible element ratios viz., Ce/Pb, Nb/U, Th/Yb, and Nb/Yb reveal their similarity with characteristics in between OIB and pelagic sediments and support the idea of the presence of an ancient subduction component in their source (Fig. 7 and 8). Depletion in sodium, silica and alumina along with enrichment in K, Ti, and P typically are similar to the aillikites (Rock, 1991; Tappe et al., 2006). The $^{87}\text{Sr}/^{86}\text{Sr}$ ranging between 0.704637 and 0.712919 and ϵNd varying between -2.3 and -4.4 relate them with the Island of Kos and Mexican lamprophyres (Fig. 9). Chalapathi Rao et al. (2014) suggested them to have been derived from mantle source which had undergone long term enrichment of incompatible trace elements and indistinguishable from that of Kerguelen mantle plume-derived basalts. Their T_{DM} (depleted mantle) model age ranges from 0.95-1.4 Ga and correlates well with that of Deccan age orangeites from the Bastar craton and with the 1.1 Ga emplacement ages of kimberlites from the Eastern Dharwar Craton,

southern India. The Gondwana lamprophyres are interpreted to be generated by a small degree of partial melting of depleted harzburgite which subsequently metasomatised by carbonate-rich fluids at lithospheric depth within garnet stability field and that the Kerguelen plume provided the heat source (Chalapathi Rao et al., 2014).

Lamprophyres of the NE India

Even though lamprophyres are reported from the NE India viz., Meghalaya plateau (Table 1) only petrographic studies were undertaken and detailed petrogenetic studies are lacking. Nongchram Fault Zone lamprophyres are comagmatic and genetically linked with nearby carbonatite (Nambiar, 2007). These lamprophyres host country rock fragments, as well as mantle derived ultramafic nodules, aggregated megacrysts and lapilli like structures. Conspicuous presence of ocelli has also been discussed as a characteristic feature of these lamprophyres. Ocelli are commonly zoned, with carbonate-rich (rarely analcime) inner zone and an outer zone rich in alkali feldspars, mica, pyroxenes and opaque minerals. Srivastava et al. (2016) from their study of early Cretaceous, potassic lamprophyres from Garo hills evinced that lamprophyres are product of mantle heterogeneity at rather than any input of mantle plume magmatism.

Deccan Large Igneous Province lamprophyres

The fact that alkaline magmatism is temporally associated with the continental flood basalt in a LIP is now well established (Rock, 1977; Queen et al., 1996; Leat et al., 2000; Riley et al., 2003; Tappe et al., 2006). Numerous lamprophyres, either in form of dykes and plugs are associated with the Deccan flood basalts (Subba Rao, 1972; Bose, 1980; Gwalani et al., 1993). These lamprophyres occur along the various rift zones such as E-W trending Narmada rift, Cambay rift and western coastal rifted margin (e.g., Melluso et al., 2002; Dessai and Viegas, 2010; Chalapathi Rao and Lehmann, 2011; Pandey et al., 2019). Most of them post-dates the Deccan Traps and their precise emplacement ages are scanty (see Table 1).

Camptonite and monchiquite (varieties of alkaline lamprophyre) and kersantite (a type of calc-alkaline lamprophyre) associated with the alkaline complexes and with the basalts of western and north-western portions of Deccan LIP are reported from: (i) the Phenaimata alkaline complex (Durgadamath, 1984); (ii) the Girnar alkaline complex (Subba Rao et al., 1971; Paul et al., 1977), (iii) the Kutchh (Jaitly et al., 1980), (iv) the Kanwad-Panwad region and exposed along Heron River sections (Sukeshwala and Avasia, 1972), (v) the Chhaktalo and Bhakhatgarh-Phulmal, Chhotaudepur areas (Chawade, 1996; Hari, 1998; Hari et al., 2000; Randive et al., 2005; Chalapathi Rao et al., 2012), and (vi) Murud Janjira area (Deshpande and Chakranarayan, 1973; Dessai et al., 1990; Dessai and Viegas, 2010). The Deccan LIP hosts the highest number of lamprophyre dykes all over the Indian shield, which is well illustrated in Fig. 1. The lamprophyre occurrences in the Deccan LIP and NW part of India can be further sub-divided into: (i) lamprophyres from the Chhotaudepur alkaline sub-province and (ii) lamprophyres from the Kutch rift zone.

The Chhotaudepur alkaline sub-province, which lies within the E-W trending Narmada rift valley, has several discrete occurrences of lamprophyre bodies exposed at Chhotaudepur, Dongargaon,

Hamirpur, Heran River, Jitnagar, Kanthari, Moradungari, Panwad, Pipliwat and Seraphalia (see Table 1). The Kutch rift zone has exposures of Mid-Cretaceous ultramafic lamprophyre at Palanpur (Karmalkar et al., 2014; Pandey et al., 2018a). Detailed mineralogical and geochemical study has not yet been published on the lamprophyres from the Phenaimata, Mundwara, Girnar complexes and the Heron river sections. However, the lamprophyres from the Chhaktalo, the Chhotaudepur, the Murud Janjira and the Kutch have been given due attention, which is discussed below.

The lamprophyres from Chhaktalo area in the Deccan Traps contain abundant pyroxene and olivine as phenocrysts that show conspicuous zoning, and have been classified as kersantite (alkali lamprophyre) and camptonite (calc-alkaline lamprophyre) as the plagioclase dominated potassic feldspar in the groundmass (Hari, 1998). This is corroborated by the bulk-rock geochemistry of these lamprophyres, which has been used to understand the associations of these lamprophyres with the Deccan volcanics as well as the carbonatites. On the basis of the presence of clinopyroxene blebs in these lamprophyres and the matrix of the carbonatites, Hari (1998) concluded that a silicate-carbonate liquid immiscibility model explains the genetic link between the two. This relation has further been established by the melt inclusions study on these olivine and clinopyroxene phenocrysts by Hari et al. (2000). These authors have shown that the mafic phenocrysts trapped bubble inclusions of CO₂ at a depth of 10-15 km at 4.6 and 3.7 kbar pressure in olivine and pyroxene, respectively. The temperature of these CO₂ melt inclusions have been found to be 1215-1245° and 850-1150°C for the olivine and pyroxene respectively. Based on these estimated thermobarometric conclusions, Hari et al. (2000) have proposed that these lamprophyres originated from the shallow mantle depths, probably, the spinel lherzolite field. Chalapathi Rao et al. (2012) have presented the mineralogy and geochemistry of the Chhotaudepur lamprophyres, which are some of the longest known lamprophyre dykes in India, in detail. Although, present in the Deccan LIP, which is considered to be a manifestation of mantle plume activity, the clinopyroxenes of the Chhotaudepur lamprophyres show affinity to the orogenic alkaline magmas due to their depletion in Ti content (Fig. 3). The mica is classified as biotite and is very high in alumina content showing affinity to the alkaline as well as calc-alkaline lamprophyres (Fig. 4). As mentioned earlier, the mixed geochemical affinity is shown by the shoshonitic lamprophyres, which have a very high content of total alkalis. Such characters are also well exhibited from the bulk rock geochemistry of these lamprophyres (Fig. 6; Chalapathi Rao et al., 2012). The trace element ratios such as Nb/U, Ce/Pb, Th/Yb and Nb/Yb in these lamprophyres highlight the involvement of OIB-type enriched mantle in their genesis, which is also exhibited for other Deccan lamprophyres (Fig. 7 and 8).

A chrome diopside megacryst has been recently recovered from the Late Cretaceous Mundwara lamprophyre (Sharma et al., 2018). Single pyroxene thermobarometry revealed that it was derived from a depth range of ~100 km, which is relatively much deeper than that of the chrome-diopside megacrysts (~40-50 km) reported in spinel-lherzolite xenoliths from the alkali basalts of Deccan age (ca. 66- 67 Ma) from the Kutch, NW India. These results highlight that the pre-Deccan lithosphere beneath the Mundwara complex was at least ~100 km thick and similar in composition to that of the cratonic lithosphere (Sharma et al., 2018). A mantle-derived ultramafic xenolith entrained the Eocene (ca. 55 Ma) lamprophyre dyke from the Dongargaon is found to have an overlapping composition with that reported from

worldwide mantle peridotite xenoliths Pandey et al., 2017c). Presence of phlogopite and apatite as phases in the xenolith provided the first direct petrographical evidence for the modal metasomatism in the post-Deccan subcontinental lithospheric mantle (SCLM) from this domain. Preservation of phlogopite and apatite in the ultramafic xenolith imply that some of the readily fusible metasomatized portions in this domain escaped wholesale melting during the eruption of the Deccan Traps, possibly due to the variable thickness of the underlying SCLM (Pandey et al., 2017c). Lamprophyre xenoliths, of an earlier episode, have been reported from the Dongargaon lamprophyre highlighting its polychromatic nature very likely due to extensional events related to the reactivation of the Narmada rift zone (Pandey et al., 2018c).

The lamprophyres exposed at the Murud Janjira constitute a part of the wide spectrum of alkaline rocks including melanephelinites, nephelinites, tephrites and nepheline syenites at the Mumbai coastal area (Melluso et al., 2002). Interestingly, the lamprophyres stand distinct from the rest of the associated alkaline rocks in terms of their geochemistry and display very high concentrations of Nb, La, Ce, Nd, Zr and Ti. Melluso et al. (2002) have published Nd isotopic data for only one and Sr isotope data for two samples (not shown here). Considering an emplacement age of 65 Ma, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio varies between 0.70415 and 0.70420, with an initial ϵNd of +4.4, which falls within the mantle array showing affinity to the OIBs in general and Reunion hotspot in particular. Based on their trace element modelling results, these authors have proposed a wide range of degree of melting took place in the genesis of these alkaline rocks with lamprophyres generated at the lowest proportions of partial melting. This wide range in degree of melting of heterogeneous, volatile-rich ($\text{CO}_2+\text{H}_2\text{O}+\text{F}$) lithospheric mantle explains the drastic compositional difference between the lamprophyres and other alkaline rocks at Murud Janjira. However, from their high initial ϵNd (+4.4) suggest that they tap an isotopically depleted sub-lithospheric (asthenospheric) mantle. Xenoliths recovered from the Murud Janjira lamprophyres (west coast of India) reveal that granulites and pyroxenites are the dominant rock types in the underlying lithosphere and that lower crust here is more mafic in composition (Dessai et al., 2004).

The lamprophyre exposed in the Kutch area has been dated to be Mid-Cretaceous (U-Pb perovskite age of 124 ± 4 Ma) by Karmalkar et al. (2014), which intrudes the Katrol Formation of upper Jurassic to Early Cretaceous age. This dyke was originally identified by Karmalkar et al. (2014) as a lamproite that originated from a mantle showing signatures of mixing between enriched and depleted domains. The authors suggested the lamproite to represent an earlier igneous event related to the rifting unlike the alkaline magmatism related to the Deccan volcanism that dominated the region. Detailed mineralogical and geochemical investigations were subsequently carried out by Pandey et al. (2018a) on this anorogenic dyke, and it has been re-classified to be a damtjernite (ultramafic lamprophyre). This silica-undersaturated potassic and primitive lamprophyre contains phenocrysts of olivine, phlogopite, and clinopyroxene in a groundmass of perovskite, nepheline and magnetite. High Mg# and low alumina content in the phlogopites of these rocks contrary to other Deccan lamprophyres show their affinity to the global ultramafic lamprophyres (Fig. 4). Pandey et al. (2018a) have shown that the geochemical characters of these Mid-Cretaceous (124 Ma) dykes are strikingly similar to the End-Cretaceous (69 Ma) ultramafic lamprophyres exposed as dykes and sills at the Tethyan Indus Suture Zone. Trace element ratios such as Ce/Pb, Nb/U, Th/Yb, Nb/Yb, Nb/La attest to

the OIB-type affinity of these rocks (Fig. 7, 8; Pandey et al., 2018a), which is further corroborated by the isotopic ratios i.e. $^{87}\text{Sr}/^{86}\text{Sr}$ ranging between 0.70460 and 0.70461 and ϵNd varying between +2.56 and -0.69 (Fig. 9). Based on high Rb/Sr, Nb and lower La/Sm a carbonatitic metasomatic melt responsible for precipitating metasomatic phlogopite-rich veins in the lithospheric mantle have been proposed as the source region for these rocks. Although, the dyke shares a temporal relation to the Kerguelen plume derived Rajmahal-Sylhet Traps and associated alkaline rocks from eastern India, it is spatially compatible with the Reunion plume derived Deccan Traps. This conundrum has been explained by Pandey et al. (2018a) by three models- (i) either it represents the earliest magmatic episode of the Reunion plume, (ii) it represents product of prolonged multiple rifting episodes in the Kutch domain as a result of far-field plate reorganization, or (iii) it represents an alkaline magmatic episode before the eruption of Rajmahal-Sylhet and Deccan volcanics. Nonetheless, the trigger for the Kutch ultramafic lamprophyre magmatism remains an open question.

Recently, Pandey et al. (2019) inferred the carbonate metasomatism of the post-Deccan SCLM in NW India, based on their study on the geochemistry of the lamprophyre dykes (sannaite and camptonite) from the Chhotaudepur alkaline province from the Narmada rift zone. These dykes are found to be intruding the Deccan basalts and therefore, provide unique opportunity to study the effects of the mantle plume on the SCLM beneath NW India.

Indian lamprophyres and their relationship with the kimberlite clan rocks (KCRs)

The volatile-rich, low-volume, ultramafic to mafic alkaline rocks such as kimberlites (Group I archetypal type), orangeites (previously termed as Group II or micaceous kimberlites) and lamproites, together with lamprophyres, tap the deep complex mantle domains and are carriers of the “mantle cargo” which includes a plethora of xenoliths and xenocrysts (including the diamond). Dawson (1987) used the term ‘kimberlite clan’ for the first time because of complex mineralogy and large variation in chemistry of the kimberlites and related rocks such as lamproites and lamprophyres. Likewise, Rock (1991) proposed a ‘lamprophyre clan’ and included kimberlites as well as lamprophyres *sensu stricto* in it. Haggerty and Birkett (2004) used kimberlite clan rocks (KCR) for some kimberlitic rocks from the Dharwar Craton as they share similarities in terms of their volatile content, mineralogy, and geochemistry and macroscopic appearance as well. The problem of identifying them as per the existing petrogenetic classification by IUGS has generated much ambiguity resulting in assigning different names without any strong affinity to a particular clan.

Amongst the KCRs, the orangeites akin more to lamproite group of rocks. Of the different varieties of lamprophyres, the ultramafic lamprophyres (UML) are grouped with kimberlites, whereas the alkaline and calc-alkaline lamprophyres are considered quite distinct and different from kimberlites. The predominance of feldspar, plagioclase, and hydrous phases (such as amphibole, and biotite) in alkaline and calc-alkaline lamprophyres and their association within the intra-plate and subduction/or post-collision related tectonic setting respectively discriminate them from the kimberlites. Out of three end-members of the UML (alnöites, aillikites and damtjernites) the aillikites share more similarities with kimberlites whereas alnöites

and damtjernites can be readily discriminated by the presence of essential groundmass melilite and nepheline, respectively (Tappe et al., 2005). Following these criteria, various West Greenland alkaline dykes, which were initially regarded as kimberlites, have been reclassified subsequently as ultramafic lamprophyres and more specifically as aillikites (Tappe et al., 2005). Kimberlites and UML despite having similarities such as silica under-saturated nature, presence of macrocrystic and phenocrystic olivine and phlogopite, still differ in their tectonic setting. Kimberlites are restricted to within the intra-cratonic settings wherein they tap the deep lithospheric mantle whereas UML are intrinsically associated with a rifted cratonic lithosphere (Tappe et al., 2009). However, based on the presence of Ti-rich phlogopite, high Na/K amphibole, and Ti-rich schorlomite garnet, Dongre et al. (2019) have identified pipe-8 of the Wajrakarur kimberlite field to be an ultramafic lamprophyre (aillikites). Much of the on-going debate hinges on the genetic link between kimberlites and ultramafic lamprophyres, and contributions from the lithospheric and/or sub-lithospheric mantle (Foley et al., 2009; Francis and Patterson, 2010; Mitchell and Tappe, 2010) as both these rock types contain significant carbonate component within their source regions.

From the Indian front, there is still a paradox regarding the nomenclature of volatile-rich ultramafic intrusions in the EDC as kimberlite, lamproite or UML as they tend to display a transitional nature. One of the best examples is the Khaderpet plug from the Wajrakarur kimberlite field of the EDC, which is associated with the carbonatite intrusions (Smith et al., 2013). Following the mineralogical genetic classification, presence of Ti-andradite and significant amounts of carbonate content necessitates us to classify the Khaderpet KCR as ultramafic lamprophyre. However, high CaO and enrichment in LREE together with the low whole-rock MgO content suggest the Khaderpet KCR be transitional between kimberlite and ultramafic lamprophyre (Smith et al., 2013). The Arkhangelsk Alkaline Igneous Province (Russia) also has a similar association of kimberlite, olivine lamproite, melilite-bearing alkaline picrite and carbonatite showing transitional affinities to kimberlite and ultramafic lamprophyres (Mahotkin et al., 2000). Likewise, the presence of Ti, Al, Ba-rich phlogopites, Na-enriched amphibole, and Ti-rich schorlomite garnet together with the slightly elevated $^{87}\text{Sr}/^{86}\text{Sr}$ initial values in pipe-8 of the Wajrakarur kimberlite field has led Dongre et al. (2019) to re-classify it as ultramafic lamprophyre (aillikite). Interestingly, Scott Smith (1989) also noted the probable presence of melilite from Pipes-2 and 5 of the Wajrakarur kimberlite field, EDC, which could give them a status of UML which needs to be corroborated through detailed mineralogical characterisation. The melilite reported by Scott Smith (1989) has compositions similar to those of hydrogrossular, which is a secondary mineral in some of the WKF intrusions (Kaur and Mitchell, 2016). According to Kaur and Mitchell (2016), the lath shaped mineral inferred to be melilite by Scott Smith (1989) is actually hydrogrossular, which is a pseudomorph after a lath shaped parent mineral (cymrite). The Palanpur damtjernite from the Kutch rift zones of NW India is the only archetypal UML to our knowledge which is neither associated with KCRs nor display any transitional nature (Pandey et al., 2018a).

As stated before, kimberlites share many mineralogical similarities with the olivine lamproites which can be of overlapping nature. In this context, Indian kimberlites serve as the best representatives since many of them from Wajrakarur, and Narayanpet kimberlite fields from the EDC and diamondiferous Majhgawan pipe of central India are neither archetypal kimberlites nor lamproites (e.g., Haggerty and

Birkett, 2004; Chalapathi Rao et al., 2005; Chalapathi Rao et al., 2012; Smith et al., 2013). Likewise, Reddy (1987) classified the ultramafic intrusions of the Wajrakarur kimberlite field to be lamproites considering the probable presence of leucite and sanidine. However, Chalapathi Rao et al. (2004) described them to be phlogopite-rich, monticellite bearing archetypal hypabyssal kimberlites on the account of their mineralogy geochemistry and isotopic parameters. Based on the spinel mineral composition and occurrence of barian lamprophyllite, Fareeduddin and Mitchell (2012) attached a lamproite status to some of these rocks. Presently, there is no strict consensus regarding their classification yet we can demonstrate that these rocks differ from each other if we use the mineralogical, geochemical and isotopic characters in unison instead of naming them solely on the basis of existing mineral-genetic classification schemes. For instance, Shaik et al. (2018) detected various populations of olivine, phlogopite and clinopyroxene from Pipe-4, WKF and referred it to be a lamproite, and attributed its genesis to the abundance of MARID-type metasomatic veins within the source wall-rock region. If that is so, this pipe should either display the isotopic characters (in Sr-Nd space) of MARID-type of 'enriched' source regions or define a mixing array between an enriched (EM-II like) and an isotopically depleted geochemical reservoir (Fitzpayne et al., 2019) which needs to be confirmed by future studies. Furthermore, it should be highlighted that the phlogopite and groundmass spinel from WKF and NKF follow the compositional trends transitional between kimberlite and orangeites (Chalapathi Rao et al., 2012). On the basis of mineral chemistry, Chalapathi Rao et al. (2012) demonstrated they should be classified as transitional varieties but if we consider their geochemical and isotopic characters they can be classified as kimberlites as well. As the compositional trends are essentially the functions of phases that are generated during the crystallisation interval, which in turn, depend upon a variety of aspects such as the magma composition, pressure, temperature and extent of late-stage magmatic oxidation they do not necessarily constitute the intrinsic parameters of the rocks. This is further attested from the evidence that the mineral compositions from the newly discovered late-stage kimberlite dykes from the Premier diatreme root of Kaapvaal craton display a marked deviation from the trends that are hitherto devised to be robust for the archetypal kimberlites (Dongre and Tappe, 2019). Two decades ago, Taylor and Kingdom (1999) questioned the robustness of existing mineralogical-genetic schemes by pointing out that the Jagesfontein kimberlite of southern Africa has petrographic and mineralogical aspects common to both kimberlite and orangeite but still isotopically it displays an archetypal kimberlite character.

It is important to highlight those recently re-classified lamproites from the EDC (Kaur and Mitchell, 2013, 2016; Kaur et al., 2013; Shaikh et al., 2017, 2018), which were initially considered to be kimberlites, are neither ultrapotassic nor peralkaline, which are mandatory signatures by the IUGS to be termed them as *bonafide* lamproites. It is significant to note that lamproites from the EDC (Krishna, Ramadugu, Vattikod, and Cuddapah; Chalapathi Rao et al., 2004, 2010, 2014, 2016; Talukdar et al., 2018) are conspicuously devoid of perovskite, which is a ubiquitous phase in the recently reclassified 'lamproites' from the WKF, EDC. Likewise, all the EDC lamproites (Krishna, Ramadugu, Vattikod and Cuddapah) were generated from an ancient enriched lithospheric mantle, as suggested by their Sr-Nd isotopic compositions, whereas all the Mesoproterozoic ultramafic intrusions from the WKF tapped an isotopically more depleted source reflecting asthenospheric imprints. Tappe et al. (2018)

also attested the asthenospheric component in kimberlite considering the Nd and Hf isotopic database of global occurrences. Many other prominent distinctions between kimberlites and lamproites were also summarized by Kononova et al. (2011).

Historically termed as micaceous kimberlites and subsequently christened as Group-II kimberlites and finally, as orangeites, these rocks share a closer resemblance with the lamproites as the mineralogical criteria established to distinguish orangeites as a separate group are now found to be not as robust as earlier thought of. Evolution of groundmass micas to a tetraferriphlogopite composition is used to distinguish them from kimberlites (Mitchell, 1995) but such evolutionary trends are also very common in lamproites (see Mitchell and Bergman, 1991). Moreover, out of the two magmatic trends of spinel evolution, the magmatic trend-2 is found to be common to both orangeites and lamproites (Dawson, 1987; Nixon, 1996). There's a similarity in their Nd–Sr–Pb isotopic content (Tainton and Browning, 1991; Tainton, 1992) as well suggesting that both were derived from a similar enriched source region within the continental lithospheric mantle. Interestingly, Nixon (1996) preferred to incorporate orangeites within the lamproite clan rather than to categorize them as another group of kimberlites. There is no denying fact that lamproites contain certain minerals, such as wadeite, priderite, zeppeite, which are unique to them. The role of metasomatism, degree of fractionation and wall-rock interaction also should be considered in evaluating the paragenesis of such exotic phases. For instance, crustal contamination of kimberlites can consequently increase the SiO₂ content, which could also generate late-stage clinopyroxene (Chakmouradian and Mitchell, 2000), which is supposed to be present in orangeites only. Our present understanding of the KCRs is considerably influenced by studies from South Africa, Greenland, Canada and Australia which may not be necessarily valid globally. We subscribe to the views of Taylor and Kingdom (1999) and Chalapathi Rao (2005) that distinction amongst the KCRs for the time being should be attempted using the combined petrographic, mineralogical, geochemical and isotopic characters until a more robust mechanism of classification emerges.

Future Directions

We have provided an overview of the lamprophyre magmatism in various Indian cratons, mobile belts and associated with large igneous provinces through geological time. It can be seen that lamprophyres are widespread in the Indian shield and are found right from the Archaean to the Eocene. All the three world-wide known groups viz., alkaline, calc-alkaline and ultramafic as well as their varieties are also documented in the Indian shield. Calc-alkaline (including shoshonitic) varieties are essentially confined to the EDC whereas the ultramafic lamprophyres are confined to the rift zones such as the Kutch and the rift-related Mahakoshal belt. The calc-alkaline lamprophyres from the EDC provide evidence for the involvement of Neoarchaean subduction-related processes in their genesis whereas the mixed orogenic-anorogenic characters displayed by some of the shoshonitic lamprophyres from EDC and Prakasam province can be explained by a subduction-accretion related metasomatism of the mantle edge, followed by the SCLM metasomatism by asthenospheric melts/fluids. The Gondwana lamprophyres are petrologically distinct in having combined characters of lamproites, kimberlites and aillikites. The Deccan lamprophyres carry a pronounced OIB-type trace element signature which is very

likely an outcome of the influence of Reunion plume. Xenolith studies on the lamprophyres provided insights into the composition of the SCLM beneath the NW and western India and brought evidence for modal metasomatism and also constrained lithospheric thickness. Repeated lamprophyre emplacement in the Dongargaon domain highlights the reactivation of the Narmada rift zone during the Cretaceous. None of the Indian lamprophyres are diamondiferous even though microdiamond was suspected in some Gondwana lamprophyres. The potential of lamprophyres as important carriers of transition metals such as Co has only been recently realized from the microprobe study of pyrite from Sidhi lamprophyres. Future studies on Indian lamprophyres should focus on precise radiometric ages on phases such as rutile, titanite and apatite by deploying state-of-the-art techniques (such as LA-ICP-MS), which can give firm controls on the time of emplacement of lamprophyres and better constrain their geodynamic models. Direct dating of the phlogopite and apatite in mantle-derived xenoliths can provide the age of the metasomatism and unravel the agent responsible for it (i.e., Deccan plume or lamprophyre itself or both). Most of the known Indian lamprophyres are located either within the rift systems or along the deep-seated faults/fractures in association with the alkaline complexes demonstrating the role of structures in controlling their emplacement. Integration of geophysical studies along with hyper-spectral remote sensing can give insights into deep-seated structures like faults, fractures and rifts along which the lamprophyres would have been emplaced. The relationship of the lamprophyres to the Kimberlite clan rocks (KCRs), focusing on the Indian examples, is also critically examined and the pit-falls in the existing classification schemes in vogue are highlighted.

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