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Post-collisional calc-alkaline lamprophyres from the Kadiri greenstone belt: Evidence for the Neoarchean convergence-related evolution of the Eastern Dharwar Craton and its schist belts



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ABSTRACT

Lamprophyres from the greenstone belts play a crucial role in deciphering tectonic and geodynamic processes operating during the Archean. This study presents a comprehensive mineralogical and geochemical study of three lamprophyre dykes with calc-alkaline to shoshonitic affinities from the Neoarchean Kadiri schist belt, eastern Dharwar craton, southern India. These rocks display porphyritic-panidiomorphic texture, typical of the lamprophyres with amphibole (magnesio-hornblende) as phenocrysts, biotite as microphenocrysts and feldspar, epidote, titanite and apatite confined to the groundmass. Alteration of biotite to chlorite is observed along with mild deformation in the amphibole phenocrysts. Based on mineralogy and major oxide geochemistry, these rocks are classified as the calc-alkaline lamprophyres. Higher Ba/Nb and low Nb/La points to their derivation from an enriched lithospheric mantle source and higher Th/Yb ratio along with negative TNT (Ti-Nb-Ta) and Zr-Hf anomalies on the primitive mantle (PM) normalized multi-element diagram indicates dehydrated fluids from the foundering slab could be the possible metasomatic agent. Fractionated HREE ratios (Gd_N/Yb_N>1.9) and higher Sm_N/Yb_N suggests that the source region lies in the garnet stability field. Higher than PM Rb/Sr along with positive correlation between K/La and Rb/La reveals presence of metasomatic phlogopite in the source region. Strong negative initial ENd along with radiogenic ⁸⁷ Sr/⁸⁶ Sr ratios further support an enriched mantle reservoir involved in their genesis. Non-modal batch melting (1-5%) of a mixed source (phlogopite-garnet peridotite) assuming 5% mixing of subducted sediment with ambient mantle wedge (depleted mantle) satisfies the multi-element concentration pattern shown by the Kadiri lamprophyres. The source enrichment can be linked to the accretion-related growth of Dharwar craton and its schist belts during Neoarchean. Our study shows that a majority of lamprophyres associated with the Archean greenstone belts display a shoshonitic character; this highlights the role of subduction-related processes in the growth and evolution of the greenstone belts © 2018 Elsevier B.V. All rights reserved.

1. Introduction

Archean greenstone belts constitute of a wide spectrum of volcanic rocks such as tholeiitic basalt, siliceous high Mg-basalts (SHMB), komatiites, arc-related basalts, boninites, adakites and lamprophyres, revealing operation of modern style geodynamic processes in the first half of the earth's history (e.g., Currie and Williams, 1993; Naqvi et al., 2006; Polat and Kerrich, 2001; Srivastava, 2008; Srivastava et al., 2004). Thus, the greenstone belt associations in different cratons provide valuable insights into Archean tectonics, magmatism and crustal growth. In comparison to the other lithounits, lamprophyres from the

* Corresponding author. *E-mail address:* nvcrao@bhu.ac.in (N.V. Chalapathi Rao). Archean greenstone belts, however, have been given less attention with only a limited published literature available (see below).

Precambrian lamprophyres are considered to be the marker horizons for mapping of Precambrian terranes and locating zones of gold mineralization (Perring et al., 1989). Recognition of Precambrian lamprophyres, particularly the Archean ones, can be very challenging as fresh and undeformed lamprophyres are seldom found in the zones of shear tectonics and low pressure metamorphism (Mathieu et al., 2018). Several Archean lamprophyres have been found from cratonic regions around the globe e.g. Nuggihalli schist belt, India (Sugavanam et al., 1994), Abitibi and Michipicoten greenstone belts, Canada (Lefebvre et al., 2005; Wyman and Kerrich, 1993), Yilgarn craton, Australia (Currie and Williams, 1993; Perring et al., 1989; Taylor et al., 1994), and Superior craton, Canada (Wyman and Kerrich, 1989). A common feature of these Archean lamprophyres is their shoshonitic or

calc-alkaline nature. Calc-alkaline lamprophyres (CALs) crystallize from the deep mantle-derived volatile-rich and crystal laden melts that are 'crustal' alike lamproites and leucitites (Rock 1987 and 1991; Stille et al., 1989). The crust like geochemical and isotopic characters in CALs are either due to the partial melting of subducted sediments (Pan et al., 2018; Su et al., 2017) or the partial melting of mantle source regions affected by subduction-related metasomatism (e.g., Guo et al., 2004; Ma et al., 2014; Pandey et al., 2017a and references therein).

The Dharwar craton of southern India is a classic granite-greenstone terrain and its evolution is a still matter of conjecture (see Jayananda et al., 2018 and references therein). Recently, Pandey et al. (2017a, 2017b) have suggested that calc-alkaline and shoshonitic lamprophyres from the western margin of the Cuddapah basin to be manifestations of multi-stage mantle modification of the sub-continental lithospheric mantle (SCLM) beneath the Dharwar craton. In this paper, integration of mineralogical, geochemical and isotopic study on the calc-alkaline meta-lamprophyres from the Kadiri schist belt, eastern Dharwar craton, is presented with an objective to understand their petrogenesis and relevance in the geodynamic evolution of the eastern Dharwar craton and its schist belt.

2. Geology of the study area

2.1. The Dharwar Craton

The Dharwar Craton of southern Indian shield is a patchwork of two distinct granite-greenstone terranes, the western and eastern Dharwar cratons, sutured along the Chitradurga shear zone (Fig. 1A). The western Dharwar craton (WDC) hosts Paleo-Mesoarchean granitoids and older greenstone belts as compared to the eastern Dharwar craton (EDC) with Neoarchean granitoids, known as the Dharwar Batholith and parallel trending intra arc originated greenstone belts (Chadwick et al., 2000). Five distinct Paleoproterozoic mafic dyke swarms, Paleo-Mesoproterozoic crescent shaped Cuddapah Basin and Mesoproterozoic (1.3–1.1 Ga) alkaline rocks such as kimberlites and lamproites constitute the Proterozoic lithostratigraphy of the EDC (Chalapathi Rao et al., 1996, 1999, 2013; Kumar et al., 2007; Osborne et al., 2011).

Based on the geochemical studies, the greenstones of EDC have been interpreted to be accreted composite belts of plume and convergent margin associated volcanics (Manikyamba and Kerrich, 2012). The plume-derived lithology includes komatiites and high Mg-tholeiitic basalts whereas the convergent margin derived volcanics include tholeiitic to calc-alkaline basalts, boninites, Mg-andesites, Nb enriched basalts and adakites. These greenstone belts are surrounded by parallel, N-S to NNW-SSE trending belts of Neoarchean (2.72–2.51 Ga) granitoids including gneissic TTGs, high Mg diorites, sanukitoids and leucogranites (Chadwick et al., 2000; Dey et al., 2012; Moyen et al., 2003 and references therein).

2.2. Kadiri schist belt

The Kadiri schist belt is a 80 km long and 0.8 to 4.8 km wide NNW-SSE trending greenstone occurring between tonalite-granodiorite to the east, hornblende-biotite granite to the west and overlain by the sedimentary cover of the Cuddapah Supergroup in the north (Fig. 1B; Kazmi and Kumar, 1991; Satyanarayana et al., 2000). Dominance of felsic volcanic rocks is unique to the Kadiri schist belt unlike other greenstone belts of the EDC, which are mainly composed of mafic volcanic rocks (Dey et al., 2013, 2014). The mafic volcanics are restricted to the northern and southern extremities of the belt. Quartz-sericite schists, conglomerates, graywacke and magnetite-quartzite constitute the sedimentary rocks exposed in the Kadiri schist belt and all the rocks have been subjected to the low-grade metamorphism of greenschist and lower amphibolite facies (Satyanarayana et al., 2000).



Fig. 1. (A) Geological map of the Dharwar craton (after Jayananda et al., 2013 and references therein) showing locations of the Udiripikonda (UKL) and Mudigubba (MUD) lamprophyres along with the study area. (B) Geological map of the study area (after Kazmi and Kumar, 1991) showing location of the meta-lamprophyres (KAD) in the NNW-SSE to N-S trending Kadiri schist belt. (C) and (D) are the field photographs of the lamprophyre dykes.

Tab	le 1			

Whole rock major oxide and trace elements data for the Kadiri lamprophyres.

bipb		PP/KAD1/1	PP/KAD3/2	N/KAD/3	N/KAD2/2	PP/KAD3/1	N/KAD/1	
sol rob <b< td=""><td colspan="8">Major oxides (wt%)</td></b<>	Major oxides (wt%)							
modem	SiO ₂	53 71	54.09	57 27	55 56	54 39	57 30	
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As5555nd.Rb429360807045Nb429360807045Mo22222nd.Mo22220.5nd.Ag120.50.50.50.5nd.Sn12112nd.Sh0.50.50.50.5nd.Sb0.50.50.50.5nd.Ce14522.1481.716La21.420.43121.616.325.8Ce45.841.861.646.137.251.5Pr5.675.2875.44.6561.Nd22.920.727.121.319.423.3Sm54.44.84.44.34.3Eu1.351.311.291.61.4Th0.60.50.60.50.50.5Py3.33.12.732.92.5Ho0.70.60.50.60.50.2Py1.71.51.31.61.61.2Hf2.52.62.62.62.42.8Ce1.90.30.30.40.30.30.4Th1.51.31.61.61.21.6	Ge	2	2	1	1	1	n.d.	
Rb429360807045Nb445444Nb22221.44Ag1.20.50.50.50.5n.d.In0.20.20.20.2n.d.1Sn12112n.d.Sb0.50.50.50.50.5n.d.Cs15.22.14.81.71.6La2.42.04312.1.616.325.8Ce45.841.861.646.13.7.251.5Pr5.675.2875.44.656.1Nd22.920.727.121.319.423.3Sm54.44.44.34.34.3Eu1.351.311.291.161.8Gd4.59.93.64.11.71.4Th0.60.50.60.60.50.50.5Py3.33.12.732.92.51.4Th0.70.660.50.60.60.50.2Py1.61.41.71.71.41.4Th0.270.240.20.250.20.2Ho0.70.62.62.62.42.8Cir1.61.41.71.71.41.21	As	5	5	5	5	5	n.d.	
Nb 4 4 5 4 4 4 Mo 2 2 2 2 1 nd. Ag 1.2 0.5 0.5 0.5 0.5 nd. In 0.2 0.2 0.2 0.2 nd. Sn 1 2 1 1 2 nd. Sb 0.5 0.5 0.5 0.5 0.5 nd. Ce 45.8 41.8 61.6 46.1 37.2 51.5 Ce 45.8 41.8 61.6 44.4 4.3 4.3 Sm 5 2.07 27.1 2.1.3 19.4 23.3 Sm 5 4.4 4.8 4.4 4.3 4.3 Eu 1.35 1.31 1.29 1.6 1.8 6.6 Gd 4.5 3.9 3.7 3.9 3.6 0.5 0.5 Dy 3.3 3.1 <t< td=""><td>Rb</td><td>42</td><td>93</td><td>60</td><td>80</td><td>70</td><td>45</td></t<>	Rb	42	93	60	80	70	45	
Mo2222221Ag1.20.50.50.50.50.50.5In0.20.20.20.20.2n.d.Sn12112n.d.Sb0.50.50.50.50.50.50.5Cs15.22.14.81.71.6La2.42.0.43121.616.325.8Ce45.84.1.861.646.137.25.1.5Pr5.675.2875.44.656.1Nd2.2.92.0.72.7.12.1.319.42.3.3Sm54.44.84.44.34.3Eu1.351.311.291.291.161.8Gd4.53.93.73.93.64.1Dy3.33.12.732.92.5Fr1.91.61.41.71.71.4Tm0.70.60.50.60.60.5Er1.91.61.31.61.61.2Lu0.270.240.20.240.250.2Hf2.52.62.62.62.42.8Ta0.30.30.10.30.20.2Ho0.20.30.30.30.30.4Mu1.71.41.11.1 <t< td=""><td>Nb</td><td>4</td><td>4</td><td>5</td><td>4</td><td>4</td><td>4</td></t<>	Nb	4	4	5	4	4	4	
Ag1.20.50.50.50.5n.d.In0.20.20.20.2n.d.Sn121.1.2.n.d.Sb0.50.50.50.50.5n.d.Cs15.22.14.81.71.6La21.420.43121.616.325.8Ce45.841.861.646.137.251.5Pr5.675.2875.44.656.1Nd22.920.727.121.319.423.3Sm54.44.84.44.34.3Eu1.351.311.291.291.161.8Cd4.53.93.73.93.64.1Tb0.60.50.60.50.50.5Dy3.33.12.732.92.5Fr1.91.61.41.71.41.4Tm0.270.230.190.240.250.2Yb1.71.51.31.61.61.2Lu0.270.230.190.30.30.2Yb1.71.51.31.61.61.2Lu0.20.20.22.62.62.42.8Ta0.30.30.30.30.21.4Pb579756.2 <tr< td=""><td>Мо</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td><td>n.d.</td></tr<>	Мо	2	2	2	2	2	n.d.	
In0.20.20.20.20.2n.d.Sn12112n.d.Sb0.50.50.50.5n.d.Cs15.22.14.81.71.6La21.420.43121.616.325.8Ce5.575.2875.44.656.1Nd2.2920.727.121.319.423.3Sm54.44.84.44.34.3Eu1.351.311.291.291.161.8Gd4.53.93.73.93.64.1Tb0.60.50.50.60.50.5Dy3.33.12.732.92.5Ho0.70.60.50.60.50.5Er1.91.61.41.71.71.4Tm0.270.240.250.250.20.2Yb1.71.51.31.61.61.2Lu0.270.262.62.62.42.8Ta0.30.30.30.20.20.2W11111n.d.Pho579756.2Bi0.40.40.40.40.4n.d.Pho579756.2Bi0.40.40	Ag	1.2	0.5	0.5	0.5	0.5	n.d.	
Sn12112nd.sb0.50.50.50.50.5nd.Cs15.22.14.81.71.6La21.420.43121.616.325.8Ce45.841.861.646.137.251.5Pr5.675.2875.44.556.1Nd22.920.727.121.319.423.3Sm54.44.84.44.34.3Eu1.351.311.291.91.161.8Gd4.53.93.73.93.64.1Tb0.60.50.50.60.50.5Pr3.33.12.732.92.5Ho0.70.60.50.60.50.2Fr1.91.61.41.71.71.4Tm0.270.230.20.250.20.2Vb1.71.51.31.61.61.2Lu0.210.230.40.30.30.20.2Vb1.71.51.31.61.61.2Lu0.20.20.20.20.20.20.2Vb1.71.71.71.41.61.41.71.6Lu0.20.20.20.20.20.20.20.2Vb1.7 </td <td>In</td> <td>0.2</td> <td>0.2</td> <td>0.2</td> <td>0.2</td> <td>0.2</td> <td>n.d.</td>	In	0.2	0.2	0.2	0.2	0.2	n.d.	
Sb 0.5 0.5 0.5 0.5 n.d. Cs 1 5.2 2.1 4.8 1.7 1.6 La 21.4 20.4 31 21.6 16.3 25.8 Ce 45.8 41.8 61.6 46.1 37.2 51.5 Pr 5.67 5.28 7 5.4 4.65 6.1 Sm 5 4.4 4.8 4.4 4.3 4.3 Eu 1.35 1.31 1.29 1.16 1.8 Gd 4.5 3.9 3.7 3.9 3.6 4.1 Gd 0.6 0.5 0.6 0.5 <td< td=""><td>Sn</td><td>1</td><td>2</td><td>1</td><td>1</td><td>2</td><td>n.d.</td></td<>	Sn	1	2	1	1	2	n.d.	
Cs 1 5.2 2.1 4.8 1.7 1.6 La 21.4 20.4 31 21.6 16.3 25.8 Ce 45.8 41.8 61.6 46.1 37.2 51.5 Pr 5.67 5.28 7 5.4 4.65 6.1 Nd 22.9 20.7 27.1 21.3 19.4 23.3 Sm 5 4.4 4.8 4.4 4.3 4.3 Gd 4.5 3.9 3.7 3.9 3.6 4.1 Tb 0.6 0.5 0.5 0.6 0.5 0.5 Dy 3.3 3.1 2.7 3 2.9 2.5 Dy 3.3 1.1 2.7 3 2.9 2.5 Er 1.9 1.6 1.4 1.7 1.7 1.4 Tm 0.27 0.24 0.2 0.25 0.2 0.2 Lu 0.27	Sb	0.5	0.5	0.5	0.5	0.5	n.d.	
La21.420.43121.616.325.8Ce45.841.861.646.137.251.5Pr5.675.2875.44.656.1Nd22.920.727.121.319.423.3Sm54.44.84.44.34.3Eu1.351.311.291.291.161.8Cd4.53.93.73.93.64.1Tb0.60.50.50.60.50.5Dy3.33.12.732.92.5Fr1.91.61.41.71.71.4Tm0.70.60.50.60.50.5Er1.91.61.41.71.71.4Tm0.270.240.20.250.20.2Yb1.71.51.31.61.61.2Lu0.270.230.190.240.250.2Yb1.71.71.71.41.41.71.4Tm0.20.30.30.30.20.2Yb1.71.61.61.21.21.41.4Lu0.270.230.190.240.250.2Yb1.71.41111.41.4Th0.20.30.30.30.40.2Yb579	Cs	1	5.2	2.1	4.8	1.7	1.6	
Ce 45.8 41.8 61.6 46.1 37.2 51.5 Pr 5.67 5.28 7 5.4 4.65 6.1 Nd 22.9 20.7 27.1 21.3 19.4 23.3 Sm 5 4.4 4.8 4.4 4.3 4.3 Eu 1.35 1.31 1.29 1.29 1.16 1.8 Gd 4.5 3.9 3.7 3.9 3.6 4.1 Dy 3.3 3.1 2.7 3 2.9 2.5 Ho 0.6 0.5 0.6 0.6 0.5 0.5 Er 1.9 1.6 1.4 1.7 1.7 1.4 Tm 0.27 0.24 0.2 0.25 0.2 0.2 Yb 1.7 1.5 1.3 1.6 1.6 1.2 Lu 0.27 0.24 0.2 0.2 0.2 0.2 Yb 1.7<	La	21.4	20.4	31	21.6	16.3	25.8	
Pr5.675.2875.44.656.1Nd22.920.727.121.319.423.3Sm54.44.84.44.34.3Eu1.351.311.291.291.161.8Cd4.53.93.73.93.64.1Tb0.60.50.60.50.50.5Dy3.33.12.732.92.5Ho0.70.60.50.60.60.5Er1.91.61.41.71.71.4Tm0.270.240.20.250.250.2Vb1.71.51.31.61.61.2Lu0.270.230.190.240.250.2Ta0.30.30.40.30.30.2W11111n.d.Th0.20.40.20.30.30.2Bi0.40.40.40.30.30.2Bi0.40.40.40.40.40.40.4Th3.73.57.13.83.2n.d.	Ce	45.8	41.8	61.6	46.1	37.2	51.5	
Nd 22.9 20.7 27.1 21.3 19.4 23.3 Sm 5 4.4 4.8 4.4 4.3 4.3 Eu 1.35 1.31 1.29 1.29 1.16 1.8 Cd 4.5 3.9 3.7 3.9 3.6 4.1 Tb 0.6 0.5 0.5 0.6 0.5 0.5 Dy 3.3 3.1 2.7 3 2.9 2.5 Ho 0.6 0.5 0.6 0.5 0.6 0.5 Er 1.9 1.6 1.4 1.7 1.4 1.4 Tm 0.27 0.24 0.2 0.25 0.2 0.2 Yb 1.7 1.5 1.3 1.6 1.6 1.2 Lu 0.27 0.23 0.19 0.24 0.25 0.2 Yb 1.7 1.5 1.3 1.6 1.6 1.2 Lu 0.2	Pr	5.67	5.28	7	5.4	4.65	6.1	
Sm 5 4.4 4.8 4.4 4.3 4.3 Eu 1.35 1.31 1.29 1.29 1.16 1.8 Gd 4.5 3.9 3.7 3.9 3.6 4.1 Db 0.6 0.5 0.6 0.5 0.5 0.5 0.5 Dy 3.3 3.1 2.7 3 2.9 2.5 Ho 0.7 0.6 0.5 0.6 0.6 0.5 Er 1.9 1.6 1.4 1.7 1.7 1.4 Tm 0.27 0.24 0.2 0.25 0.25 0.2 Yb 1.7 1.5 1.3 1.6 1.2 1.2 Lu 0.27 0.23 0.19 0.24 0.25 0.2 Hf 2.5 2.6 2.6 2.4 2.8 Ta 0.3 0.3 0.2 0.2 0.2 W 1 1 1 1 nd. Th 0.2 0.3 0.3 0.2 <	Nd	22.9	20.7	27.1	21.3	19.4	23.3	
Eu1.351.311.291.291.161.8Gd4.53.93.73.93.64.1Tb0.60.50.60.50.65.5Dy3.33.12.732.92.5Ho0.70.60.50.60.60.5Er1.91.61.41.71.71.4Tm0.270.240.20.250.20.2Vb1.71.51.31.61.21.2Hf2.52.60.240.250.20.2Hf2.52.62.62.42.80.2Ta0.30.30.40.30.20.2W111111.4Th0.20.60.240.20.20.2Hf2.53.60.40.30.30.2W11111n.dTh0.20.40.20.30.30.2W11111n.dTh0.40.40.40.40.40.41.4Th3.73.57.13.83.2n.dU0.80.81.70.80.7n.d	Sm	5	4.4	4.8	4.4	4.3	4.3	
Gd 4.5 3.9 3.7 3.9 3.6 4.1 Tb 0.6 0.5 0.5 0.6 0.5 0.5 Dy 3.3 3.1 2.7 3 2.9 2.5 Ho 0.7 0.6 0.5 0.6 0.5 Er 1.9 1.6 1.4 1.7 1.7 1.4 Tm 0.27 0.24 0.2 0.25 0.25 0.2 Yb 1.7 1.5 1.3 1.6 1.2 1.2 Lu 0.27 0.23 0.19 0.24 0.25 0.2 Hf 2.5 2.6 2.6 2.6 2.4 2.8 Ta 0.3 0.3 0.3 0.2 0.2 MW 1 1 1 nd. nd. Pb 5 7 9 7 5 6.2 Bi 0.4 0.4 0.4 0.4 nd. nd. Th 3.7 3.5 7.1 3.8 3.2 nd. </td <td>Eu</td> <td>1.35</td> <td>1.31</td> <td>1.29</td> <td>1.29</td> <td>1.16</td> <td>1.8</td>	Eu	1.35	1.31	1.29	1.29	1.16	1.8	
Tb 0.6 0.5 0.5 0.6 0.5 0.5 Dy 3.3 3.1 2.7 3 2.9 2.5 Ho 0.7 0.6 0.5 0.6 0.6 0.5 Er 1.9 1.6 1.7 1.7 1.4 Tm 0.27 0.24 0.2 0.25 0.25 0.2 Yb 1.7 1.5 1.3 1.6 1.2 1.2 Lu 0.27 0.23 0.19 0.24 0.25 0.2 Hf 2.5 2.6 2.6 2.6 2.4 2.8 Ta 0.3 0.3 0.2 0.2 0.2 0.2 W 1 1 1 1 nd. 1 1 TI 0.2 0.4 0.2 0.3 0.3 0.2 Bi 0.4 0.4 0.4 0.4 0.4 0.4 0.4 Th 3.7	Gd	4.5	3.9	3.7	3.9	3.6	4.1	
Dy3.33.12.732.92.5Ho0.70.60.50.60.60.5Er1.91.61.41.71.71.4Tm0.270.240.20.250.2Yb1.71.51.31.61.61.2Lu0.270.230.190.240.250.2Hf2.52.62.62.62.42.8Ta0.30.30.40.30.30.2W1111n.d.TI0.20.40.20.30.2Pb579756.2Bi0.40.40.40.40.4n.d.Th3.73.57.13.83.2n.d.U0.80.81.70.80.7n.d.	Tb	0.6	0.5	0.5	0.6	0.5	0.5	
Ho0.70.60.50.60.60.5Er1.91.61.41.71.71.4Tm0.270.240.20.250.250.2Yb1.71.51.31.61.2Lu0.270.230.190.240.250.2Hf2.52.62.62.62.42.8Ta0.30.30.40.30.30.2W11111n.d.Tl0.20.40.20.30.3n.d.Pb579756.2Bi0.40.40.40.40.4n.d.Th3.73.57.13.83.2n.d.U0.80.81.70.80.7n.d.	Dy	3.3	3.1	2.7	3	2.9	2.5	
Fr1.91.61.41.71.71.4Tm0.270.240.20.250.250.2Yb1.71.51.31.61.61.2Lu0.270.230.190.240.250.2Hf2.52.62.62.62.42.8Ta0.30.30.40.30.30.2W11111n.d.Tl0.20.40.20.30.3n.d.Pb579756.2Bi0.40.40.40.40.4n.d.Th3.73.57.13.83.2n.d.U0.80.81.70.80.7n.d.	Но	0.7	0.6	0.5	0.6	0.6	0.5	
Tm0.270.240.20.250.250.2Yb1.71.51.31.61.61.2Lu0.270.230.190.240.250.2Hf2.52.62.62.62.42.8Ta0.30.30.40.30.2W1111n.d.TI0.20.40.20.30.3n.d.Pb579756.2Bi0.40.40.40.4n.d.n.d.Th3.73.57.13.83.2n.d.U0.80.81.70.80.7n.d.	Er	1.9	1.6	1.4	1.7	1.7	1.4	
Yb 1.7 1.5 1.3 1.6 1.6 1.2 Lu 0.27 0.23 0.19 0.24 0.25 0.2 Hf 2.5 2.6 2.6 2.6 2.4 2.8 Ta 0.3 0.3 0.4 0.3 0.3 0.2 W 1 1 1 1 n.d. TI 0.2 0.4 0.2 0.3 0.2 W 1 1 1 n.d. n.d. TI 0.2 0.4 0.2 0.3 0.3 n.d. Pb 5 7 9 7 5 6.2 Bi 0.4 0.4 0.4 0.4 n.d. Th 3.7 3.5 7.1 3.8 3.2 n.d. U 0.8 0.7 0.8 0.7 n.d.	Tm	0.27	0.24	0.2	0.25	0.25	0.2	
Lu0.270.230.190.240.250.2Hf2.52.62.62.62.42.8Ta0.30.30.40.30.30.2W1111n.d.TI0.20.40.20.30.3n.d.Pb579756.2Bi0.40.40.40.40.4n.d.Th3.73.57.13.83.2n.d.U0.80.81.70.80.7n.d.	Yb	1.7	1.5	1.3	1.6	1.6	1.2	
Ht2.52.62.62.62.42.8Ta0.30.30.40.30.30.2W1111n.d.TI0.20.30.3n.d.Pb579756.2Bi0.40.40.40.40.4n.d.Th3.73.57.13.83.2n.d.U0.80.81.70.80.7n.d.	Lu	0.27	0.23	0.19	0.24	0.25	0.2	
Ta0.30.30.40.30.30.2W1111n.d.TI0.20.40.20.30.3n.d.Pb579756.2Bi0.40.40.40.40.4n.d.Th3.73.57.13.83.2n.d.U0.80.81.70.80.7n.d.	Hf	2.5	2.6	2.6	2.6	2.4	2.8	
W I 1 1 1 n.d. TI 0.2 0.4 0.2 0.3 0.3 n.d. Pb 5 7 9 7 5 6.2 Bi 0.4 0.4 0.4 0.4 n.d. Th 3.7 3.5 7.1 3.8 3.2 n.d. U 0.8 0.8 1.7 0.8 0.7 n.d.	Ta	0.3	0.3	0.4	0.3	0.3	0.2	
110.20.40.20.30.3n.d.Pb579756.2Bi0.40.40.40.40.4n.d.Th3.73.57.13.83.2n.d.U0.80.81.70.80.7n.d.	VV	1	1	1	1	1	n.d.	
PD 5 / 9 / 5 6.2 Bi 0.4 0.4 0.4 0.4 n.d. Th 3.7 3.5 7.1 3.8 3.2 n.d. U 0.8 0.8 1.7 0.8 0.7 n.d.	11 Dl	0.2	0.4	0.2	0.3	0.3	n.d.	
bit 0.4 0.4 0.4 0.4 0.4 n.d. Th 3.7 3.5 7.1 3.8 3.2 n.d. U 0.8 0.8 1.7 0.8 0.7 n.d.	PD	5	/	9	/	5	6.2	
In 3.7 3.5 7.1 3.8 3.2 n.d. U 0.8 0.8 1.7 0.8 0.7 n.d.	B1	0.4	0.4	0.4	0.4	0.4	n.d.	
U U.8 U.8 1./ U.8 U./ n.d.	111	3./	3.3	/.1	3.8	3.2	n.a.	
	U	0.0	0.0	1,7	0.0	0.7	n.a.	

^a Total Fe and n.d. is not determined.

The rocks show superposed folding, interpreted to be a result of three phases of folding (Dey et al., 2013).

lution of Kadiri schist belt. Jayananda et al. (2013) obtained a U-Pb SIMS

zircon age of 2551 \pm 10 Ma on a rhyolite sample while Dey et al. (2014)

obtained LA-ICP-MS U-Pb zircon ages of 2558 \pm 18 Ma, 2523 \pm 39 Ma

The mafic volcanic rocks include tholeiitic basalts and high Mg ba-Kadiri schist belt. salts, basaltic andesite and dacite of calc-alkaline affinity, all considered to be derived from a tholeiitic parental melt through magmatic differentiation or fractional crystallization (Satyanarayana et al., 2000). Based on the geochemistry of these mafic rocks these authors recommend an island arc and active continental margin tectonic setting for the evo-

and 2510 ± 10 Ma for the eastern (granodiorite), western (leucogranite) and foliated gneiss, respectively, associated with the

2.3. Lamprophyre magmatism in EDC

Numerous Mesoproterozoic lamprophyre dykes are clustered in the EDC to the east of the Cuddapah Basin and are collectively termed as Cuddapah Intrusive Province (CIP) or Prakasam Alkaline Province (PAP) (see Madhavan et al., 1998). Calc-alkaline lamprophyres exposed at Mudigubba and a rare occurrence of a shoshonitic lamprophyre at

Table 2 Sm-Nd and Rb-Sr isotopic compositions of the Kadiri lamprophyres.

Sm-Nd compositions								
Samples	Sm (ppm)	Nd (ppm)	$^{147}{ m Sm}/^{144}{ m Nd}$	$^{143}{ m Nd}/^{144}{ m Nd}$	$^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{initial}}$	εNd _{present}	εNd _{initial}	T _{DM} in Ma
PP/KAD3/1 N/KAD/1	4.3 4.3	19.4 23.3	0.1340 0.1115	0.511475 0.511151	0.510508 0.510346	-22.7 -29.0	-13.9 -17.1	2821 2693
Rb-Sr compositions								
Samples		Rb (ppm)	Sr (ppm)		⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr		$^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}}$
PP/KAD3/1 N/KAD/1		70 45	490 469		0.4138 0.2794	0.714678 0.719290		0.708164 0.714891

The initial Sr and Nd isotopic values are calculated considering 1.1 Ga emplacement age of the lamprophyres. CHondritic Uniform Reservoir (CHUR) values: ¹⁴³ Nd/¹⁴⁴ Nd = 0.512638 and ¹⁴⁷ Sm/¹⁴⁴ Nd = 0.1967 and Depleted Mantle (DM) values: ¹⁴³ Nd/¹⁴⁴ Nd = 0.513114 and ¹⁴⁷ Sm/¹⁴⁴ Nd = 0.222.

Udiripikonda, within the Wajrakarur Kimberlite Field (WKF), have been reported from the western margin of the Cuddapah Basin (Pandey et al., 2017a, 2017b and references therein). Meshram et al. (2015) have reported alkaline lamprophyres from the Bayyaram area, which lies at the northeastern margin of the craton. This study incorporates three lamprophyre dykes, which are exposed in the Kadiri schist belt to the SSW of Kadiri (14°05′17.5″N and 78°08′56.9″E) intruding quartz feld-spar porphyry (Suresh et al., 2006). The dykes are free from xenoliths and exhibit mild deformation.

3. Analytical methods

Polished thin sections were studied under Carl Zeiss AXIO SCOPE.A1 microscope and mineral chemistry was analyzed using a CAMECA-SXFive electron microprobe (EPMA) at the Department of Geology, Banaras Hindu University. Wavelength dispersive spectrometry, LaB₆

filament along with LIF, PET, LPET, LTAP and PC1 crystals were positioned for the quantitative analyses. An accelerating voltage of 15 kV, a beam current of 10 nA (for major and minor elements) and 40 nA (for rare earth elements) and beam diameter of 1 µm were the analyzing parameters. Diopside (Ca), peridot (Mg), SrSO₄ (Sr), FeS₂ (Fe), orthoclase (K), rutile (Ti), NaCl (Na), apatite (P), CaSiO₃ (Si), kyanite (Al), fluorite (F) and rare earth element glasses (REE) were the standards used for calibration. Counting time for the major and minor elements were 10s, while for REEs were 60s. The error on major element concentrations was <1% and for trace elements varied between 3 and 5%. The analytical results for all the minerals are shown in Supplementary Table 1.

Six rock samples were powdered using a Retsch BB50 jaw crusher and Retsch RM100 motor grinder at the Department of Geology, Banaras Hindu University for the whole-rock geochemical analysis. Five samples were analyzed for major oxides and trace elements at Activation



Fig. 2. Photomicrographs and BSE images showing (A) glomerophyric texture formed due to clustering of amphibole phenocrysts (sample PP/KAD3/1), (B) porphyritic texture with bimodal size distribution of amphibole (sample PP/KAD3/1), (C) feldspar and apatite confined to the groundmass and biotite, which occurs as microphenocrysts, altering to chlorite (sample N/KAD2/2), and (D) very large phenocrysts of amphiboles with resorbed boundaries (sample N/KAD2/2).



Fig. 3. (A) Si (apfu) vs. mg# for the classification of the calcic- amphiboles and (B) SiO₂ (wt %) vs. TiO₂ (wt%) content (after Rock, 1991) for the Kadiri (KAD) and Mudigubba (MUD) lamprophyres. The dataset from the later is taken from Pandey et al. (2017a).

Laboratories, Ancaster, Canada. Alkaline fusion and ICP-OES (Thermo-Jarrell-Ash ENVIRO II) was deployed for the analysis of major elements, V, Sc, Sr, Ba, Zr and Y. Multi-acid digestion and ICP-MS analysis (Perkin Elmer Sciex ELAN 6000) was used for measurements for the rest of the trace elements including rare earth elements. The internal standards used for the analyses were STM1, MRG1, DNC1, W2 and SY3 and the precision was ~5% and 5–10% for the major oxides and trace elements, respectively. One rock sample (N/KAD/1) was analyzed for the major oxides and trace elements at the Department of Earth Sciences, Indian Institute of Technology, Kanpur following the procedure described in Chandra et al. (2018). The results are shown in Table 1.

For the Sr and Nd isotopic measurements, two representative samples were dissolved using equal proportions of ultra-pure HF and HNO_3 in 15 ml Savillex Teflon vials at 120 °C for 24 h. The acid mixture was subsequently evaporated and treated with 1 ml concentrated HNO_3 and HCl for another 24 h. Strontium and neodymium separation from the rock matrix was carried out using ion exchange column chromatography. Strontium and rare earth elements (REEs) were eluted in 3 and 6 N HCl, respectively using BioRad AG50W X8 (100–200 mesh) resin. The Sr cut was subsequently used using a smaller column filled with the same resin whereas REE fraction was

processed using BioRad AG50W X8 (200–400 mesh) resin. Neodymium was separated from the rest of the REEs using 0.2 M 2-Hydroxyisobutyric acid (pH = 4.495) and further purified using smaller columns filled with BioRad AG50W X8 (100–200 mesh) resin. The Sr and Nd isotopic measurements were carried out using a Thermal Ionization Mass Spectrometer (TIMS, Thermo Scientific Triton Plus) at the Centre for Earth Sciences, Indian Institute of Science using a methodology described in Banerjee et al. (2016). Instrumental mass fractionation was corrected by normalizing measured ⁸⁷ Sr/⁸⁶ Sr and ¹⁴³ Nd/¹⁴⁴ Nd ratios with ⁸⁶ Sr/⁸⁸ Sr = 0.1194 and ¹⁴⁶ Nd/¹⁴⁴ Nd = 0.7219, respectively, using an exponential law. The JNdi-1 Nd isotopic standard and SRM-987 Sr isotopic standard analyzed during the course of this study yielded values of ¹⁴³ Nd/ ¹⁴⁴ Nd = 0.512120 ± 8 (2SD, n = 3) and ⁸⁷ Sr/⁸⁶ Sr = 0.710265 ± 9 (2SD, n = 3), respectively. The results are shown in Table 2.

4. Results

4.1. Petrography and mineralogy

In thin sections, the samples exhibit porphyritic texture constituted by phenocrysts of amphiboles (up to 1 cm length), which are clotted, and impart a glomerophyric texture to the rock (Fig. 2). The restriction of feldspar to the groundmass and porphyritic texture are typical characteristics of the lamprophyres owing to their high volatile contents. Amphibole phenocrysts are often sheared and dislocated due to fractures. Dark mica is present as microphenocrysts and show signs of alteration to chlorite (Fig. 2C). Occurrence of apatite as inclusions in the amphiboles suggest that the it was the earliest crystallizing phase. The groundmass comprises of epidote, titanite and very minor amounts of quartz.

Apatite: The light rare earth element (LREE) concentration in the apatites is as high as 0.7 wt%. Along with titanite and epidote, apatite is the principal REE-reservoir in the lamprophyre melt. Fluorine is the dominant anion ranging from 2.0 to 3.69 wt% (Supplementary Table 1). The fluorine content in apatite is higher than that in mica in these samples (see below) because of the former's earlier crystallization; as it is well known that fluorine prefers to partition in the crystals than the melt with which it is in equilibrium (see Talukdar et al., 2018 for a detailed discussion).

Amphiboles: The amphiboles in Kadiri lamprophyres are classified as magnesio-hornblende and actinolite (Fig. 3A). Although, the samples show signs of low grade metamorphism, the pristine nature of the amphiboles is evident from their Si content such that most of the data fall in the magnesio-hornblende field rather than actinolite (Fig. 3A). Amphiboles are dominated by Na in A-structural site and depletion in TiO₂ (< 0.3 wt%) which is in line with the calc-alkaline nature of the lamprophyre melt (Fig. 3B). This is further corroborated by their very low K content contrary to the rocks of alkaline series, which have amphiboles with higher K content. [Ca + (Mg + Fe²⁺)_C] shows good correlation with [Na + (Fe³⁺)_C] (r² = 0.822) suggesting substitution of the later cations at the expense of divalent cations of the B and C sites.

Mica: Low mg# (0.49–0.57) in the mica of the Kadiri lamprophyres are comparable to those shown by the CIP lamprophyres, classifying them as biotites (Fig. 4B; Supplementary Table 1). The MgO and TiO₂ content in these biotites are higher and lower, respectively, than those from the Udiripikonda shoshonitic lamprophyre although they show similar Al₂O₃ contents. These biotites fall outside the compositional field defined for those from the minettes and the Roman Province lavas but plot close to the field of mica from kimberlites (Fig. 4A). Although, a negative correlation trend between Al₂O₃ and TiO₂ (a trait common to the lamproites) is observed, the micas are much depleted in TiO₂ content with higher Al₂O₃ abundance compared to the lamproites from the Kimberley, Mediterranean region and eastern Dharwar craton (Fig. 4A). Such high alumina content is characteristic of mica from calc-alkaline lamprophyres (Fig. 4C). Chlorite occurs as



Fig. 4. (A) TiO₂ (wt%) vs. Al₂O₃ (wt%) variation diagram (Mitchell and Bergman, 1991) for the mica showing their trend similar to the lamproites but with lower TiO₂ and higher Al₂O₃ content compared to them. Also shown is the data for the UKL (Pandey et al., 2017b) and CIP (Madhavan et al., 1998) lamprophyres along with the lamproites from the eastern Dharwar craton (Talukdar et al., 2018 and references therein). (B) SiO₂ (wt%) vs. mg# plot classifying studied dark micas as biotites. Dataset for the Mediterranean lamproites are from Fritschle et al. (2013). (C) mg# [Mg/(Mg + Fe²⁺)] vs. Al₂O₃ (wt%) diagram (after Rock, 1987) showing biotites from the KAD falling in the global calc-alkaline field with Al₂O₃ content higher than those of the lamproites.

an alteration product of the biotite (see Fig. 2C), which is classified as clinochlore and pennine.

Feldspar: The average composition of feldspar analyzed in the studied samples is $Or_{9,44}Ab_{55,61}An_{34,95}$ (Supplementary Table 1) and can be classified as andesine to labradorite. Predominance of plagioclase over orthoclase classifies these lamprophyres as spessartite in particular.

Titanite: Occurring as a groundmass phase, it is the principal carrier of rare earth elements (REEs) and high field strength elements (HFSEs) along with apatite and epidote. The Al₂O₃ and V₂O₃ content in the titanite ranges from 0.60 to 2.78 and 0.18 to 0.51 wt%, respectively (Supplementary Table 1). Interestingly, BaO content is high in the titanite and range from 1.09 to 1.33 wt%. According to Frost et al. (2000), titanite crystallization is favoured in calcium-rich metaluminous oxidized melts with intermediate SiO₂ content.

4.2. Whole rock geochemistry

The studied rock samples are intermediate in composition (SiO₂ > 52 wt%) and have total alkali (Na₂O + K₂O) content ranging from 3.7–5.2 wt%. These are metaluminous as molar Al₂O₃/(Na₂O + K₂O) and molar Al₂O₃/(CaO + Na₂O + K₂O) ranges from 1.93 to 2.47 and 0.58–0.75, respectively. Molar (K₂O + Na₂O)/Al₂O₃, ranging between 0.40 and 0.52, is compatible with the calc-alkaline melts. The Zr content varies between 92 and 106 ppm and the low Ni (70–100 ppm) and Cr (216–590 ppm) content indicates differentiated nature of the melt (Table 1). There exists a good correlation between the concentrations of U and Th and the highly mobile elements such as Cs, Rb, which indicates that the post-magmatic alteration has not mobilized these

elements (Supplementary Fig. 3). The chondrite normalized REE patterns show fractionated La_N/Yb_N , which varies between 7.3 and 17.1 (Fig. 6A). Fractionated HREE (Gd_N/Yb_N > 1.9) is a characteristic of these samples and suggestive of residual garnet in their source regions. The primitive-mantle normalized multi-element pattern for the KAD replicates those of average calc-alkaline lamprophyres and global subducting sediment (GLOSS) (Fig. 6B). It shows conspicuous negative anomalies at Nb, Ta, Zr, Hf and Ti and a positive spike at Pb. The Nb and Ti anomalies are not at all correlated with the MgO content, which indicate that these are the source characters and are not affected by differentiation processes (Fig. 6B).

4.3. Sr-Nd isotope geochemistry

The calculated initial ⁸⁷ Sr/⁸⁶ Sr and ¹⁴³ Nd/¹⁴⁴ Nd isotope ratios considering 1.1 Ga emplacement age, for the two samples are 0.708164–0.714891 and 0.510508–0.510346, respectively (Table 2). These values are estimated considering the Kadiri lamprophyres to be a part of wide-spread 1.1 Ga tectonomagmatic event responsible for major deep mantle derived alkaline magmatism in the EDC (Chalapathi Rao et al., 2013). Initial ε Nd along with radiogenic Sr isotope ratios points to an enriched mantle reservoir as the source for these rocks and plot away from the mixing curve between mantle reservoir and lower as well as upper continental crust (Fig. 7). Initial ε Nd for these samples are much lower than the granitoids associated with the Kadiri schist belt (Dey et al., 2014). The depleted mantle model age is obtained to be Neoarchean (2693–2821 Ma) for these rocks, probably, indicating the time period when such an enriched mantle reservoir was created.



Fig. 5. (A) Na₂O (wt%) vs. K₂O (wt%) plot showing calc-alkaline to shoshonitic nature of the KAD alike MUD samples, which straddle the calc-alkaline and shoshonitic boundary. UKL, on the other hand, exhibits shoshonitic to ultrapotassic nature. (B) SiO₂ (wt%) vs. K₂O (wt%) diagram (based on Rock, 1987) classifying KAD and MUD as calc-alkaline lamprophyres (CALs), while UKL has a mixed character to the alkaline and calc-alkaline lamprophyres.

5. Discussion

5.1. Magma intensive parameters and crystallization conditions

For the intermediate and silicic volcanic rocks, variation in Mn concentrations of apatites is considered to be a function of oxygen fugacity (Miles et al., 2014). Application of this Mn-in-apatite oxybarometer on the studied samples results in oxygen fugacity $(\log fO_2)$ range of -10.6 to -12.1. Average $\log fO_2$ value obtained based on crystallization conditions of amphiboles is calculated to be -13.4 (Ridolfi et al., 2010). Saturation temperature of apatite in basaltic magma depends upon the apatite/liquid partitioning of phosphorous (Watson, 1979) and the calculated temperature obtained from this method ranges from 1016 to 1021 °C (Supplementary Table 1; Supplementary Fig. 4).

Applying the empirical amphibole thermobarometric equations of Ridolfi et al. (2010) yields a pressure and temperature range of 41 to 100 MPa and 710 to 779 °C, respectively (Supplementary Fig. 4), which is consistent with the temperature range of 699–738 °C and 707–739 °C, calculated using pressure dependent and independent equations of Putirka (2016), respectively. These results are in line with the low P-T stability of magnesio-hornblendes compared to the P-T

stability of other Ca-amphiboles of magnesio-hastingsite-pargasitekaersutite series (Supplementary Fig. 4; Ulrych et al., 2018).

In calc-alkaline lamprophyre melt Ti is preferentially incorporated into the structure of mafic mica and partitioning of Ti is temperaturedependent (Krmíček et al., 2014; Righter and Carmichael, 1996). Application of Ti-in biotite thermometry provides a temperature range of 1063–1150 °C (\pm 50 °C) for biotite crystallization (Supplementary Table 1). Experimental studies have shown that higher K₂O and relative paucity of H₂O in the melt favours the appearance of biotite as liquidus phase and progressive crystallization yields melt rich in water favouring subsequent amphibole crystallization and fractionation (Bucholz et al., 2014).

5.2. Classification: Calc-alkaline to shoshonitic nature

Profusion of amphiboles and dominance of plagioclase over alkali feldspar classifies the lamprophyres under study as calc-alkaline lamprophyres in general and spessartites in particular. Lower Ti concentrations in the amphiboles are consistent with those found in CALs (Rock, 1991; Fig. 3B). Moreover, higher yet variable Al₂O₃ content (14.8–18.8 wt%) with moderate mg# (~0.50) in the biotite of the samples is typical of the compositional range exhibited by the CALs (Rock, 1991; Fig. 4C). The mineralogical observations are also consistent with the whole rock geochemistry of the samples.

The K₂O/Na₂O range of 0.5–1.2 in the present samples is a characteristic of shoshonitic volcanic rocks (Fig. 5A). Of all the lamprophyres variety, CALs have the highest K₂O and SiO₂ content (Rock, 1987). The K₂O and SiO₂ content ranges from 1.3 to 2.2 and 53.7 to 57.3 wt%, respectively, which is consistent with the global CALs (Fig. 5B). Of all the varieties of the lamprophyres, CALs have the lowest TiO₂ and P₂O₅ concentrations and TiO₂ (0.6–0.9 wt%) and P₂O₅ (0.2–0.3 wt%) range in KAD samples are slightly lower than the average CAL data (TiO₂ = 1.1 and P₂O₅ = 0.6 wt%; Rock, 1991, p. 78). Other major oxide concentrations in the KAD samples are also similar to those of Archean and global CALs (see Supplementary Fig. 1).

In TAS (total alkali silica) diagram (not shown), the Kadiri and Mudigubba lamprophyres show basalt-basaltic andesite-andesite series (calc-alkaline) with silica over-saturated character. Also, the samples do not show kinking towards total Fe_2O_3 end on the AFM diagram, suggesting constant Fe/Mg ratio in the melt while its evolution towards increasing alkalis, which is observed in calc-alkaline magma series owing to the oxidizing conditions. High Th coupled with lower Co content in the present samples, is also a signature of the calc-alkaline and shoshonitic volcanics (Hastie et al., 2007).

5.3. Source contamination or crustal contamination?

Distinction between arc-related magmatic suite or the melts from a subduction modified mantle wedge (source contamination) and those affected by the open system processes while their ascent to the surface (crustal contamination) is confusing but important to decipher to make reasonable petrogenetic arguments. Although the dykes under study intrude felsic rocks, they do not show any crustal xenolith or xenocryst. Abundance of Ni (>70 ppm) and Cr (>216 ppm) in the KAD samples is consistent with their mantle derivation, showing effects of crustal assimilation. Contamination of mantle derived melts by crustal material reveals not only considerable depletion of Nb and Ta but also positive anomalies of Zr and Hf in primitive mantle normalized multi-element diagram. However, the samples under study show negative anomalies of Nb, Ta as well as Zr and Hf, thereby, precluding crustal contamination. This is also supported by contamination-sensitive trace element ratios (e.g., Rb/Nb), which remains constant with variation in SiO₂. Higher Th/La ratios are characteristic of upper and average continental crust (0.34 and 0.28, respectively; Rudnick and Gao, 2003). Alike, the Mudigubba lamprophyres, KAD samples have substantially low Th/La (<0.23; Table 1), which is definitely a source character. There exists a



Fig. 6. (A) Chondrite normalized rare earth elements plot showing fractionated pattern for the KAD samples. (B) Primitive mantle (PM) normalized multi-element plot compared to average Mudigubba and Udiripikonda lamprophyres (Pandey et al., 2017a, 2017b), average CAL (Rock, 1991) and global subducting sediment (GLOSS; Plank and Langmuir, 1998). Also shown is the MgO (wt%) vs. Nb (Nb/Nb* = Nb/ $\sqrt{U * La}$) and Ti anomaly (Ti/Ti* = Ti/ $\sqrt{Eu * Gd}$) in the inset.

negative correlation between the La/Sm and Ba/La ratios for the studied samples, thus by, further ruling out crustal contamination as such a relation is observed by the subduction fluid-related enrichment of the mantle source (Pandey et al., 2017a). Trace element ratios such as Nb/U and Ce/Pb are sensitive to the contamination by crustal material as



Fig. 7. εNd_{initial}- ⁸⁷ Sr/⁸⁶ Sr_{initial} isotope variation diagram for the KAD samples. Compositional fields for the different Phanerozoic lamprophyres are also shown. Data sources are given in electronic appendix.

crust in enriched in U and Pb compared to Nb and Ce, respectively (Rudnick and Gao, 2003). Crustal contamination also supplements SiO₂ in the melt and a negative correlation between these trace element ratios with SiO₂ would be observed when the melt engulfs crustal material. In the present samples, there is a no correlation between Ce/Pb with SiO₂ ($r^2 = 0.004$), while a fair correlation exists between Nb/U and SiO₂ ($r^2 = 0.71$). This observation highlights a limited role of crustal contamination in controlling trace element behavior of the studied lamprophyres.

Moreover, the $\varepsilon Nd_{(T)}$ of the samples are much lower than the granitoids associated with the Kadiri schist belt (see Dey et al., 2014). Also, these values fall much below the crustal limit on a $\varepsilon Nd_{(T)}$ vs. crustal age plot of DePaolo (1981) suggesting an enriched negative εNd mantle reservoir rather than crustal involvement during magma ascent.

5.4. Mantle source heterogeneity

As observed in the KAD samples (Fig. 6B), the HFSE depletion or high LILE/HFSE ratios are considered to be the hallmark of the magmas generated by subduction-related processes and attributed to (i) previous melt depletion episode of the peridotitic mantle wedge prior to the metasomatism, (ii) interaction of an ascending melt pocket by a depleted mantle reservoir, (iii) presence of residual phase capable of holding HFSEs ($D_{HFSE} > 1$), (iv) fractionation of mobile elements in the foundering crustal slab, and (v) extremely low solubility of HFSEs such as Nb and Ta in fluids transported from slab to wedge during subduction (see Woodhead et al., 2011 and references therein).



Fig. 8. (A) Nb (ppm)-Nb/Ta, (B) Zr/Hf-Nb/Ta, (C) Nb/U-Ce/Pb and (D) Ba/Rb-Rb/Sr (after Furman and Graham, 1999) variation diagrams for the Kadiri lamprophyres. Non-modal batch melting curve for the primitive mantle (Sun and McDonough, 1989) and fractionation curve of different hypothetical assemblages have been shown in (A). The hypothetical fractionating assemblage are A (OI:Cpx:Amph = 1:1:3), B (equal proportions of amphibole and rutile) and C (OI:Cpx:Rut = 1:1:3). Note that fractionation of Ti-bearing phase such as rutile shoots up the Nb/Ta ratio to the superchondritic values, while fractionation of amphiboles can only yield subchondritic Nb/Ta ratios. Also, the melting of a four phase PM free from any hydrous phase (modal proportion = $Ol_{0:60}$ Opx_{0.14} Grt_{0.07}; melting mode = $Ol_{0.01}$ Opx_{0.08} Cpx_{0.36} Grt_{0.54}) requires extensively high proportion of melting to explain the HFSE budget of KAD samples. The partition coefficients used in the calculations have been taken from GERM Partition Coefficient (Kd) Database (https://earthref.org/KDD/). Chondritic Nb/Ta and Zr/Hf values in (B) are from Münker et al. (2003). Mixing curve considering upper continental crust (UCC) and sub-continental lithospheric mantle (SCLM) as end members have also been shown in (C). For data sources see electronic appendix.

The HFSEs like Nb and Ta are considered to be the "geochemical twins" due to their similar behavior owing to similar ionic radii (size) and charge. Therefore, the Nb/Ta ratio is typically not affected by fractionating processes like partial melting and crystal fractionation (Jochum et al., 1986). However, in certain circumstances such as presence of a residual phase with potential to accommodate these elements differentially, this pair is fractionated (Stolz et al., 1996 and references therein). Titanium bearing phases such as rutile, ilmenite and titanite have $D_{Ta} > D_{Nb}$, and therefore, their presence in the source or fractionation yields melts with superchondritic (>19.9; Münker et al., 2003) Nb/Ta ratios (Klemme et al., 2005; Schmidt et al., 2004). Subchondritic Nb/Ta ratios in the melts are, on the other hand, manifestation of fractionation or presence of low Mg# amphiboles as a residual phase (Foley et al., 2002; Tiepolo et al., 2000) or are inherited from the rutile bearing eclogitic sources with superchondritic Nb/Ta values (Rudnick et al., 2000). Upper mantle amphiboles have high Mg# (e.g., Coltorti et al., 2007; Ulrych et al., 2018), which are incapable of fractionating Nb and Ta (Foley et al., 2002; Tiepolo et al., 2000). Therefore, subchondritic Nb/Ta ratios in the KAD samples are not because of the presence of residual amphiboles, but are attributed to the fractionation of low Mg# amphiboles (Fig. 8A, B).

The variation in incompatible trace element ratios such as Nb/U and Ce/Pb reflect different geochemical reservoirs (Hofmann et al., 1986). Studied samples have Nb/U (2.9–5.7) and Ce/Pb (6.0–9.2) ratios well below the mantle array (Nb/U = 47 ± 10 and Ce/Pb = 25 ± 5) defined by global MORBs and OIBs (Hofmann et al., 1986) and are similar to those of upper continental crust (Fig. 8C; Rudnick and Gao, 2003). This

reflects the contamination of the mantle source region by the crustal material via subduction, which could have elevated the LREE/HFSE ratios.

Mantle metasomatism generated hydrous phases in the wedge above subducting slab occur as enriched pods or veins and on partial melting, generate alkaline magmas of unusual composition (Foley, 1992b; Sudo and Tatsumi, 1990). Potassic and ultrapotassic characters of the volcanic rocks are considered to be the manifestation of the presence of phlogopite in the mantle source (Conceição and Green, 2004; Foley, 1992a; Förster et al., 2017). Interestingly, the hydrous phases in the mantle govern the LILE budget of the melts equilibrating with them. For example, Rb and Ba are strongly compatible in phlogopite while moderately compatible in amphibole and therefore, melt in equilibrium with phlogopite in the mantle would have higher Rb/Ba and Rb/ Sr ratios compared to those in equilibrium with amphibole (Furman and Graham, 1999 and references therein). High Rb/Sr ratios in KAD samples (ranging from 0.09 to 0.20) compared to the primitive mantle (0.03; Sun and McDonough, 1989) corresponds to the presence of phlogopite as the residual phase (Fig. 8D). This observation is further corroborated by a positive correlation between Rb/La and K/La.

Volcanic rocks that interact with the continental crust during their ascent to the surface or with a subduction component in their mantle source have higher Th/Yb content (Pearce, 2008). Higher Th/Yb ratios than the mantle array defined by MORB and OIB is characteristic of Kadiri lamprophyres, further confirms subduction-induced metasomatism of the source. In this regard, the KAD samples are comparable to those from the lamprophyres from Mudigubba and Archean shoshonitic



Fig. 9. (A) Nb/Yb vs. Th/Yb (Pearce, 2008) and (B) Primitive mantle normalized Ta/La-Hf/ Sm diagram. Calculated mixing curve between UCC and N-MORB is also shown in (A). Arrays for the fluid- and melt-related subduction as well as carbonatite metasomatism are after La Flèche et al. (1998). Dataset for the Archean shoshonitic lamprophyres include those from the Yilgarn block, western Australia (Currie and Williams, 1993; Taylor et al., 1994) and the Superior Province, Canada (Wyman and Kerrich, 1989, 1993).

lamprophyres from Australia and Canada (Fig. 9A). Modification of the mantle wedge in a subduction setting is achieved either by the fluids dehydrated from the foundering slab or by the partial melts of the slab itself. Given the fact that, fluids from the subducting slab have mobility preferences for La and Sm as compared to Ta and Hf, respectively (Johnson and Plank, 2000), melts in equilibrium with fluid-related subduction modified mantle would have lower Ta_N/La_N and Hf_N/Sm_N ratios as observed for the EDC lamprophyres and Archean shoshonitic lamprophyres from Australian and Canadian shield (Fig. 9B).

5.5. Petrogenesis

Supplementary Fig. 2 shows variation of major oxides caused by the differentiation or fractionation of mineral phases. With evolving composition (decreasing MgO), CaO/Al₂O₃ remains constant initially and decreases rapidly suggesting fractionation of olivine followed by clinopyroxene. Interestingly, Sr concentration increases with evolving melt, which is contrary to what is expected during plagioclase fractionation. Plagioclase fractionation can also be ruled out as there is no Eu anomaly observed on the chondrite normalized REE pattern (Fig. 6A). Yttrium is sequestrated considerably in calcic-amphiboles and therefore fractionation of amphibole would decrease the Y/Ce ratio along with decreasing MgO and Fe₂O₃ as observed in the studied samples. This observation is consistent with sub-chondritic Nb/Ta ratios caused by amphibole fractionation as discussed above.

The generation of Kadiri lamprophyres can be modeled by the melting of phlogopite *veined* enriched depleted mantle (*E*-DMM) that underwent fractionation of olivine, clinopyroxene and amphiboles (Fig. 10A). Considering global subducting sediment (GLOSS; Plank and Langmuir, 1998) affected by the fluid generated while subduction, as one end member and depleted mantle -as another, we have estimated the composition of a fluid-related subduction metasomatized mantle source having 5% sediment influx (see Fig. 10B). Composition of melt generated by 1–5% melting of this source in the garnet phlogopite zone (OI 55%, Opx 19%, Cpx 7%, Grt 11%, Phl 8%) fits well with observed multi-element pattern for the Kadiri lamprophyres (Fig. 10B) and also replicates the pattern shown by the average CALs. We, therefore, suggest that Kadiri lamprophyres are generated by the fractionation of melt from 1 to 5% partial melting of a depleted mantle modified by subduction fluid-discharged incompatible elements.



Fig. 10. Trace element modelling of the Kadiri lamprophyres. (A) Yb (ppm) vs. Ce/Yb variation for the KAD samples with non-modal batch partial melting curves of enriched depleted mantle source (*E*-DMM) for different mantle lithologies. Source modal proportions, melting mode and data source are given in the electronic appendix. The degree of partial melting on each curve is shown by horizontal lines and is same for all. Trend for the melt composition modification after crystal fractionation (Ol:Cpx:Amph = 2:2:1 proportion) is also shown for the melt composition formed by 2% non-modal batch melting of phlogopite-lherzolite. (B) Multi-element pattern of KAD samples compared to average CALs and calculated melt compositions generated by 0.1, 1 and 5% partial melting of a phlogopite-lherzolite source. Patterns for partial melts of both E-DMM (smooth line) and a calculated source (broken line) are shown. Calculated source is the 5% mixture of global subducting sediment (GLOSS; Plank and Langmuir, 1998) in depleted mantle (DM). The crystal/fluid mobility coefficient for subducting sediment are from Johnson and Plank (2000) and the partition coefficient used in calculations are taken from GERM Partition Coefficient (Kd) Database (https://earthref. org/KDD/). The melt composition from calculated source replicates the multi-element pattern exhibited by the Kadiri lamprophyres except for the HREEs.



Fig. 11. Tectonic discrimination diagram for the Kadiri lamprophyres. (A) TiO₂/Al₂O₃ vs. Zr/Al₂O₃ (Muller and Groves, 2000) and (B) Hf-Th-Nb/2 (Krmíček et al., 2011, 2016) plots showing an orogenic setting for the KAD samples. Data sources for Archean shoshonitic lamprophyres are same as mentioned in Fig. 9.

5.6. Geodynamic implications

Both major oxides and trace element tectonic discrimination diagrams reveal orogenic or arc-related setting involved in the genesis of the Kadiri lamprophyres (Fig. 11). Based on our geochemical study, it is evident that the source regions of the Kadiri lamprophyres were modified by fluid-related metasomatic process in a subduction setting during the Neoarchean, and subsequently underwent partial melting during the Mesoproterozoic.

Lamprophyre magmatism towards the western margin of the Cuddapah basin in EDC has been shown to be a result of subduction-related evolution of Dharwar SCLM during amalgamation of the eastern and western blocks (Pandey et al., 2017a). Interestingly, Manikyamba and Kerrich (2012) infer Archean greenstone belts of the eastern Dharwar Craton as a composite terrane of accreted plume- and arc- derived magmatic sequences. According to them, the Cenozoic style subduction was operational during Neoarchean and the EDC greenstones were assembled as a part of global accretionary orogen at ~2.7 Ga, which is also responsible for the gold mineralization in these greenstones. In a recent review, Jayananda et al. (2018) have discussed crustal accretion growth of the Dharwar Craton in five different episodes (3.45– 3.30, 3.23–3.15, 3.00–2.96, 2.7–2.6 and 2.56–2.52 Ga), linked to greenstone volcanism in space and time. Additionally, a Neoarchean arc-setting has been invoked for the genesis of volcanics from the Kadiri schist belt, southern India (Dey et al., 2013; Manikyamba et al., 2015, 2017). Our results are therefore, consistent with the previously proposed uniformitarian models for the evolution of EDC and Kadiri schist belt.

6. Conclusions

The lamprophyres from the Kadiri schist belt are classified, based on mineralogy and whole-rock major oxide geochemistry, to be calc-alkaline ones in general and spessartite in particular. Apatite is the earliest crystallizing phase and its crystallization temperature varies between 1016 and 1021 °C. The crystallization of phenocrysts amphiboles occurred near the earth's surface in a temperature range of 700-770 °C. These rocks appear to be derived from an old SCLM source modified by metasomatism via subduction-related fluids. The trace element ratios suggest stability of metasomatic phlogopite veins (metasomes) in the garnet peridotite and the SCLM source was developed by the mixing of incompatible elements carried out by the subduction-related fluids in a depleted mantle wedge. 1-5% melting of such a mixed source that subsequently underwent fractionation of olivine, clinopyroxene and amphibole generated the Kadiri lamprophyres. The Neoarchean convergence-related growth of the Dharwar Craton and its schist belt could have created an enriched mantle reservoir as indicated by the strong negative ɛNd values for these rocks. Our study highlights that a majority of lamprophyres associated with the Archean greenstone belts share a similarity in having a shoshonitic character thereby highlighting the role of subduction-related processes in the growth and evolution of the greenstone belts.

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