Petrogenesis of macrocrystic and aphanitic intrusions in Mesoproterozoic diamondiferous pipe 2 kimberlite, Wajrakarur kimberlite field, eastern Dharwar craton, southern India

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(Received September 26, 2013; Accepted August 9, 2014)

Mesoproterozoic Pipe 2 kimberlite intruding granitic gneisses in the Wajrakarur kimberlite field (WKF) of Eastern Dharwar craton, southern India, is one of the first discovered pipes from this field. The two different intrusions belonging to coherent facies are observed in this kimberlite which are texturally distinct i.e., macrocrystic (with abundant macrocrysts) as well as aphanitic (devoid of or very fewer macrocrysts). Petrographic observations give evidence of presence of veined metasomatic mantle in the source region. Distinct geochemical variation is observed between macrocrystic (Mg# 75.4–76.6, SiO₂: 34.3–35.4 wt%, MgO: 18.7–20.4 wt%) and aphanitic samples (Mg# 74.7–75.5, SiO₂: 30.4–31.8 wt%, MgO: ~21 wt%), furthermore aphanitic samples are relatively more enriched in trace and rare earth elements. Geochemical studies point out that aphanitic and macrocrystic varieties of Pipe 2 kimberlite to be products of the same mantle source but have experienced different evolutionary histories. The inferred primary magma of Pipe 2 kimberlite (for both aphanitic and macrocrystic) is suggested to have a composition of ~33 wt% SiO₂, Mg# ~ 75.6 and ~460 ppm Ni. Pipe 2 primary magma can be derived by using forward melting model assuming ~1% partial melting of a source enriched in light REE by a factor of ~11 x chondrite and almost chondritic heavy REE with 2% residual garnet. Differences between aphanitic and macrocrystic varieties in their chondrite normalized REE abundance patterns can be explained by about 5% crystal fractionation of primary magma and not by variations in the degree of partial melting. The primitive mantle normalized trace element patterns exhibit significant negative K, Sr, P, Ti and Hf anomalies that are interpreted to be characteristic of the primary magma. Combined petrology and whole rock geochemistry including compatible and incompatible element abundances and their ratios confirm that Pipe 2 kimberlite intrusions are archetypal Group I kimberlites similar to other kimberlites of EDC and not lamproites.

Keywords: Wajrakarur kimberlite field, Eastern Dharwar craton, geochemistry, geochemical modeling, petrogenesis

INTRODUCTION

Kimberlites are complex potassium-bearing, ultramafic rocks having deep mantle origin. Although rare and volumetrically insignificant they invite considerable interest owing to their entrained mantle xenoliths (e.g., Gregoire *et al.*, 2003) and xenocrysts such as diamonds (e.g., Roubouts, 2003) thereby constituting “windows to the Earth’s mantle”. Their extreme magma composition (low SiO₂, high trace element and volatile contents) render an understanding of the melting processes undergone by their mantle source regions a challenging task.

Kimberlite bulk-composition is not straight forward to define because of (i) the frequent presence of mantle xenoliths, (ii) contamination with country rocks and (iii) its susceptibility to alteration. However, multiple pulses

of kimberlite magmas are reported to form several distinct geological units in the same pipe or intrusion (Sparks, 2013). Therefore, evolved kimberlites, which are poor in or devoid of macrocrysts, such as aphanitic varieties can give a true indication of the liquid path. Several studies investigated the trace element geochemistry of kimberlites with a view to constrain the petrogenetic processes involved in their evolution (e.g., Fraser and Hawkesworth, 1992; Tainton and McKenzie, 1994; Beard *et al.*, 1998; Price *et al.*, 2000; Le Roex *et al.*, 2003; Chalapathi Rao *et al.*, 2004; Harris *et al.*, 2004; Becker and Le Roex, 2006; Coe *et al.*, 2008; Tappe *et al.*, 2011, 2013; Toyama *et al.*, 2012).

The Mesoproterozoic kimberlites are most abundant in the Eastern Dharwar craton (EDC) of southern India (Chalapathi Rao *et al.*, 2013). In fact, the Indian cratons reportedly host the largest yet known number of Mesoproterozoic kimberlites in the world (Haggerty and Birkett, 2004; Chalapathi Rao and Srivastava, 2009) and offer an excellent opportunity to study and understand

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Fig. 1. Geological map of southern India showing location of Pipe 2 kimberlite modified after Patel *et al.* (2009). EDC, Eastern Dharwar craton; WDC, Western Dharwar craton; BC, Bastar craton; EGMB, Eastern Ghat Mobile belt; CG, Clopet granite; GG, Godavari graben; NKF, Narayanpet kimberlite field; RKF, Raichur kimberlite field; WKF, Wajrakarur kimberlite field; KLF, Krishna lamproite field; ZP, Zangamrajupalle lamproite.

the composition, nature and evolution of the Proterozoic lithospheric mantle prior to the make up of the Gondwana supercontinent. Pipe 2 kimberlite situated 2.5 km east of Wajrakarur is a part of the well known Wajrakarur kimberlite field (WKF) of Eastern Dharwar craton, southern India (Chalapathi Rao *et al.*, 2004). It actually consists of two intrusions Pipe 2 east and Pipe 2 west. Pipe 2 west has been an acknowledged centre of detailed petrological studies due to its large and fresh outcrops whereas till date such studies have not been undertaken for Pipe 2 east intrusion. Pipe 2 west is diamondiferous (Rau *et al.*, 2005) whereas no such information is available for Pipe 2 east. Two textural variants of kimberlites belonging to coherent facies (i.e., macrocrystic and aphanitic) are recognized for first time within this pipe. The occurrence of these two texturally different intrusions only in Pipe 2 kimberlite in the Wajrakarur area makes it a unique occurrence amongst ~100 kimberlites in Eastern Dharwar craton. Based on mineralogical studies this kimberlite was speculated to be an unusual lamproite like intrusion and not considered to be a *bona fide* kimberlite (Reddy, 1987;

Kaur and Mitchell, 2013). Present paper details the petrology and geochemistry of both the intrusions of this Mesoproterozoic diamondiferous kimberlite pipe from Wajrakarur field with the objective of evaluating their petrogenesis and constraining the composition of source magma(s).

GEOLOGICAL SETTING

The Eastern Dharwar craton (EDC) of southern India exposes a granite–greenstone terrain composed predominantly of greenstone belts, gneisses, granitoids, late-to-post tectonic intrusive granites (Closepet Granite and its equivalents of ~ 2,500 Ma), platformal Proterozoic sedimentary basins (the Cuddapah, Kaladgi and Bhima basins) and widespread mafic dyke swarms. A recent review of the geology of the EDC has been provided by Naqvi (2005) and Ramakrishnan and Vaidyanadhan (2008).

Multidisciplinary surveys led by the Geological Survey of India and other agencies have resulted in the dis-

covery of the several kimberlites in the EDC. These kimberlites are confined to four distinct fields, the Wajrakarur, the Tungabhadra, the Raichur and the Narayanpet kimberlite fields (Fig. 1). Majority of kimberlites in Wajrakarur kimberlite field are diamondiferous and occur in four distinct clusters: northern Wajrakarur–Lattavaram cluster (11 pipes); south-eastern Chigicherla cluster (5 pipes); south-western Kalyandurg cluster (6 pipes) and newly discovered southern Timmasamudram cluster (4 pipes). The “pipes” are numbered in order of their discovery. The present study is centered on Pipe 2 kimberlite which is one of the earliest discovered pipes from WKF. It is situated 2.5 km east of Wajrakarur village (Fig. 1). The field setting and characters of its western and eastern lobes are outlined below:

Pipe 2 west kimberlite (15°01′49″:77°24′49″) is a crescent shaped body. The outcrop trend N75E–S75W and have a length of 380 m and a maximum width of 70 meters. It was discovered by Rao and Phadtre (1966). The rock is melanocratic, hard, compact, encloses fragments of country rocks and has well exposed outcrops. The processing of bulk materials in recent years by Geological Survey of India revealed that this pipe is diamondiferous.

Pipe 2 east kimberlite (15°01′42″:77°24′35″), located 100 m south of Pipe 2 west and constitutes its satellite body. It was discovered by Dhakate and Nayak (2002), and measures 500 m × 120 m with NE–SW trend. Only preliminary studies have been carried out for this intrusion (Chalapathi Rao and Srivastava, 2009). The rock is fine grained, greenish colored and appears to be intensely altered.

SAMPLING AND ANALYTICAL TECHNIQUES

As far as possible, the freshest outcrop samples were chosen for this study. Special care was taken to hand pick and removes all visible crustal, mantle xenoliths and calcite veins before subjecting them to geochemical studies. However inherent alteration in the samples due to the exposure of the kimberlites to tropical weathering for millions of years could not be eliminated.

Mineral chemistry analyses were obtained on a CAMECA SX100 and CAMECA SX5 Electron Probe Micro Analyzers (EPMA) installed at Geological Survey of India, Hyderabad and Indian Institute of Technology, Mumbai, India respectively. An acceleration voltage of 15 kV, beam current of 20 nA, beam diameter of 1 μ m and a counting time of 10 s were used.

Whole rock major and trace element analyses were carried out at the Activation Laboratories Ltd. Ancaster, Ontario, Canada. ICP-OES (Model: Thermo-JarretAsh ENVIRO II) was used to analyze major elements, whereas

ICP-MS (Model: PerkinElmer Sciex ELAN 6000) was used to determine trace and rare earth element (REE) concentrations. The precision is <5% for all analyzed elements when reported at 100 × detection limit. Standards, including SY-3, W-2, DNC-1, BIR-1 and STM-1 were run along with the samples to check accuracy and precision. The analytical procedure is detailed by Gale *et al.* (1999) and is also available in the Activation Laboratories Ltd. website (<http://www.actlabs.com>).

PETROGRAPHY AND MINERAL CHEMISTRY

The main Pipe 2 west body has typical inequigranular texture imparted by two populations of olivine and phlogopite set in a fine grained groundmass of microphenocrystal olivine, phlogopite, secondary serpentine, perovskite and apatite. Groundmass is poor in spinel and is preserved mostly in olivines. The pipe is richly macrocrystic and olivine macrocrysts are generally free from serpentinization whereas phlogopite macrocrysts are deformed and fractured along cleavage. This is a macrocrystic textural variety of Pipe 2 kimberlite. A very significant fabric is seen (Fig. 2) in which phlogopite vein traverses the olivine macrocryst. A solitary phlogopite macrocryst is deformed and resorbed by the kimberlite magma and probably a part of deformed mantle xenolith intersected by phlogopite vein. We interpret this as an evidence of modal mantle metasomatism of mantle by phlogopite-rich fluid.

On the other hand the satellite body i.e., Pipe 2 east is of very fine grained nature and very poor in macrocrysts. Sporadic occurrences of ilmenite macrocrysts are present. Groundmass is rich in abundant microphenocrysts of olivine, secondary serpentine, spinel and perovskite. Phlogopite is a rare or very poor groundmass phase in Pipe 2 east. It is poor in mantle xenoliths but rich in crustal xenoliths. The mineral chemistry data is presented in Table 1.

Phlogopite

Phlogopite is a very rare phase in aphanitic Pipe 2 east whereas ubiquitous in macrocrystic Pipe 2 west intrusion where it occurs as a microphenocryst in groundmass and also as a large macrocrysts (Fig. 2). All the phlogopites are enriched in TiO₂ (values upto 1.4 wt%) and poor in Al₂O₃ (7–9.7 wt%) in macrocrystic variety whereas poor in TiO₂ (0.61 wt%) and enriched in Al₂O₃ (12.73 wt%) in aphanitic one. The phlogopite macrocrysts are appears to be less aluminous than the groundmass phenocrysts. In TiO₂ versus Al₂O₃ plot (Fig. 3a) for discriminating between phlogopite from kimberlites and lamproites they show more affinity towards archetypal kimberlites than the lamproites and aillikites. FeO_T content varies from 5.2–7.18 wt% in both the varieties. K₂O

Fig. 2. Field photograph of Pipe 2 west kimberlite (A); Pipe 2 east kimberlite (B). Inequigranular macrocrystic texture in Pipe 2 west kimberlite imparted by subhedral to anhedral olivine, uncrossed nicols (C); fine grained aphanitic texture in Pipe 2 east kimberlite, uncrossed nicols (D); Olivine macrocryst intruded by phlogopite vein in Pipe 2 west kimberlite, uncrossed nicols (E); deformed phlogopite macrocryst in Pipe 2 west kimberlite, crossed nicols (F).

contents ranging upto 9.8 wt% which is close to ideal phlogopite composition. BaO content varies upto 1.8 wt%. The phlogopite vein shows lower K₂O (upto 8.7 wt%), TiO₂ (upto 0.3 wt%) and Al₂O₃ (upto 6.2 wt%) contents than the macrocrystic and aphanitic varieties.

Spinel

Spinel is omnipresent in kimberlites and occur as subhedral to strongly euhedral crystals in groundmass. Groundmass of macrocrystic variety is devoid of or very poor in spinels as compare to aphanitic samples. Gener-

Table 1. Representative mineral analysis of phlogopite, spinels and olivine

<i>Phlogopite</i>														
Oxide (wt%)	1	2	3	4	5	6	7	8	9	10	11	12	13	P2A*
	macro	macro	vein	vein	macro	macro	macro	vein	vein	vein	macro	macro	macro	apha
SiO ₂	41.32	41.12	43.96	43.02	41.49	41.47	43.25	43.91	44.23	44.21	42.61	42.74	42.70	33.00
TiO ₂	1.46	1.26	0.33	0.34	1.27	1.42	1.00	0.21	0.29	0.27	1.48	1.40	1.26	0.61
Al ₂ O ₃	9.71	9.24	5.84	6.02	9.66	9.55	7.00	6.28	5.58	5.72	7.18	7.12	8.57	12.73
Cr ₂ O ₃	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.06	0.00	0.02	0.00	0.00	0.04
FeO	5.33	5.30	9.23	11.74	5.20	5.26	6.54	7.89	10.93	10.58	6.55	6.53	5.51	7.18
MnO	0.04	0.06	0.14	0.18	0.00	0.00	0.00	0.08	0.20	0.12	0.02	0.05	0.04	0.16
MgO	23.95	23.75	24.63	24.28	24.15	23.99	23.85	25.76	24.27	24.54	23.29	23.20	24.11	24.40
CaO	0.00	0.00	0.22	0.15	0.00	0.00	0.00	0.20	0.19	0.16	0.00	0.00	0.00	0.09
Na ₂ O	0.46	0.55	0.08	0.14	0.51	0.52	0.95	0.14	0.15	0.08	0.99	1.07	0.73	0.06
P ₂ O ₅	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
K ₂ O	9.47	9.53	8.70	8.30	9.51	9.62	9.89	8.41	8.72	8.73	9.82	9.78	9.81	9.39
BaO	1.76	1.74	0.10	0.01	1.81	1.68	1.08	0.09	0.09	0.12	1.07	1.12	0.92	0.00
Total	93.50	92.56	93.24	94.21	93.60	93.51	93.56	92.97	94.71	94.54	93.04	93.01	93.64	87.80

<i>Spinel</i>							
Oxide (wt%)	1	2	3	4	P2A*	P2A-1*	P2A-2*
	apha	apha	apha	macro	apha	apha	apha
SiO ₂	0.01	0.74	0.35	0.10	0.00	0.00	0.00
TiO ₂	0.03	11.03	16.68	8.72	10.26	10.82	10.46
Al ₂ O ₃	0.02	2.97	4.50	0.27	7.38	1.13	7.31
Cr ₂ O ₃	0.36	0.04	0.04	0.15	29.90	0.23	27.40
Fe ₂ O ₃	47.86	36.96	30.16	46.68	19.63	46.97	22.03
FeO	39.54	34.63	31.58	39.01	15.04	36.27	15.86
MnO	0.33	0.88	1.08	0.79	0.62	0.77	0.57
MgO	8.67	5.24	7.86	3.23	16.87	2.16	16.97
CaO	0.05	0.40	0.38	0.06	0.19	0.47	0.11
Na ₂ O	0.00	0.04	0.03	0.05	0.00	0.00	0.00
K ₂ O	0.03	0.04	0.02	0.02	0.00	0.00	0.00
P ₂ O ₅	0.03	0.03	0.01	0.01	0.00	0.00	0.00
ZnO	0.08	0.16	0.06	0.02	0.00	0.00	0.00
Total	97.00	93.15	92.75	99.09	99.89	98.82	100.71
Fe ²⁺ /(Fe ²⁺ +Mg)	0.84	0.88	0.81	0.93	0.33	0.90	0.34
Ti/(Ti+Cr+Al)	0.06	0.70	0.70	0.94	0.19	0.84	0.21

<i>Olivine</i>							
Oxide (wt%)	1	2	3	4	5	P2A-1*	P2A-2*
	macro	macro	macro	macro	macro	apha**	apha**
SiO ₂	40.75	41.26	41.63	40.80	39.87	39.32	39.16
TiO ₂	0.10	0.05	0.01	0.00	0.15	0.09	0.34
Al ₂ O ₃	0.03	0.03	0.03	0.01	2.21	4.98	1.84
Cr ₂ O ₃	0.04	0.04	0.07	0.00	0.12	0.31	0.26
FeO	10.81	10.34	8.26	8.60	5.19	4.68	7.55
MnO	0.16	0.18	0.11	0.14	0.15	0.05	0.06
MgO	47.07	47.03	48.57	48.88	38.23	35.31	36.39
CaO	0.18	0.23	0.08	0.13	0.43	0.42	0.33
Na ₂ O	0.01	0.02	0.04	0.03	0.00	0.00	0.01
K ₂ O	0.00	0.00	0.00	0.00	0.05	0.05	0.00
P ₂ O ₅	0.00	0.00	0.00	0.00	0.02	0.01	0.02
ZnO	0.12	0.02	0.02	0.03	0.00	0.00	0.00
Total	99.25	99.14	98.80	98.54	86.42	85.22	85.96
Fo	88.44	88.55	91.19	90.89	92.73	93.01	89.50
Fa	11.39	10.96	8.70	8.97	7.06	6.92	10.42

Note: macro, macrocrystic; apha, aphanitic.

*Data from Chalapathi Rao and Srivastava (2009).

**Serpentinised olivines.

Fig. 3. (a) TiO_2 vs. Al_2O_3 (wt%) variation plot for phlogopite of Pipe 2 kimberlite. Data for WKF and NKF kimberlites are from Chalapathi Rao *et al.* (2004); Cuddapah and Krishna lamproites, Eastern Dharwar craton, are from Chalapathi Rao *et al.* (2010). Field of kimberlite is taken from Dawson and Smith (1977) and aillikite is from Tappe *et al.* (2006). (b) $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg}^{2+})$ vs. $\text{Ti}/(\text{Ti} + \text{Cr} + \text{Al})$ (mol fraction) for groundmass spinel from Pipe 2 kimberlite. Kimberlite Trend 1 and 2 are from Mitchell (1986, 1995a). Lamproite field is from Mitchell and Bergman (1991). (c) MgO (wt%) vs. Al_2O_3 (wt%) of spinels of this study. Data for aphanitic variety of Pipe 2 kimberlite from Chalapathi Rao and Srivastava (2009) also plotted for comparison.

ally two trends are shown by groundmass spinels from kimberlites: magmatic trend 1 or the magnesian ulvospinel trend; and magmatic trend 2 or the titanomagnetite trend (Mitchell, 1995a). Magmatic trend 1 is recognized as the characteristic spinel compositional trend of archetypal kimberlites (Mitchell, 1986). Magmatic trend 2 is uncommon in archetypal kimberlites while typical for orangeites and this trend is characterized by rapid MgO depletion (Mitchell, 1995a). However, spinels of very similar composition to trend 2 are also found in some lamproites (Mitchell and Bergman, 1991) and in certain ultramafic lamprophyres such as aillikites (Tappe *et al.*, 2005). Interestingly aphanitic samples show affinity towards magmatic trend 2 indicating rapid depletion of MgO in their source magma (Fig. 3b). However, all the samples with

the exception of two samples with high Cr spinels (Cr_2O_3 : 27.4–29.9 wt%; data from Chalapathi Rao and Srivastava, 2009) show strong affinity to kimberlite trend 2 spinels than the lamproite trend (Fig. 4a) and mostly confined to the field of Dharwar craton kimberlites (Fig. 3c).

Olivine

In macrocrystic variety both macrocrysts as well as microphenocrysts of olivines are present whereas in aphanitic variety macrocrysts are rare and the intrusion is abundant in altered microphenocrysts of olivine. Olivines have compositions from Fo_{88} to Fo_{93} . Olivines in aphanitic variety are pseudomorphed to serpentine while in macrocrystic variety they are comparatively fresh and macrocrysts occur as broken fragments in the

Fig. 4. Variation diagrams showing Mg# versus selected major oxides and La versus selected trace elements in Pipe 2 kimberlite. Symbols are black diamond and black circles for macrocrystic, gray diamonds and gray circles for aphanitic. Black and gray circles are data from Chalapathi Rao et al. (2004) and Chalapathi Rao and Srivastava (2009) also plotted for comparison.

Table 2. Major (in wt%) and trace (in ppm) element compositions

	P2/a macro	P2/b macro	P2/c macro	P2/d macro	P2/e apha	P2/f apha	P2/g apha	Primary magma	3/PR2B* macro	4/PR2* macro	7/PR2* macro	8/PR2A* macro	Pipe-2** macro	Pipe 2A** apha
SiO ₂	34.36	35.38	35.46	35.02	31.47	31.80	30.47	33.08	33.70	33.22	35.38	33.10	35.29	31.81
Al ₂ O ₃	6.10	6.41	6.41	6.58	4.55	4.95	4.34	5.53	5.79	5.60	6.07	5.38	6.45	4.76
Fe ₂ O ₃	12.36	12.15	12.67	12.48	14.00	14.55	13.77	13.46	12.58	13.27	11.96	12.90	12.46	14.37
MgO	20.40	18.78	19.98	19.54	21.78	21.74	21.81	21.70	18.60	20.31	17.30	19.69	18.63	21.88
CaO	12.75	14.76	14.32	14.15	12.79	13.00	13.15	12.88	15.60	12.88	16.50	15.79	14.33	12.24
Na ₂ O	1.04	1.38	1.15	1.17	0.02	0.03	0.02	0.54	0.39	0.17	0.45	0.62	1.46	0.01
K ₂ O	2.17	2.08	2.09	2.21	0.04	0.06	0.04	1.12	2.26	2.47	0.92	2.16	2.20	0.05
TiO ₂	2.40	2.42	2.47	2.49	3.07	3.16	3.10	2.78	2.58	2.68	2.29	2.59	2.54	3.06
P ₂ O ₅	0.83	0.85	0.84	0.84	0.49	0.54	0.46	0.69	0.93	0.78	0.90	0.69	0.78	0.54
MnO	0.21	0.21	0.21	0.22	0.24	0.24	0.24	0.23	0.22	0.24	0.21	0.22	0.20	0.24
LOI	5.30	4.47	4.39	3.94	9.95	9.87	10.45	7.59	6.55	7.78	7.22	5.72	6.11	11.07
Total	97.94	98.90	99.99	98.63	98.38	99.94	97.83	98.94	99.20	99.40	99.20	98.86	100.50	99.93
Mg#	76.60	75.40	75.80	76.00	75.50	74.70	75.20	75.65	74.60	75.20	74.10	75.10	75.00	75.00
Trace elements (including REE)														
Ba	1732	2775	2186	2209	190	411	189	1071.5	3368	1197	2449	1836	3108	193
Sr	1357	1023	779	818	247	337	253	847	1167	741	1189	605	903	358
Rb	191	177	172	187	7	9	6	100	238	245	196	131	191	9
Pb	8	11	10	10	12	9	16	8.5	8.05	9.24	10.6	11.83	—	—
Th	21.1	21.3	22	22.3	26.3	25.9	26.5	23.5	19.4	13.5	18.1	22.1	21	25.1
U	3.7	3.7	3.8	3.8	4.7	4.7	5.1	4.2	3.56	2.6	3.3	3.79	3.8	3.56
Ta	12.3	12.3	13	13.1	15.7	16.1	16.3	14.2	11	8.43	11.1	12.63	13.8	16.8
Hf	2.9	4.1	3.5	3.8	5.6	5.8	5.8	4.35	5.01	3.34	4.02	4.47	3.9	6.9
Zr	126	185	151	166	263	272	262	199	215	129	159	174	148	289
Nb	188	197	201	207	241	247	256	217.5	199	145	192	209	198	241
Cs	2	1.4	1.4	1.6	0.8	1	0.8	1.5	3.24	1.43	1.82	1.91	—	—
Zn	90	100	100	100	90	100	120	95	—	—	—	—	—	—
Sc	19	20	19	19	24	24	25	21.5	24.5	25.3	22.9	15.6	20	25
Y	17	18	18	19	22	22	22	19.5	19.7	12.9	17.1	19	21	25
Cr	890	820	820	870	890	890	920	890	809	980	903	1259	760	870
Co	72	66	68	73	72	70	81	71	—	—	—	—	—	—
Ni	480	410	460	460	460	440	460	460	503	575	557	1316	390	460
Cu	100	100	100	100	80	90	100	95	125	111	89.1	77.3	—	—
V	156	167	148	159	45	53	46	104.5	172	152	95.7	107	149	38
La	144	145	151	151	186	192	193	168	132	94.3	130	143	155	190
Ce	257	257	269	268	327	335	336	296	233	168	232	259	272	334
Pr	27	27.2	28.4	27.9	33.9	34.9	35	30.95	24.7	17.7	24.77	25.57	28.4	33.8
Nd	95.8	98.5	99.9	100	120	123	124	109.4	87.7	64.9	87.3	95.6	98.6	115
Sm	14.3	14.6	15.1	15	17.9	18.6	18.4	16.45	13.27	9.76	12.9	14.4	14.4	16.7
Eu	3.77	3.86	4	4	4.87	4.87	4.89	4.32	3.48	2.61	3.83	4.02	4.5	5.3
Gd	9.7	9.9	10.1	10.5	12.1	12	12.5	10.85	18.2	9.3	16.7	17.6	10.1	11.6
Tb	1.2	1.2	1.2	1.2	1.4	1.4	1.5	1.3	1.2	0.79	1.16	1.27	1.3	1.4
Dy	5	5.3	5.3	5.5	6.2	6.5	6.5	5.75	5.09	3.39	4.74	5.11	5.6	6.4
Ho	0.8	0.8	0.8	0.9	1	1	1	0.9	0.83	0.52	0.74	0.86	0.9	1.1
Er	1.9	1.9	2	2	2.2	2.3	2.3	2.1	2.04	1.2	1.74	1.82	2.2	2.4
Tm	0.22	0.23	0.23	0.24	0.26	0.27	0.28	0.245	0.24	0.14	0.21	0.25	0.25	0.3
Yb	1.2	1.2	1.2	1.3	1.4	1.4	1.5	1.3	1.41	0.92	1.22	1.4	1.3	1.5
Lu	0.16	0.17	0.17	0.18	0.19	0.19	0.21	0.175	0.19	0.11	0.17	0.18	0.17	0.18
La/Yb	120	120.83	125.83	116.15	132.857	137.14	128.67	129.23	93.62	102.5	106.56	102.14	119.23	126.667

Note: macro, macrocrystic; apha, aphanitic. *Data from Chalapatih Rao et al. (2004). **Data from Chalapatih Rao and Srivastava (2009).

Fig. 5. (a) Chondrite normalized (values from Evensen *et al.*, 1978) REE abundances for kimberlite samples of this study. (b) Primitive mantle normalized trace element patterns for kimberlite samples under study. Normalizing values are from Sun and McDonough (1989). Data for Zangamrajupalle lamproite is from Chalapatih Rao *et al.* (2004). Only kimberlite samples under study are plotted to aid clarity.

groundmass. High magnesian composition of Pipe 2 kimberlite reflects that of its source.

GEOCHEMISTRY

Major element geochemistry

New major and trace element data for the Pipe 2 kimberlites are presented in Table 2. Pipe 2 kimberlite shows low SiO_2 content (30.47–35.46 wt%) displaying its mafic, ultramafic nature. SiO_2 content in macrocrystic variety is comparatively higher (34–35 wt%) than the aphanitic variety (30–31 wt%). Distinction based on MgO content is obvious in macrocrystic and aphanitic varieties. Macrocrystic Pipe 2 west shows lower MgO content (18.78–20.4 wt%) whereas aphanitic Pipe 2 east shows slightly higher MgO (~21 wt%). However $\text{Mg\#}$ (Mg/

Mg+Fe) is not consistent with the MgO content and values are slightly overlapping ($\text{Mg\#}$: 74–76). Marked geochemical difference is observed between macrocrystic and aphanitic varieties. $\text{Fe}_2\text{O}_{3(\text{T})}$ concentrations in all the samples vary from 12.15 to 14.55 wt% with higher values in aphanitic. Macrocrystic samples shows higher concentrations of Al_2O_3 (6.1–6.5 wt%), CaO (12.75–14.76 wt%), Na_2O (1.04–1.38 wt%), K_2O (2.08–2.21 wt%) and P_2O_5 (0.83–0.84 wt%) whereas aphanitic samples shows lower Al_2O_3 (4.34 to 4.95 wt%), CaO (12.79 to 13.15 wt%), Na_2O (0.02–0.03 wt%), K_2O (0.04 to 0.06 wt%) and P_2O_5 (0.46–0.54 wt%) concentrations. K_2O content of aphanitic variety is very low which may be due to very low abundances of modal phlogopite while that of macrocrystic is high reflecting their higher modal phlogopite. The TiO_2 content of macrocrystic samples is however low (~2.4 wt%) while aphanitic samples are showing high concentrations of TiO_2 varying from 3 to 3.16 wt%. When plotted against $\text{Mg\#}$, SiO_2 and Al_2O_3 show broad positive correlation whereas CaO and TiO_2 show negative correlation (Fig. 4).

Trace element geochemistry

The transition metals Ni (410 to 480 ppm) and Cr (820 to 920 ppm) in all the samples are higher and shows restricted range in abundance. The Pipe 2 kimberlite shows considerably lower values of Ni and Cr than other EDC kimberlites (Ni: 930–1079 ppm and Cr: 943–965 ppm; data source: Chalapatih Rao and Srivastava, 2009). Trace and rare earth elements also show considerable difference in their abundances in macrocrystic and aphanitic variety. High field strength elements (HFSE) which are immobile during hydrothermal alteration are reasonably high in abundances in aphanitic (La: 186–193 ppm, Th: 25–26 ppm, Nb: 241–256 ppm, Total REE = 714–737) whereas large ion lithophile element concentrations like Rb (7 to 9 ppm) and Ba (189 to 411) are comparatively lower. However macrocrystic samples shows highest content of Rb (172–191 ppm) and Ba (1732–2775 ppm). In the bivariate plots HFSE elements (such as Nb, Th and Hf) shows broad positive correlation with La while LILE elements (like Rb and Sr) shows broad negative correlation (Fig. 4).

All the samples of this study shows similar fractionated ($\text{La/Yb} = 116\text{--}137$) chondrite normalized REE pattern with higher La abundances in the range 600–800 times chondrites and low HREE abundances of 6–8 $\times$ chondrite (Fig. 5a). Aphanitic particularly shows higher abundances in REE than the macrocrystic. The steep slope of the REE patterns coupled with low HREE suggests derivation from the garnet-stability field (e.g., Gaffney *et al.*, 2007).

Primitive mantle normalized trace element pattern also shows enrichment of aphanitic samples over the

macrocrystic except for elements Rb, Ba, K, Sr and P. All the samples show parallel patterns with depletions in K, Sr, Hf and Ti. Aphanitic samples show additional depletions at Rb, Ba and P (Fig. 5b). Three samples from macrocrystic exhibit small positive Ba anomaly. Negative troughs at Rb, Ba, K, Sr and P in aphanitic samples are more pronounced than the macrocrystic. These negative anomalies are known from Group I kimberlites of South Africa (e.g., Le Roex *et al.*, 2003; Harris *et al.*, 2004) and India (Chalapathi Rao and Srivastava, 2009) and are considered to be characteristic feature of kimberlites. Trace element pattern also shows distinction between Pipe 2 samples and lamproite from Zangamrajupalle from Cuddapah basin (Chalapathi Rao *et al.*, 2004) which is more enriched in trace elements (Figs. 5a and b).

PETROGENESIS

Kimberlites generally entrain numerous xenoliths, large portion of which is crustal (e.g., Dawson, 1980; Mitchell, 1995a). Therefore before drawing any conclusions on genesis and source region of Pipe 2 kimberlite, it is important to evaluate the extent of crustal contamination and alteration.

Crustal contamination and deuteritic alteration

All xenoliths and visible altered or veined material was removed before powdering and analysis to minimize the effects of alteration and secondary contamination. Still it is likely, that some assimilation might have occurred and could not be avoided due to low-melting temperature of crustal xenoliths. Clement's (1982) contamination index (C.I.) values <1 are considered uncontaminated, although Clement (1982) reported C.I. values up to 1.5 for crustally uncontaminated kimberlites. The aphanitic samples show C.I. values close to ~1.5, whereas macrocrystic samples have slightly higher C.I. values range from 1.8–2. Kjarsgaard *et al.* (2009) evaluated the contamination index (C.I.) and concluded need of its utilization in conjunction with other geochemical screens. Fesq *et al.* (1975) shown that Si/Mg values of >1.2 implies crustal contamination. The Si/Mg values for aphanitic samples are within range (i.e., <1.2) while macrocrystic samples shows values close to ~1.2 signifying the crustal contamination to be not a significant factor. Although C.I. values, Al₂O₃ and Na₂O contents are slightly higher in macrocrystic, evidence against crustal contamination comes from lower values of SiO₂ (34–35 wt%) and higher MgO (18–20 wt%) content. Petrographic study reveals that the macrocrystic variety is fairly fresh whereas extensive serpentinization is observed in aphanitic variety. Widespread serpentinization could be due to water-rich character of high temperature fluids (hydrothermal flu-

ids) which results in pervasive deuteritic alteration (hydrothermal alteration). This hydrothermal fluid can alter the initial concentrations of fluid mobile LIL elements (e.g., Rb, Ba, Sr and K) whereas concentrations of high field strength elements will be remain robust. Figure 4 shows immobile incompatible element La behaves coherently with other HFS and LIL elements which contradicts the pronounced effects of hydrothermal alteration. On multielement plot (Fig. 5b) Rb, Ba, K and Sr shows negative anomalies wherein they are more pronounced in aphanitic samples as compared to macrocrystic ones. The reasons for these anomalies are dealt separately in a later section. The more scatter in abundance of these fluid mobile elements, however, indicates possible effects of deuteritic alteration in aphanitic variety. Since the presence of olivine crystallization, the whole rock MgO should be significantly depleted in aphanitic variety than the macrocrystic samples. However fine grained aphanitic samples shows more abundances of MgO (~21 wt%) than macrocrystic (18–20 wt%). Under hydrothermal alteration in fine grained rocks like basalts Mg element shows mobility and increase in abundances (Mottl, 1983). Interestingly, Sparks *et al.* (2009) shown that the composition of kimberlite magma during eruption undergoes large volume changes in chemically open system due to strong alteration, notably by serpentinisation, which leads to increase in SiO₂ and MgO in bulk rock chemistry. Therefore the mobility and enrichment in MgO in fine grained aphanitic variety can be attributed to effects of alteration and serpentinisation although in this case the Mg numbers remains more or less robust.

Close to primary magma composition

To propose the close to primary kimberlite magma compositions one has to take into consideration that the magmas should be least affected by alteration, crustal contamination and fractional crystallization. In addition, high Mg numbers, high content of Ni and Cr also imply primitive nature of magmas. Owing to presence of both aphanitic and macrocrystic varieties in Pipe 2 kimberlite as well as in view of the mobility of MgO due to alteration and serpentinisation, the primary magma composition is taken as average of least SiO₂ rich macrocrystic sample (P2-1) and most SiO₂ rich aphanitic sample (P2-6). The average most closely represents the primary Pipe 2 kimberlite magma composition and contains ~33 wt% SiO₂, Mg# ~ 75.6 and 460 ppm Ni (Table 2).

Fractional crystallization

Only phenocryst poor or aphanitic rocks like Pipe 2 east kimberlite will give a true indication of the liquid path. On the other hand macrocrystic kimberlite does not represent a liquid composition and Le Roex *et al.* (2003) have shown that it represents a partial cumulate of man-

tle derived minerals dominated by olivine. Harris *et al.* (2004) have shown that the compositions of the macrocrystic kimberlites reflect variable entrainment of mantle lherzolite and megacryst phases into primary kimberlite magma. Figure 6 shows strong positive correlation between Mg# and Ni. The Ni and Mg# tend to be buffered during mantle melting processes by olivine and orthopyroxene due to which coherent correlation is not expected during variable degrees of partial melting (Harris *et al.*, 2004). Therefore, compositional variation shown by aphanitic and macrocrystic samples is more consistent with crystal fractionation process and it is evident that up to ~5% fractionation of olivine is responsible for the observed variation shown by aphanitic samples. Evidence for involvement of minor phlogopite as a fractionating phase is found in more pronounced negative Rb and K anomalies in aphanitic samples. But the role of hydrothermal fluid in scatter of this highly mobile element cannot be ruled out. Evidence against considerable amount of fractionation of phlogopite comes from relative low modal abundance of phlogopite in aphanitic samples. The Ti depletion is of almost same magnitude in aphanitic and macrocrystic variety and therefore precludes the possibility of involvement of ilmenite/perovskite fractionation. The compositions of macrocrystic kimberlite are inferred to reflect entrainment of mantle material such as garnet lherzolite (Le Roex *et al.*, 2003; Harris *et al.*, 2004). Such type of entrainment could lead to an increase in Ni, Cr and Mg# contents in macrocrystic variety. However, it is clear that addition of such mantle derived material will elevate the absolute REE instead of diluting the abundances and trends in Fig. 6 and REE abundances of macrocrystic kimberlite show that such entrainment of mantle material is negligible in bringing out the observed differences in macrocrystic variety. Therefore it is clear that aphanitic and macrocrystic varieties of Pipe 2 kimberlite have experienced different evolutionary histories.

Partial melting

Experimental data reveals that Group I and Group II kimberlite like magmas can be produced by very low degrees of partial melting of carbonated garnet harzburgite or lherzolite (Canil and Scarfe, 1990; Dalton and Presnall, 1998; Ulmer and Sweeney, 2002). Most models of kimberlite petrogenesis also focus on their formation by a small amount of partial melting of upper mantle peridotite. Trace elements can be used to model this process if a reasonable mineralogy of the source, trace element content of the source and percent melting can be assumed and if it is known how the trace element partition between the source and melt. Le Roex *et al.* (2003) and Becker and Le Roex, (2006) in their modeling for South African kimberlites employed partition coefficients

Fig. 6. Ni vs. Mg number for kimberlite samples under study. Olivine fractionation curve calculated assuming equilibrium crystallization. $D^{Ni} = 124/MgO - 0.9$ (Hart and Davis, 1978). Circle shows composition of inferred primary magma composition. Only kimberlite samples under study are plotted to aid clarity.

for volatile poor basaltic system given by Spath *et al.* (2001) which are at the low end of all measured ranges for these mineral melt pairs. Recently in an alternate approach Tappe *et al.* (2011, 2013) utilized new sets of “bulk” peridotite/melt partition coefficients (Brey *et al.*, 2008; Dasgupta *et al.*, 2009) to calculate trace element patterns for partial melts of carbonated peridotite between 6 and 10 GPa. This alternate modeling shows that strong metasomatic enrichment (e.g., Le Roex *et al.*, 2003) of the source region is not a requirement as long as the system is CO_2 saturated. We however, adopted trace element modeling approach of Le Roex *et al.* (2003) to estimate the source composition of Pipe 2 primary kimberlite magma in an effort to test whether the Southern African model is applicable for the Indian samples.

Figure 7a shows the chondrite normalized REE abundances of the inferred primary magma of Pipe 2. Here by semi-quantitative forward modelling we have estimated the source composition of close to primary kimberlite magma of Pipe 2 for very small (1%) degree of partial melting. The calculated source composition is enriched in LREE ($\sim 11 \times$ chondrite) and HREE abundances almost equal to chondrite. It is notable that the calculated source composition falls within the field of garnet lherzolites from Kaapvaal craton (Gregoire *et al.*, 2003). Changes in the degree of partial melting do not change the HREE content of calculated magma composition but leads to a range of LREE abundances. Therefore, the sub-parallel chondrite normalized REE patterns shown by the aphanitic kimberlite samples do not represent a suite of primary magmas derived by different degrees of melting but are consistent with the fractional crystallization trend. The source composition is calculated at 1% partial melt-

Fig. 7. (a) Chondrite normalized rare earth element and (b) primitive mantle normalized incompatible element abundances in the calculated mantle source regions determined by semi quantitative forward modeling from close-to-primary kimberlite magmas assuming $F = 1\%$ and residual modal mineralogy is $ol:opx:cpx:gt = 0.63:0.23:0.12:0.02$ reported by Harris *et al.* (2004). Partition coefficients from Spath *et al.* (2001). Normalizing values are from Sun and McDonough (1989). The field of Kaapvaal craton lherzolite is from Gregoire *et al.* (2003) plotted for comparison.

ing and with 2% residual garnet. The HREE are sensitive only to the amount of residual garnet and therefore any change or increase in the percentage of residual garnet will increase the HREE abundances (reflecting the high HREE partition coefficients for garnet) and elevate the HREE of calculated source to be greater than the chondrite value and out of garnet lherzolite field. Therefore, the 1% degree of melting is model dependant and also consistent with experimental evidences (e.g., Dalton and Presnall, 1998).

Primitive mantle normalized trace element diagram shows marked negative anomalies in K, Sr, P, Ti and Hf (Fig. 5b). Negative anomalies are present in both the macrocrystic and aphanitic samples, wherein the aphanitic samples shows more pronounced negative anomalies at Rb, K and Sr. Presence of large Rb and K anomalies only

in aphanitic samples reflects the combined role of very less amount of phlogopite fractionation and also the deuteric alteration in this fine grained variety.

Negative Ti and Nb anomalies always cannot be directly ascribed to the convergent margin setting; they may also reflect crustal contamination (Pearce and Peate, 1995; Polat *et al.*, 2009). Furthermore, Nb and Ti depletion have also been explained in terms of the fractionation of Fe–Ti phases with high melt-mineral partition coefficients during fractionation processes (Foley *et al.*, 2000; Hoffmann *et al.*, 2012; Klemme *et al.*, 2002). A positive correlation between the Nb and Ti would imply the fractionation of Fe–Ti phases; however, the moderately negative correlation between Ti anomalies and Nb (Fig. 8a) and absence of supporting Nb and Ta anomalies suggests that ilmenite or perovskite fractionation was insignificant in causing the Ti depletions, cannot be ascribed to convergent margin setting and is characteristic of source magma.

REE and HFSE behave coherently during partial melting of mantle and at the early stages of subsequent fractional crystallization which results into smooth trace element pattern. Any decoupling caused by some processes will result in a positive or negative HFSE anomaly. The subduction-related lavas (or subducted pelagic sediments) mainly exhibit the Hf and other HFSE anomalies (Pearce *et al.*, 1999). In Fig. 8b, the $Gd/Yb > 1$ implies downward slope of HREE and negative Hf anomaly correlates positively with HREE slope. This implies that Hf potentially controls by the crystal fractionation or subduction related process or is an inherent character of source magma. On primitive mantle trace element pattern Hf is the only HFSE which shows negative anomaly which negates the possible role of subduction. Negative Hf anomalies are constant and of same magnitude for both macrocrystic and aphanitic varieties, arguing against the cause being related to some crystal fractionation process. Therefore, the coherent relation of HREE with Hf anomaly is suggestive of primary kimberlite composition. Moreover recent results from kimberlite trace element modeling also support our conclusion that the Hf anomaly is source inherited (Tappe *et al.*, 2011, 2013).

Negative Sr anomaly is also shown by both the macrocrystic and aphanitic samples and is more pronounced in aphanitic variety. Aphanitic samples are subjected to pronounced deuteric alteration which can also give rise to more scatter in large ion lithophile elements like Sr. Negative anomaly in Sr is also a characteristic of garnet lherzolite source (Gregoire *et al.*, 2003). Therefore, it is possible to impart the same in resultant primary kimberlite composition and is an intrinsic character of kimberlite source. However, Sr depletion can be accounted by the presence of clinopyroxene (e.g., Smith *et al.*, 1985) or calcite (Keshav *et al.*, 2005) in the source

Fig. 8. (a) Plot of Ti/Ti^* vs. Nb (ppm); (b) plot of Hf anomaly vs. $(Gd/Yb)_n$; (c) variation of Th/Tb vs. Th/Ta ; and (d) Nb/Yb vs. Th/Yb diagram (Pearce, 2008; Pearce and Peate, 1995) for kimberlite samples under study.

region or even by an initial depletion due to melt extraction (e.g., Chalapathi Rao *et al.*, 2004). Depletion at P indicates a residual phosphate bearing phase such as apatite or presence of a complex K–Ba–P rich metasomatic mineral phase (Mitchell, 1995b).

DISCUSSION

Recently, based on mineralogical studies Pipe 2 west was speculated to be an unusual lamproite like intrusion and not considered to be a *bona fide* kimberlite (Kaur and Mitchell, 2013; see also Reddy, 1987). Pipe 2

kimberlite have initial $^{87}Sr/^{86}Sr$ ratio of 0.7021 and $^{143}Nd/^{144}Nd$ ratio of 0.51133 (Chalapathi Rao *et al.*, 2004). These correspond to ϵNd_i value of +1.96. Because isotopes do not fractionate during partial melting or fractional crystallization process, they should be the most useful indicators of source variations. The initial Nd isotopic signature for Pipe 2 kimberlite is higher than bulk earth and similar to Group I kimberlite source regions. In the bivariate plots (La/Nb versus Ba/Nb and Th/Nb versus Ce/Pb) involving highly mobile as well as least mobile incompatible elements during hydrothermal alteration, Pipe 2 kimberlite display marked geochemical affinities

towards Group I kimberlite of Southern Africa (Figs. 9a and b) than the lamproites. Comparatively lower incompatible elements ratios of Pipe 2 kimberlite ($\text{La/Nb} < 0.78$; $\text{Ce/Pb} < 37.22$) are distinct from lamproites which are highly enriched in these elements.

However, despite their observed geochemical difference in aphanitic and macrocrystic samples ratio-ratio plot between Th/Tb and Th/Ta (Fig. 8c) shows that the overall trend showing ratio of ~ 10.9 indicates the same mantle source.

Fabric indicates (Fig. 2) the introduction of phlogopite vein into olivine macrocryst and frequently overgrows and therefore post dates the enclosing olivine. Late crystallizing hydrous minerals are generally considered as a product of modal mantle metasomatism (Kempton *et al.*, 1988). Lloyd *et al.* (1991) reported phlogopite veins of similar nature in orthopyroxene free Group I mantle xenoliths. Petrographic observation in Pipe 2 kimberlite strongly indicates that veined phlogopite is also a late crystallizing phase and is partially resorbed by the kimberlite magma. Phlogopite veins enrichment in olivine macrocryst suite closely follows the infiltration of phlogopite and provides evidence for the introduction of Al, Ti and K rich hydrous silicate melt into mantle xenolith giving rise to mantle modal metasomatism.

The modelling of trace elements shows that the melting of garnet lherzolite source for about 1% can produce the observed trace and REE pattern of close to primary kimberlite magma. The source of Pipe 2 close to primary kimberlite magma is enriched in LREE (La : $\sim 11 \times$ chondrite) and depleted in HREE (Lu : $1 \times$ chondrite, Fig. 7a). This source is also enriched in the highly incompatible LILE and HFSE element relative to primitive mantle (Fig. 7b). The highly fractionated REE patterns of primary kimberlite magma coupled with low HREE suggests derivation from the garnet-stability field. The occurrence of diamond in the Pipe 2 kimberlite also indicates that the source region extended well into the diamond stability field at depths of >150 km. High concentrations of the compatible elements (e.g., Ni, Cr), high Mg# and very low concentration of HREE also indicate a source that had experienced a previous depletion event (Tainton and McKenzie, 1994; Beard *et al.*, 2000; Le Roex *et al.*, 2003). Incompatible elements ratios shown by Pipe 2 kimberlite are more enriched than those of OIB (Fig. 8d) which is also a characteristic of Group I kimberlites of Kaapvaal craton (e.g., Le Roex *et al.*, 2003) and many EDC kimberlites (e.g., Chalapathi Rao and Srivastava, 2009) and requires a trace element enriched (metasomatised) source region. Metasomatism (enrichment) of mantle source regions can be attributed to source enrichment processes like: 1) Subduction derived melts (e.g., Szabo *et al.*, 1996; Murphy *et al.*, 2002; Gaffney *et al.*, 2007; Coe *et al.*, 2008) and; 2) metasomatizing alkaline fluids

Fig. 9. Variation of (a) La/Nb vs. Ba/Nb and (b) Th/Nb vs. Ce/Pb for kimberlite samples under study. Data for kimberlite from Le Roex *et al.* (2003); for orangeites from Coe (2004) and for lamproite from Chalapathi Rao *et al.* (2010).

or melts derived from the upwelling (asthenospheric) mantle, enriching the overlying sub-continental lithospheric mantle (SCLM) (e.g., Wyllie, 1987; McKenzie, 1989; Foley, 1992; Le Roex *et al.*, 2003; Becker and Le Roex, 2006; Tappe *et al.*, 2012). Furthermore, Tappe *et al.* (2013) recently demonstrated that geochemical affinity between kimberlites and OIB's can be generated by the melting of OIB type material such as seamount chains being transported into subduction zones enriching the overlying asthenosphere with OIB type melts which subsequently sampled by the kimberlites.

Our petrogenetic study reveals absence of any subduction related signatures in Pipe 2 kimberlite. Thus, a previously depleted as well as subsequently enriched mantle source is inferred in its genesis (see also Chalapathi Rao *et al.*, 2004). A two stage model involving the source which has experienced initial depletion event and subse-

quent enrichment by an upwelling mantle plume in generation of Group I kimberlites from Kimberley, South Africa is also suggested by Le Roex *et al.* (2003). We envisage here that OIB like fluids or melts derived from a convective asthenosphere initially metasomatized an already depleted sub-continental lithospheric mantle. Subsequent low degrees of partial melting ($F = 1\%$) of this metasomatized source (SCLM) gives rise to the primary kimberlite magma carrying OIB like incompatible trace element signatures.

CONCLUSIONS

Newly analyzed and available mineral chemical and whole rock geochemical data along with detailed petrography clearly point towards the kimberlitic nature of Pipe 2. Petrographic observations reveals infiltration of phlogopite veins in olivine macrocryst suite which gives evidence for the introduction of Al, Ti and K rich hydrous silicate melt into source rock giving rise to mantle modal metasomatism and also for presence of veined mantle in source region. The aphanitic and macrocrystic varieties have distinct variation in their geochemistry where aphanitic samples seem to be more enriched in trace and rare earth elements.

The sub-parallel REE patterns shown by the aphanitic and macrocrystic samples do not represent a suite of primary magmas derived by different degrees of melting but consistent with the fractional crystallization trend. Up to ~5% fractionation of olivine in primary magma appears to be responsible for observed variation shown by aphanitic samples. Therefore aphanitic and macrocrystic varieties of Pipe 2 kimberlite are inferred to be products of same mantle source (primary magma) but have experienced different evolutionary histories.

Simple batch melting model shows that average close to primary Pipe 2 kimberlite magma could have formed by very small degrees (1%) of partial melting of a previously metasomatized garnet lherzolite source with 2% residual garnet. Marked negative anomalies in K, Sr, P, Ti and Hf are present in both the macrocrystic and aphanitic samples. Depletions in Ti and Hf are not consistent with fractionation and do not confirm convergent margin setting moreover are characteristics of source magma. Therefore the melts derived from convecting mantle, rather than those linked with subduction related processes, are inferred to be agents of metasomatism in an already depleted sub-continental lithospheric mantle. Subsequent low degrees of partial melting ($F = 1\%$) of this metasomatized source (SCLM) is responsible for the generation of primary Pipe 2 kimberlite magma.

Acknowledgments—AD acknowledge financial support from Department of Science and Technology, New Delhi in the form of major research project grant under Fast Track Scheme for

Young Scientists (No. SR/FTP/ES-175/2010). NVCR thanks Head, Department of Geology, Banaras Hindu University, Varanasi, for support and encouragement. Journal reviewers Sebastian Tappe and Nitin Karmalkar, as well as editor Axel Hofmann provided constructive comments on this manuscript, for which we are sincerely grateful.

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