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Diamond Prospectivity of Mesoproterozoic kimberlites from the Wajrakarur field, southern India: Perovskite oxybarometry and bulk-rock transition element geochemistry constraints

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ABSTRACT

Prognostication of the primary diamond host rocks such as kimberlites and lamproites is traditionally carried out by deploying proven techniques such as indicator (xenocryst) mineral chemistry and pressure-temperature estimates on co-existing phases in mantle xenoliths. However, in the recent past new methodologies - such as estimation of redox nature of the magmas from perovskite oxybarometry and response of first-row transition elements to oxygen fugacity- essentially involving the bulk-composition of the host rocks have also emerged for predicting the diamond prospectivity. Here, we test the applicability of such host rock models to the well-characterized Mesoproterozoic kimberlites from the Wajrakarur field, eastern Dharwar craton, southern India, whose diamond incidence is well-established. We demonstrate that a combination of perovskite oxybarometry and transition element geochemistry in conjunction with petrography can impose better first order controls on the prognostication of the primary diamond host rocks rather than by applying them individually, in isolation. We also highlight that such a combined approach holds as much promise as the well-established and age-old prognostication techniques that are currently in vogue, for inferring the diamond prospectivity of the primary host rocks.

INTRODUCTION

Kimberlites are of considerable economic and academic significance owing to their diamond potential and their great depths (> 150 km) of derivation. Even though the global records show that kimberlite pulses have been recorded right from the Proterozoic to the Quaternary, the Mesoproterozoic and the Cretaceous are particularly important periods when a majority of such episodes took place (Dawson, 1989; Janse and Sheahan, 1995; Heaman et al., 2004). In India, several kimberlite fields are known from the Eastern Dharwar craton (EDC) and the Bastar craton (Fareeduddin and Mitchell, 2012). Whereas the kimberlites from the EDC are of Mesoproterozoic age (Kumar et al., 2007; Chalapathi Rao et al., 2013a), belong to the Group-I variety and vary in their nature from non-diamondiferous to diamondiferous, those from the Bastar craton have been recently established to be of end-Cretaceous age and belong to Group-II kimberlites (orangeites) and are diamondiferous (Lehmann et al, 2010; Chalapathi Rao et al., 2011a). It has been well acknowledged that diamond prospectivity of a kimberlite is a function of interplay between a number of factors such as (i) depth of generation of the magma, (ii) presence of diamondiferous roots in the underlying cratonic mantle, (iii) wall-rock (peridotite and eclogite) disrupting magmatic process which incorporates such xenoliths and their xenocrysts (including diamond) into the magma, (iv) very rapid magma ascent which can non-destructively transport the diamonds to the surface and (v) oxygen fugacity of the ascending magma. Of all these, the oxygen fugacity (fO_2), an intensive variable, is known to exercise an important control on the diamond survival (Gurney, 1989; Birkett, 2008; Scott-Smith and Smith, 2009). In this study, we investigate the redox conditions of the Mesoproterozoic kimberlites of the Wajrakarur field, Eastern Dharwar craton, southern India, by estimating oxygen fugacity (fO_2) from Fe-Nb oxybarometry on their perovskites so as to evaluate fO_2 influence on their diamond prospectivity.

We also compare the results obtained from perovskite oxybarometry with those obtained from recently developed geochemical models (Birkett, 2008) for estimating diamond prospectivity by the deployment of bulk-rock first-row transition element content of kimberlites. This model has been demonstrated (Chalapathi Rao et al., 2011b) to hold good to explain the non-prospectivity of the Krishna lamproites, eastern Dharwar craton, as also inferred from results from bulk-rock processing.

METHODOLOGY AND SAMPLING

Perovskite ($CaTiO_3$) is an important groundmass phase in kimberlites and forms at the final phase of magmatic crystallization. It occurs in a number of paragenesis including as (i) fine grained ground mass phase associated with other liquidus phases, (ii) reaction-induced rims on earlier-crystallized Ti-bearing oxides, (iii) relict fragments in complex multiphase pseudomorphs comprising Ti-oxide phases and calcite, (iv) xenoliths of upper mantle rocks together with other xenocrysts such as Nb-titanate, Nb-rutile, spinel and Mg-ilmenite and (v) inclusions

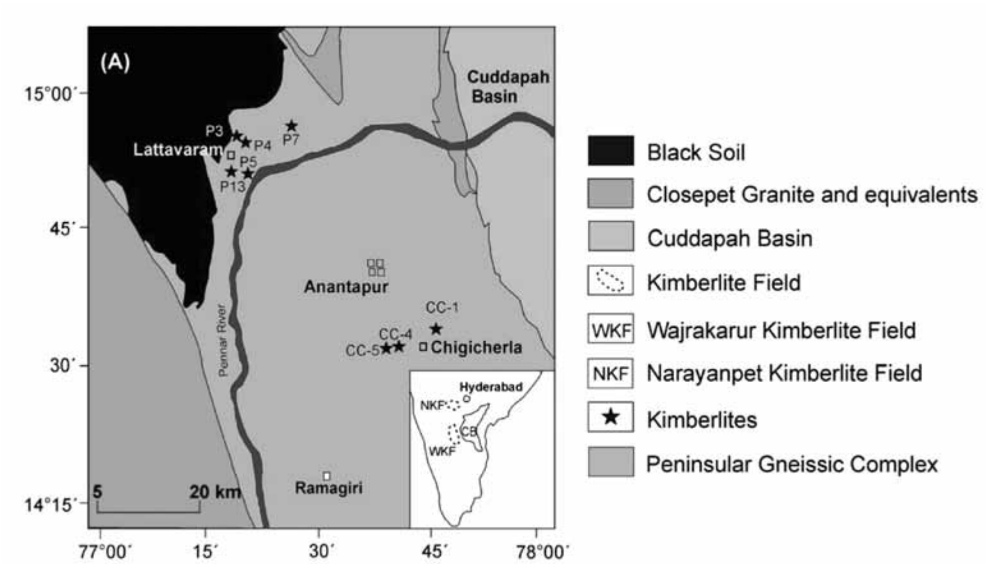

Figure 1A. Location map (after Nayak and Kudari, 1999) of Wajrakarur Kimberlite Field (WKF) showing distribution of Lattavaram kimberlite cluster (P3, P4, P5, P7 and P13) and Chigicherla kimberlite cluster (CC-1, CC-4 and CC-5).

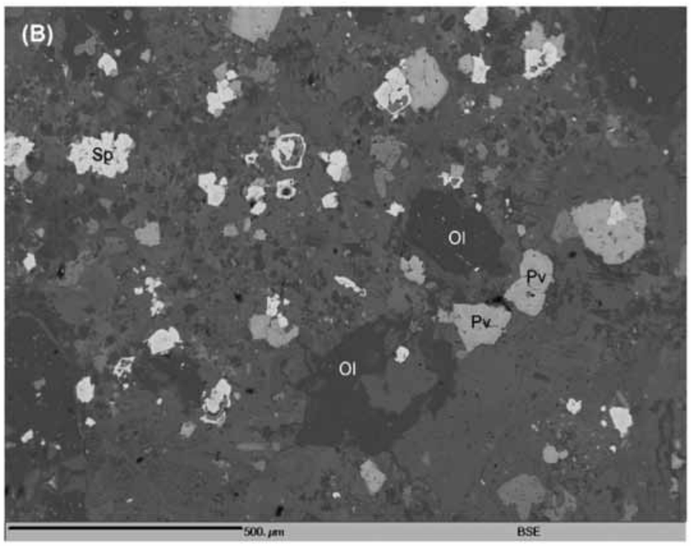

Figure 1B. Back Scattered Electron (BSE) image of perovskite from CC4 kimberlite of this study. Abbreviations: Pv = Perovskite; Sp = spinel; Ol = olivine.

in diamond. Low silica activity is invoked for the crystallization of perovskite in igneous rocks, in general (Carmichael and Nicholls, 1967; Chakmouradian and Mitchell, 2000; Mitchell, 2002) and for those in kimberlites (Canil and Bellis, 2007), in particular.

Mesoproterozoic kimberlites in the Eastern Dharwar craton occur in two separate groups: the non-diamondiferous Narayanpet field (NKF) and the well-known diamondiferous Wajrakarur field (WKF) – both of which were emplaced at ~1100Ma (Kumar et al., 2007; Chalapathi Rao et al., 2013a) (Fig.1A). In the WKF kimberlites, perovskite is a ubiquitous accessory mineral and occurs as the groundmass liquidus phase (Fig.1B; Chalapathi Rao et al., 2004; 2013a). In this present study, REE concentrations of perovskite from two distinct clusters (most of which are diamondiferous) of the Wajrakarur kimberlite field viz., (i) Lattavaram cluster (Pipes 3, Pipe 5, Pipe 7 and Pipe 13) and (ii) Chigicherla cluster (CC-1, CC-2, CC-4 and CC-5) are used to estimate fO_2 of their magmas and the data has been culled from the available literature.

Based on the experimental studies, Bellis and Canil (2007) developed a method to estimate the fO_2 during the crystallization of kimberlites by using the Fe content of perovskite. The basic premise of perovskite oxybarometry

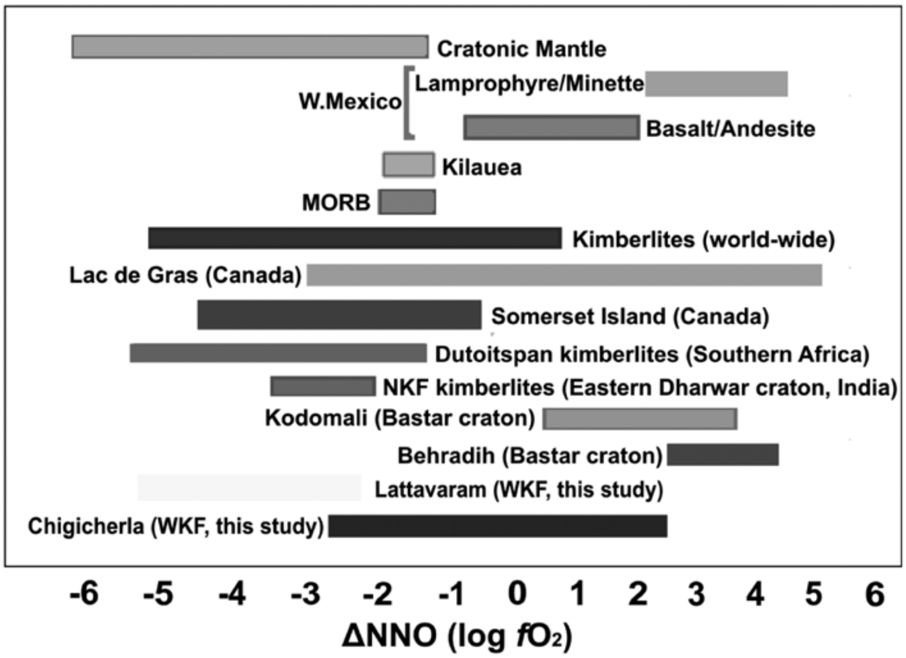

Figure 2. Estimated oxygen fugacity (log fO_2)(ΔNNO) conditions of the kimberlites of Lattavaram [WKF] (Yellow box) and Chigicherla [WKF] (Greyish box) of this study are compared with those recorded by cratonic mantle lithosphere, mantle-derived magmas and global kimberlites (Canil and Bellis, 2007); Dutoitspan kimberlites (Oglive-Harris et al., 2009); NKF kimberlites (Chalapathi Rao et al., 2012); Behradih and Kodomali orangeites (Chalapathi Rao et al., 2013b).

is that (i) Fe will increasingly occur as Fe^{3+} in kimberlite melts with increasing fO_2, (ii) all Fe detected in perovskite is assumed to be Fe^{3+} and (iii) Nb levels at a given fO_2 affect the Fe content within the perovskite (Bellis and Canil, 2003). The empirical relation, given below, describes the covariation of Fe and Nb cations (per three oxygens) in perovskite with fO_2 relative to the NNO (nickel-nickel oxide buffer), with uncertainties quoted at the 2σ level:

$$\Delta NNO = -\,[0.50_{(\pm0.021)} \times Nb + Fe_{(\pm0.031)} - 0.030(\pm0.001)]/0.004_{(\pm0.0002)}$$

It is well-known that with increasing fO_2 diamond in kimberlite magma oxidizes to CO_2 and that prolonged residence times in high fO_2 conditions would increase diamond resorption (Federtchouk et al., 2005) thereby leading to a decrease in a kimberlite diamond grade. It should be pointed out here that perovskite is a late stage crystallization product of kimberlite that would only reveal the redox state at the time of intrusion but exclude records oxidation evolution the kimberlite magma has undergone from depths of at least 150 Km at which diamonds nucleated and grew.

RESULTS AND DISCUSSION

We have applied the oxybarometry of Bellis and Canil (2007) to perovskite from the kimberlites of the WKF and their ΔNNO estimates are presented in Table 1 together with the published information available for diamond incidence in these pipes. The kimberlites of Lattavaram cluster, including the non-prospective P-5, exhibit a tight ΔNNO range from -2.18 to -5.14 whereas those from Chigicherla cluster display a considerable range from -2.88 to +2.88 (Fig.2). Both these clusters show a similarity with the ΔNNO values of kimberlites world-wide and prospective diamondiferous kimberlites located elsewhere such as Dutoitspan, southern Africa, and Somerset Island, Canada (Fig.2). Published ΔNNO values for non-prospective NKF (Chalapathi Rao et al., 2012) exhibit a range from -1.94 to -3.24, which are far more uniform than other kimberlites world-wide, and in case of those from prospective MKF exhibits a range from +0.71 to +4.28 which is clearly "anomalous" given their high diamond grade (Chalapathi Rao et al., 2013c) (Fig.2).

In order to additionally constrain the results obtained from perovskite oxybarometry, we have deployed the geochemical model, involving bulk-rock transition elements, proposed by Birkett (2008). According to this model, the evolution of kimberlite or lamproite magmas from reducing mantle conditions can play an important role in distinguishing between prospective (macro diamonds with economic value) or non-prospective (either non-diamondiferous or having diamonds with no commercial value). This character can be monitored through the response of first-row transition elements (Sc to Zn), which

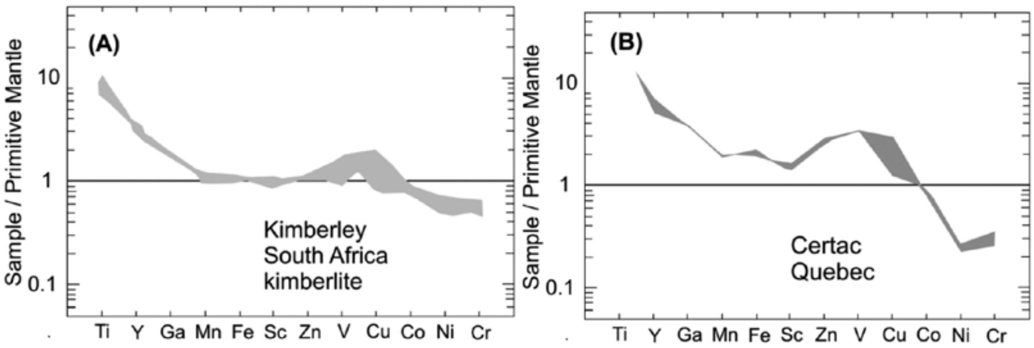

Figure 3. Primitive-mantle normalized (Sun and McDonough, 1989) fields of samples from (A) prospective Kimberley mine, South Africa (Le Roex et al., 2003) and (B) non-prospective Certac kimberlites, Quebec, Canada (Birkett, 2008).

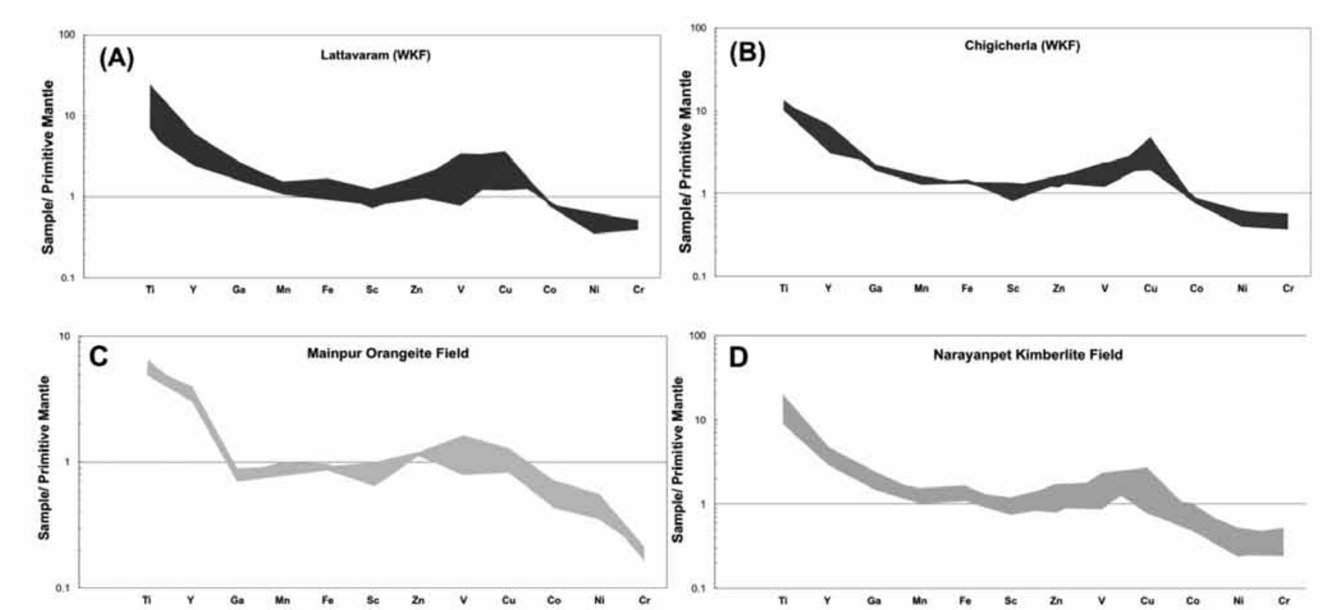

Figure 4. Primitive-mantle normalized (Sun and McDonough, 1989) spectra for samples of various occurrences of Chigicherla kimberlites (data from Chalapathi Rao, 1998; Chalapathi Rao et al., 2013a) [WKF] (Fig A); Lattavaram kimberlites (data from Chalapathi Rao, 1998; Chalapathi Rao et al., 2013a) [WKF] (Fig B); Mainpur orangeites (data from Chalapathi Rao et al., 2013b) (Fig C) and Narayanpet kimberlites (data from Chalapathi Rao et al., 2012) (Fig D).

are sensitive to the fO_2 of the mantle. Primitive-mantle normalized elemental profile for prospective kimberlites are typically flat and show no inflection from Ga to Cr and also, this interval is generally sinuous (Fig.3A). Whereas the non-prospective occurrences show curved or inflected profile with concave-down shape from Ti to Cu and then a sharp change through Co to low Ni and Cr (Fig.3B). Here, we calculate the primitive-mantle normalized values of first-row transition elements (Sc to Zn), along with Ga and Y from the published datasets for (i) WKF samples from Lattavaram and Chigicherla (Chalapathi Rao et al., 1998; Chalapathi Rao et al., 2013a) (Fig.4 A and B), (ii) Mainpur orangeites (Chalapathi Rao et al., 2013c) (Fig.4C) and (iii) Narayanpet kimberlites (Chalapathi Rao et al., 2012) (Fig.4D) in order to compare them with primitive-mantle normalized multi-element spectra of prospective and non-prospective kimberlites (Fig. 3A and B).

In the case of all the samples from WKF, including the non-diamondiferous P-5 (Table 1) the nature of the spectra is of flat-type (Fig. 4 A and B) and resembles (*sensu-lato*) with the spectra of typical kimberlite of Kimberley, South Africa (Fig.3A). Similar multi-element patterns have been duplicated by the samples from Mainpur orangeite field (Fig.4 C) as well as from the Narayanpet kimberlite field (Fig.4D).

The ΔNNO values calculated from perovskite in Lattavaram kimberlites are well fitted with values of global kimberlites and therefore their diamondiferous nature is

Table 1. Perovskite oxybarometry results of the kimberlites of this study. Perovskite major oxide data sources: Chalapathi Rao (1998), Chalapathi Rao et al., (2004); Chalapathi Rao and Srivastava (2009); Chalapathi Rao et al., (2013a and b). ΔNNO for Narayanpet field is from Chalapathi Rao et al., (2012) and for Kodomali and Behradih (Mainpur field) is from Chalapathi Rao et al. (2013b). Diamond incidence data is from Neelakantam (2001).

Pipe name	Name of the cluster/ field	ΔNNO range	Prospective/ Non-prospective	Diamond incidence (ct/ 100t)
Wajrakarur kimberlite field (WKF)				
P3	Lattavaram	- 4.16 to – 5.14	Prospective	0.28
P4	Lattavaram	- 4.79 to – 5.06	Prospective	0.25
P5 (Muligiripalle)	Lattavaram	- 3.21	Non-Prospective	Nil
P7 (Venkatampalle)	Lattavaram	- 3.12	Prospective	7.89
P13 (Tummatpalle)	Lattavaram	- 2.18	Prospective	Nil
CC-1 (SW-Chigicherla)	Chigicherla	+ 1.94 to + 2.79	Prospective	0.30
CC-2 (Chigicherla N)	Chigicherla	- 0.66 to + 2.79	Prospective	0.35
CC-4 (Gollapalle W)	Chigicherla	- 2.88	Prospective	3.55
CC-5 (NE-Gollapalle)	Chigicherla	- 2.18	Prospective	1.28
Narayanpet kimberlite field (NKF)				
Narayanpet	Narayanpet	- 1.9 to - 3.24	Non-prospective	Nil
Mainpur Orangeite field (MOF)				
Kodomali and Behradih	Mainpur	+ 0.71 to + 4.28	Prospective	Prospective but no data is available

correlatable with perovskite oxybarometry and which is further attested by their flat primitive-mantle normalized transition-element spectra. In comparison, the Chigicherla kimberlites show a much wider range in their ΔNNO values but their multi-element profiles are flat and their prospectivity is also directly supported by their similar diamond incidence as those from Lattavaram cluster (Table 1). Despite having the range of ΔNNO values as well as flat spectra like prospective occurrences, the NKF kimberlites are non-prospective. From the conspicuously low olivine macrocrysts content, the paucity of diamonds in NKF has been petrographically explained to due to emplacement processes such as volatile content and rate of magma ascent could have played more significant role in determining diamond potential (Chalapathi Rao et al., 2004; 2013a; Field et al., 2009). On the other hand, the Mainpur orangeites- in spite of their diamondiferous nature, display a range within the non-prospective field and have been termed 'anomalous' (Chalapathi Rao et al., 2013c); but their prospective nature is also supported by the flat-shaped profiles of their transition-element plots. Our study demonstrates that combined perovskite oxybarometry and bulk-rock transition element geochemistry coupled with detailed petrography has as much potential in imposing first order controls on prognostication of the primary diamond host rocks rather than by applying them in isolation in view of the multiple factors (above) which can potentially decide upon the presence of diamond in its host rock. Such a combined approach holds as much promise as the well-established and age-old, diamond prognostication techniques such as pressure-temperature estimates on co-existing minerals in mantle xenoliths and xenocryst (indicator) mineral (e.g., garnet, chromite, diopside, spinel) chemistry in inferring diamondiferous nature of the primary host rock. As diamond exploration, processing and mining necessarily involve huge investments prognostication models involving bulk-rock composition, such as those discussed in this paper, should be applied to more primary host rock data sets to further evaluate their sensitivity and efficacy.

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