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PHYSICAL AND INFRARED CHARACTERISTICS OF DIAMONDS FROM BEHRADIH KIMBERLITE, BASTAR CRATON, INDIA

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Introduction

Peninsular India is known for several occurrences of diamonds hosted by kimberlites and lamproites in three cratonic blocks, viz. Bastar Craton, Bundelkhand Craton and Dharwar Craton (Fig. 1). In the Bastar Craton, eluvial diamonds were first reported in the early 1990s from around Payalikhand in the state of Chhattisgarh. Investigations in the last two decades by the Geological Survey of India and the Directorate of Geology and Mining, Chhattisgarh (DGM), have led to the discovery of several kimberlites in the Bastar Craton. These kimberlites are distributed in two fields, viz. Mainpur Kimberlite Field (MKF) and Tokapal Kimberlite Field (TKF). The MKF has six intrusions, out of which four have been found to be diamondiferous. The TKF contains two intrusions, both of which are barren. Lamproite occurrences in the Bastar Craton are known from Nuapada in Odisha and Khadka in Chhattisgarh. The kimberlite and lamproite fields of the Bastar Craton are broadly aligned in a NNE–SSW trend and occur in the eastern part of the craton, close to its margin with the Proterozoic Eastern Ghats Mobile Belt.

Natural diamonds most commonly contain nitrogen as a substitutional impurity, with material categorised by the dominant form of N-bearing defect in the lattice. One of the most effective and widely used methods of investigation of structurally bound nitrogen aggregation state in diamonds is Fourier-transform infrared spectroscopy (FTIR). Infrared characteristics of Indian diamonds are poorly known. Jha et al. (1995) studied infrared characteristics 10 macrodiamonds from two intrusions in the MKF, namely Payalikhand and Behradih, and found that the diamonds have IaA–IaB spectral characteristics with low N-aggregation. However, since the number of diamonds studied by Jha et al. (1995) was small, there is scope of refinement of their conclusions. The present work was undertaken to retrieve a sizable number of both

micro- and macro-diamonds from drill core samples of the Behradih kimberlite and characterise them on the basis of their morphological and infrared characteristics.
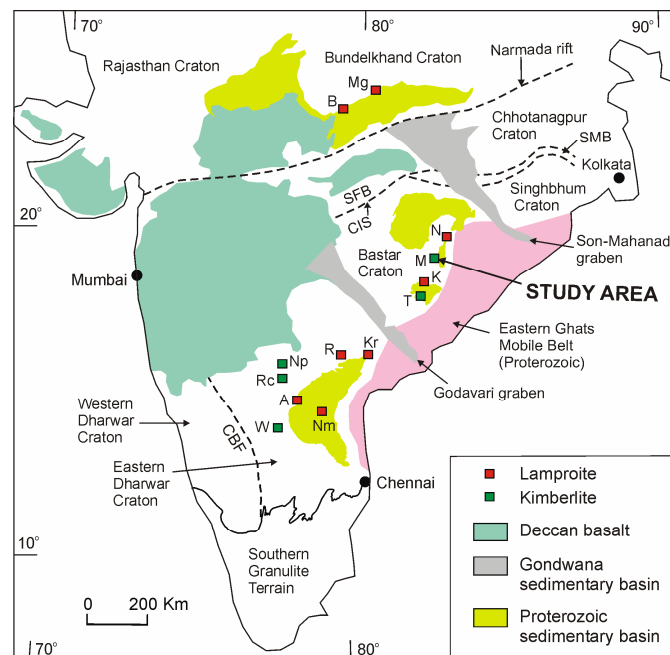
Fig.1. Schematic geological map of India showing occurrences of kimberlites and lamproites. CBF – Chitradurga Boundary Fault; CIS – Central India Shear Zone; SFB – Satpura Fold Belt; SMB – Singhbhum Mobile Belt; A – Aliabad; B – Bunder; K – Khadka; Kr – Krishna; M – Mainpur; Mg – Majhgawan; N – Nuapada; Nm – nallamalai; Np – Narayanpet; R – Ramadugu; Rc – Raichur; T – Tokapal; W – Wajrakarur.

Behradih kimberlite

The six kimberlite intrusions of the MKF are distributed in two clusters, namely Behradih cluster with Bajaghati, Behradih, Kodomali and Kosambura kimberlites, and Payalikhand cluster with Jangra and Payalikhand kimberlites (Fig. 2). The two clusters are located in a WNW-trending, ~ 15 km long corridor within the Archaean Bundeli granitoid. The Payalikhand cluster occurs close to the western margin of the Khariar basin in the southeastern part of the MKF. The Khariar basin is a N–S trending Neoproterozoic platformal basin with surface dimension of ~ 80 km × 30 km. Sedimentary rocks of the basin that are exposed close to the MKF include sandstone (Devdahra Sandstone) and shale (Kulharighat Formation) of the Pairi Group.
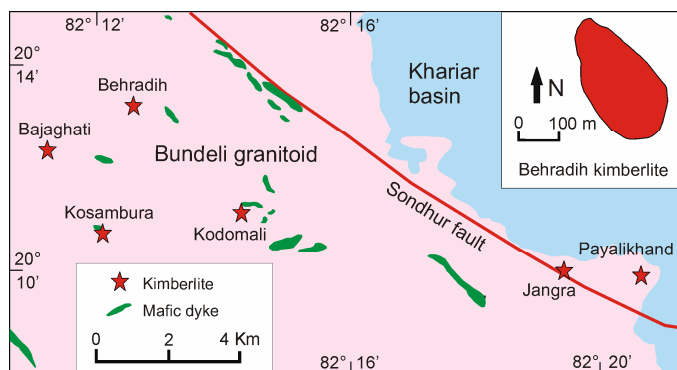
Fig.2. Generalised geological map of Mainpur Kimberlite Field. Inset shows surface outline of Behradih kimberlite.

The Behradih kimberlite (82° 12′ 06″ : 20° 12′ 54″) is a diatreme facies intrusion with surface dimension of ~ 300 m × 160 m, and is the largest among all kimberlites in the MKF. The intrusion is covered by a thick blanket of completely weathered rock and has been explored by the DGM by drilling four angular and one vertical drill holes down to a depth of ~ 200 m depth. The drill data indicate a reserve of ~ 6.7 mt of kimberlitic material up to a depth of 100 m.

Petrographic study of the Behradih kimberlite shows that the rock has a macrocrystal and magmaclastic texture. The kimberlite consists of macrocrysts and microphenocrysts of olivine and phlogopite, pelletal lapilli, and autolith, all set in a groundmass of serpentine, diopside, calcite, spinel, perovskite and apatite. Geochemical and Sr and Nd isotopic data indicate that the kimberlite has affinity towards South African Group-II kimberlite (orangeite) (Chalapathi Rao et al., 2011). Lehmann et al. (2010) dated the Behradih and Kodomali kimberlites as 65 My old. This is different from most other kimberlites in India which were emplaced ~ 1100 Ma.

Behradih diamonds

The MKF was explored by M/s B. Vijay Kumar Chhattisgarh Exploration, Raipur, in technical collaboration with M/s Oropa Ltd. (now M/s Sihayo Gold Ltd.) until the year 2000. During prospecting, the Behradih kimberlite yielded abundant microdiamonds (< 0.5 mm size) as well as macrodiamonds (> 0.5 mm size). Total 9 bulk samples with a combined weight of ~ 318 kg yielded 391 microdiamonds (262 of –0.1 mm, 141 of –0.15 mm, 55 of –0.21 mm, 28 of –0.3 mm, 5 of –0.43 mm size), and 6 macrodiamonds (3 of –0.6 mm, 2 of –0.85 mm, 1 of –1.18 mm size) (Oropa, 2000). The DGM recovered 4 macrodiamonds with a total weight of 0.459 ct from 2.7 tonnes of pit material from the Behradih kimberlite (Verma and Saxena, 1997) which translates to a grade of 17 cpht.

For the present study, –5 mm fractions of drill core material weighing a total of ~ 125 kg was processed by caustic soda dissolution (CSD) and another ~ 300 kg by dense media separator (DMS) for diamond incidence. The CSD yielded 86 microdiamonds of < 0.6 mm size, whereas the DMS yielded 35 macrodiamonds with sizes in the range of 0.6–2.2 mm and total weight of 0.29 ct. This translates to a diamond incidence of ~ 90 cpht. The physical and infrared characteristics of these micro- and macrodiamonds are outlined below.

Microdiamonds

The microdiamonds are mostly colourless. Octahedral morphology (Fig. 3) accounts for nearly 70% of the population. Other forms include dodecahedron (~ 10%) and combination of dodecahedron and octahedron (~ 5%), the rest being irregular or broken fragments. The faces of octahedral crystals range from flat (Fig. 3A) to stepwise (Fig. 3B). Intergrowth of octahedra (Fig. 3C) with stacked lamellae is not uncommon. Octahedral crystals are sometimes distorted along the L4 axis (both flattened and elongated) and frequently show polycentric growth. A large proportion of octahedral crystals are resorbed to different degrees. The initial stage of resorption is expressed in trigonal etch pits, usually negatively oriented. Further resorption process has resulted in rounding of edges and apices that have lead to the formation of combined octahedral-dodecahedral crystals with shear-like striations (Fig. 3D). Some of microdiamonds bear protomagmatic spallation surfaces.
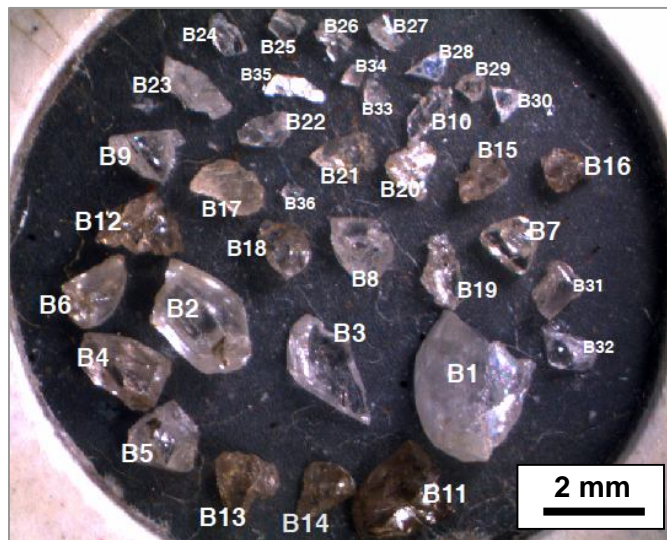
Macrodiamonds

The majority of Behradih macrodiamonds are clear, colourless and inclusion-free crystals, while a small population consists of brown and white crystals (Fig. 4). The studied crystals are mostly broken fragments, but several grains exhibit identifiable rhombical dodecahedral faces, while a few grains show octahedral faces.

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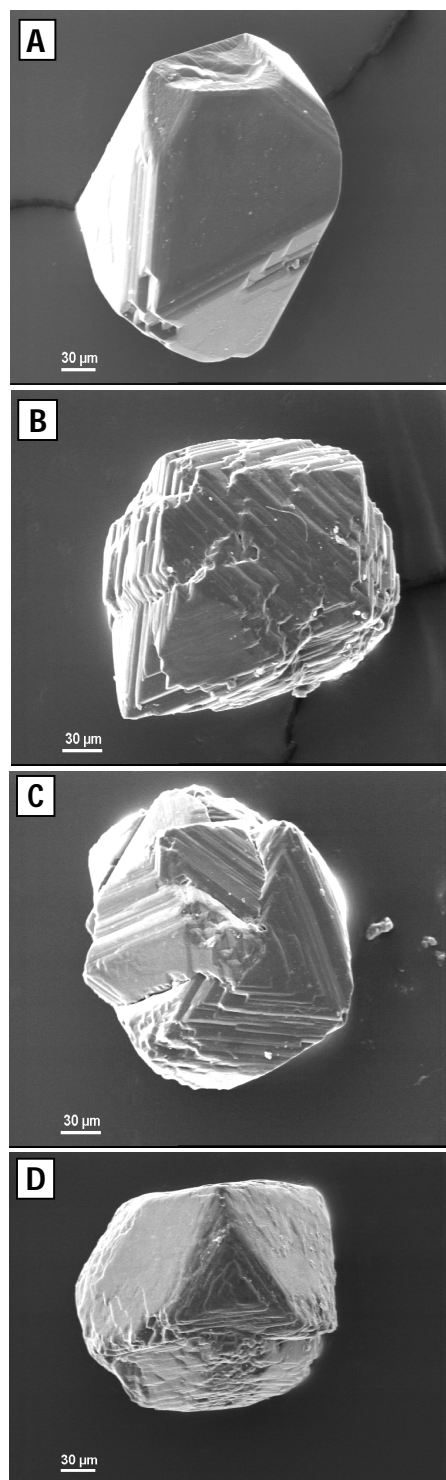
Fig.3. SEM images of Behradih microdiamonds. Length of bar scale is 30 micron. See text for description.

A few macles occur in the sample set and rarely contain negatively oriented etch marks. One of the macrodiamonds (an

irregular form) shows dissolution pits shaped like negative quadrangular pyramids. Black inclusions, probably graphite, are noticed in a few crystals.

Fig. 4. Photograph of macrodiamonds from the Behradih kimberlite.

Jha et al. (1995) studied the physical characteristics of MKF macrodiamonds with 11 grains from the Payalikhand kimberlite and 7 grains from the Behradih kimberlite. They observed that all the diamonds are brown coloured with rounded dodecahedral form, except for one partially resorbed octahedron. However, our study shows that the Behradih macrodiamond population is dominated by clear, colourless and inclusion-free crystals.

Infrared characteristics

Sixteen macrodiamonds from the Behradh kimberlite were analysed by FTIR for structurally bound nitrogen aggregation state. Thirty three absorption spectra were obtained using a Brucker Vertex 80 Infrared spectrometer (fitted with Hyperion 3000 microscope) at the Indian Institute of Technology, Bombay. The spectral resolution was 4 cm^{-1} and recording was done by averaging the signals of 100 scans. The number of spectra per sample was in the range of 1–3 (Table 1). Concentrations of N_A and N_B nitrogen impurities were determined from the absorption coefficients measured for the corresponding bands in IR spectra using the following equations:

$$N_A = K_A * \mu_{1282(A)}; \quad N_B = K_B * \mu_{1282(B)} = K_B' * \mu_{1175(B)};$$

where, N_A and N_B are the concentrations of A- and B-centres in at.ppm, respectively;

Table 1. Results of IR spectral decomposition. Sample numbers correspond to those in Fig. 4.

Sample no.	Shape	Color	No. of spectra	N_A, ppm	N_B, ppm	N_{tot}, ppm	% N_B	P, cm^{-1}
B-1	D–F	CL	3	471	228	699	37	11.8
B-2	D–F	CL	3	573	313	886	35	8.0
B-3	D–F	CL	2	640	310	950	33	10.1
B-4	I	CL	2	312	118	430	27	7.2
B-5	O–F	CL	2	511	417	929	45	10.7
B-6	D–F	CL	2	431	292	725	40	9.1
B-7	M	CL	2	362	409	771	53	28.3
B-8	Fr	CL	2	523	253	776	33	14.2
B-9	M	CL	2	456	270	726	37	15.1
B-11	I	BR	2	347	130	477	27	8.8
B-12	Fr	BR	2	307	145	457	32	9.0
B-13	Fr	BR	3	343	96	439	22	8.8
B-14	I	BR	1	279	79	358	22	8.3
B-15	Fr	BR	1	282	246	528	47	15.1
B-18	I	CL	2	550	341	891	38	18.3
B-23	Fr	W	2	415	241	656	37	13.9

Note: D – rhombical dodecahedron, O– octahedron, M – macle, F – fragment, Fr – fraction, I – irregular, CL – colourless, BR – light brown to brown, W – Frosted white.

K_A = 16.5 ± 1 at.ppm (Boyd *et al.*, 1994), K_B = 79.4 ± 8 at.ppm (Boyd et al., 1995) and K_B' = 26.6 at.ppm (Khachatryan, 2003) are the coefficients for A- and B-centres, respectively; μ_{1282} and μ_{1175} are the values of absorption peaks at frequencies of 1282 cm^{-1} and 1175 cm^{-1}, respectively; $\mu_{1282(A)}$ and $\mu_{1282(B)}$ for A- and B-centres in each analysis were calculated according to Bokii et al. (1986). The results of these calculations are in full agreement with the results calculated with the use of the method by Mendelssohn and Milledge (1995).

All the Behradih macrodiamonds belong to the IaAB diamond type with a predominance of A-centre (a pair of nitrogen atoms jointly replacing a single carbon atom) over B-centre (an aggregate of nitrogen atoms tetrahedrally arranged around a vacancy). The total nitrogen content (N_{total}) of the diamonds falls in the range of 358–950 at.ppm, based on which they are classified as Group 2 of medium-nitrogen diamond to which the majority of natural diamonds belong, or more precisely to Group 2a with a relatively higher nitrogen content, 400–1000 at.ppm (Kaminsky and Khachatryan, 2001) (Fig. 5). The proportion of aggregated nitrogen [%N_B = 100N_B/(N_A + N_B)] in the diamonds varies from 22 to 45 %, based on which the Behradih diamonds belong to Groups 2 ('intermediate') and 3 ('low-aggregated diamond') of Kaminsky and Khachatryan (2001) (Fig. 6). This parameter, which depends on the mantle residence temperature and age of diamond (Evans, 1992), indicates that the Behradih diamonds formed at c. 1100–1125°C, assuming a diamond age of c. 3

Ga, like for the most of peridotitic diamonds in different parts of the world. However, this estimate needs to be corrected when the real age of diamonds from the Bastar Craton is known.
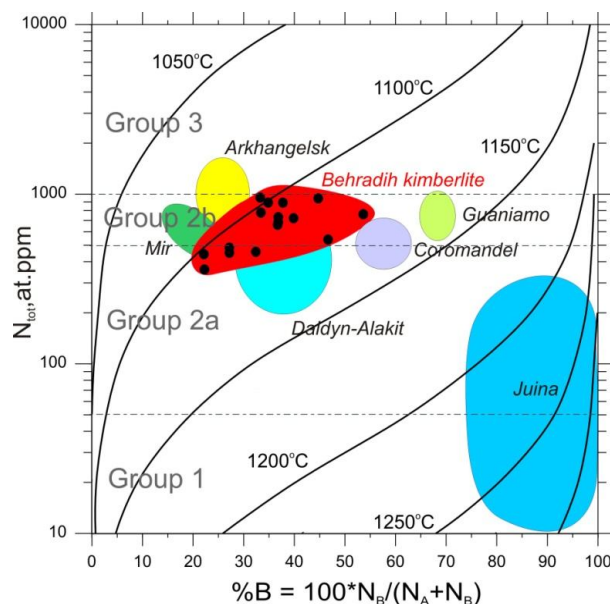

Fig.5. Temperature estimates for diamonds from different areas (after Kaminsky and Khachatryan, 2001). Isotherm curves for 3 Ga after Taylor and Milledge (1995).

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It is notable that our calculated range of $\%N_B$ and estimated range of mantle residence temperature for the Behradih diamonds are significantly higher than those of Jha et al. (1995), who reported 5–23 $\%N_B$ and an average mantle residence temperature of ~ 1080°C for both Behradih and Payalikhand diamonds.

In terms of N_{total} and $\%N_B$, the Behradih diamonds are similar to those from major primary diamond deposits in Siberia (Mir, Daldyn-Alakit area) and Archangelsk. Diamonds from the Urals and the Slave Craton, Canada belong to the same group, while diamonds from placer deposits in Venezuela (Guaniamo area) and Brazil (Coromandel, and particularly Juina area) have more aggregated nitrogen. According to the classification of Khachatryan (2010) for diamonds from primary and placer deposits in Siberia, these are Type IV diamonds, very characteristic for the Mir pipe and placer deposits in the Urals. Such diamonds, most frequently, have layer-by-layer octahedral or sectorial-zonal internal structure and may contain both peridotitic-type and eclogitic-type mineral inclusions.

Concentration of *'platelet'* (linear defects several atoms thick; Woods 1986) in the diamonds was calculated in arbitrary units (cm^{-1}) as a function of the absorption coefficient value measured at 1365 cm^{-1}. These values are within the range of 8.0–28.3 cm^{-1} (Table 1). By this parameter, the Behradih diamonds are close to the ones from the Arkhangelsk and Daldyn-Alakit deposits as well as from the Urals and Slave Province, Canada.
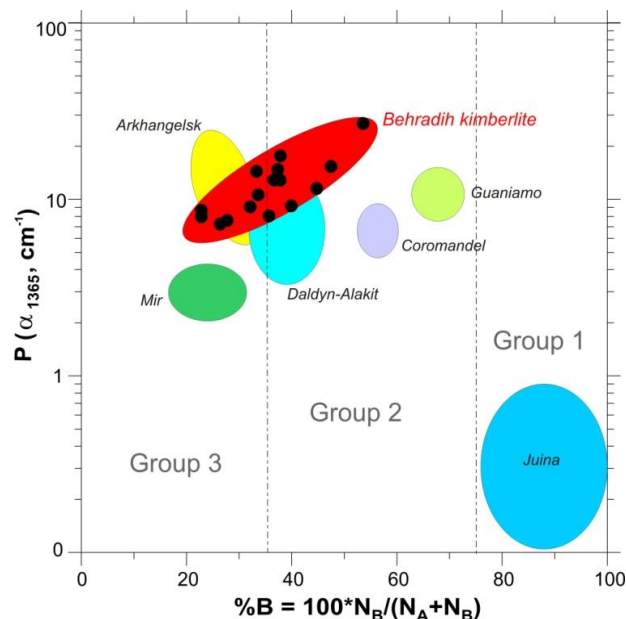
Fig.6. Distribution of 'platelets' (P) and aggregated nitrogen proportion [$\%N_B = 100*N_B/(N_A + N_B)$] in diamond from different regions (after Kaminsky and Khachatryan, 2001). P is an average 'platelet' content in diamond in arbitrary units as a function of the absorption coefficient value measured at 1365 cm^{-1}.

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