1. Introduction

The discovery of diamonds in the State of Bahia occurred in the Chapada Diamantina region, in 1821, nearly a century after the first finds in Brazil, which took place in the State of Minas Gerais (Leonardos, 1937). From 1844 onwards, Bahia had a remarkable production of diamonds and carbonados (Barbosa, 1991), which has gradually declined until today. The mining regions around the municipalities of Lençóis, Andaraí and Mucugê, within the surroundings of the established National Park of Chapada Diamantina boundaries, produced the greatest economic impact on Bahia’s diamond production (Sampaio, 1994).

The exploration of diamonds occurs mainly in alluvial deposits of the Paraiguaçu, Santo Antônio and São José rivers, in which the diamonds are considered a product of disintegration and reworking of the Mesoproterozoic Tombador Formation conglomerates (Bonfim and Pedroira, 1990). The primary source of such diamonds is unknown; due to the absence of typical satellite minerals, the diamond’s genesis in Chapada Diamantina, as well as in all the Espinhaço range, is still controversial (Chaves et al., 1998; Almeida-Abreu and Renger, 1999).

The oldest known primary source of diamonds in the São Francisco craton is the Neoproterozoic kimberlites of Brauna Field (642±6 Ma, U-Pb in perovskite, Donatti Filho et al., 2012), located northeast of the State of Bahia, and the Mesoproterozoic kimberlites of Salvador Field (1.152 Ga, Rb-Sr in phlogopite, Williamson and Pereira, 1991), located northwest of Chapada Diamantina (Nannini et al., 2017).

The upper limit for the sedimentation of the Tombador Formation is suggested as 1394±14 Ma (U-Pb in zircons) (Gruber et al., 2011). In this way, the kimberlitic affinity intrusions known in the State of Bahia are younger than the primary sources required for the diamonds present in the Tombador Formation conglomerates (Pereira and Fuch, 2005; Pereira, 2007).

The study of inclusions in diamonds has changed and shaped our understanding about diamond genesis, and is the only means to determine the process of diamond formation (Stachel and Harris, 2008).

Studies of diamonds and their associated mineral inclusions in Brazil are surprisingly scarce. One exception is the diamonds from the Juína area, in the State of Mato Grosso, widely studied due to their superdeep paragenesis (Kaminsky et al., 2009). The Juína diamonds are unique in comparison to other Brazilian diamond populations (Meyer and Svisero, 1975; Chaves et al., 2005; Tappert et al., 2006).

On the other hand, mineral inclusions in diamonds from Chapada Diamantina have never been widely studied. The only records we were able to find are in the works of Meyer and Svisero (1975)
and Svisero (1978), when they studied mineral inclusions in Brazilian diamonds.

The present study presents data from the analysis of syngenetic mineral inclusions and their assemblage in 23 diamonds from Chapada Diamantina, Bahia, and also emphasizes the morphological and infrared spectroscopic characteristics of the diamond hosts. Data about the aggregation state of nitrogen in the diamonds from Chapada Diamantina have not been found in literature.

2. Geological Setting

The Chapada Diamantina, located in the central part of the State of Bahia, is inserted in the geological context of the São Francisco Craton, which consists of an Archean/Paleoproterozoic basement and Paleomesoproterozoic and Neoproterozoic covering sediments of the Espinhaço and São Francisco Supergroups, respectively (Figure 1). The basement rocks are mainly composed of medium to high grade metamorphic rocks of the Gavião Block and granitoids associated with metamorphic-migmatitic events (Barbosa et al., 2012a).

The covering rocks begin with a succession of continental and marine metasedimentary and metavolcanic rocks of the Espinhaço Supergroup, which comprises, from base to top, according to Guimarães et al. (2012), the Serra da Gameleira Formation, Rio dos Remédios Group (composed of Novo Horizonte, Lagoa de Dentro and Ouro Fino Formations), Paraguaçu Group (composed of Mangabeiras and Açuruí Formations), Chapada Diamantina Group (composed of Tombador and Caboço Formations) and Morro do Chapéu Formation.

The carbonatic and siliciclastic rocks of the São Francisco Supergroup rest on an erosional unconformity of regional character overlaying the crystalline basement rocks, the Chapada Diamantina Group and the Morro do Chapéu Formation. The São Francisco Supergroup comprises the Bebedouro and Salitre Formations, which are covered by Cenozoic surficial deposits.

The most important diamond occurrences of Chapada Diamantina are related to the Tombador Formation. This formation includes 3 siliciclastic lithofacies associations, being the lower and the intermediate composed of metarenites and metaglamers, the latter carry detrital diamond. Diamonds are mostly recovered in colluviums and alluviums due to erosion and subsequent reworking of diamondiferous conglomerates of the Tombador Formation (paleoplacer) (Barbosa et al., 2012b).

Figure 1
Geology and tectonic features of Chapada Diamantina and the São Francisco Craton with locations of the studied garimpos (Modified from Dalton de Souza et al., 2003).
3. Materials and methods

This study presents the results of the analysis of inclusions in 23 diamonds (Figure 2) from 4 garimpos in the Chapada Diamantina region, being 12 from Garimpo Santa Rita, Andaraí; 7 from Córrego Cachorrinho, Lençóis; 3 from Garimpo Barraanco, Igaratú; and 1 from the Limoeiro river, Andaraí (Figure 1). The samples were kindly ceded by Diamond Brazil Project from the Geological Survey of Brazil (CPRM).

![Figure 2 Pictures of the 23 diamonds analyzed in this study. The numbers in the upper left corner of the pictures are the codes of the samples. The characteristics of the diamonds can be ascertained in Table 1.](image)

All diamonds were examined microscopically to determine visible morphological features, surface textures and colors. Subsequently, the diamonds had a face polished for better visualization of the inclusions. The concentration and aggregation state of nitrogen impurities in the diamonds were determined by Fourier transform infrared (FTIR) spectroscopy, using a Perkin-Elmer Spectrum 400 instrument, equipped with a 5x beam condenser, from the Gemological Research Laboratory of the Center for Mineral Technology (CETEM). Raman spectra were recorded in back-scattering geometry with a Raman microspectrometer (Horiba model LabRam HR) from the Technological Characterization Sector of CETEM, with a laser beam of 632.8 nm. The recording times were in the order of 7 minutes.

4. Results and discussion

Diamond characteristics

The 23 studied diamonds have a weight range of 0.02 to 0.13 carats, with the exception of one crystal of 1.10 ct. Their characteristics are presented in Table 1. The majority of the diamonds have faint and very light yellow body colors, sometimes with a brownish hue. The dominant shape is the dodecahedron, which comprises more than half of the studied diamonds; the presence of macles is also notable. Transition forms between octahedron and dodecahedron, as well as fragmented crystals, also occur.
The surface textures observed in the diamonds are mainly related to processes that took place in the late stages of resorption in the kimberlitic melt (enhanced luster), and during the residence in a placer environment (network patterns). The first developed possibly due to a late-stage high-temperature (~1000°C) etching (Phaal, 1965); and the second is related to a natural etching in placer environment due to a preferential attack linked to a minor dislocation of carbon atoms along octahedral planes (Emara and Tolansky, 1957).

Another feature observed, but not related to any specific feature of the dissolution conditions, are the hillocks, which Khokhryakov and Pal’yanov (2015) suggest to be related to strong deformation in the diamond crystals.

Percussion marks on the crystal’s surface have not been observed; such absence is not directly related to the distance of transport from the kimberlitic source, but most likely to the stream-bed gradient and the stream-bed lithology (Robinson, 1979).

A common feature is the presence of green and brown radiation spots on the crystal surface. According to Vance et al. (1973), the radiation damage on diamonds can be caused by the presence of radioactive element-rich minerals or solutions in contact with diamonds in placer environments or in the kimberlite.

Raal (1969) recognized that the diamonds from the uranium rich sediments of Witwatersand are all colored in various shades of green. Diamonds with green and brown coats are characteristically associated with pre-Cambrian conglomerates, as in the case of some deposits in Africa, Brazil and Venezuela (Vance et al., 1973).

Only a small parcel of diamonds in kimberlites present radiation spots; the presence of spots in diamonds of kimberlites seems to be directly associated with the weathering mantle (Harris et al., 1977).

In the case of Chapada Diamantina, the vast occurrence of spotted diamonds strongly suggests that such irradiation has occurred during the long-term residence of the diamonds in the conglomerates of the Tombador Formation. The radioactive elements are present in minerals such as zircon, known to occur in the sediments of Tombador Formation. (Svisero, 1978; Gruber et al., 2011).

The presence of brown spots points to a thermal event in the diamond’s history following the irradiation damage. It is widely accepted that the green radiation spots turn brown in response to heating at about 550 - 600°C (Vance et al., 1973; Nasdala et al., 2013; Eaton-Magaña and Moe, 2016). The coexistence of green and brown spots in the same diamond indicates that, after heating, the diamond subsequently received additional radiation damage (Vance et al., 1973).

However, in all the Espinhaço range, metamorphism does not exceed greenschist facies (Sussenberger et al., 2014). Haralyi and Rodrigues (1992)

![Table 1 Characteristics of the diamonds from Chapada Diamantina studied in this work.](image-url)

| Sample | Origin     | Weight (ct) | Color | Shape | Type          | Spots       | Assemblage |
|--------|------------|-------------|-------|-------|---------------|-------------|------------|
| 206    | G. Sta Rita | 0.099       | FY    | Flat  | IaAB          | Green, Brown| Ol         |
| 208    | G. Sta Rita | 0.050       | FY    | Tran  | IaAB          | Green, Brown| Ol         |
| 209    | G. Sta Rita | 0.031       | VLY   | Dod   | IaAB          | Brown       | Ol         |
| 215    | G. Sta Rita | 0.081       | VLY   | Twin  | IaAB          | Green       | Ol+Prp     |
| 230    | G. Sta Rita | 0.028       | VLY   | Dod   | IaAB          | Brown       | Ol         |
| 237    | G. Sta Rita | 0.076       | FY    | Dod   | IaAB          | Brown       | En         |
| 246    | G. Sta Rita | 0.038       | VLB   | Dod   | IaA           | Brown       | Ol         |
| 252    | G. Sta Rita | 0.050       | FY    | Tran  | IaA           | Green, Brown| Ol         |
| 253    | G. Sta Rita | 0.033       | FY    | Dod   | IaA           | Green       | Ol         |
| 275    | G. Sta Rita | 0.025       | NC    | Twin  | Ila           | Green       | Ol         |
| 301    | C. Cachorrinho | 0.056     | FY    | Dod   | IaB           | Brown       | Ol+En+Prp  |
| 303    | C. Cachorrinho | 0.079     | FY    | Oct   | IaB           | Brown       | Ol         |
| 308    | C. Cachorrinho | 0.032     | VLB   | Dod   | Ila           | Brown       | Chr        |
| 311    | C. Cachorrinho | 0.057     | VLY   | Dod   | IaAB          | Green       | Ol         |
| 315    | C. Cachorrinho | 0.027     | FY    | Und   | IaAB          | Brown       | Ol         |
| 327    | C. Cachorrinho | 0.030     | FY    | Tran  | IaAB          | -           | Ol         |
| 333    | C. Cachorrinho | 0.052     | VLY   | Und   | -             | -           | Ol         |
| 361    | G. Barranco  | 1.104       | VLY   | Tran  | IaAB          | Green, Brown| Ol+En      |
| 367    | G. Barranco  | 0.109       | FB    | Dod   | IaAB          | Brown       | Ol+En      |
| 374    | G. Barranco  | 0.129       | VLY   | Dod   | IaAB          | Brown       | Ol         |
| 444    | Limoeiro River | 0.074     | FY    | Und   | IaA           | -           | Ol+En      |
| 585    | G. Sta Rita  | 0.028       | LB    | Dod   | IaAB          | Brown       | Ol         |
| 589    | G. Sta Rita  | 0.087       | VLB   | Dod   | IaAB          | -           | Ol         |

Colors are classified according to the classification scheme of GIA: C = colorless, NC = near colorless, FY = faint yellow/ FB = faint brown, VLY = very light yellow/ VLB = very light brown, LY = light yellow/ LB = light brown.
Dod = dodecahedroid, Tran = transitional, Oct = octahedron, Und = undefined.
Ol = olivine, Prp = pirope, En = enstatite, Chr = chromite.
suggest that locally the diamondiferous conglomerates may have reached higher temperatures than those of the regional metamorphism. Anyway it is still an unsolved question.

Nitrogen concentrations range from 16.6 to 172 atomic ppm, and 2 diamonds have no detectable nitrogen, being classified as type IIa, according to the classification scheme of Robertson et al. (1934). The observed aggregation states are variable (Figure 3); more than half of the diamonds are type IaAB (Figure 3a), which means that they have similar concentrations of nitrogen as A and B centers, indicated by the 1282 and 1175 cm$^{-1}$ absorbance peaks, respectively (Breeding and Shigley, 2009). The other diamonds show a predominance of poorly aggregated nitrogen (A centers) (Figure 3b).

The infrared spectra of 16 diamonds also reveal a 3107 cm$^{-1}$ peak (Figures 3a, 3b and 3c), which is related to an impurity of hydrogen strongly linked to carbon and weakly linked to nitrogen (Fritsch et al., 2007).

The aggregation from A center (two nitrogens) to B center (four nitrogens surrounding a vacancy) occurs at low rates. Curiously, all 4 diamonds classified as type IaA were from the Andaraí region, and the 2 diamonds classified as type IaB were from Lençóis. The characteristic of nitrogen aggregation in diamonds can be used to identify distinct time temperature populations among pipe and alluvial diamonds, as the degree of aggregation depends on the mantle residence time of diamond, its nitrogen content, and the temperature history (Taylor et al., 1990).

Mineral inclusions

Inclusion studies are currently the only means to determine the source paragenesis and the physical and chemical conditions of diamond formation (Stachel and Harris, 2008). The syn-genetic mineral inclusions analyzed in situ by Raman micro spectroscopy were identified based on Raman peak positions, which allowed the estimation of the major element composition of the minerals: forsterite, enstatite, pyrope and chromite (Figure 4). Such minerals belong to the peridotitic suite (Meyer and Tsai, 1976), which indicates a mantle source origin consistent with the majority of other Brazilian diamonds (Meyer and Svisero, 1975, Chaves et al., 2005; Tappert et al., 2006).
Olivine is the most common mineral inclusion found in diamonds from Chapada Diamantina, occurring in almost all analyzed samples. Forsterite occurs as single inclusions and non-touching inclusions combined with enstatite, pyrope or both (Figure 5a).

The Raman spectrum of forsterite (Figure 4a) can be divided into two wavenumber regions, up to 400 cm⁻¹ and from 400 to 1000 cm⁻¹. The last region consists mainly of internal SiO₆ vibrations. The low wavenumber region shows mixed modes of external SiO₆ and Mg vibrations; the indicated peaks at 304 and 326 cm⁻¹ have the largest Mg character (Kolesov and Geiger, 2004). This region presents strong differences compared to the spectrum of fayalite (Chopelas, 1991).

The studies of Svisero (1978) revealed, for the olivine inclusions of Chapada Diamantina, forsterite number ((Mg x 100) / (Mg + Fe)) around 92, and CaO contents of 0.03 wt%.

Orthopyroxene was the second most common mineral inclusion identified. Enstatite occurs either as single inclusion, and associated with olivine (plus pyrope in one case). Olivine + enstatite is the most common inclusion pair among the studied diamonds (Figure 5b).

The most prominent vibrational modes in Raman spectrum of Figure 4b are consistent with the orthopyroxene end-member enstatite; the observed frequencies decreases with iron content, as in the case of olivines (Huang et al., 2000). All the enstatites analyzed showed strong fluorescence. The two main modes below 600 cm⁻¹ are characterized by metal-oxygen stretching modes. The two modes in the range from 600 to 700 cm⁻¹ are related to Si-O-Si bend, and the ones from 900 to 1100 cm⁻¹ are generally assigned Si-O stretching vibrations (Huang et al., 2000). The indicated peaks at 299, 399, 416 and 442 cm⁻¹ are characterized by Mg-O stretching, that usually appear in Mg rich samples (Huang et al., 2000).

Svisero (1978) found Mg numbers of 93.8, CaO contents of 0.14 wt%, and Cr₂O₃ contents of 0.62 wt% for a single enstatite inclusion in a diamond from Chapada Diamantina.

Pyrope garnet was only found in two diamonds, one from Andaraí and another from Lençóis. The first occurs associated with olivine (Figure 5c), and the second with olivine and enstatite (Figure 5a).

In the Raman spectrum of the pyrope garnet (Figure 4c), the peaks observed at higher energies correspond to SiO₆ internal stretching modes, and the others, at medium and lower frequencies, are related to SiO₆ internal bend modes. Stretching frequencies of pyrope often occur at higher energies, when compared to other garnets (Hofmeister and Chopelas, 1991).

No assessment could be made about major elements, but some coincidence with additional bands related to increased TiO₂ content (Gillet et al., 2002), indicated by the arrows in Figure 4c, was observed. According to Stachel and Harris (2008), TiO₂ contents in garnet exceeding 0.04 wt % point to metasomatic re-enrichment, since the titanium should have been largely removed during the intense melt depletion inferred for cratonic peridotites.

The hypothesis of possible high TiO₂ contents are not consistent with the data of Svisero (1978) for a pyrope garnet from Chapada Diamantina associated with olivine. The studies of Svisero (1978) revealed TiO₂ contents <0.01 wt%, and also Cr₂O₃ contents of 9.34 wt%, Mg numbers between 88.43 and CaO contents of 5.09 wt%.

Chromite inclusions were found in only one diamond from Lençóis (Figure 5d). To our knowledge, this is the first report of chromite in diamonds from Chapada Diamantina; according to Svisero (1978) chromite inclusions are not abundant in Brazilian diamonds. Raman spectra of chromites usually consist of a major broad peak near 685 cm⁻¹, and a few other less intense ones; according to Wang et al. (2004), this feature is generated by the vibration of the AⁿO₆ (A = Cr⁺³, Fe⁺³, Al⁺³) octahedron. However, the Raman spectrum obtained in this study shows the main peak strongly shifted (Figure 4d). The abnormally high wavenumber position of this peak is recognized for high chromium content in mantle chromites (Wang et al., 1994). Some of the most Cr-rich chromite grains found in nature are found as inclusions in diamond (Barnes and Roeder, 2001).

The Mg rich character of forsterite and enstatite inferred by Raman spectroscopy, the typical mineral assemblages of the analyzed diamonds.
Pyrope) and the absence of clinopyroxene, that also have not been reported in previous studies as inclusions in diamonds from Chapada Diamantina, largely indicate a harzburgitic source rock for the studied diamonds (Stachel and Harris, 2008). The correlation with the high Mg numbers and low calcium contents of forsterite and enstatite, and the composition of the garnets analyzed for Svisero (1978), corroborate that such peridotitic diamonds may have formed in depleted harzburgitic sources (Boyd and Finnerty, 1980, Stachel and Harris, 2008).

5. Conclusions

The analyzed alluvial diamonds from Chapada Diamantina have characteristically faint to very light yellow body colors, typically with green and/or brown radiation spots on their surface. A common feature is the network pattern, which reflects the long-term residence in placer environments of such diamonds. The high abundances (>80%) of spotted diamonds is evidence of a long time exposure to radiation. The absence of diamond indicator minerals, the sorting of diamonds by size, shape, and quality, and the surface textures, all indicate that the Chapada Diamantina diamonds have been reworked in sedimentary environments, suggesting farther primary sources, which may have been obscured by erosion and sedimentation.

Based on the analytical data obtained in this work, it is not possible to distinguish between different diamond populations by using morphological criteria, which may be a result of the small number of samples examined. The noticeable relationship between the aggregation state of nitrogen and the studied deposits, despite the small number of samples, suggests that a population of diamonds may have experienced a higher temperature and/or longer storage in the mantle than others.

The diamonds contain abundant olivine inclusions, followed by enstatite, pyrope and chromite. The coexistence of olivine with pyrope and/or enstatite, besides the absence of clinopyroxene, allows to conclude that such minerals belong to the harzburgitic paragenesis, which resemble results from other Brazilian deposits (Meyer and Svisero, 1975, Chaves et al., 2005; Tappert et al., 2006) and corroborates the studies of Svisero (1978), in which chemical data are consistent with depleted harzburgitic source rocks.

The non-destructive character of this study precluded further comprehension on the conditions of diamond formation in the sublithospheric mantle under the São Francisco craton. Nevertheless, the current indications are that diamonds from the São Francisco craton have similar origins to those demonstrated on other cratons elsewhere in the world; these are most predominantly harzburgitic in origin, dodecahedral in shape and faint yellow in color. In addition, the diamonds from Chapada Diamantina should have probably originated under the same conditions and as products of the same process.

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