10IKC-198

JUINA-5 KIMBERLITE (BRAZIL): A SOURCE OF UNIQUE LOWER MANTLE DIAMONDS

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INTRODUCTION

The Juina-5 pipe is located within a discrete kimberlite cluster 30 km to the south of Collier-4 pipe and the intervening well-described Juina alluvial placer. Juina-5 diamonds are different in appearance and many other properties to those of the alluvials. Most notably they carry a distinctive sublithospheric Na- and K-rich mineral assemblage never before encountered in a natural environment. Here we describe a set of inclusions found in such diamonds, characterize them, propose the manner of their origin and review the other superdeep diamond occurrences in the Juina Kimberlite field. New data on diamonds from Collier-4 kimberlite and Cinta Larga river are also presented.

GEOLOGICAL SETTINGS

The Juina Kimberlite Field (92-95 Ma; Heaman et al. 1998, Kaminsky et al. 2009b) is partly intruded in Mesoproterozoic terrains of the Rio Negro-Juruena province and in Pre-Cambrian sediments of the Casa Branca Formation, at the SW border of the Amazon Craton (Fig. 1).

In the Casa Branca Formation two paleoplacers are recognized separated by a 35 meters sediment layer (Haralyi 1991). These paleoplacers are also found in the *Chapadão* area (Fig. 2), a high topographic outlier of the Casa Branca Formation over Mesoproterozoic sediments, which are interpreted as the source of alluvial diamonds of the Cinta Larga Basin (rivers Mutum, Porcão, São Luiz, Cinta Larga; Haralyi 1991). In the *Chapadão* area Kaminsky et al. (2009a) reported the presence of a kimberlite cluster named Pandrea, although other workers regard the occurrence as a paleoplacer.

Dating of the Juina-5 kimberlite is in process using zircon megacrysts from mini-bulk sampling. Macroscopic aspects of the Juina-5 kimberlite and their xenocrysts compositions are given by Araujo et al. (this volume).

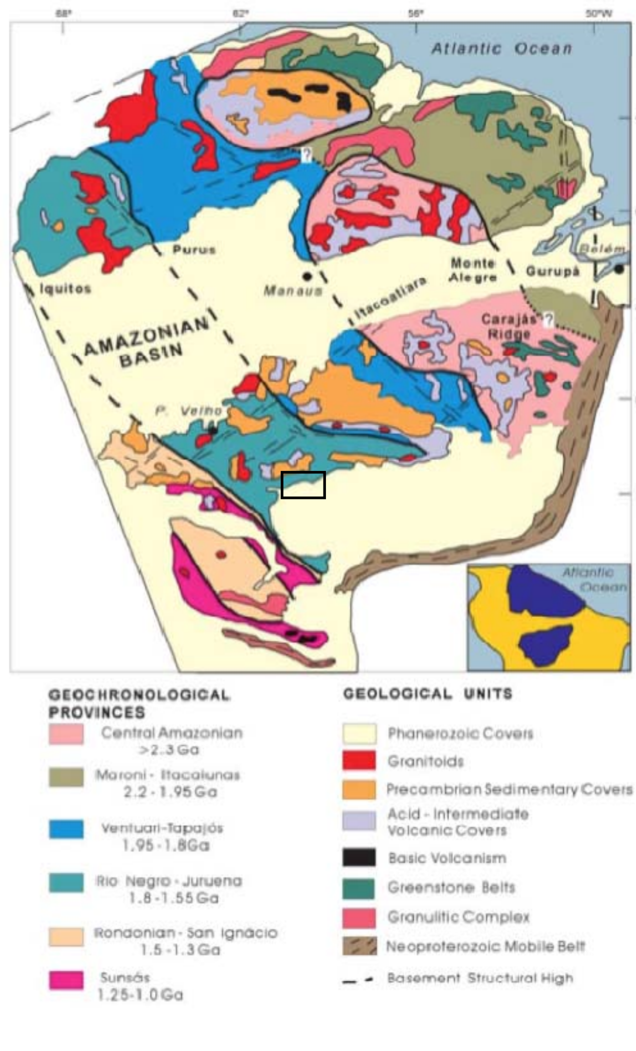

Fig. 1 – Amazon Craton Provinces (Tassinari et al. 2000) and location of Juina Kimberlite Field (rectangle).

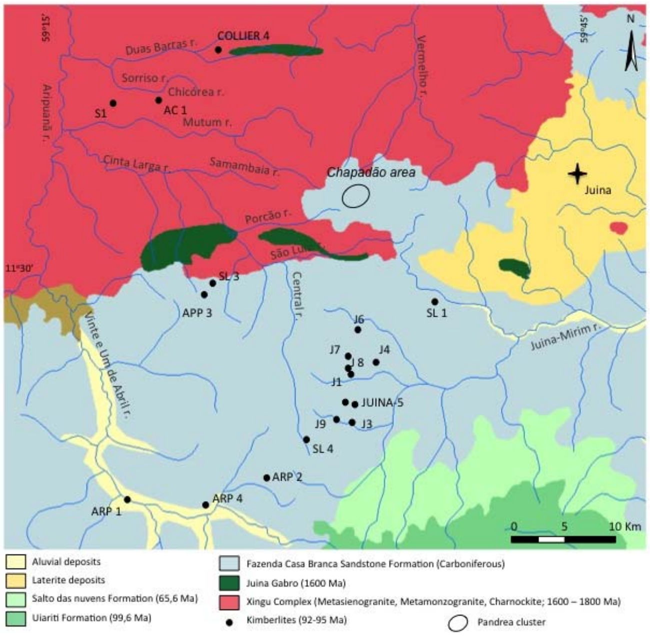

Fig. 2 – Geological map of Juina area (Silva et al. 1980) and location of kimberlites (Haralyi 1991). J5 – Juina-5. Location of Pandrea cluster from Kaminsky et al. (2009a).

MATERIALS AND METHODS

Over 500 diamonds, mainly 2-3mm in size, from the Juina-5 pipe were carefully examined for inclusions under optical microscope. Except for the carbon isotope analyses, all other procedures were done at School of Earth Sciences in the University of Bristol. Samples with inclusions were morphologically characterized and polished along dodecahedral planes for inclusion exposure and production of parallel plates. Infrared spectra of diamonds were acquired using a SpectraTech infrared microscope coupled to a Nicolet Nexus Fourier transform infrared spectrometer. Spectra were collected from 600 to 4000 cm^{-1}, at $2cm^{-1}$ steps, 64 scans and 60 μm spatial resolution. Backscattered electron images were acquired using a Hatachi S3500N scanning electron microscope. EMPA of the bulk inclusions were determined with a Cameca SX100 electron microprobe at the University of Bristol (20 nA and 20 kV) calibrated against silicate and oxide standards. The electron beam size was chosen as the minimum necessary to encompass the entire inclusion, and ranged from 15 to 50 microns in diameter.

Carbon isotope data were acquired at the Carnegie Institution of Washington with a Cameca ims 6f. The standard error of each measurement was always nearly identical to that estimated from Poisson statistics (0.3 ‰). To correct for instrumental mass fractionation (IMF), all data were normalised to an internal diamond standard (Mao $\delta^{13}C$ -6.5 PDB), which was measured throughout the analytical sessions and mounted in the same sample holder as the unknowns. Details on this method are given elsewhere (Hauri et al. 2000, Walter et al. 2011).

RESULTS

Juina-5 diamond characteristics

Diamonds from the Juina-5 pipe are mostly etched broken octahedra (42%), rounded dodecahedra (14%) and combination forms (44%). Macles are abundant among them (46%).

Cathodoluminescence imagery (CL) of central plates and sections (Fig. 3) reveals a weak octahedral internal zonation accompanied by resorption, stress, macle development and brecciation simultaneous with growth. After-growth diamond features are plastic deformation, development of cracks and deep etch channels.

Within one hundred and ten samples measured by infrared spectroscopy, 90% are nitrogen (N) free Type-II, with minor occurrences of N-containing type IaA-1aB stones having >90% of N aggregation. $\delta^{13}C$ of twelve Type-II diamonds studied to-date varies from -27 to -1‰.

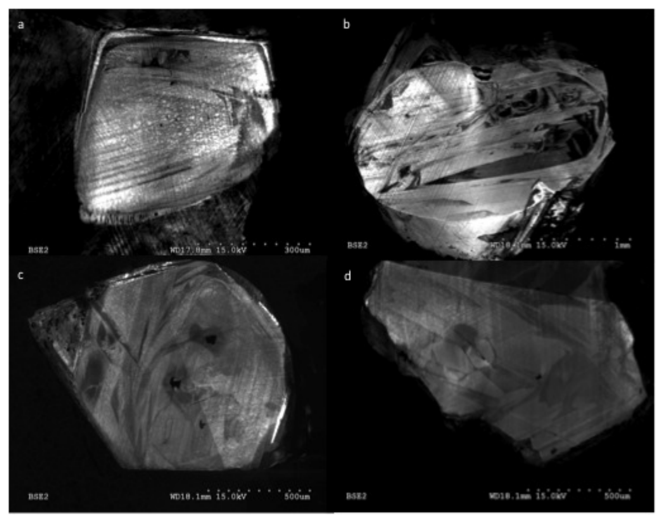

Fig 3. Internal structure of Juina-5 diamonds from CL images of their central plates. a. Ju-5-2, Octahedral growth followed by plastic deformation and resorption; b. Ju-5-13, octahedral growth with brecciation and plastic deformation; c. Ju-5-43, octahedral growth with blocky texture d. Ju-5-47, octahedral growth, brecciated structure and plastic deformation.

Juina-5 diamond Inclusions

The inclusion size differs from 10 to 60 microns and can be explained by the small size of the studied diamond-hosts. BSE imagery and EMP analyses of inclusions revealed single and composite inclusions, the last having mafic composition with enrichment in silica, aluminium, titanium and distinctive enrichment in sodium and potassium.

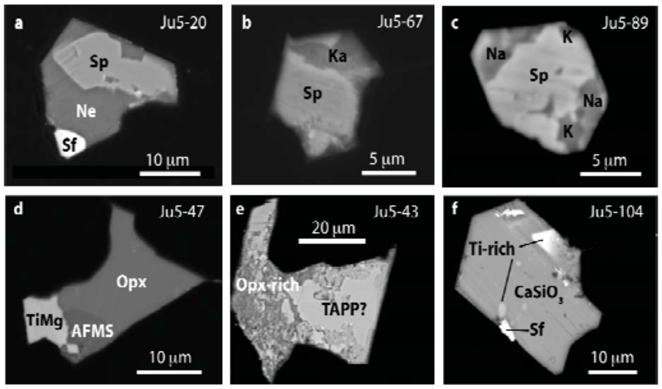

Fig. 4 – Back-scattered electron micrographs showing composite inclusions in diamonds from Juina-5. **a.** Ju5-20 - spinel (Sp) $(Mg,Fe)Al_2O_4$, nepheline (Ne) $(NaAlSiO_4)$, and sulfide (Sf) **b.** Ju5-67 - spinel and a nepheline-kalsilite (Ka) phase $((Na,K)AlSiO_4)$. **c.** Ju5-89 - spinel, and a mixture of micron sized Na-rich (Na) and K- rich (K) silicate regions, and with a bulk composition similar to Ju5-67. **d.** Ju5-47 - orthopyroxene (opx), titano-magnetite (TiMg), and an Al-, Fe- and Mg-rich silicate phase with a spinel stoichiometry (AFMS). **e.** Ju5-43 - complex mixture of orthopyroxene, Ti-, Al-, and Fe-rich phase similar to tetragonal almandine pyrope phase (TAPP). **f.** Ju5-104 - $CaSiO_3$ plus micron-sized Ti-rich phases (e.g. $CaTiO_3$) and a small sulfide (Walter et al. 2011).

Single-phase inclusions comprise SiO_2, omphacite, wollastonite, K-feldspar, MgFeAl spinel, olivine, ferropericlase, sphene and low-Ni sulphides. Frequent composite inclusions consist of majoritic garnet with clinopyroxene rims; TAPP (tetragonal almandine-pyrope) + Opx-phase; hercynite + nepheline, kalsilite or orthopyroxene (Fig. 4), most of which are former high PT-minerals of Transition zone or Lower Mantle, re-equilibrated at lower pressure during upward transportation within the different levels in the Upper mantle.

Collier-4 and associated alluvial diamond

Additional diamonds from Juina Field have been studied. They are diamonds from Collier-4 pipe and Cinta Larga, Duas Barras, Porcão and São Luiz rivers (Fig. 2). A detailed morphology study showed that Collier-4 and alluvial diamonds have higher percentage of resorbed stones (46%) than Juina-5 diamonds (14%). Usual CL features include planar and step-like layer-by-layer octahedral growth, agate-like growth, polycrystalline growth, lamination lines, and dark-CL re-filling textures. Resorption features have been recorded inside some diamonds.

The FTIR study of one hundred and thirty four diamonds revealed a high abundance of Type II stones (> 71% for alluvial diamonds and >89% for Collier-4 diamonds). The N content of the Type I diamonds is low overall, with mean at 264 ppm; one sample from São Luiz has N up to 1063 ppm. The percentage of B centers is high, usually > 90%, except for two samples with 38% (Collier-4 kimberlite) and 70% (Duas Barras river).

Hydrogen peaks at 3107, 1405, 2785 and 3236 cm^{-1} were only found in Type I diamonds suggesting favorable mechanism for incorporation of N and H.

Diamonds from the Collier-4 kimberlite have $\delta^{13}C$ from -26.3 to –4.9‰ and alluvial diamonds from -13.8 to -3‰. This range is in agreement with previous works, as discussed below.

DISCUSSION

Diamond-forming fluids in the lower mantle

The bulk compositions of hercynite + nepheline or kalsilite composite inclusions are identical to the compositions of such Na- and K-rich phases as “calcium ferrite” phase (CF) and “New Aluminium phase” (NAL), synthesized by high PT experiments and representing the Lower Mantle mineralogy of basaltic compositions. Former Al-, Ti- and Fe-rich Mg-perovskite and Ti-rich Ca-perovskite, re-equilibrated during ascent to lower-pressure phases, complete the new main mineral assemblage of the deep mantle found in Juina-5 and Collier-4 diamonds.

Walter et al. (2011) suggested that primary NAL, CF-phase and Ca-Ti-perovskites have originated when diamond-forming fluids incorporated basaltic components from oceanic lithosphere subducted into the Lower Mantle, representing the first petrological evidence that material from subducted slabs can reach and penetrate into the Lower Mantle. Such fluids also contributed to the carbon isotopic composition of these diamonds, extending the lower limit of the $\delta^{13}C$ of lower mantle diamonds to -27‰. The nature of very negative $\delta^{13}C$ of diamonds is under discussion but there are strong evidences suggesting that our results are best explained by recycling of organic carbon (Walter et al. 2011).

Comparison between Alluvial and kimberlite diamonds

Diamonds from Juina area have been investigated over two decades due to the abundant occurrence of inclusions formed at depths ranging from the Upper Mantle to the Lower Mantle. It is undoubtedly the best representative occurrence to study the mineralogy of the deep mantle. Juina diamonds have both the largest variety and amount of super-deep inclusions reported so far.

Although diamond occurrences are confined to a restricted area in Juina, there are differences amongst their populations regarding inclusion compositions and $\delta^{13}C$ range. The diamonds occur in several kimberlite pipes (Fig. 2), paleoplacers and recent alluvial deposits.

Mineral assemblages included in Juina diamonds are assigned to depths comprising the entire range from the Upper Mantle to Lower Mantle. Most common super-deep inclusions are lower-pressure representatives of former majorite, ferropericlase (fper), Ca-Ti-perovskite (CaTiPvk), Ca-perovskite (CaSiPvk), Mg-perovskite (MgSiPvk), olivine, Ca-Mg-carbonate and tetragonal-almandine-pyrope phase (TAPP) found both in alluvial diamonds (Wilding et al. 1991, Harte and Harris 1994, Harte et al. 1994, Hall et al. 1994, Hutchison et al. 1999, Kaminsky et al. 2001, 2009a, Hayman et al. 2005) and diamond from kimberlites (Walter et al. 2008, Kaminsky et al. 2009a, Bulanova et al. 2010). In addition, Collier-4 diamonds also present composite inclusions formed of CaAlSi-phase and kyanite, which was interpreted as the CAS-phase stable in the Lower Mantle (Calcium Aluminum Silica phase). An inclusion of “K-feldspar” in a Collier-4 diamond was suggested to correspond to K-hollandite, a synthetic KAlSi-phase stable in the conditions of the Lower Mantle (Bulanova et al., 2010).

Another important signature of super-deep diamonds is carbon isotope composition. $\delta^{13}C$ composition for diamonds from kimberlites and alluvial deposits are presented in Fig. 5. Alluvial diamonds show striking similar $\delta^{13}C$ range (-13.2 to -2.5‰) compared to those for diamonds from Aripuanã-1 pipe and the postulated Pandrea cluster (from -13.2 to -2.7‰). The diamonds from Juina-5 and Collier-4 pipes, however, have a very distinctive $\delta^{13}C$ range, varying from -27 to -1‰, and show no particular mode. The differences of mineral assemblages included in diamonds from the Juina area and their $\delta^{13}C$ range suggests the existence of kimberlites with different diamond populations.

A mantle plume is largely accepted as the mechanism to transport Juina diamonds from the Lower Mantle to the base of the lithosphere (Hutchison et al. 1999, Bulanova et al. 2010). The Juina kimberlite magmatism has been attributed to the passage of the Trindade mantle plume (Gibson et al. 1997), which is also a possible candidate to transport the super-deep diamonds (Kaminsky et al. 2009a, Bulanova et al. 2010).

CONCLUSIONS

Diamonds from the Juina Kimberlite Field are the best representatives of super-deep diamonds worldwide. The Juina-5 super-deep diamonds are distinctive due to the Na-K- Al – Si- rich composition of their inclusions, which are in accordance with chemistry of a basaltic component of a subducted plate descending into the Lower Mantle. Moreover, most of Juina-5 diamonds containing these inclusions have light carbon isotope composition, extending the previous range of $\delta^{13}C$ of the Lower Mantle to values down to -27‰. This is the first petrological evidence that the basaltic component of a subducted plate enters the Lower Mantle and preserves recycled crustal carbon.

A compilation of the data reported for Juina field diamonds suggests the occurrence of different diamond populations, probably reflecting different portions of preserved parts of the exhumed deep mantle.

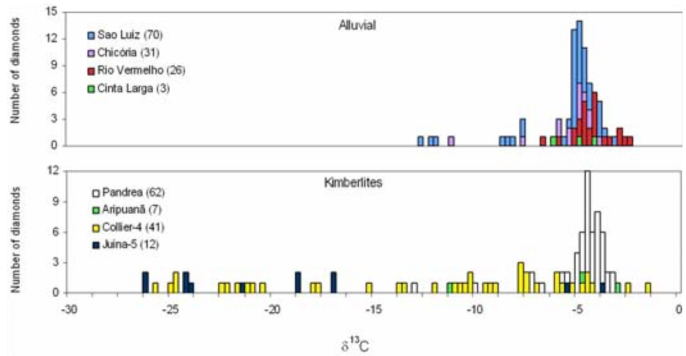

Fig. 5 – Carbon isotope composition of diamonds from alluvial deposits (top) and kimberlites in Juina Kimberlite Field. São Luiz (Hutchison 1999, Kaminsky et al. 2001, this work); Chicória, Rio Vermelho, Pandrea, Aripuanã-1 (Kaminsky et al. 2001, 2009a), Cinta Larga, Juina-5 (this work), Collier-4 (Kaminsky et al. 2009a, Bulanova et al. 2010, this work). Number in parenthesis are number of stones analysed.

Acknowledgements

We thank Rio Tinto Desenvolvimentos Minerais for providing samples, This research was partly funded by CNPq (Conselho Nacional de Desenvolvimento Cientifico e Tecnológico).

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