Diamonds from the Machado River alluvial deposit, Rondônia, Brazil, derived from both lithospheric and sublithospheric mantle

A.D. Burnham [a,*], G.P. Bulanova [a], C.B. Smith [a], S.C. Whitehead [a], S.C. Kohn [a], L. Gobbo [b], M.J. Walter [a]

[a] School of Earth Sciences, University of Bristol, Wills Memorial Building, BS8 1RJ, United Kingdom
[b] Rio Tinto Desenvolvimentos Minerais Ltda., Brasília, Brazil

ABSTRACT

Diamonds from the Machado River alluvial deposit have been characterised on the basis of external morphology, internal textures, carbon isotopic composition, nitrogen concentration and aggregation state and mineral inclusion chemistry. Variations in morphology and features of abrasion suggest some diamonds have been derived directly from local kimberlites, whereas others have been through extensive sedimentary recycling. On the basis of mineral inclusion compositions, both lithospheric and sublithospheric diamonds are present at the deposit. The lithospheric diamonds have clear layer-by-layer octahedral and/or cuboid internal growth zonation, contain measurable nitrogen and indicate a heterogeneous lithospheric mantle beneath the region. The sublithospheric diamonds show a lack of regular sharp zonation, do not contain detectable nitrogen, are isotopically heavy ($\delta^{13}C_{PDB}$ predominantly -0.7 to -5.5) and contain inclusions of ferropericlase, former bridgmanite, majoritic garnet and former $CaSiO_3$-perovskite. This suggests source lithologies that are Mg- and Ca-rich, probably including carbonates and serpentinites, subducted to lower mantle depths. The studied suite of sublithospheric diamonds has many similarities to the alluvial diamonds from Kankan, Guinea, but has more extreme variations in mineral inclusion chemistry. Of all superdeep diamond suites yet discovered, Machado River represents an end-member in terms of either the compositional range of materials being subducted to Transition Zone and lower mantle or the process by which materials are transferred from the subducted slab to the diamond-forming region.

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1. Introduction

Although the vast majority of the world's diamonds are characterised by being inclusion-free (96%–99%), and ~28% of inclusions are trace element-poor olivines and chrome spinels (Stachel and Harris, 2008), they have continued to draw keen interest from petrologists and geochemists. While diamonds undoubtedly offer a selective view of the deep Earth, in particular of the highly depleted Archaean cratonic mantle (Stachel and Harris, 2008), the fidelity with which the chemistry of inclusions is preserved makes them a valuable scientific resource. Around 5%–10% of diamonds are derived from beneath the base of the lithosphere (i.e. sublithospheric, or "superdeep") and are direct evidence of the mixing and recycling processes that lead to mantle-derived lavas with diverse isotopic and elemental characteristics (e.g. Pietruszka et al., 2013).

The minerals that are included in these superdeep diamonds may only represent a single fragment of a single geological event in a rock's life cycle, but this information is essential for reconstructing the geological history of subducted material. Variations in the characteristics of diamonds and their inclusions within and between localities testify about the spatial and/or temporal variability of the source region: they reveal, for example, the presence of multiple lithologies and a wide range of carbon isotopes in the Transition Zone and lower mantle (e.g. Harte, 2010; Stachel, 2001). A combination of results obtained from superdeep diamond studies and experiments constrains the extent to which C might be recycled into the lower mantle (e.g. Thomson et al., 2016). Additional well-characterised suites of superdeep diamonds are essential to establishing both the average and the range of lithologies present in the deep mantle.

The Juina region in Mato Grosso State, Brazil, has been studied extensively because of the high abundance of sublithospheric diamonds there, both in kimberlite pipes (e.g. Bulanova et al., 2010; Kaminsky et al., 2009; Thomson et al., 2014a) and in alluvial deposits (e.g. Harte et al., 1999b; Hayman et al., 2005; Kaminsky et al., 2001; Zedgenizov et al., 2014a). These extraordinary diamonds have a wide range of carbon isotopic compositions, $-28.3‰$ to $+0.4‰$, and contain a variety of mineral inclusions, often rich in incompatible elements (e.g. the rare earth elements (REE), Ti, Zr, Na and K). Many of these diamonds appear to have formed by redox freezing of a slab-derived carbonatite melt as it percolated into the highly reduced deep mantle (Bulanova

et al., 2010; Burnham et al., 2015; Thomson et al., 2016, 2016-in this issue; Walter et al., 2008; Walter et al., 2011). The kimberlites of the Juina region were emplaced at ~92–95 Ma (Heaman et al., 1998).

The Machado River alluvial diamond deposit, situated in Rondônia State, Brazil, lies approximately 250 km west of the Juina region (Fig. 1). Numerous kimberlites with Triassic ages are situated upstream of the deposit (Masun and Scott Smith, 2008), as is the Cretaceous Parecis Formation, which consists of diamondiferous sandstones and conglomerates. The Machado River deposit has previously been described as containing both lithospheric and superdeep diamonds (Bulanova et al., 2008). Further investigation has confirmed this view. Here, we present our extended data set on the external and internal morphology, mineralogy and geochemistry of Machado River diamonds, including the remarkable superdeep population, and suggest a model for their formation. We also discuss the heterogeneous nature of the Machado River diamonds and their possible primary sources.

2. Methods

Diamonds were examined under a binocular microscope to observe morphological features (size, colour, shape and surface textures); of these, 45 stones were selected for further study and prepared for analysis by polishing along the dodecahedral plane on a diamond-impregnated steel scaife. Diamonds and their inclusions were studied by cathodoluminescence (CL) and in backscattered electron mode using a Hitachi S-3500N scanning electron microscope. Energy-dispersive spectroscopy (EDS) allowed preliminary estimates of mineral compositions.

Wavelength dispersive electron probe microanalysis (EPMA) of the inclusions was performed using a Cameca SX-100 electron probe at the University of Bristol. Calibration standards were a mixture of natural minerals and synthetic oxides and metals, and the data were processed using the PAP matrix correction.

Secondary ion mass spectrometry (SIMS) analysis of trace elements in the inclusions was performed at the Edinburgh Ion Microprobe Facility (EIMF) using the ims-4f ion probe by the method described in Bulanova et al. (2010), with additional analysis of Co, Ni, Cu, Zn and Ga at high mass resolution using the Cameca 1270 ion probe. Si was used as the internal standard for all minerals except ferropericlase (Mg). Secondary standards were used to validate interference corrections. No secondary standard was available for ferropericlase and the results are likely to have larger errors.

Laser ablation inductively coupled mass spectrometry (LA-ICP-MS) of one inclusion was performed using a 193 nm excimer laser and a HelEx ablation cell coupled to an Agilent 7700 mass spectrometer with He as the carrier gas. A background was collected for 20 s followed by a usable ablation period of 30 s. The isotopes measured were ^{7}Li, ^{23}Na, ^{25}Mg, ^{27}Al, ^{29}Si, ^{31}P, ^{39}K, ^{43}Ca, ^{45}Sc, ^{47}Ti, ^{75}As, ^{85}Rb, ^{88}Sr, ^{89}Y, ^{90}Zr, ^{93}Nb, ^{133}Cs, ^{137}Ba, ^{139}La, ^{140}Ce, ^{141}Pr, ^{146}Nd, ^{147}Sm, ^{153}Eu, ^{157}Gd, ^{159}Tb, ^{163}Dy, ^{165}Ho, ^{166}Er, ^{169}Tm, ^{172}Yb, ^{175}Lu, ^{178}Hf, ^{181}Ta, ^{232}Th and ^{238}U. NIST610 glass was used as an external standard before and after the analyses, and Si (determined by EPMA) was used as the internal standard.

Carbon isotope ratios were measured using two instruments: (1) a Cameca 1270 ion probe at EIMF following the method described in Burnham et al. (2015); (2) the SHRIMP SI at the Australian National University with a beam current of 15 nA, analytical spot size of ~30 μm diameter and calibrating relative to a selection of standards. Diamond P28 was analysed using both instruments to ensure inter-comparability of the two data sets. Carbon isotopic compositions were found to differ systematically depending on the standard used.
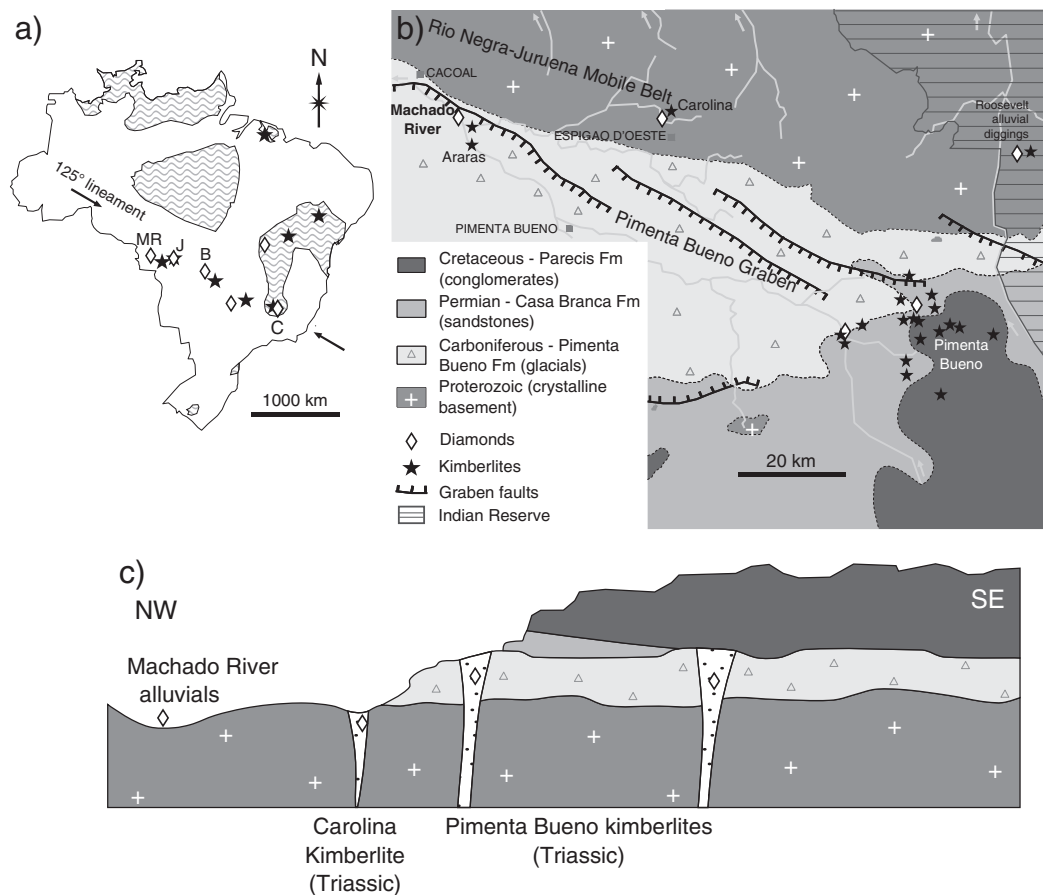

Fig. 1. (a) Map of Brazil showing cratonic (Transamazonian, i.e. >2 Ga) areas (wavy lines) and selected kimberlite and diamond occurrences (B, Batovi; C, Coromandel; J, Juina-5; MR, Machado River); (b) simplified geological map of the source region for the samples and (c) schematic cross-section.