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In-situ analysis of diamonds and their inclusions from the Diavik Mine, Northwest Territories, Canada: Mapping diamond growth

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ABSTRACT

Results are presented here of an in-situ study of diamonds from the A154 South kimberlite pipe at the Diavik diamond mine, Northwest Territories, Canada. One hundred and ten diamonds were selected from run of mine production on the basis of morphology and visible inclusions. Diamonds that crystallized as cubes have a higher incidence of fluorescence in response to UV light than those that have crystallized in the octahedral primary form. Fifty-one diamonds were cut and polished to expose included mineral grains and to allow for imaging of internal structure. Mineral inclusions were analysed in-situ for major element composition using electron microbeam methods. Internal zonation of the diamonds was imaged using cathodoluminescence in thirteen P-type diamonds, two U-type diamonds, nine E-type diamonds, and two diamonds with only sulfide inclusions of indeterminate paragenesis. Inclusions of $Fe \pm Cu \pm Ni$ sulfide, magnesian chromite, ferropericlase, chromian diopside, forsteritic olivine, omphacite, and enstatite occur in order from most to least abundant. The chromite inclusions are lower in Mg than the worldwide average. At least six of the sulfide inclusions are significantly heterogeneous. Equilibration temperature and pressure conditions for the diopside inclusions indicate that the diamonds equilibrated in a region of geothermal gradient with an equivalent surface heat flow of 42 mW/m^2 over a range from 51–57 kbar and 1170–1260 °C.

1. Introduction

Protogenetic and syngenetic diamond inclusions provide the only reliable source of mantle material that has remained unaltered since encapsulation. The two most common parageneses for diamond are P-type (peridotitic) and E-type (eclogitic) (see Meyer, 1987). A rarer third class, U-type (ultra-deep), also occurs (see Stachel et al., 2005). Though studying mineral inclusions in diamond has led to a number of findings regarding the nature of the mantle in various North American localities (e.g. Davies et al., 2004; Donnelly et al., 2007; Schulze et al., 2008), understanding of the formation of diamond and the factors that affect it in the mantle remains incomplete. Many diamonds have been found to be Archean in age (e.g. Richardson et al., 1993; Pearson and Shirey, 1999). This means that there has been a large window of time for many diamonds to be subject to a variety of mantle processes (e.g. growth, resorption, deformation, etc.) prior to their ascent in commonly much younger kimberlites. However, limitations of established diamond research methods have resulted in an incomplete understanding of the factors and mechanisms affecting growth and subsequent evolution of diamonds and their mineral inclusions.

Many previous studies have focused on breaking/fragmenting/combusting the host diamond to liberate the included minerals for analysis (e.g. Jaques et al., 1989; Wang, 1998; Tappert et al., 2005a,b; Donnelly et al., 2007). Analysis of the properties of the diamond typically utilizes just a few fragments of the stone. The main benefit to this mode of study is a large number of samples can be processed efficiently and rapidly. Another advantage is that most of the inclusions greater than ~30–50 μm in size can be liberated. The disadvantages lie in that much of the contextual information regarding the data is lost and possible heterogeneity in the diamond is difficult to evaluate based on analysis of a few fragments. This method also has serious drawbacks when used on diamonds with mineral inclusions of different parageneses (e.g. Wang, 1998; Tappert et al., 2005a), as the spatial relationships between the mineral grains themselves and the different growth zones of the host diamond are lost upon crushing.

An alternative method that seeks to overcome the limitations of the fragmentation method is cutting/polishing diamonds to expose mineral inclusions and analyzing the phases in-situ (for details, see sections 2 and 3). Imaging the internal growth structure of the diamonds and noting the relative positions of the inclusions allows for better interpretation of the data gained. The data can be obtained using microbeam methods for point analysis (e.g. SIMS, EMPA). This overcomes the problems of diamond heterogeneity and loss of spatial context (e.g. Klein-BenDavid et al., 2004; Schulze et al., 2004; Janson et al., 2008, abs. 295). A second benefit to these methods is that very small mineral inclusions (i.e. <10 μm) can be found and analyzed if exposed on the working surface.

In this study, we present the initial findings from an in-situ study of one hundred ten macrodiamonds from the 55–56 Ma A154 South kimberlite pipe, Northwest Territories, Canada (Graham et al., 1999).

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Diamonds from this pipe have previously been studied by Davies et al. (2004) and Donnelly et al. (2007) primarily by fragmenting the diamonds to retrieve mineral inclusions. The purpose of this study is to further our understanding of the mechanisms of the variety of events that affect diamonds during their formation and residence in the mantle. We also aim to define better the nature of the environment in which diamonds form. By correlating the characteristics of the mineral inclusions with those of the surrounding diamond using in-situ methods, we may understand better the history of events that affected the samples.

2. Samples

The one hundred ten diamonds were selected at the Harry Winston Diamond Corporation sorting office in Toronto, Ontario. All the samples are from the A154 South kimberlite pipe at the Diavik Diamond Mine. These diamonds do not represent a random statistical population of diamonds from Diavik, but they were selected on the basis of visible inclusions and interesting morphology. Cubes and cuboid shapes in particular were of interest as the Diavik population has a large percentage of cubes that are translucent–transparent ("gemmy"). More common black to grey to yellow coated cubes (e.g. Janson et al. this conference, abs. 295) occur as well. The samples range in size from approximately 0.5 mm to 4 mm.

Fifty-one of the one hundred ten diamonds have been cut and polished along a single plane to expose mineral inclusions and/or internal structure. Twenty-six of these have one or more primary mineral inclusions exposed by polishing that were large enough (>5 µm in diameter) to analyze by electron microprobe methods.

3. Methods

Diamonds were separated by hand and catalogued by colour, morphology, inclusions, size, and UV fluorescence (wavelength = 255 nm). The planes created by cutting and polishing the diamonds were imaged in reflected light and with BSE and SE methods using a Jeol scanning electron microscope. Mineral inclusions were initially identified using EDS spectra.

The internal structures of these diamonds were imaged using cathodoluminescence (CL) with a Vickers Instruments Nanolab LE2100 at the Royal Ontario Museum. The beam potential used was 15 kV at 0.272 nA with a working distance of 30.4 µm.

Mineral inclusions were quantitatively analysed with a Cameca SX-50 electron microprobe using WDS methods at the Duncan Derry Lab, University of Toronto. A 1 µm wide beam with an accelerating voltage of 20 kV and a beam current of 45 nA or 50 nA was used for sulfide, ferropericlase, olivine, and chromite inclusions. A 15 kV beam 1 µm wide at 30 nA was used for orthopyroxene and clinopyroxene inclusions, due to the higher concentrations of mobile elements (i.e. K, Na) in those minerals. Only analyses with totals of 100% ± 1.5 were accepted. An exception was made for sulfide analyses, with totals of 100% ± 2 were accepted due to the fine exsolution of different phases that made assumptions of stoichiometry difficult (see Section 7.5). For the silicate and oxide analyses, Fe is reported as $FeO_{(total)}$. For chromite, the FeO and Fe_2O_3 contents were calculated using ideal stoichiometry assuming Fe was the only element that occupies more than one site in spinel.

4. Morphology

Octahedral, cubic, and combined forms dominate the diamonds selected for this study (Fig. 1). Polycrystalline samples (boart) and fragments with no determinable habit are also present. The selection of the diamonds on the basis of morphology has skewed the population towards cubic and mixed growth forms.

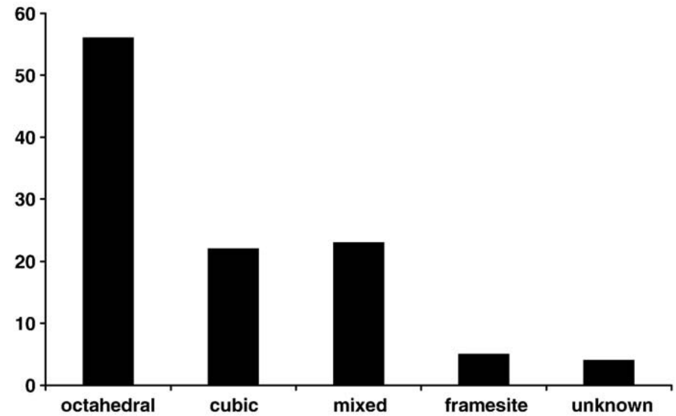

Fig. 1. Distribution of primary forms for the diamonds in this study. $n = 110$.

4.1. Octahedral forms

The sample population includes octahedra that span the continuum from sharp-edged unresorbed octahedra to trioctahedroida to tetrahexahedroida ("rounded dodecahedra") as described by Robinson (1979). Stepped growth indicated by triangular plates on the {111} faces are common. Negative trigons, elongate hillocks, terraces, knob-like asperities, shield laminae, and serrate laminae are common surface features (Fig. 2, *top row*). Six distorted octahedra are present, most of which have a brown, pink, or beige tint. One macle is present. Examples of two or three intergrown octahedra occur. Nine stones, classified as octahedra, have pseudo-skeletal, extremely stepped growth on the {111} faces, approximating cuboid or cubo-octahedral morphologies.

4.2. Cubic forms

Coated and gemmy cubes are present. Resorption ranges from comparatively unresorbed flat {100} surfaces to highly resorbed "hopper" shapes with concave {100} faces (e.g. Welbourn et al., 1988). Negative tetragons, pointed plates, crescentic steps, and chiastic patterns are common features on the resorbed cubes (Fig. 2, *bottom row*). Examples of two to four intergrown cubes occur.

4.3. Mixed Forms

Twelve stones, termed "naval mine" type, represent a resorbed subset of the mixed growth category (e.g. Zedgenizov and Harte, 2004) and have characteristics of tetrahexahedroida with stubby "arms" that terminate as unresorbed relict {111} faces (Fig. 3). Two of these have botryoidal textures on the surfaces between the arms. Cubic resorption features are present on some of these diamonds.

5. Internal structure

Polished planes of the diamonds were imaged using CL. Both simple and complex growth patterns are present (Fig. 4). The CL response of cubic diamonds is much lower than that of the octahedral diamonds. Neither raising the voltage of the beam to 30 kV, nor raising the beam current to maximum of 0.6 nA resulted in a stronger CL response for the cubic diamonds. Fibrous coatings on both cubes and octahedra have minimal CL response (e.g. Fig. 4: AB17). Chromite inclusions appear to be restricted to outer or intermediate zones of gem-quality diamonds. The diamond surrounding these inclusions tends to have a much brighter CL response than normal (e.g. Fig. 4: AB38a). Many of the unresorbed octahedra have complexly zoned cores with simpler growth zonation in the rims (e.g. Fig. 4: AB15b). Some trioctahedroida/tetrahexahedroida