The art and science of diamond analysis, and what the results can tell us

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Several nondestructive and destructive analytical methods are useful to characterize the physical properties of diamonds that influence their value, and to provide information that can be used to optimize their recovery in the mining and treatment processes. Geologically relevant information regarding the growth environment, mantle residence conditions, and effects of the host magma on the diamonds during transport to the surface of the Earth may also be revealed by such studies.

INTRODUCTION

The economic value of diamonds is based on size, colour, shape, and clarity; these attributes translate into the 4Cs that form the basis of polished diamond valuation. The profound effect of diamond size on value results in the need to extrapolate revenue predictions from parcels of mostly small diamonds recovered during the early stages of economic assessment of diamond deposits to the commercial sizes expected during mining. This process is fraught with complications and risk, as a single diamond population (among numerous populations present at a deposit) may be responsible for most of the revenue potential.

The inherently low diamond content of both primary and secondary diamond deposits complicates the technical aspects of diamond valuation, and hence any early indications of revenue potential are beneficial in assisting the economic evaluation process. The likely presence of large gem-quality diamonds or those with attractive colours is difficult to assess from small parcels. Equally, early indications of a more detrimental economic nature, *e.g.* a fine size frequency distribution or poor-quality diamonds, may lead to financial savings through prompt walk-away decisions or re-prioritization.

Depending on the aim of acquiring the diamond characterization information; whether for valuation, ore dressing/metallurgical purposes, or geological population discrimination; different analytical techniques may be used. However, simple observations when valuing diamonds may prove as useful as analytical methods that are time-consuming and/or dependent on expensive instruments. The characteristic colour and morphology of Type II diamonds from the Letšeng mine in Lesotho allowed Bowen *et al.* (2009) to achieve a 96% accurate identification of these high-value diamonds based on their visual characteristics. The use of different instruments and analytical techniques is thus often a matter of personal choice, time and cost constraints, experience, and access to equipment.

ROUGH DIAMOND VALUATION

Valuation of rough diamonds is highly subjective and is based on assumptions around what a buyer will be prepared to pay for the potential polished outcome from an uncut stone. Size, colour, shape, and clarity are the main factors influencing rough diamond value, but fashion trends in jewellery vary over time and have in some instances been influenced by diamond producers, for example by promotion of a particular colour of diamond described with appealing terminology such as 'cognac' or 'champagne'. Other factors, such as UV fluorescence, can affect the value (adversely in the case of colourless and pale-coloured diamonds with strong blue fluorescence, and positively in the case of fancy coloured diamonds with unusual fluorescence).

Proprietary instruments are used for automated sorting of uncut diamonds for size, colour, shape, and clarity at facilities such as the Diamond Trading Company Botswana (DTCB), which has the capacity to sort 45 million carats annually. Diamonds may also be graded for colour against a set of master stones, although colorimeters have been commercially available to assist in colour determination since the 1970s. Instruments such as those produced by Zvi Yehuda Ltd. are now also capable of indicating UV fluorescence colours, Type IIa diamonds, and whether a diamond is suitable for high-pressure high-temperature (HPHT) treatment to improve the colour. Sophisticated diamond imaging technology has been available for the last 30 years and continues to evolve (*e.g.*, Sarine Loupe™), providing diamantaires with greater confidence in their value assessments based on diamond shape and clarity. Since the advent of advanced treatments to enhance the colour of diamonds and the ability to produce gem-quality synthetic diamonds, numerous instruments have been developed to verify the characteristics of diamonds in their natural and untreated state (Welbourn, Cooper, and Spear, 1996), including instruments adapted to analyse diamonds while still mounted in jewellery (IIDGR, 2017).

DIAMOND RECOVERY

In order to maximize diamond value returns from the processing plant, a sound technical understanding is required of liberation efficiency, top and bottom cut-off sizes, recovery efficiency for all unit processes, as well as the impact of diamond damage across the complete flow sheet. As each diamond deposit is unique, many additional factors, such as the size of the deposit, grade, diamond size frequency distribution and potential for large stones, nature of the host kimberlite (hardness, density, dilution *etc.*) must also be taken into account to optimize economic diamond recovery. The optimal solution for one deposit may not be appropriate for another. Many hard-rock deposits contain multiple kimberlite facies with very different physical properties, requiring compromises or flexibility in plant design. Recent years have seen the introduction of sensor-based X-ray transmission instruments in diamond recovery to simplify processes and enhance the recovery of large stones (*e.g.*, van Niekerk *et al.*, 2016; Armstrong, 2017).

GEOLOGICAL INFORMATION: DIAMOND STUDIES, AND RECENT ADVANCES

Geologists are involved in the diamond pipeline from early exploration to providing input as mine geologists and mineral resource evaluators. Geological studies of diamonds have provided information that has been used to refine prospecting methods. Academic studies of mineral inclusions in diamonds (*e.g.*, Stachel and Harris, 2008 and references therein) have increased our understanding of diamonds and the geological processes that led to their presence in kimberlite, lamproite, and related rocks. Radiometric dating of silicate inclusion composites (*e.g.*, Richardson *et al.*, 1984) confirmed the xenocrystic relationship of diamonds to their host magmas and the considerable age difference between most diamonds and their host rocks. Dating of smaller numbers of sulphide inclusions has improved our understanding of the timing of, and triggers for, diamond-forming events, as has more recent dating of individual silicate inclusions rather than composites made up from large numbers of inclusions (Koornneef *et al.*, 2017; Timmerman *et al.*, 2017).

Nondestructive Raman analyses are now routinely used to identify inclusions, and have also indicated the presence of previously unrecognized fluid rims around most inclusions in gem-quality diamonds (Nimis *et al*., 2016). The study of fluids and their role in diamond formation is now not limited to only fibrous and/or coated diamonds, and it has been found that carbonate-bearing high-density fluids are involved in the growth of monocrystalline gem or near-gem diamonds, in addition to fibrous and/or coated diamonds (Jablon and Navon, 2016). Redox reactions have proven not to be viable for significant diamond formation in harzburgitic substrates (Luth and Stachel, 2014), necessitating diamond formation from water-rich fluids (Stachel, Chacko, and Luth, 2017) as proposed by Huizenga, Crossingham, and Viljoen (2012).

Using equations of state, shifts of Raman inclusion peaks as a function of pressure, and X-ray diffraction (XRD) measurements of diamond-hosted inclusions at ambient conditions, calculations for the pressure of formation of diamonds can be made assuming perfectly elastic behaviour of the host diamond (*e.g.*, Angel *et al*., 2015). Pressures of formation have been particularly poorly constrained for diamonds of eclogitic paragenesis because of thermodynamic and other limitations in applying geothermobarometric calculations to eclogitic compositions. The increase in the number of Raman and XRD analyses has helped in the identification of sublithospheric inclusions from the transition zone and lower mantle. Smith *et al*. (2016) have convincingly shown that the rare inclusions present in large, high-value Type II diamonds are dominated by metallic compositions, majoritic garnets and former calcium silicate perovskite inclusions, indicative of a sublithospheric origin for these extremely valuable diamonds.

Diamond Population Studies

Many academic studies of diamonds have been biased towards inclusion-bearing diamonds because of the inherent geological context provided by the inclusions. However, a recent study of representative diamonds from samples with excellent geological control from Orapa mine (Chinn *et al*., 2017) has shown that inclusion-bearing diamonds may not represent all the different diamond populations present at a given occurrence. Although diamonds represent some of the deepest and oldest geological samples on the planet, care should be taken when extrapolating findings from restricted samples to model global geological processes.

Characterization of diamonds according to colour, morphology, and surface features (*e.g*. deformation and etch features) using a stereomicroscope provides a framework for understanding the sequence of events that contributed to the ultimate physical appearance of a diamond (Robinson *et al*., 1989). Desktop scanning electron microscopy (SEM) makes it possible to characterize etch features in the detail necessary to interpret their formation conditions. Etch features can be ascribed to mantle or kimberlitic processes, and information can be obtained regarding the presence and composition of fluid species, temperature, and pressure during the resorption/etching event (Fedortchouk and Zhang, 2011; Zhang *et al*., 2015). Such studies are particularly relevant for refining models of kimberlite eruption processes, but require stringent sample control of the studied diamonds to allow for integrated petrographic studies of the different kimberlite facies that host the diamonds (Fedortchouk, Chinn, and Kopylova, 2017).

Fourier transform infrared (FTIR) spectroscopy is a nondestructive analytical technique used to identify nitrogen-free Type II diamonds. Type IIa diamonds have become the subject of increased academic and commercial interest owing to the high dollar per carat value realized for pink and colourless Type IIa diamonds and blue Type IIb diamonds. Because the nature (aggregation state) of nitrogen defects in Type I diamonds is dependent on temperature and time, which are variables of interest to geologists, FTIR characterization of diamonds has become routine. Complementary information is provided from cathodoluminescence images of polished diamond plates, which reveal growth zonation patterns. Carbon and nitrogen stable isotopic analyses using secondary ion mass spectroscopy (SIMS) on polished plates reveal complex changes in isotopic ratios in many diamonds, related to multistage growth. The isotopic fractionation trends in discrete growth zones can be compared with predicted trends for different fluid compositions. Temperature estimates from geothermobarometric calculations using xenocrysts and/or diamond inclusions are compared with temperature constraints from nitrogen aggregation systematics. Radiogenic ages from diamond inclusions allow for the findings to be interpreted with respect to the composition and age of the diamond-forming substrate, refining our models for diamond genesis within a global framework. However, a comprehensive understanding of diamond formation, mantle residence, and transport to the surface of the Earth will be obtained only through time-consuming, detailed research, often requiring many analytical techniques, most of which require polishing of diamond plates and dissolution of inclusions for radiometric dating.

CONCLUSIONS

Advances in analytical technology have not bypassed the diamond industry, with new or improved instruments available to aid in repeatable analysis of the physical characteristics of diamonds that control their value and provide information useful for optimizing their recovery. Increased understanding of the geological controls on diamond formation and destruction have implications for diamond exploration, and has been provided by dating of individual silicate inclusions, as opposed to composites that appear to have comprised more than one genetic population and hence yielded average ages.

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