ARTICLE

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Assessing the diamond potential of kimberlites from discovery to evaluation bulk sampling

Abstract The economic evaluation of diamond-bearing kimberlites is usually carried out in four stages. Expenditure tends to increase by an order of magnitude at each successive stage. At the end of each stage, the sample results should be critically appraised before deciding to proceed to the next phase. In the first stage, even before individual kimberlite bodies have been discovered, the indicator mineral geochemistry will give a first rough idea of the diamond potential. The relative abundance of harzburgitic pyropes (subcalcic chrome-rich) is often directly correlated with the diamond grade. In the next stage, when the kimberlite body has been discovered, a relatively small sample of a few hundred kilograms will be enough to recover sufficient microdiamonds to allow an extrapolation of the size distribution towards the commercial-sized diamonds and a rough estimate of their grade. If positive, the third stage should be a limited bulk sampling programme (order of 200 tonnes) to determine the commercial-sized diamond grade, expressed as carats per tonne. The aim of the final stage is to obtain a parcel of the order of 1,000 carats to estimate the average commercial value of the diamonds. The robustness and reliability of the grade and value estimates can be verified with extreme value analysis and by obtaining the confidence limits with bootstrapping.

Keywords Diamond · Evaluation · Extreme value analysis · Microdiamond · Size distribution

The economic context

The value of rough uncut natural diamond production is of the order of US$7 billion per year. With existing mines continuously being depleted, the incentive for finding new diamond deposits is strong. In recent years, between US$350 to 500 million is spent annually on diamond exploration worldwide. Mining or exploration companies often spend US$1 to 10 million each on specific projects. The main diamond exploration target is kimberlite. As a rough appreciation, one could state that, worldwide, only 10% of the kimberlites are diamond-bearing and only 1% contain diamonds in economic quantities. Kimberlite provinces may contain 100 bodies within a 30×30-km area, with only a few of them having economic diamond grades. The cost of testing the diamond content of kimberlites may run into the millions of dollars. With so many potential targets to test, it is imperative to find efficient means to discriminate as early as possible between barren or poor-grade kimberlites and kimberlites with true diamond potential. This note discusses the optimal techniques to assess the diamond potential at each stage in the evaluation process and to prioritize kimberlite targets for further costly testing. The discussion on the evaluation techniques is valid for any volcanic source rock of diamonds. While for convenience the term 'kimberlite' is used, the techniques are equally applicable to lamproites and other lamprophyric diamond-bearing rocks.

Exploration stage: the use of indicator mineral chemistry

Kimberlite is the dominant primary source rock of diamonds at the Earth's surface. Diamonds are formed at depths of more than 150 km (more than 50 kbar lithostatic pressure) in a relatively cool environment (950 to 1,250 °C). The Earth's mantle at depths of 150 km or more is, however, in most places too hot to have diamonds crystallized out from carbon. Temperatures above 1,250 °C at 150 km result in graphite being formed. The Archean cratons, not disturbed since 2.5 billion years by any major thermal–tectonic event, have deep and cool lithospheric keels surrounded and underlain at depth by the hotter asthenosphere. The

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Archean cratons tend, therefore, to have low geothermal gradients, resulting in the right pressure and temperature conditions for diamond formation at depths of 150 km or more. Kimberlite volcanism, originating from the base of the lithosphere, can bring the diamonds in a sudden explosive event to the surface. Kimberlite volcanism is a rare event, seemingly restricted to well-defined time periods. An important worldwide event occurred for instance about 1,100 million years ago (Premier in South Africa, Madhya and Andra Pradesh kimberlites in India, Mali, Argyle lamproite in Australia); another example are the Cretaceous kimberlites of West Africa, Southern Africa and Central Africa.

The kimberlite event may be related to plumes rising from great depths in the lower mantle into the base of the lithosphere. Highly volatile magmas are generated, and the resulting kimberlite volcanism brings not only diamonds, but many other, much more common minerals from great depths to the surface. At depths of 150 km, the mantle, or base of the lithosphere, is mainly composed of lherzolite, a rock containing olivine, clinopyroxene and orthopyroxene. CO_2, H_2O and other volatiles, generated at greater depths and rising through the base of the lithosphere, react with the lherzolite, depleting it in calcium. The resulting metasomatized lherzolite has a harzburgite composition, containing mainly olivine and orthopyroxenes. A common accessory mineral of both lherzolite and harzburgite is pyrope garnet. Pyropes, being much more abundant than diamonds, are more easy to recognize in stream sediments and other erosion products of kimberlites. The sampling of sediments for pyrope garnets, therefore, is an efficient exploration tool for kimberlites. The peridotitic mantle pyropes are rich in chrome and magnesium. The

harzburgitic pyropes are, just as their harzburgite mother rock, depleted in calcium, relative to the lherzolitic pyropes (Sobolev 1977). The lherzolitic pyropes show a positive correlation between their chrome and calcium content: both element abundances increasing with depth (Gurney 1984). Other useful indicator minerals of kimberlite are eclogitic garnets with Na_2O contents higher than 0.06 wt% (Gurney 1984), magnesium-rich ilmenite, chrome-diopside and chromite. The chemical composition of the indicator minerals can be used as an early evaluation tool of the diamond potential of kimberlites, even before they are actually discovered.

Sobolev (1977) in Russia, and Gurney (1984) in Southern Africa, found a positive correlation between the relative abundance of harzburgitic pyropes in kimberlites and their diamond content. The following formula can be derived from Gurney's observation that 85% of the pyrope inclusions in diamonds have a chrome-content greater than:

$$Cr_2O_3 = -11.637 + 3.606 \ CaO$$

This linear function, displayed on a Cr_2O_3 versus CaO scatter plot (Fig. 1), is used by Gurney to separate harzburgitic (chrome-rich, calcium-poor with good diamond potential) from lherzolitic garnets. If the Cr_2O_3 content is less than 0.05 wt% and the CaO content less than 3.5 wt%, the garnets are not of mantle origin, but crustal, and of no relevance to diamonds.

Apart from lherzolite and harzburgite, also eclogite is a common rock type at the base of the lithosphere. Eclogite, composed of clinopyroxene and pyrope–almandine garnets, is a possible source rock for diamonds, which can be sampled by the ascending

Fig. 1 The relative abundance of harzburgitic garnets compared with lherzolitic garnets for a kimberlite in Angola with a diamond grade of 0.12 carats/ t, as discernible on a Cr_2O_3 versus CaO plot for peridotitic garnets
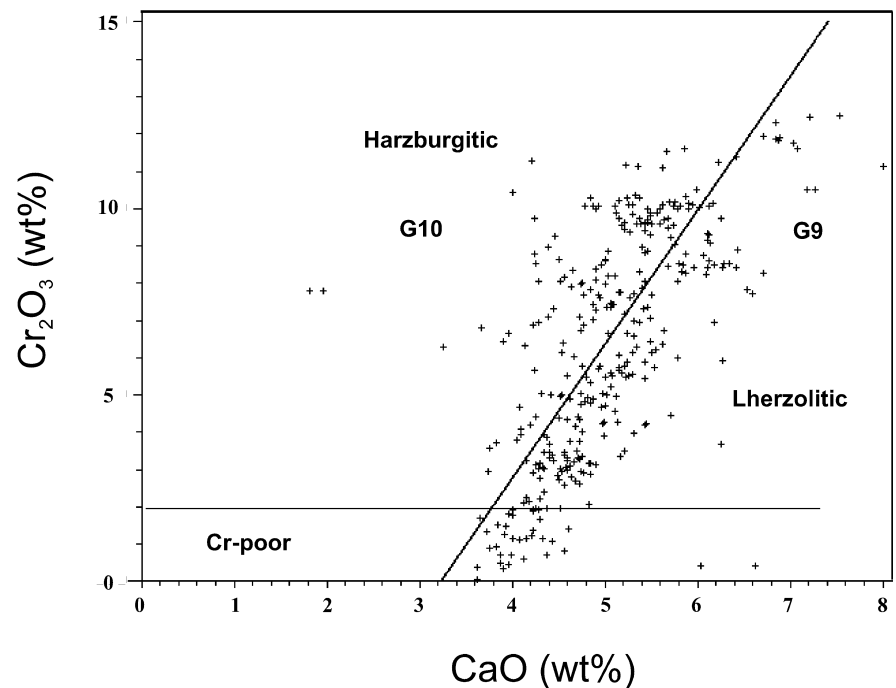
kimberlite magma. Eclogitic garnets with a Na_2O content greater than 0.06 wt% are considered good indicators for eclogitic diamonds (Gurney 1984). The high sodium content in garnet is considered to indicate equilibration at pressures high enough to be compatible with the presence of diamond.

Alternative indicators for the diamond potential of a kimberlite or a lamproite are magnesium-rich chromites. Chromites with a Cr_2O_3 content in the 58–70 wt% range, TiO_2 below 0.6 wt% and MgO in the 11–17.5 wt% range are common as inclusions in diamonds (Meyer and Boyd 1972; Sobolev 1977; Daniels 1991).

During the ascent of the kimberlite magma to the surface, diamonds are transiting during a short period of time in an oxidizing environment at lower pressure and temperature, and may become resorbed. The oxidation state of the kimberlite magma is reflected by the composition of ilmenite. Ilmenite with MgO content below 5 wt% indicates a highly oxidizing environment with no preservation of diamonds. Ilmenite with MgO content higher than 12 wt% on the other hand indicates excellent diamond preservation conditions.

The chemical analyses required on the indicator minerals can be done by electron microprobe. Therefore, they are a cheap (order of US$10 per grain) and quick method to assess the diamond potential of a kimberlite at an early stage during exploration. Griffin et al. (1989) developed a new technique based on the nickel content of the peridotitic garnets to assess the diamond potential of kimberlites and lamproites. Determination of the nickel content in garnets requires the use of a proton microprobe. Only few proton microprobes are geared for this type of analysis, and the nickel technique, therefore, is more costly and less practical. A recent and exhaustive review on the use of indicator mineral geochemistry in diamond exploration is given by Fipke et al. (1995).

Discovery stage: the use of microdiamonds

The chemical composition of the indicator minerals, which led to the discovery of a kimberlite body, can give a qualitative idea of the diamond potential. The method, however, is not without exceptions. Attempts have been made to make even rather precise predictions on the diamond grade based on the chemistry of the indicator minerals. The latter, however, can never quantify the degree of dilution by country rock fragments, a major factor in grade variations within a kimberlite body. For instance, it is not uncommon for a kimberlite pipe to have a diamond grade of 0.2 carats/tonne (t) in the tuffs of the crater facies, 0.8 carats/t in the diatreme breccia and 1.5 carats/t in the underlying hypabyssal kimberlite. The different facies may have a similar indicator mineral geochemistry, but with diamond grade variation largely influenced by the mechanics of kimberlite explosion and degree of mixing with barren country rock fragments. Therefore, the

indicator mineral geochemistry should be combined with a parameter directly related to the amount of country rock dilution in the crater or diatreme. A useful indicator of dilution is the magnesium and chromium content of the kimberlite, which should normally be directly correlated with the pure kimberlite component of the rock.

Commercial-sized uncut diamonds for the gem industry are larger than 1 mm. Smaller diamonds cannot be cut and polished at a profit. Some Russian mines recover finer diamonds, down to 0.4 mm, to be used for industrial purposes as diamond powder. Many mines recover diamonds only down to 1.5 mm, as the value content of the smaller diamonds is negligible. Kimberlite bodies with economic grades have commercial stone densities in the range of 1 to 100 stones per tonne. Assessing the grade of commercial-sized diamonds, therefore, requires large samples. Typically, a bulk sampling programme costs several US$ 100,000, if not several US$ millions. Before embarking on this costly exercise, the microdiamond content of smaller samples (on the order of a few hundred kilograms) may give a semiquantitative indication of the commercial-sized diamond grade. Microdiamond analysis allows targets to be prioritized for bulk sampling and is an important argument in justifying continuing expenditure on evaluation sampling.

By dissolving the kimberlite rock in hydrofluoric acid or by caustic fusion, the microdiamonds are liberated. Microdiamonds are usually recovered down to 0.1 mm (Fig. 2). The frequency of the microdiamonds increases exponentially with decreasing size. The microdiamond stone density in economic kimberlite bodies is often in the range of 1 to 10 stones per kg. Samples of a few tens of kilograms, taken in a spatially representative way from the kimberlite, combining to a total sample size of several 100 kg, may yield enough microdiamonds and diamonds in the range 0.1 to 2 mm to allow a reliable extrapolation of the size distribution of the microdiamonds and to roughly estimate the grade of the commercial-sized diamonds.
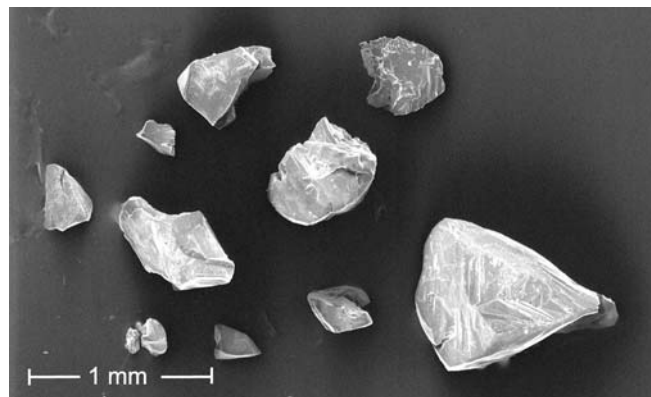

Fig. 2 A set of microdiamonds from the Theunissen kimberlite dyke, South Africa

Microdiamond recovery techniques

The most common technique for recovering microdiamonds is by caustic fusion of the kimberlite core or rock samples, as for instance used by Lakefield Research of Canada, a commercial laboratory. Sample bags with kimberlite rock pieces, not exceeding 10 cm in dimension, possibly weighing 5 to 10 kg, are put, without any further handling except weighing, together with NaOH granules into a kiln, and heated overnight at 450 °C to dissolve the kimberlite rock by caustic fusion. If the rock is rich in carbonate, the kiln charge has to be reduced by half as the carbonate reacts vigorously with the caustic soda. The residue of the caustic fusion is cooled. After cooling, the residue passes over a 0.1-mm screen (if recovery is down to 0.1 mm) and is thoroughly cleaned with warm water for a day. The caustic soda remnants are further removed by adding a small amount of HCl, if necessary. The caustic fusion and the washing on the 0.1-mm screen usually reduces the original sample from say 10 kg to a few grams. The residue is dried in an oven at 110 °C on its 0.1-mm screen. After drying, the residue is screened at say 2 mm and the coarse fragments returned for inspection. If the kimberlite rock is rich in silica, the residue may contain large fragments (e.g. granite xenoliths). If the large fragments are indeed country rock xenoliths, they can be discarded. If they are silicified kimberlite (as occurs in hot climates), they may require a new caustic fusion attack.

A strong hand magnet can be used to separate the magnetic minerals from the dry residue. This should be done with great care to avoid the sticking of diamonds on magnetic minerals. After this first magnetic pass, the residue may pass through a magnetic separator, with magnetic separation set at 20,000 gauss. Both the magnetic and non-magnetic fractions are sent to the observation laboratory, where trained mineral observers pick out the microdiamonds. Sometimes clear spinels or zircons may resemble diamonds. If in doubt, the grain can be studied under a scanning electron microscope, where the diamond diagnosis is done by elimination (carbon is not directly measured, but the absence of Si, Al, Mg or other common elements, points to diamond). Each sample and fraction should at least be picked twice by two independent observers. The microdiamonds can be weighed if a high-precision balance is available (required precision is 0.0001 mg to weigh microdiamonds with 0.1 mm diameter), else they can be measured under the microscope in their x, y, z directions and a theoretical weight attached to them. The theoretical weights can be corrected by weighing 20 microdiamonds together and by back-calculating the correction over each grain.

An alternative method, such as used by the laboratory of Scientific Services in South Africa, is the chemical dissolution of the kimberlite core or rock samples with hydrofluoric acid. The kimberlite rock sample is crushed down to minus 10 mm, for instance in a roller crusher. Samples of say 10 kg are mixed with 10 l of HCl acid, diluted with 4 l of water in a large plastic container, agitated for several hours, diluted again with water and allowed to settle overnight. Next day, the sample is de-slimed over a 0.1-mm screen. The residue is mixed with about 15 l of HF acid, with the exothermic reaction raising the temperature to about 80 °C, and agitated for several hours. At the end of the day the mixture is diluted with plenty of water and allowed to settle overnight and de-slimed over a 0.1-mm screen the next morning. The sample is mixed with 4 l of HF for several hours, diluted with water and de-slimed over a 0.1-mm screen. The residue is dried. The HF leach residue is mixed with NaOH grains, the temperature is raised so as to melt the NaOH granules (caustic fusion at 300–400 °C) and, as a result, the Ca- and Mg-fluoride grains and coatings are dissolved. After the caustic fusion, the residue is washed and screened on a 0.1-mm screen, the same screen as used before (the screen will be discarded after treating each sample to avoid contamination). The caustic fusion residue is mixed with HF, if mainly silicates remain, and heated to boiling temperature for 4 h. If the remaining material consists of mainly oxides, the third HF attack may be replaced by a HCl attack. The residue is screened and dried in a nickel crucible. Depending on the results of the three acid attacks, the residue may be treated for a second time by caustic fusion if many Ca or Mg fluorides are present. The next step is to fuse (300–400 °C) bifluoride powder (KHF$_2$) with the residue for about 30 min to dissolve the most refractory silicates such as zircons, to let the mixture cool, dissolve in water and screen at 0.1 mm. Final clean-up of the remaining grains is done by boiling in aqua regia for 2 h. After dilution with water and screening, the concentrate (usually 1 g or less from an initial 10 kg sample) is dried and sent for picking by the mineral observers, using similar techniques as described for the caustic fusion method.

The cost of recovering the microdiamonds by caustic fusion or by hydrofluoric acid is similar and of the order of US$350 per 10 kg of kimberlite. Other methods are sometimes used to liberate and recover microdiamonds from the kimberlite rock. Attrition milling in stages can liberate finer and finer diamonds without breaking them. The fine diamonds can be recovered from the kimberlite gangue by dense media separation and by picking under the binocular microscope.

Microdiamond size distribution

Kimberlites with economic diamond grades contain between 1 to 10 microdiamonds (larger than 0.1 mm) per kg. Microdiamond counts can be misleading though. Several examples are known of kimberlites or lamproites with high microdiamond counts (order of 1 per kg), but with uneconomic macrodiamond (larger than 1 mm) grades. In those cases, the size distribution of the microdiamonds shows that the frequency of stone occurrences drops at such a rate with size that, by the time one reaches the macrodiamond sizes, the frequency of occurrence has dropped to uneconomic grades.

At the smallest sizes recovered, close to the 0.1 mm bottom screen, the frequency may drop with decreasing size due to poor recovery efficiencies of the finest microdiamonds. The finest microdiamond tend to float in water and may be lost during the treatment process; they are also harder to recognize under the binocular microscope. The drop in frequency at the smallest sizes and the exponential decrease in frequency with increasing size result in a microdiamond size distribution with a similar skewness as the lognormal distribution. The logarithmic variances of the microdiamond size distribution are high: they can vary from 3 to 9. Due to their lognormal-like appearance, the microdiamond size distributions are often nearly linear on a cumulative lognormal graph. Deviation from the 2-parameter lognormal model can often be corrected by adding a third parameter τ. The lognormal frequency density distribution is:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma(x+\tau)} \exp\left[-\frac{1}{2}\left(\frac{\log(x+\tau)-\zeta}{\sigma}\right)^2\right]$$

with x the stone size in carats, σ the logarithmic standard deviation and ξ the logarithmic mean.

Grade prediction based on microdiamond size distributions

At several hard-rock diamond mines combined data are available on microdiamonds (0.1–1 mm) and

commercial-sized diamonds (larger than 1 mm). When the size distributions of the microdiamonds are combined with those of the commercial-sized diamonds and plotted on a cumulative lognormal graph, nearly linear plots appear, indicating a lognormal-type of distribution (Rombouts 1995). The lognormal nature of the combined micro- to macrodiamond (larger than 1 mm or weighing more than 0.01 carat) distribution is of great practical use. If samples are so small that only microdiamonds are recovered, a linear extrapolation on a lognormal graph may give a reasonable approximation of the macrodiamond grade.

The microdiamond sizes need to be plotted on a lognormal graph (Fig. 3). Both the number and weight frequencies can be plotted. The distribution will have a linear portion, especially in the middle. At the extremities, the chance occurrence of larger stones and the poor recovery efficiency of the finest stones may cause serious deviations from log-normality. A lognormal line is fitted to the linear portion. The logarithmic mean and the logarithmic variance of the newly fitted lognormal distribution is used to solve the integration of the lognormal distribution between 0.01 and 100.0 carats to obtain the macrodiamond grade. The integration will give a total grade, assuming complete liberation, down to 0.01 carat. To allow for poor liberation, a factor can be applied to the weight contribution for the 0.01–0.1 carat-size fraction.

The lognormal integration can only be used if the samples are spatially representative. The macro- and microdiamond grades can seriously vary within a kimberlite pipe. These differences are facies related. Within a homogeneous kimberlite facies, the diamond grades and stone occurrences are homogeneous and reproducible due to the thorough random mixing. The stone occurrences tend to follow a normal, Poisson or lognormal distribution. The stone density distributions are continuous, unimodal and not very skew.

The stone density distribution is so homogeneous that the stone counts can be used to detect hidden facies differences. Grade variations due to facies can be especially extreme in the hypabyssal zone, where separate columnar vents can create strong variations over short distances in the horizontal plane (Clement 1982). In the diatreme zone, the thorough mixing by the explosion of the last eruptive event creates a homogeneous grade distribution. Grade variations in the diatreme are gradual and can often be related to the degree of dilution by country rock xenoliths. In the crater and epiclastic zones, grade variations can be correlated with subhorizontal or basin-shape layers, with the best grades in coarse tuffs or epiclastic gravels.

An alternative method is to plot the microdiamond sizes on an extreme value graph (Fig. 4). The microdiamond stone sizes are plotted versus the cumulative grade on a doubly logarithmic scale. If the samples are large enough, the distribution will tend to an asymptote, corresponding to the maximum grade. From this maximum grade, the contribution of the microdiamonds should be deducted to obtain the macrodiamond grade. As with the lognormal extrapolation method, care should be taken to account for poor liberation during industrial recovery of the diamonds in the 0.01–0.1 carat size category.

Fig. 3 Microdiamond size distribution (> 0.1 mm, or 0.00001 carat) of a kimberlite, showing lognormal extrapolation towards commercial-sized diamonds (>1 mm, or 0.01 carat). The abscissa follows the normal cumulative probability law. The sample of 52 kg contained 58 stones, weighing in total 0.0169 carats, and thus yielding a microdiamond grade of 0.32 carats/t. The lognormal extrapolation based on a logarithmic variance of 5.4 and a logarithmic mean of the weight distribution of –6.57 gives a grade of 0.06 carats/t for stones larger than 1 mm after integration of the lognormal size distribution above 0.01 carats or 1 mm
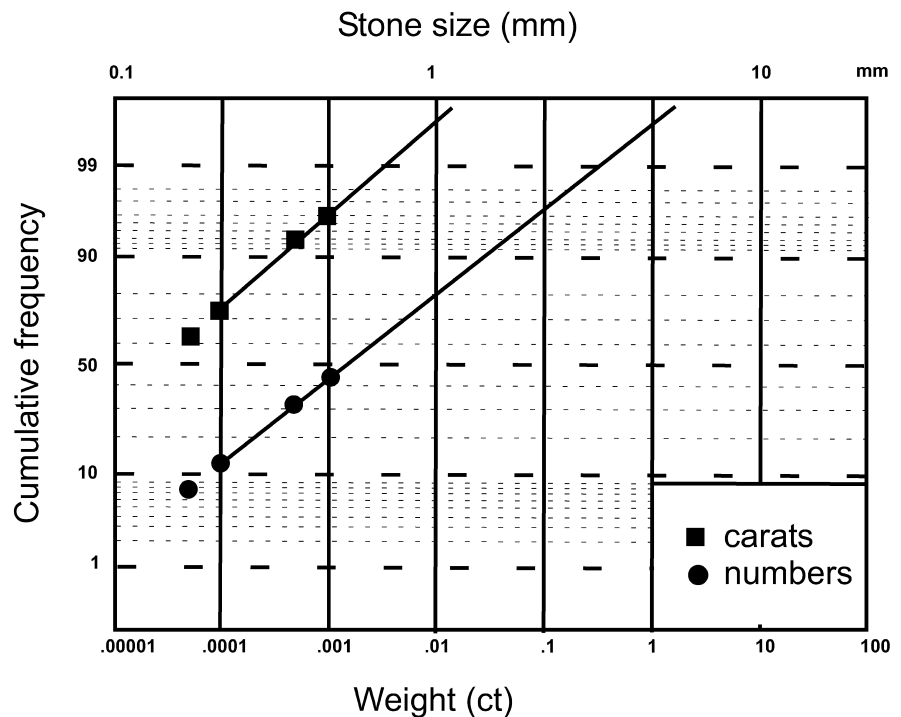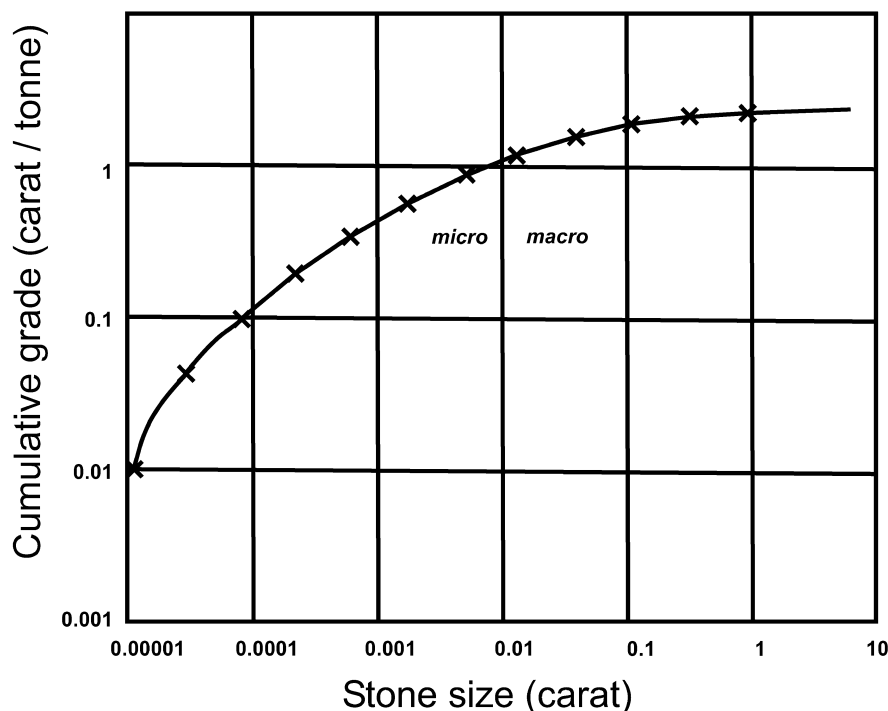
Fig. 4 Extreme value graph of microdiamond sizes: the contribution of individual microdiamonds to the grade on a log–log graph. The kimberlite sample yielded a total diamond grade of 2.80 carats/t of all stones larger than 0.1 mm. The contribution of the stones between 0.1 and 1 mm is 1.25 carats/t, while stones larger than 1 mm contribute 1.55 carats/t

First-stage bulk sampling: estimating the grade (carats/t) of the commercial-sized diamonds

The initial drill holes or trenches in a newly discovered kimberlite body may have yielded a few hundred kilograms of material for microdiamond analysis. If the samples are spatially representative, and taken without bias (for instance no selection of sample material with the aim of avoiding barren country rock fragments), the extrapolation of the microdiamond size distribution may give a first order of magnitude estimate of the macrodiamond grade in carats/tonne. If the estimate is > 0.1 carat/t, more drilling and/or trenching can be justified to firm up the diamond grade.

An estimate of the diamond grade as carats/tonne is likely to be fairly accurate if the total sample volume reaches 200 t or more. Ideally, samples will be obtained from a large diameter drilling programme or else by trenching or pitting along an unbiased regular grid. Drilling has the advantage of extending the grade information from the surface to depth. As with the microdiamond technique, samples should be spatially representative and unbiased. Better to have 100 samples of 2 t each taken from a regular grid covering the whole kimberlite body to be estimated, rather than have say two samples of 100 t. A reasonable grade estimate will usually be available after as little as 10 t of sampling, firming up steadily with more sampling. If the grade results of the individual samples are plotted in an ordered way against the resulting average, showing the contribution of each sample to the average, more sampling will lead to the appearance of an asymptote. Once a clear asymptote is reached, the average grade estimate

is robust and will be little changed by additional sampling.

The outlay of the drilling grid or pitting and trenching patterns should take into account the likely grade variations with facies. The ascending kimberlite magma follows deep fractures. Once the highly volatile magma comes within 1 to 2 km from the surface, the confining pressure of the overlying rock pile (lithostatic pressure) is not sufficient anymore to prevent a violent explosion toward the surface. An explosion breccia pipe is formed with a crater at the top. The crater is made up of nearly horizontal tuff layers, marking the fall back of volcanic and country rock fragments from the air. Within the crater tuffs, diamond grade usually varies from layer to layer, with the best diamond grades in the coarser tuffs and in the tuffs with the highest kimberlite content. Often a good correlation is obtained between diamond grade and the chromium and magnesium contents of the tuffs, reflecting the higher proportion of kimberlite at the detriment of barren country rock fragments. Tuffs often form larger units of fining-upward sequences of several tens of metres in thickness. Underneath the crater, the diatreme breccia in the explosion pipe tend to have the most homogeneous grade. Even though several kimberlite explosion events may have existed within a kimberlite volcano, the last explosive event tends to mix with the former events, thoroughly homogenizing the breccia mixture. In large pipes, the diatreme may consist of two or more columnar breccia bodies, each with its own diamond grade. Grade variations within one breccia column are often limited by the degree of country rock dilution. The centre of the explosive breccia pipe may have the best grades, whereas the margins with more

country rock fragments have lower grades. Underneath the explosion pipe, the root zone and the feeder dykes, following the deep fractures, show less mixing and greater grade variations over short distances in the horizontal plane. Several ascending kimberlite pulses can be recognized, each with its own diamond grade, forming irregular columnar bodies in the root zone.

Samples of the order of 1 or 2 t show a strong grade variability. The sample variance is strongly influenced by the stone size variance, whereas the stone density (occurrence) variance is less important. The stone density distribution is fairly homogeneous in a kimberlite or lamproite facies unit. The variance in stone sizes, however, is large. In space, samples tend to be weakly correlated within a distance of a few tens of metres. The spatial dependence can be modelled with a spherical variogram, which has a high nugget effect mainly due to the stone size variance, and a range of a few tens of metres.

Second-stage bulk sampling: estimating the commercial value (US$/carat) of the diamonds

Unlike metals, diamonds do not have a unit value. The grade, expressed as carats per tonne, has only economic meaning if the average value of the diamonds is known, expressed as US$ per carat. Both estimates can be combined in a US$ per tonne value. Diamonds are highly variable, with prices per carat varying from less than US$1 to several thousand US$ per carat. This wide variation requires parcels of the order of 1,000 carats before a reasonably accurate estimate can be obtained of the average commercial value, expressed as US$/carat. Depending on the grade, drilling, pitting or trenching will have to continue in a spatially representative way to obtain about 1,000 carats. If the grade is 1 carat/t, only 1,000 t are needed, but if the grade is 0.2 carats/t, 5,000 t are needed. Bulk sampling should remain spatially representative. Trenching and pitting at the surface only in a crater facies kimberlite may not be representative of the commercial value of the diamonds at depth. Craters often contain fining-upward tuff units that can be related to separate kimberlite explosion events, with different diamond populations. The fining-upward sequence affects the diamond population as well, with larger diamonds preferentially settling in the coarser tuffs at the base. In the diatreme facies, diamond qualities tend to be the most homogeneous, as thorough mixing has occurred and usually only one to three different vent pipes can be recognized. In the hypabyssal facies, however, boundaries between individual vents can be sharp. Several vents are often present in the root zone, with each vent having its own diamond population, both as regards grade and quality. The sampling grid, by drilling, underground bulk sampling, or pitting and trenching at the surface, should make allowance for these likely quality variations related to facies differences.

Rough uncut diamonds are sold in parcels. Only diamonds larger than 10 carats are valued and sold individually. From the large number of diamonds sold each year, prices can be attached to certain robust quality categories, as is done in the TERRAC software package (Rombouts 1991). Each diamond can be given a price, corresponding to its quality. The quality categories are dependent on the weight, the form, the colour, the colour intensity and the amount of inclusions and cleavages in the stone. The breakdown of the rough diamond parcel in theoretical individual stone values allows a statistical treatment of the commercial value of the diamonds.

The extension of the sampling programme from 200 t in total (cf. first stage bulk sampling) to enough tonnes as to yield sufficient carats (order of 1,000 carats) for commercial valuation can be continuously monitored by calculating the confidence limits and applying extreme value analysis to the diamond values. As soon as confidence limits and extreme value analysis show that a reliable average carat price has been obtained, no further additional sampling will be necessary, unless to fulfil the conditions of spatial representativity.

Confidence limits using the bootstrap method

The uncertainty of a grade or value estimate can be quantified by calculating the confidence limits. Classical methods are parametric and based on the standard deviation of the mean. The lower central confidence limit (set at e.g. 80, 90 or 95%) is:

$$\text{Lower} = \text{mean} - k_1 \frac{\sigma}{\sqrt{n}}$$

while the upper central confidence limit is:

$$\text{Upper} = \text{mean} + k_u \frac{\sigma}{\sqrt{n}}$$

with n samples and σ the standard deviation; k_l and k_u are factors depending on the shape of the distribution. The parametric method requires the acceptance of a distribution model. An elegant way of doing this and defining the factors k_l and k_u is by using Pearson's system of frequency curves (Elderton and Johnson 1969; Rombouts 1994).

The rapidly increasing desktop computer power in recent years has made the non-parametric methods for calculating the confidence limit feasible in practice. The non-parametric methods do not require a distribution model and, thus, are universally applicable. A convenient, but computer-intensive method is bootstrapping. The population of n samples is assumed to be the real distribution and n–1 random samples are drawn by computer from the complete sample population. The average of the n–1 'computer' samples is calculated. This procedure is repeated at least 100 times and preferably several hundred times. Say this is done 1,000 times, the resulting 1,000 calculated averages are ordered from

small to large values and the central confidence limits are used: the values corresponding in ranking to 10 and 90% of the total are the 80% central confidence limits.

The acceptable risk on the estimate can be quantified. For instance, the risk can be considered acceptable if the 80% central confidence limits are within 15% of the estimated average value. Alternatively, one can focus on the lower confidence limits. If the 80 or 90% central lower confidence limit is above the break-even or other limiting grade, the risk may be considered acceptable. If not, additional sampling is necessary. The method is applicable to both the grade estimate (carats/t) and the value estimate (US$/carat and US$/t).

Extreme value graphs

While the confidence limits can quantify the uncertainty level of the estimated average grade or value, the extreme value graph can visualize the robustness of the estimate. In the extreme value graph, the sample grades or stone values are plotted in an ordered sequence from small to large versus the cumulative average grade or value on a doubly logarithmic scale. If sampling cover is extensive, the distribution will tend to an asymptote, corresponding to the average grade or value. Such a graph shows the contribution of individual large values to the average (Fig. 5). It is not uncommon for diamond exploration parcels to have one single stone contributing to 30% or more of the total value. The graph may also detect diamond populations without a mean. On some diamond deposits, no matter how extensive the sampling, the average commercial value will never tend to a mean, but remains largely influenced by the chance occurrence of a few very large good-quality stones, also at the mining stage.

Diamond deposits without a commercial average value

When the ordered stone values X^* are plotted against the cumulative average value on a log-log plot (cf. the extreme value graph), the graph should tend to a horizontal asymptote if the mean exists. The horizontal asymptote represents the true mean value. If W is the cumulative weight in carats of all stones with values less than the ordered value X_i, then the plot is:

$$\left(X_i^*, \frac{\sum_{i=1}^{j} X_i^*}{W}\right) j = 1, \ldots, n$$

and the average value:

$$\frac{\sum_{i=1}^{j} X_i^*}{W} = US/carat$$

If instead of W, the volume of ore in tonnes, V, is used, then the plot is:

$$\left(X_j^*, \frac{\sum_{i=1}^{j} X_i^*}{V}\right) j = 1, \ldots; \ldots, n$$

and the average value content is:

$$\frac{\sum_{i=1}^{j} X_i^*}{V} = US\$/tonne$$

If in the plots no horizontal asymptote appears, two reasons can be found for the non-asymptotic behaviour:

1. The convergence of the cumulative average value to the true mean value is slow and much more data are needed to get some sort of asymptotic behaviour. Usually this can be attributed to the high variance of the stone values. In this case, more sampling is needed and bootstrapping the resulting distribution can quantify the central confidence limits.
2. The mean does not exist and convergence will never be attained. The sample mean remains – in theory – a stochastic variable. In practice, as any deposit has a finite number of stones that will be mined, there is a final mean grade, namely the sum of all stone values divided by the total stone weights (if variable is US$/carat) or by the total volume mined (if variable is US$/tonne). If V_{tot} is the total volume mined, the average value content Av in US$/tonne is, for instance, simply:
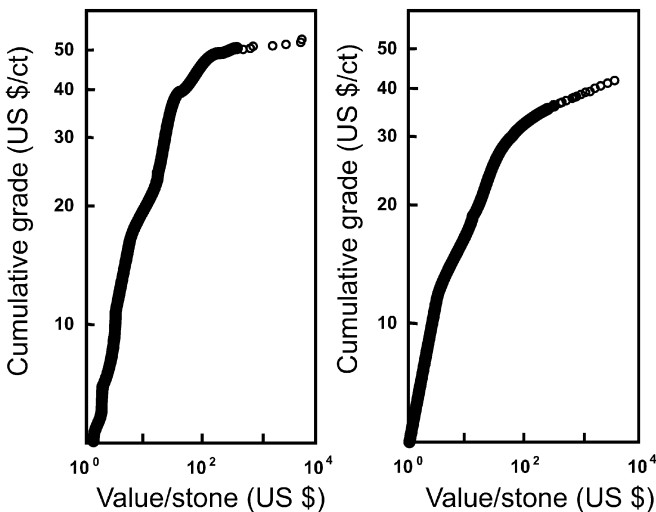

Fig. 5 Extreme value graph showing contribution of individual stones to the average US$/carat value. Left a distribution tending towards an horizontal asymptote, right a distribution with no horizontal asymptote appearing. The case on the *right* is the most common in kimberlite samples containing less than 1,000 carats, while the case on the *left* is typical of alluvial deposits

$$Av = \frac{\sum_{i=1}^{n_{tot}} X_i^*}{V_{tot}}$$

The case with no mean can be detected by studying the tail of the stone value distribution. If the tail is Pareto-type or log-hyperbolic, with a Pareto index $\alpha < 1$ or a log-hyperbolic index $\gamma > 1$, there is no mean (Caers and Rombouts 1996). Examples of such a case are the Snap Lake kimberlite in Canada and the Bellsbank kimberlite in South Africa. The tail indexes can be obtained from QQ or UH plots as discussed in Caers and Rombouts (1996).

Conclusion

The cost of testing the diamond potential of a kimberlite increases exponentially at each stage. The analytical cost for the indicator mineral geochemistry at the regional exploration stage is of the order of US$ 1,000. Once discovered, the initial drilling and microdiamond testing of the kimberlite body may cost of the order of US$ 20,000. If positive, the first stage evaluation sampling of about 200 t to assess the grade as carats/tonne often can cost between US$ 1 to 10 million, depending on logistics and amount of overburden. The next stage to obtain a 1,000-carat parcel for diamond valuation may cost of the order of US$ 10 million, especially if underground sampling is required. A proper statistical analysis of the results obtained before proceeding to the next stage, therefore, is an essential – low cost – exercise. The microdiamond testing allows the grade of the commercial-sized diamonds to be predicted to a reasonable order of magnitude. The first stage 200-t sampling should give a fairly accurate grade estimate and a first rough indication of the commercial value of the diamonds. Even parcels of 1,000 carats or more may not yield a steady average carat value. This could be because no mean exists. Extreme value analysis and, in particular, the estimation of the tail index parameter allows estimates to be made of the average carat value (US$/carat) and of the average value content of the ore (US$/tonne) with increasing sample or ore volume, even if no theoretical mean exists. At any stage in the evaluation process, bootstrapping the sample results allows the confidence limits to be obtained, quantifying the uncertainty and risk of the grade and value estimates.

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