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EXPLORATION AND EVALUATION OF DIAMOND DEPOSITS

by

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RESUME

Les méthodes indirectes les plus utilisées dans la prospection des kimberlites diamantifères sont les prélèvements des minéraux satellites et la géophysique aéroportée. Cependant, la prospection directe pour diamant est souvent plus efficace, comme aucun concept préalable sur l'origine des diamants n'est nécessaire. La détection des diamants dans les alluvions demande un prélèvement d'au moins quelques mètres cubes. La méthode est coûteuse, mais les résultats sont sûrs et directs.

Dans l'évaluation des gisements diamantifères, la surestimation doit être évitée. Les limites d'un bloc ne peuvent pas être basées sur les résultats d'échantillons individuels, mais sur des observations indépendantes comme les limites de faciès kimberlitiques ou les contours de l'élévation de la roche-mère dans un gisement alluvionnaire.

Une nouvelle méthode d'estimation du prix moyen par carat est présentée, basée sur l'estimateur t de Sichel, qui est plus efficace que la méthode classique d'évaluation commerciale.

Enfin, un modèle géométrique du coefficient de variation des tailles des diamants dans une kimberlite est présenté.

ABSTRACT

The techniques of indicator mineral sampling and airborne geophysics, the most commonly used exploration methods for kimberlites, are discussed. However, direct bulk sampling for diamonds is often more effective, as no a priori concepts on the origin of the diamonds are necessary. The method is expensive, but results are sure and direct.

When evaluating a deposit, overestimation should be avoided. The limits of the block to be estimated should not be based on individual sample results, but on independent observations, such as limits of kimberlite facies or bedrock contours in alluvial deposits.

A new method for estimating the average carat price at the exploration stage is presented. The method is based on Sichel's t estimator and is more efficient than the traditional commercial valuation on a parcel obtained from a special bulk sample.

Finally, an attempt is made to present a geometric model for the coefficient of variation of diamond sizes in kimberlites.

SAMENVATTING

De traditionele, onrechtstreekse exploratiemethoden voor kimberliet worden besproken. Deze zijn de bemonstering van riviergrint voor indicatormineralen en de aëromagnetometrie en aëroradiometrie. De rechtstreekse exploratie voor diamant is, alhoewel duur, dikwijls efficiënter, vermits er

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geen a priori hypothesen omtrent de uiteindelijke bron van de diamanten nodig zijn. Diamant is zeldzaam en de rechtstreekse exploratie vergt monsters van verschillende kubieke meters.

Tijdens de evaluatie van een diamantafzetting moet vooral de overestimatie vermeden worden. De blokgrenzen mogen niet gebaseerd zijn op de resultaten van individuele monsters, maar moeten gebaseerd zijn op onafhankelijke waarnemingen zoals faciësgrenzen in een kimberliet of isophypsen van de basis van het grint in alluviale afzettingen.

Een nieuwe methode om de gemiddelde karaatprijs te bepalen tijdens de exploratiefase wordt voorgesteld. De methode is gebaseerd op de t estimator van Sichel en is efficiënter dan de traditionele methode.

Er wordt ook een geometrisch model voorgesteld om de variatie-coefficiënt van de diamantgewichten in een kimberliet te verklaren.

MOTS CLE

Diamant, géostatistique.

KEY WORDS

Diamonds, geostatistics.

SLEUTELWOORDEN

Diamant, geostatistiek.

This paper is divided in two : Part I describes the exploration and Part II the evaluation of diamond deposits. Part I is meant as a general didactic overview of past practices in finding diamond deposits. Part II presents the latest developments on diamond valuation techniques.

PART I : EXPLORATION

1. INTRODUCTION

Since the dawn of civilisation, Man has been washing alluvial gravels, while looking for gold, silver, copper, tin and precious stones. It seems plausible, that in this way diamonds were first found by chance in India and appreciated as precious stones for their hardness and brilliance. After the hindou civilisation extended towards South East Asia in the second century AD, diamonds were also found in Borneo. Commercial exchanges between the Orient and Europe are very old and diamonds were introduced into Europe through Persia and the Middle East. From the 16th century onwards, the diamond trade in Europe was dominated by the Portuguese, thanks to their commercial empire in Asia. It is no surprise then, that Portuguese prospectors discovered diamonds in Brazil in 1727. From then onwards Brazil remained the world's leading producer till the latter part of the 19th century.

The first diamond was discovered in South Africa by chance in 1866. Three years later, prospecting of the Vaal river gravels started on a massive scale. The great turnaround occured in 1871, when the volcanic mother rock of the diamonds was recognised in Kimberley. The understanding of the relationship of the kimberlites as primary source of the diamonds and their dispersal by erosion in the downstream river gravels allowed the application of more selective prospecting methods. The South African prospectors quickly realised when washing kimberlite, that they contained heavy minerals, which were very typical and much more abundant than diamonds. These heavy minerals, called indicator minerals, are dispersed in the drainage system and enriched in the gravels because of their high specific gravity in the same way as diamonds do.

2. EXPLORATION FOR KIMBERLITES

2.1. INDICATOR MINERALS

After a century of intense exploration, following the discovery at Kimberley, close to thirty kimberlite deposits are presently mined. The occurrence of diamondiferous kimberlites seems almost entirely restricted to the old cratons, which did not undergo any major tectono-thermal event since 1500 million years (Clifford, 1966 ; Janse, 1984) (Fig. 1). It seems therefore safe to restrict the exploring of kimberlites to these cratons, which are in places covered by younger subhorizontal strata. The restriction of diamondiferous kimberlites to the cratons can be explained

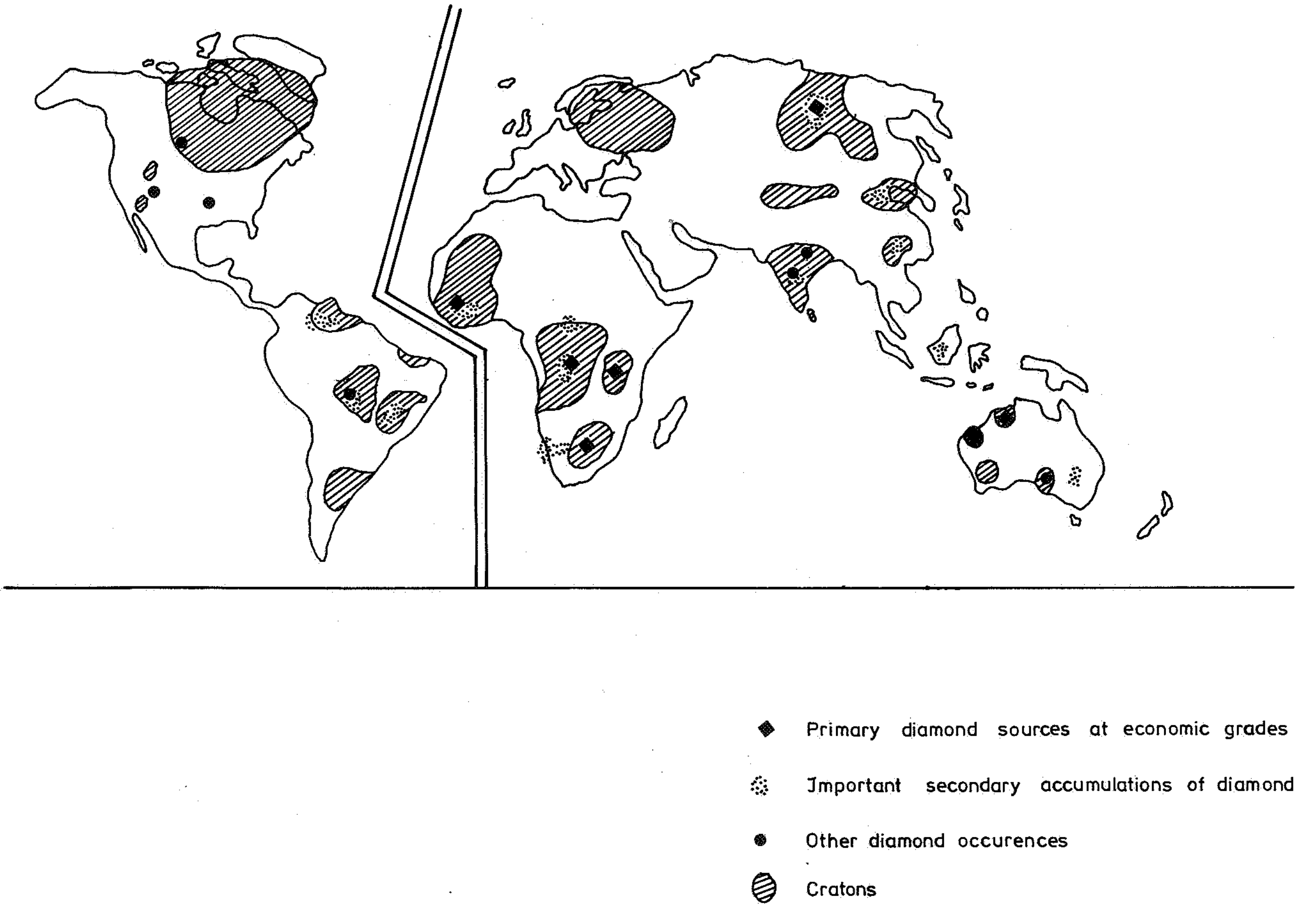

Figure 1. : Relationship between diamond occurrences and cratons. Recent work by Cluff Resources seems to indicate that the Copeton secondary deposits of Australia are in fact primary and related to lamprophyric volcanism.

by the hypothesis that diamond formation demands certain conditions of high pressure and relatively low temperature, which are believed to exist at depths of 200 km underneath the cratons with a low geothermal gradient. The homogenity and relative coolness of the cratons allow sudden crack propagation from great depths. The ascent of kimberlite magma in a matter of a few hours avoids the total resorption of diamonds, when travelling through the shallower and lower pressure parts of the crust.

The kimberlitic indicator minerals are the chrome and magnesium rich varieties of pyrope, ilmenite and diopside. In certain areas other indicators are used, such as olivine in Siberia and uranium-poor zircon at Pteropus Creek in Australia (Atkinson, 1989). The kimberlitic pyropes, ilmenites and chrome-diopsides can be recognised by their colour, resp. red, black and green, and by their frosted and rounded surface. Ilmenites can be detected till 20 km downstream of their source, while pyropes seldom beyond 2 km in a tropical environment. The occurrence of chrome-diopsides is limited to a radius of a few hundred metres around the kimberlite. The ilmenites are often coated with grey perovskite or leucoxene close to their source. The coating quickly disappears downstream due to fluvial abrasion.

The indicator minerals are recovered from the river gravels by gravimetric concentration. Samples consist of 20 litres of gravel, taken from optimal trapsites such as rockbars and valley narrowings. The gravel is washed and screened on 4, 2 and 1 mm sieves. The plus 4, plus 2 and plus 1 mm fractions are jigged, and the minus 1 mm fraction panned on site and the concentrate examined for indicator minerals. The minus 2 mm fractions are sent to the laboratory for study under the binocular microscope and for eventual chemical analysis by microprobe for such elements as Cr, Mg, Ca and others. The size of the indicator minerals can exceed 4 mm close to their source, but remain below 2 mm after a few kilometres.

Kimberlites do not occur as isolated bodies, but show a tendency to group in larger provinces of the order of 1000 km^2. A large scale regional survey should try to detect these provinces. Samples are taken at a density of 1/50 km^2, at distances of 10 to 20 km along the rivers. Within a kimberlite province, samples should be taken at a density of 0.5 to 1/km^2. Individual kimberlite bodies can then be detected by applying a soil sampling grid of say 50 X 50 m. In the tropics, one team with a vehicle can take on average two samples per day in the dry season if the sampling density is 1/50 km^2, five if 1/20 km^{2}and ten if 1/1 km^2. In one dry season 10,000 km^2 can be covered by one team if the sampling density is 1/50 or 1/20 km^2, and 1000 km^{2}if 1/1 km^2. Prospecting for heavy minerals will often be combined with a geochemical stream sediment sampling programme, such as for uranium and vanadium in the Karroo of Southern Africa and for gold and base metals on Archean terrains containing greenschist belts.

On average, only 1 % of kimberlites are of economic interest, the others being barren or of too low grade. The abundance of pyropes, especially the chrome rich subcalcic variety (Gurney, 1984), is considered a good indication for the diamond potential of a kimberlite. Recently, Griffin and co-workers (1991) found that the nickel content of chrome-pyrope garnet, equilibrated with mantle olivine, increases with temperature. This "nickel thermometer" can be used to differentiate garnets of diamond-rich from garnets of diamond-poor pipes. Diamondiferous pipes from cratonic areas contain a large proportion of garnets with nickel temperatures in the range of 950-1250° C, while diamond-poor pipes show nickel temperatures below 950°C. The ilmenites of diamondiferous kimberlites are poor in Fe+++and rich in Cr and Mg.

The exploration for kimberlites by way of indicator minerals has had considerable success in Siberia, where the Mir and Udachnaya pipes were discovered, and in South Africa where the Premier pipe was discovered. If drainage is poor, samples can be taken by "loaming". In arid areas, wind can enrich heavy minerals in a thin deflation layer at the surface. Loaming of surface samples resulted in the discovery of the Mwadui pipe in Tanzania and the Orapa, Lethlakane and Jwaneng deposits in Botswana.

The indicator minerals method implies a priori concepts on the origin of diamonds. The primary source of diamonds is believed to be kimberlites. In 1976, diamondiferous lamproites were discovered in Australia. Lamproites contain the same indicator minerals as kimberlites, but in low quantities and smaller sizes. Other minerals, such as chrome-spinels, andradite, K-richterite, priderite and even diamonds are more common and more likely to be detected in downstream gravels. Their precise determination however is difficult by naked eye and can often only be done by chemical and mineralogical analyses.

In Brazil and West Africa, the presence of diamonds in the alluvials seems strongly correlated to the presence of favas, phosphatic "beans" of barium, calcium and rare earths. Favas are unknown in kimberlites and their origin is enigmatic. Their concentric layering points to a secondary origin. Possibly they are the result of biogenic or kimberlite-derived phosphate deposition combined with kimberlite-derived barium and rare earths in water or soils.

2.2. OTHER METHODS

Airborne geophysical surveys cover large areas in a short time span. Their success hinges on the contrast between the physical parameters of the kimberlites and the country rock. The detection of the kimberlites is often due to the geometric interpretation as a pipe-like geophysical anomaly. The most used methods are magnetometry and radiometry. Kimberlites can display a higher magnetic susceptibility and a potassium radioactive anomaly. Line spacing should be less than the dimensions of the kimberlite pipes and flying altitude should preferably remain under 100 m. Results are ambiguous : the kimberlites in the Lesotho Lowlands show a clear magnetic and radiometric anomaly, while several kimberlites in Tanzania and Botswana seem geophysically featureless. In smaller areas (less than 10,000 km^2), electromagnetic methods are often used. The INPUT method is the best performer, but more costly. The electromagnetic method detects the increased conductivity due to the alteration of kimberlites to clays. The cost of an airborne magnetic and radiometric survey is of the same order as an indicator mineral survey on the same scale ($15 to

30/km^2). Anomalies are followed up with ground geophysics and indicator mineral sampling along a 50 x 50 or 25 x 25 m grid. A geophysical survey allows not only the detection of other substances such as uranium and massive sulphides, but also a global interpretation of geological structure.

Other methods used in diamond exploration are the geological interpretation of aerial and satellite photographs. Kimberlites often create depressions with different vegetation cover. Dykes and pipes are often located along major lineaments, easily visible on Landsat or Spot photographs. However, these methods are rarely convincing by themselves and are rather used as a support for other exploration methods such as geophysics and indicator mineral sampling.

3. BULK SAMPLING FOR DIAMONDS

In Australia, over the last twenty years, probably more than 100 million dollars have been spent on diamond exploration, using mainly geophysics and indicator mineral sampling. Sofar, the Argyle lamproite is the only economic primary diamond deposit found. The Argyle lamproite has no clear geophysical signature, nor does it show a clear indicator mineral dispersion. Its discovery was due to the recognition of diamonds in a heavy mineral concentrate obtained from gravels washed downstream of the pipe. This seems to suggest that direct exploration for diamonds would be more efficient, as no preliminary concepts on the origin of diamonds are necessary. Important accumulations of diamonds occur in consolidated sedimentary rocks in Venezuela, Guyana, Brazil, Ghana, Borneo and Central Africa. Their ultimate primary source rocks are yet unknown. Indicator minerals are less resistant than diamonds and do not survive many sedimentary cycles. Detection of these deposits is only possible by using diamonds as indicator minerals. Diamonds are rare, and can only be detected in gravels if samples consist of at least several m^3, taken from good tapsites, such as the basal gravels downstream of rockbars. Exploration costs are high ($ 1000-2000 per sample), but results are sure and direct. The development of the sampling density from recognition of diamond provinces to individual deposits is similar as for indicator mineral sampling, apart from the obviously much larger sample volumes. Bulk sampling for diamonds will initially indicate alluvial deposits. Diamonds become larger and more abundant closer to the source and this observation can lead to the detection of primary deposits. Bulk sampling for diamonds has been extensively used in the exploration of alluvial deposits in Africa and South America. Alluvial sources still supply a significant proportion of total diamond production. In West Africa and South America, alluvial deposits are more economic to mine than their primary source rocks. In case of a discovery of an alluvial deposit, the same bulk sampling equipment can be used to evaluate the deposit.

Bulk samples are taken from the basal gravel layer in an alluvial profile. Basal gravels are often overlain by running sand and their extraction by hand can be difficult and dangerous. For this reason, preferably a hydraulic excavator is used, fitted with a circular clamshell grab (Fig. 2). An hydrostratic head is created inside the pit, by pumping water into it. After excavation, the gravel is taken by tractor and trailer to the prospecting washplant. This plant contains a trommel and scrubber, vibrating screens and a heavy mineral concentrating system (Fig. 3). The trommel and scrubber should disintegrate the gravel and avoid clayballing. The screens separate the fraction to be concentrated. This fraction is often from 0.5 to 16 mm, but can vary depending on the expected granulometry of diamonds in the area. The concentrating system can be based on jigs, on a rotary pan or on a dense media cyclone. Rotary pans are best suited for washing kimberlites and gravels with a high clay content. Their adjustment requires experience and continuous supervision. The recovery is not always efficient, as concentrating conditions inside the pan are difficult to keep constant. Therefore, rotary pans are better not used in a regional survey. Dense media cyclones are reliable and allow the recovery of diamonds down to 0.5 mm. They are costly and require considerable maintenance and supervision. It is advisable to use them only in countries where sufficient technical back-up is available. Jigs are mechanically simple and easy to maintain. The recovery is very satisfactory down to 1 mm. They are the ideal concentrating method for projects with poor logistical back-up, if security is adequate.

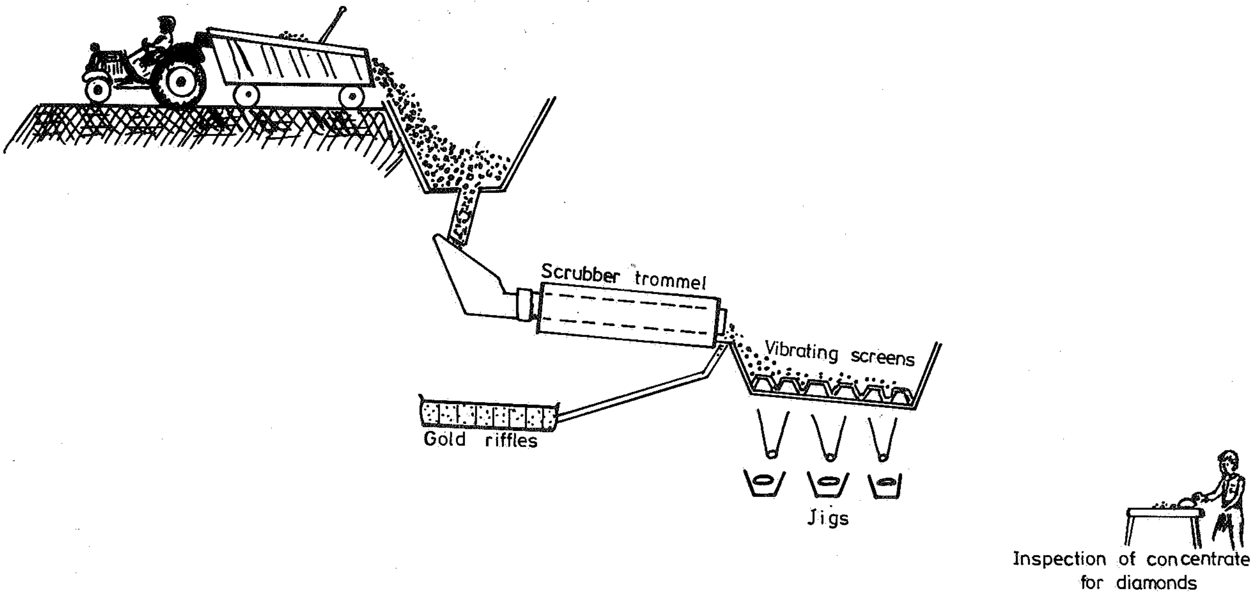

Figure 2. : Cartoon of alluvial diamond sampling.

PART II : EVALUATION

1. DEVELOPMENT SAMPLING

As soon as a discovery is made, the grade of the deposit should be determined to assess its economic potential. The development sampling grid should be regular and samples should be of unit volume to facilitate reserve calculations. Grid density should allow the detection of all meaningful geological structures, influencing diamond distribution, such as different kimberlite facies, or channels in alluvial deposits. The unit volume of the samples should be large enough to detect on average at least one stone per sample. If the density of stone occurrences is high (say several tens of stones per m^3) then the unit volume can be increased to allow definition of the correlation between adjoining samples. Clear a priori rules do not exist and every deposit will need sound geological judgement to determine the optimal grid. Some examples will illustrate the approach to be followed.

Jwaneng, Botswana

The Jwaneng pipe is covered by 60 m of Kalahari sediments. Development sampling

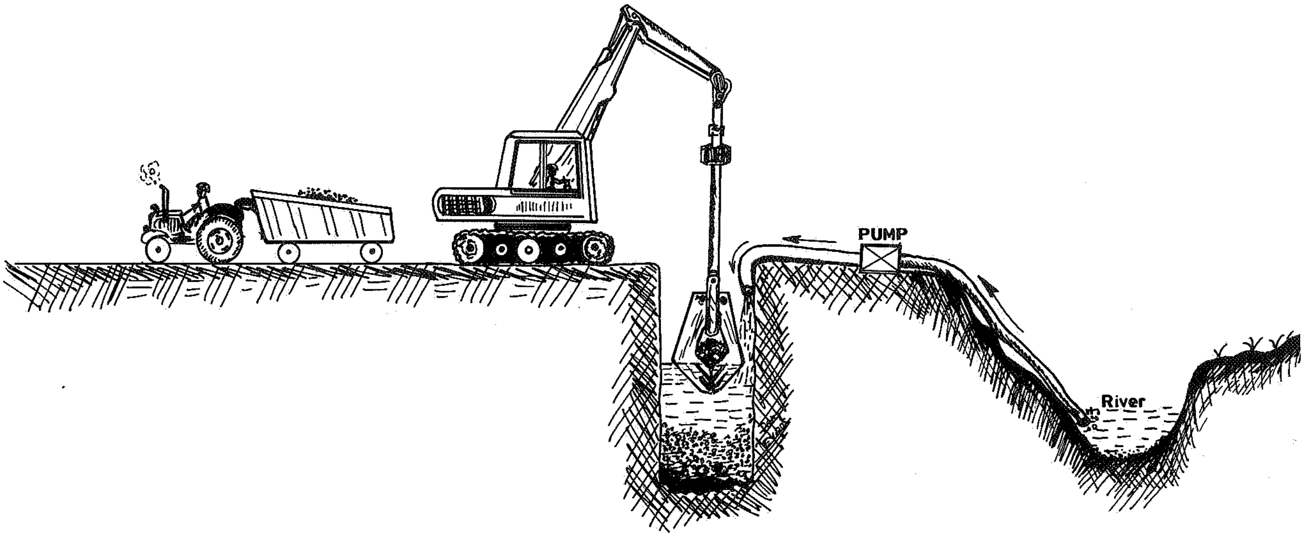

Figure 3. : Cartoon of a prospecting washplant.

was done with 380 mm diameter drillholes along a 50 x 50 m grid till a depth of 200 m. Unit sample volume consist of 6 m thickness taken from each borehole. The drilling results were confirmed with six pits of 3 x 3 m till a depth of 165 m (Atkinson, 1989).

Argyle, Australia

Development sampling on the lamproite was done on a 100 x 100 m grid of 16 m^3 samples. In the richer parts, reserves were developed with 200 mm drillholes alongs a 50 x 50 m grid. Each sample represented 20 m of thickness in the borehole. The grades were further confirmed with six pits of 2 x 2.4 m till depths of 43 to 64 m (Atkinson, 1989).

Gbenko, Guinea

The diamonds from the Gbenko alluvial deposit are concentrated in a thin basal gravel layer of 450 mm thickness. Reserves calculations can be reduced to two dimensions and planar grades are used. The grid of 100 x 50 m allows for anisotropy, the deposit being twice as long as it is wide. Unit samples cover 8.85 m^2 and are taken by Poclain excavator fitted with a circular clamshell.

2. ORE RESERVES CALCULATIONS

The grade of a block can be calculated with some confidence if it contains at least 50 samples. Ore reserve calculations are greatly simplified if the sampling grid is regular and if samples are all of unit volume. If not, samples will have to be weighted according to their zone of influence or support. The results of individual samples should not be used to define block boundaries as this will inevitably result in an overestimation bias. The variance of the sample results is much higher than the variance of the grade of their respective zones of influence and the extension of the grade of an individual sample result to its zone of influence will result in the underestimation of poor grade areas and the overestimation of richer areas. Block boundaries should be based on independent observations such as facies boundaries in kimberlites or bedrock contours in alluvial deposits.

The average grade of a block is estimated by the arithmetic mean of the grades of the samples. The t estimator (Finney, 1941 ; Sichel, 1949, 1952) is more efficient when the grade distribution is lognormal (Fig. 4).

t estimator of variable z (n samples)

$$t = e^{\bar{x}}\left[1 + \frac{1}{2}V + \frac{n-1}{2^2\,2!(n+1)}V^2 + \frac{(n-1)^2}{2^3\,3!(n+1)(n+3)}V^3 + \cdots\right]$$

with $\bar{x} = \frac{1}{n}\,\Sigma x$

$$V = \frac{1}{n}\Sigma(x - \bar{x})^2$$

$$x = \ln(z)$$

Figure 4. : Calculation of the t estimator. After Sichel, 1952.

However, the presence of barren samples will often exclude its use. The arithmetic mean of the sample results becomes meaningful for mine planning purposes, if its confidence limits are known. Too wide confidence limits could indicate the need for infill sampling or for larger unit volume samples. The calculation of the confidence limits depends on the form of the grade distribution. The confidence limits are derived from the Pearsonian shape coefficients of the mean and the tables of Johnson *et al.* (1963).

If sample results can be fitted to a two or three parameter lognormal distribution, the confidence limits are better calculated with the formulas of Sichel (1966). In the low grade/high value deposits where barren samples are common, such as the Namibian and Guinean deposits, the confidence limits are obtained from the lognormal stone size distribution and the compound Poisson distribution of stone densities (Sichel, 1973 ; Rombouts, 1987a).

The estimate of the average grade and its confidence limits allow a formal classification of ore reserves. For instance, if the 80 % central confidence limits are used, Proven Reserves have a lower confidence limit above the cut-off grade, while Uneconomic blocks have the upper confidence limit below the cut-off grade. If the confidence limits overlap the cut-off grade, additional sampling can narrow the confidence limits till the conditions of Proven or Uneconomic are met. If not, the block is considered Probable or Marginal, depending on the estimated average grade being resp. above or below the cut-off grade.

3. COMMERCIAL VALUATION

The average grade of the block, expressed as ct/T or ct/m^3, is multiplied with the average price per carat to obtain the value contained in the ore. While samples and number of diamonds recovered during development sampling are often considered sufficient to calculate with confidence the grade of a block, it is traditionally believed that some additional large bulk sampling is necessary to obtain enough diamonds for commercial valuation. Commercial valuers obtain the average carat price by dividing the total value of the submitted parcel by their total weight, which equals the division of the average price of the individual stones by their average weight. This is a correct procedure if the parcel is considered the total population and sold on its own. However, at the exploration stage, the parcel represents a sample of a larger population (the entire deposit) and it is the average carat price of the latter that needs to be estimated. A new method is proposed here, which presents a more efficient way of estimating the average carat price at the exploration stage.

The distribution of the values of individual stones is often well approximated by a lognormal distribution with a high logarithmic variance (Rombouts, 1987b). For instance, the Gbenko deposit contains stones with individual values ranging from 10 cents to 10 million dollars, and the logarithmic variance is close to 3.5. Sichel (1952) has demonstrated that in such cases the t estimator is much more efficient than the arithmetic mean (Fig. 4). For the range of logarithmic variances encountered in deposits with a high gem content, the efficiency of the arithmetic mean is only about a third of the t estimator (Fig. 5). This means that the estimation of the average carat price, based on the division of the t estimator of the individual stone values by the t estimator of stone sizes, requires only one third the number of stones in comparison to the traditional method. As this can obviate the need for a large bulk sample, important economies can be made at the exploration stage by applying this method. An added disadvantage of the traditional method is that bulk samples are taken from a restricted part of the deposit. The moving averages of the stone size standard deviation of the Gbenko deposit show that serious variations exist (Fig. 6). The average carat price is proportional to the stone size standard deviation and bulk samples risk to be not representative for the whole deposit. In Guinea, production results confirmed that the number of diamonds recovered from the development sampling grid are sufficient to obtain reliable estimates of the average carat price, if the t estimator method is used. Simulations on production parcels showed that even for distribution which fitted poorly the lognormal law, the t estimator remained much more efficient than the traditional method.

When valuing the individual stones, it is good practice to also note the form, the colour, the presence of inclusions and the degree of resorption of the stones. Certain stone characteristics can often be correlated with kimberlite trends and this can be useful information in deciding on priority areas for exploration. For instance, in Sierra Leone and Guinea, kimberlites with a high proportion of large, clear and well crystallised octahedral diamonds are associated with faults, marking the extension of an oceanic transform fault, perpendicular to the African coastline. These faults reflect a major crustal weakness, canalising the sudden rise of kimberlitic magma from deeper levels in the upper mantle, with more favourable and stable conditions for diamond crystallisation. The higher temperatures at these deeper levels favour the formation of colourless and well formed octahedral diamonds. Kimberlites along other fault directions seem to have shallower sources with less stable conditions for diamond formation. They show a high proportion of spotted and irregular stones.

4. CUT-OFF SIEVE SIZES

The distribution of the sizes and values of the stones recovered during the development sampling can be plotted on lognormal graph paper (Fig. 7). If the distributions are two parameter lognormal, they will plot as straight lines. The distribution of carats per size class is a moment distribution of the number of stones distribution, and both will plot as parallel lines. The distribution of dollars per size class often has a different logarithmic variance and will not be parallel. During exploration the size range of the stones recovered

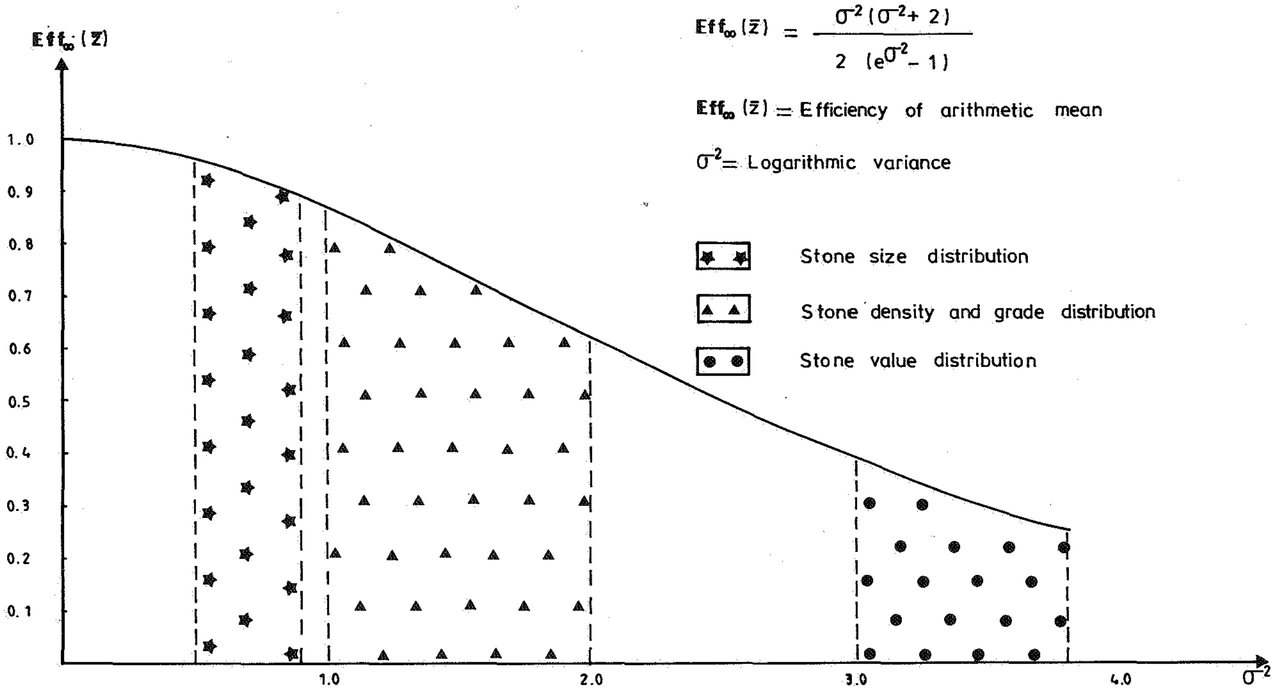

Figure 5. : Efficiency of the arithmetic mean relative to the maximum likelihood estimator for a lognormal distribution, with more than 100 samples.

will be as complete as possible. However, the recovery on an industrial scale of the complete size range is not economic. The industrial recovery will be based in most cases on a gravimetric concentration in a dense media cyclone, followed by extraction of the diamonds from the heavy mineral concentrate by X-ray fluorescence (Sortex). The process is costly and is optimised if the size fractions with a poor value content are eliminated in advance. For instance, the Sortex of the Gbenko operation treats only the fraction between 2 and 60 mm, as this fraction contains more than 99 % of the total value. The fraction between 2 and 28 mm is treated in the dense media cyclone, while the fraction between 28 and 60 mm is sent directly to the Sortex. The fraction of the ore with grain size below 2 mm represents 80 % by volume, but only 0.05 % by value, and it is clear that by eliminating this fraction important savings are made. In hard kimberlites, the optimal size to which the ore can be reduced by crushing needs to be determined. At Orapa, only the fraction between 1.65 and 25 mm is sent to the dense media cyclone (Allen, 1981).

The percentage lost in weight and value of the diamonds for different cut-off sieve sizes can be derived from the lognormal size and value graphs or by using the formulas for the truncation of lognormal distributions. If the granulometry of the ore and its heavy mineral content is known, it becomes relatively easy to determine that optimal cut-off sieve sizes.

5. LOCAL ESTIMATION

Ore reserve calculations are based on estimating the grade of blocks containing at least 50 samples. However, inside the block the grade is not necessarily uniform. If grades within the block are highly variable, serious production variations can occur if ore is not properly blended. The estimation of the grade of selective mining units requires the spatial component of the variance of the samples to be known. Using the variograms of the samples, the grade of the selective mining units can be estimated with kriging. This method is applied on the Argyle lamproite and the Upper Smoke Creek alluvial deposit, which display spherical variograms (Deakin *et al*, 1989). Unfortunately, many diamond deposits show very erratic sample results because of the discrete nature of stone occurrences in samples. The variograms do not show any structure and kriging is impossible. If the coefficient of variation (i.e. standard deviation divided by arithmetic mean) of the grades of the selective mining units can be derived from production records, their grades can be estimated by appling a moving average scheme, whose results show the same coefficient of variation. The optimal moving average scheme can be found by iteration. For instance in Gbenko, selective mining units of 2500 m^2 are best estimated with a 700 x 400 m moving average of the 100 x 50 sampling grid of 8.85 m^2 unit samples. The estimates are two parameter lognormally distributed and display circular variograms with ranges equal to the size of the moving average cell. As the grades of the selective mining units and the estimated grades by moving averages have

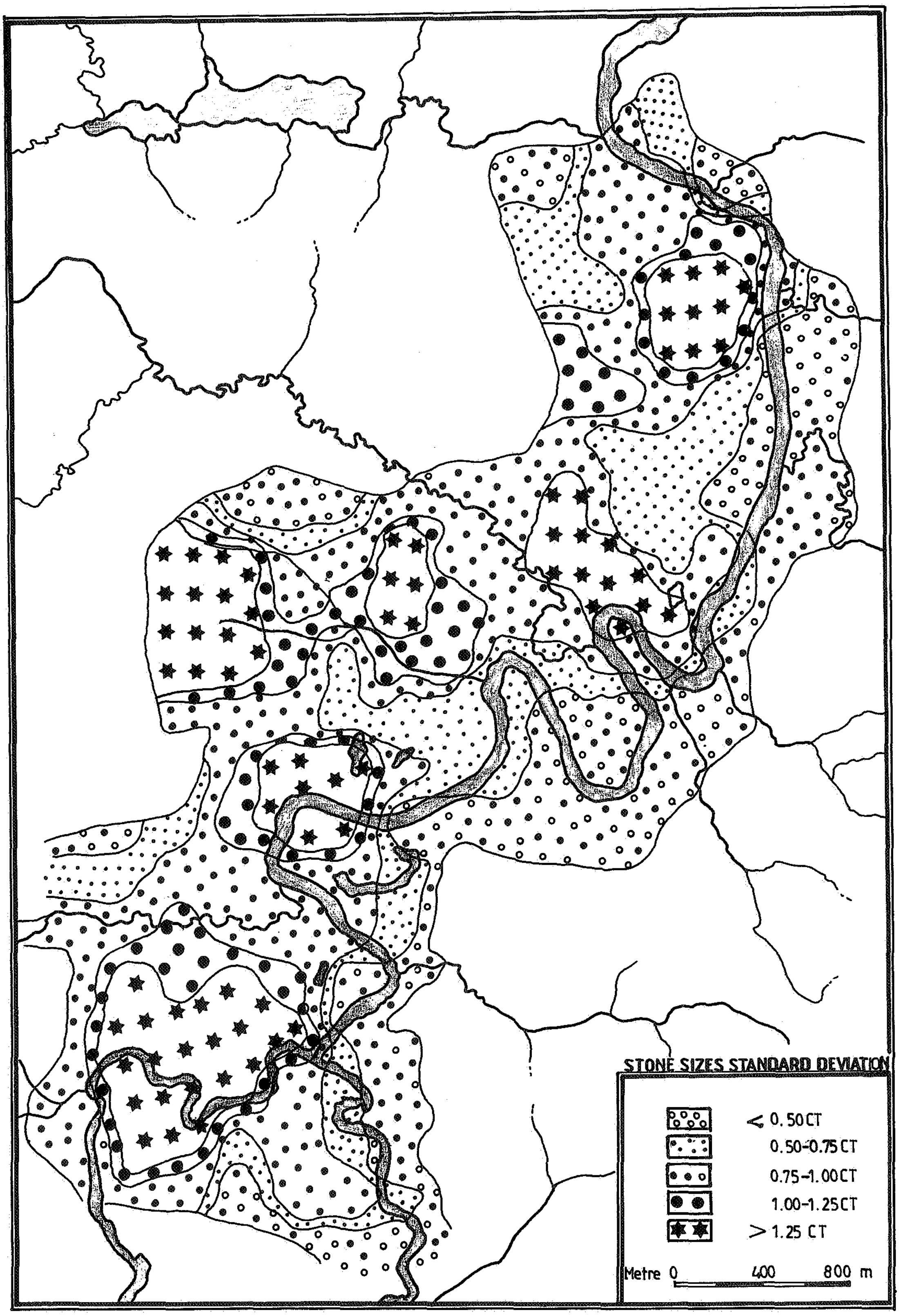

Figure 6. : Moving average map of stone sizes standard deviation, Gbenko deposit, Guinea.

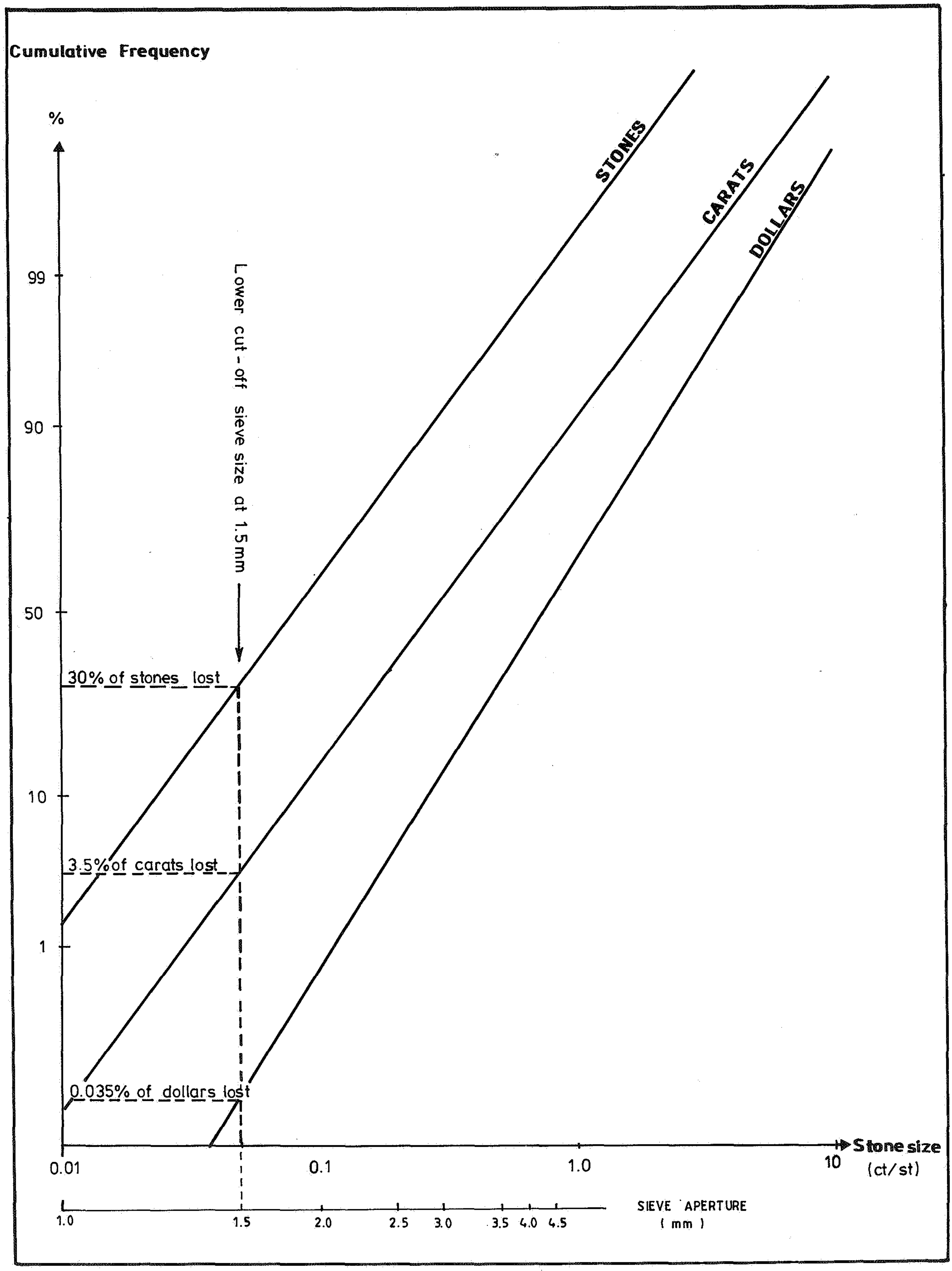

Figure 7. : Cumulative lognormal graph of number of stones, carats and dollars per size interval, illustrating the effect of cut-off sieve sizes.

identical coefficients of variation, a systematic bias in overestimating rich units and underestimating poor units is avoided.

6. A GEOMETRIC MODEL FOR THE COEFFICIENT OF VARIATION

The coefficient of variation of diamond sizes within a homogeneous kimberlite is often between 1.0 and 1.1 and it is tempting to propose at the end of this article a geometric model to explain this. In case of lognormality, this coefficient of variation corresponds to a logarithmic variance of about 0.75.

If the conditions for diamond crystallisation are favourable in the earth's mantle, carbon molecules will diffuse by random walk to the nearest nucleation seed to crystallise as diamonds. The nucleation seeds can be supposed to appear at random in space but, if thermodynamic conditions are stable, at a constant rate in time and per unit volume. A two dimensional visualisation of this model are the raindrops falling into a pool (Evans, 1945).

Around each raindrop concentric circles develop which move outward. In three dimensions the circles become spheres and Gilbert (1962) found that the sizes of these spheres obey the following law :

$$s = 1.066\ m$$

with s the standard deviation and m the arithmetic mean of the sizes of the cells. The coefficient of variation of 1.066 is very similar to the coefficient of variation of the size distribution of diamonds in homogeneous kimberlites. If the melt is homogeneous, the number of carbon molecules crystallising at each nucleation seed will be proportional to Gilbert's raindrop cells. During the ascent of the kimberlite magma, resorption will modify the size distribution, as resorption is proportional to surface rather than to volume. However, if resorption is limited and if diamonds are large and well crystallised, the geometric "raindrop" model seems a reasonable first attempt to quantify the coefficient of variation of diamond sizes.

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