RESOURCE ESTIMATION PROCEDURES AT THE EKATI DIAMOND MINE™, CANADA

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Resource Estimation Procedures At The Ekati Diamond Mine™, Canada

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ABSTRACT

Primary economic diamond deposit modelling has rarely been documented in the public domain. This paper presents information collected from significantly diamondiferous kimberlite pipes located in the Canadian Arctic near Lac de Gras. The resource estimation process is widely accepted as a cyclical iteration of data collection and evaluation processes. A resource database is often assembled from a large inventory of exploration data. These data must be methodically quality checked before accepting the information for interpretive analysis. The foundation of a deposit model is based on grade, volume, and density models. Defining these models is an iterative process of statistical analyses and interpretation. As a deposit progresses along a path towards development, reducing risk to acceptable levels is critical for identifying and realizing the maximum value of a deposit.

1. INTRODUCTION

The recent discovery and mining of the Ekati kimberlite pipes provides a useful example of a geological evaluation and resource estimation process for primary economic diamond deposits. The Ekati Diamond Mine™ (Ekati) is a joint venture between BHP Billiton (operator, 80%) and the two original prospectors involved in its discovery (Chuck Fipke and Stewart Blusson). The Ekati property is situated in the Lac de Gras kimberlite field in the east-central portion of the Slave Province in the Northwest Territories of Canada.
The first kimberlite (Point Lake) at Lac de Gras was discovered in 1991. Two years later in 1993, the Panda kimberlite was drill confirmed and five years later, in 1998, became the primary source of ore feed at the opening of the Ekati Diamond Mine™. The original process plant throughput was designed at 9,000 tonnes per day and kimberlite was mined from the Panda open pit as a single source until 2002. Currently, a blended stream of ore is processed from open pit operations at Panda, Misery and Koala as well as an underground operation at Koala North. Several other kimberlite pipes are at various stages of economic evaluation. Diamond production from Ekati over the period October, 1998 to December, 2002 is summarized in Table 1. The Ekati resources (as of end June 2002) comprise 114 M tonnes at 1.3 cpt (1.0 mm cut-off) for a total of 146 M carats. Pipes for which resources have been reported include Panda, Koala, Koala North, Misery, Fox, Sable, Pigeon, Beartooth, Lynx and Jay (Table 2).

This contribution describes the resource estimation approaches applied to kimberlite ore evaluation at Ekati. Diamond valuation and stone size distribution models are considered proprietary and are discussed only in general terms. Detailed descriptions of statistical and geostatistical methods employed in resource estimation are beyond the scope of this paper and the reader is referred to Rombouts (1995) and Thurston (1998) for detailed accounts of application of such methods to kimberlite evaluation.

2. DATA ACQUISITION AND THE RESOURCE EVALUATION PROCESS AT EKATI

2.1 Definition of terms

Comprehensive evaluation of diamond resources is a complex process and involves numerous parameters (or resource elements), many of which differ from those required for other mineral commodities. These elements (as employed by BHP Billiton) are listed and defined in Table 3.
2.2 The resource evaluation process

A broadly similar, staged evaluation approach has been followed for most of the 150 kimberlite occurrences discovered to date on the Ekati property. The key stages in this process include:

*Discovery* – in most cases, individual kimberlites within the property were discovered based on coincident geophysical anomalies (magnetic, electromagnetic and gravity), with varying support from indicator mineral dispersion features. With the exception of a few outcropping kimberlites, initial confirmation was via core drilling. In most cases, the discovery and initial exploration holes were angled and offset from the pipe, thereby generally providing between two and four initial pierce points. These, together with information on the pipe outline derived from geophysical data, provide an initial indication of the size of the body and permit first-pass estimates of potential kimberlite tonnages.

*Early-stage evaluation* – initial exploration holes are logged and sampled for petrography, indicator mineral and microdiamond analysis to facilitate an initial evaluation of the diamond potential of the kimberlite.

*Delineation drilling* – where initial results indicate economic potential, additional delineation drilling and, in most cases, further sampling (for petrography, indicator minerals and microdiamonds) are carried out to better define the morphology of the kimberlite and to confirm its economic potential. As the evaluation process advances, additional delineation programs are generally undertaken to further constrain pipe models and to provide the basis for resource estimates.

*RC drilling and sampling* – pipes with demonstrated potential based on initial evaluation and delineation work are tested for commercial size diamonds by means of vertical wide-diameter reverse circulation drill sampling undertaken during winter from the frozen lake surface. This approach was selected as the most cost effective means of obtaining a spatially representative, adequately-sized sample of the Ekati Kimberlites, most of which occur under lakes and, therefore,
are not readily accessible to surface excavation. The diameter of drill holes employed historically ranges from 27 to 71 cm, but from 1995 onwards, the hole diameter was standardized to between 31 and 35 cm. Logistical difficulties precluded cost effective drilling and sampling of wider RC holes from the lake surface. The final spatial density and distribution of RC drill holes varies considerably and depends on a number of factors including pipe size, geological complexity and grade characteristics relative to economic cut-offs (Table 4).

Drill material was composited over 30 m intervals to provide samples typically ranging from 5 to 9 tonnes. This sample configuration was chosen to ensure that the majority of samples yielded at least 30 diamonds (to mitigate the effect of variable diamond particle size) while still providing a reasonable degree of vertical spatial resolution (increased sample size would require longer samples that severely limit the resolution obtainable). Notwithstanding the above, the size of individual samples is relatively small and results in a high inherent nugget effect, typically ranging from 30 to 80% of the total sample variance. In general, an initial 100 to 200 tonne sample is taken from each prioritized kimberlite pipe and, if encouraging results are obtained, more extensive sampling campaigns are undertaken (Fig. 1) to provide sufficient grade and diamond value data to support classification of resources at indicated and measured levels. BHP Billiton reports its resources according to the current (1999) version of the Joint Ore Reserves Committee classification system (JORC).

*Underground excavation and sampling* – in the case of the Panda and Fox kimberlites, underground drifts (and raises in the case of Fox) were excavated into the pipes, primarily to provide important additional information on the size distribution and value of the diamonds. The underground samples yielded large diamond parcels (> 2,000 carats) for valuation purposes and, due to the large sample sizes (ca. 40 to 70 tonnes each) and very close spacing of samples (ca.
3 m), provided key data on the effect of increased sample support on grade statistics and on spatial continuity of diamond grades.

Following initiation of mining, on-going evaluation work is undertaken with both delineation and RC drilling typically carried out from within the open pit. This generates critical data for evaluation of the lower portions of the ore bodies that are less accessible to drilling from surface and permits drilling of wider diameter RC holes providing better spatial resolution of grade data (smaller sample intervals corresponding to planned benches or levels). The latter is particularly important where significant vertical changes in geology and/or diamond grade occur over scales of less than 30 m (e.g. Koala, see below).

2.3 Diamond recovery, tonnage and sample grade estimation

All samples are processed through a 10 to 25 tonne per hour DMS plant and an X-ray and grease table diamond recovery circuit with an effective lower diamond size cut-off of approximately 1 mm. Direct determination of the density of RC kimberlite samples is not possible due to the loss of ash and silt sized material during drilling and sample collection. Sample tonnes are therefore estimated based on measured volumes (derived from detailed down-hole caliper data) and bulk density for the appropriate kimberlite type / phase and level in the pipe estimated based on core samples (see following Density modeling section). Sample grades are determined based on the measured total weight of + 1 mm diamonds recovered and estimated sample tonnages. The samples incorporate xenolithic material intersected by the RC drill holes, as a result, internal dilution of the resource (generally < 10 %) is accounted for in the RC sample grade data. Plant recovery factors have been developed for specific kimberlite types to account for differences in lower screen-size cut-off and plant configuration between the sample and production processing plants. The recovery factors are based on partition curves and plant audit data. The plant recovery
factors are applied to resource grade estimates when converting to reserve grades (i.e. recovered grades).

2.4 Quality control

The sample collection process is designed to ensure that a representative, unbiased and uncontaminated sample is collected intact at the drill. A closed-loop circulation system was introduced for undersized material and water. This allowed larger and deeper holes to be drilled as the drill hole wall could be conditioned with products that prevented the walls from collapsing prior to reaching the target depth. Density tracers are used to monitor and adjust the density of the heavy medium in the DMS plant and ensure efficient recovery of heavy mineral concentrates from grade samples. To control the effectiveness of diamond extraction, the tailings concentrate fractions have been audited for missed stones with an additional X-ray pass and a double grease table pass. Hand sorting is an efficient method of diamond recovery from concentrate and concentrates are routinely double picked (by different sorters). Third pass auditing has been useful to confirm hand sorting efficiencies.

RC drilling has been noted as a potential source of stone damage from the bit itself or high-pressure transport around sharp corners. However, diamond population studies of parcels from RC samples and mine production indicate no additional stone damage associated with drilling.

3. RESOURCE GEOLOGY

Reliable resource estimates are founded on a clear understanding of the geology of the kimberlite ore body. This understanding is reflected in geological models that form the framework for resource evaluation and provide the basis for selection and application of specific evaluation methods. In this section, the geological characteristics of kimberlites on the Ekati property are
briefly reviewed and the modeling of kimberlite pipe shells and internal geology are discussed, with specific emphasis on implications for the resource estimation process.

3.1 Overview of kimberlite geology

Geological setting and age

To date, 150 kimberlites have been discovered at Ekati. They range in age from ca. 45 to 74 Ma (Creaser et al., this volume) and intrude Archean metasediments and granitoids of the Slave Craton. No Phanerozoic cover rocks are currently preserved but fossil-bearing sedimentary xenoliths attest to the presence of late Cretaceous and early Paleocene sediments at the time of kimberlite emplacement (Nassichuk and Dyck, 1997; Sweet et al., this volume). The geological features of the Ekati kimberlites are discussed by Nowicki et al. (this volume).

Internal geology

Most of the Ekati kimberlites take the form of pipes, usually with the steep (75° to 85°), inward tapering sides typically associated with volcanic diatremes. In detail, however, pipe morphologies are highly variable and features such as outward dipping (overhanging) side walls, and elongate and irregular, often fault controlled, pipe geometries are common (Fig. 2). The kimberlites are mostly small with surface areas generally not exceeding 5 ha (mostly range from 0.2 to 3 ha) but rare larger pipes (up to ca. 20 ha) are present. Most of the kimberlites form discrete, single pipe intrusions. One known exception to this is the Misery pipe which occurs within a complex of multiple, apparently overlapping intrusions (Mustafa et al., 2003). Where deep drilling has been carried out, pipe depths of 400 to 600 m have been established. Although the size of the pipe is considerably reduced at depth (e.g. ca. 20 m diameter of Panda at 550 m below surface) and the overall pipe morphologies become less regular, drilling undertaken to date does not provide any clear evidence for complex root zones as described in the classic southern African kimberlite
model (e.g. Field and Scott Smith, 1998). While zones rich in country rock xenoliths / blocks are fairly common adjacent to pipe margins within kimberlites, wall rocks are typically not brecciated. Narrow (typically < 1 m) kimberlite dykes are common on the periphery of and, in some cases, adjacent to pipes but never transect / intrude them.

The pipes are overwhelmingly dominated by xenolith-poor volcaniclastic kimberlite (VK), often to depths in excess of 300 to 400 m. Tuffisitic kimberlite breccia (TKB), as defined for the "classic" southern African diatreme kimberlite model (Clement and Reid, 1989; Field and Scott Smith, 1999), is extremely rare (TKB present at Fox). Hypabyssal (magmatic) kimberlite occurs primarily as volumetrically insignificant narrow dykes, as described above. However, at a few localities (e.g. Leslie, Grizzly, Pigeon), a large proportion of the pipe is occupied by magmatic kimberlite. In the case of Leslie, this material fills almost the entire pipe with only a small remnant of probable volcaniclastic kimberlite remaining (Berg and Carlson, 1998). Drilling results to date do not provide any evidence for the presence of hypabyssal root zones.

The majority of pipes are dominated by variably bedded, fine to coarse-grained, olivine bearing, partially to extensively resedimented and/or reworked volcaniclastic kimberlite (RVK). In addition to ubiquitous, mostly small (<5 cm) mudstone clasts and scattered xenoliths of granitic (and minor metasedimentary) country-rock, variable proportions of very fine-grained, black, disaggregated mudstone are present in the matrix of these rocks. Organic material, including abundant, carbonized to fresh, coniferous wood fragments, is also commonly present. The resedimented volcaniclastic kimberlite is interpreted as pyroclastic material, originally deposited on the margin (tuff ring or cone) of the crater, that has fallen back into the pipe and undergone varying degrees of reworking and incorporation of surficial material (mudstone and plant material) (Kirkley et al., 1998; Nowicki et al., this volume). Distinctive, competent, generally homogeneous, juvenile lapillus-rich volcaniclastic kimberlite is present within many of the Ekati
pipes, typically in the lower portions of these bodies and in some cases interbedded with RVK. This material generally includes scattered mudstone and granite xenoliths but has a serpentine dominated matrix with minimal or no incorporated mudstone. It is interpreted to be of primary volcaniclastic (PVK) origin (i.e. has undergone minimal or no resedimentation or reworking).

**Diamond content**

Diamond grades for the Ekati kimberlites are highly variable and the majority of the approximately 150 known kimberlite occurrences on the property are characterized by a low microdiamond content. Approximately one-quarter of the total known kimberlites have been bulk sampled to establish preliminary grade data. The bulk sample grades range from less than 0.1 carats per tonne to nearly 5 carats per tonne (cpt). Diamond characteristics of Ekati sample populations are described elsewhere in this volume (Gurney *et al.*, this volume).

**3.2 Pipe models**

Three-dimensional wire-frame models of the pipe shell, i.e. the ore body, are constructed from geophysical data (geophysical anomalies provide indication of pipe outline at surface) and drill-hole pierce points of the kimberlite / wall-rock contact, mostly obtained from delineation core drilling. Clearly, a considerable amount of interpolation and geological interpretation is required and simplifying assumptions need to be made in order to facilitate reproducible pipe models. The final pipe shell used for the resource estimate is a “best fit” model that satisfies all constraints imposed by the drill information, is geologically reasonable, and minimises the curvature of pipe-wall segments between drill intersections (i.e. where a range of “fits” are possible, the middle case is chosen thereby neither increasing or decreasing ore volume by introducing unsubstantiated curvature/variation of the pipe wall). Nonetheless, the model is based on relatively few data
points and is clearly a simplification of the real pipe morphology. Hence a significant amount of uncertainty in pipe volume is possible.

Uncertainty in pipe volume is generally estimated using a multiple model approach involving the generation of two additional pipe models: 1) a “best case” or P10 model - the highest volume pipe model that still honours the drilling data and is geologically reasonable and; 2) a “worst case” or P90 model - the lowest volume pipe model that still honours the drilling data and is geologically reasonable. Volumes derived from these models are taken to represent the 90th and 10th percentiles, respectively, of possible resource volumes permitted by the available data. The original “best-fit” model is regarded as the median (P50) case. While this approach is unlikely to accurately reflect the true uncertainty in pipe volume, it provides a reasonable indication of the reliability of the volume estimate and the contribution of the pipe shell uncertainty to the overall risk associated with the resource estimate (see risk assessment section below). Geostatistical approaches to estimating pipe volume uncertainty are currently being investigated but, the potential for significantly improving volume uncertainty estimates by using such methods is limited by the low data (i.e. pierce point) densities available for most pipes.

Initial pipe models (generally based on 3 to 10 drill holes) are relatively crude approximations of the true intrusion shape, but provide an initial indication of the dimensions of the ore body and the potential resource volume. Further delineation work allows construction of more tightly constrained pipe models with the ultimate goal to reduce the uncertainty of ore volume estimates to less than ± 15 % (at the 90 % confidence level) for feasibility level resource estimates. However, even at this level of information, pipe models are generally substantially smoothed and, while they are adequate for open pit mine planning and construction, tighter constraints on the position of the pipe margin are generally required to permit reliable planning of underground mining operations. Thus, additional, close-spaced drilling is generally required prior to
development of underground mines. The smoothing effect of the modeling process is illustrated in Fig. 3 showing pipe models for the Panda and Koala North kimberlite pipes. The upper portion of these models is based on contact mapping and surveying in open pits developed on these bodies and clearly illustrates the irregular, often structurally-controlled outline of the kimberlites in detail.

### 3.3 Internal geological models

Internal models are constructed to separate pipes into geologically distinct phases or domains with potentially different grade and/or density characteristics that are likely to affect the resource estimate. The models are based primarily on core drill intersections of the kimberlites. The degree to which internal geological variations can be reliably modeled depends on a combination of the extent of drilling and the complexity and internal geometry of the kimberlite material intersected. In general, it is only possible to model phases that are large (i.e. dimensions significantly greater than drill spacing) and show a high degree of spatial continuity. In addition, it needs to be recognized that extrapolating geological contacts between relatively wide-spaced drill holes provides an approximation of the true character of the deposit and models require continuous updating as new information is obtained. At Ekati, internal geological models can be broadly subdivided into four categories that illustrate the interplay between geological modeling and resource estimation. These are illustrated in Fig. 4 and briefly described below.

**Internal model 1: Single domain, uniform lithology (e.g. Koala North)**

This represents the simplest case in which the pipe is dominated by a single geological domain with a uniform character throughout. At Koala North, the pipe is almost entirely filled by massive to vaguely bedded, poorly sorted RVK that displays only minor, mostly gradational localized variations in coarse olivine and xenolith content. This is reflected in the RC sample grade data by
a relatively small range in grade values and a lack of any clear spatial grade trends. While too few grade samples are available for Koala North (n = 36) to investigate directional structure, omnidirectional variograms suggest a relatively long range (115 m). However, the variography demonstrates that grade variability is strongly dominated by the nugget effect (i.e. random variation).

**Internal model 2: Single domain, complex lithology (e.g. Panda)**

In this case, the kimberlite infilling the pipe shows a high degree of geological variability, associated with complex pipe infill processes (predominantly reworking of varied pyroclastics intermixed with surficial sediments). However, the scale and geometry of geological units is such that it precludes reliable interpolation / modeling based on drill data. This is compounded when lithological units are steeply dipping as these are poorly resolved by vertical or steeply inclined drill holes. In these situations, the high degree of geological variability generally translates into highly variable local grades. On the scale of mining (e.g. on a bench scale), however, these variations are typically smoothed out and, for the purpose of estimating overall grade, the pipe can be modeled as a single domain but with a recognized high degree of internal variability that cannot be adequately resolved by available drilling data. These types of phases display a wide range of RC grade values and very limited spatial continuity (ranges < 15 to 20 m). Where lithological units are steeply dipping, a higher degree of continuity is evident down-hole (as indicated by vertical variograms) than horizontally. This is well illustrated by variography undertaken on RC and underground sample data for Panda (Figs. 5A and 5B). The RC data indicate limited, relatively long range vertical continuity but no horizontal structure on the scale of drilling. The reason for this is well illustrated by the underground sample data, generated from significantly larger samples taken at short intervals along a nearly horizontal drive excavated into the Kimberlite (see data acquisition section above). These data yield a well-defined
spherical variogram with a considerably lower nugget effect but a short range (30 m) suggesting very limited horizontal grade continuity.

*Internal model 3: Two domains (e.g. Pigeon, Fox, Sable)*

Geological models involving two major domains are common at Ekati. Each domain can be internally simple or complex and, within each, the same considerations outlined above for models 1 and 2 apply. In most cases, the domains display different grade and/or density characteristics and, from a resource estimation perspective, it is critical to treat each separately. There are examples where despite an apparent distinctive and mappable geological change, the grade characteristics of the domains do not differ significantly (e.g. Lynx and Beartooth).

*Internal model 4: Multiple domains (e.g. Koala)*

More complex, multi-domain kimberlite models are less commonly applicable at Ekati, largely because the pipes are relatively small and the drilling density and hole angles do not facilitate reliable modeling of small, irregular geological units, particularly where these are steeply oriented. The Koala pipe is a notable exception where multiple domains are present and occur as a series of horizontal to sub-horizontal geological units that are readily identifiable in drill intersections. These are interpreted to reflect distinct phases of pipe infill with lithological differences reflecting varied depositional processes (e.g. gravity driven mass-flow; settling of fine sediment through water; possible direct air-fall deposition) and possible multiple phases of eruption (Nowicki *et al.*, this volume). Variation in diamond content is closely correlated with these lithological variations and reliable resource estimation requires separate sampling and grade modeling of each domain. Nearly barren units may be distinguished from moderate to high grade units directly impacting mine planning and material handling.
Regardless of the specific geological model, reliable resource estimation requires that each domain present is sampled in an independent and spatially representative fashion. Because sampling is carried out by means of vertical drill holes, to achieve a given degree of confidence, a higher drilling density (closer spacing) is required for domains with steeply dipping internal geometry (greater horizontal variability) than is necessary for horizontally or sub-horizontally stratified domains. However, resolution of vertical grade variations in such stratified bodies is hampered by the relatively long sample interval and, in these cases, sampling with wider diameter drill holes (e.g. 45 cm) and shorter sample intervals is preferable.

4. DENSITY MODELING

Density models are required to estimate resource tonnes (based on pipe / domain volume) and also for estimation of RC sample tonnes. The models are generated from measured density values for a large number of drill core samples. The laboratory method for determining the dry bulk density of kimberlite core samples was refined by independent study to provide consistent results specifically for the volcaniclastic kimberlite encountered at Ekati. This is characterized by low degrees of compaction (at shallower levels) and significant proportions of mud, fine-grained ash, unstable mineralogy (highly susceptible to weathering) and swelling clay which can result in samples that slake easily when immersed in water.

The density of the wall-rock material is modeled with a suite of at least 50 to a maximum of 200 spatially representative density determinations to provide a reliable mean density value. For example, a model density of 2.73 dry metric tonnes per m$^3$ is used for the granodiorite surrounding the Panda-Koala-Fox kimberlite cluster.
Density models for kimberlite domains are more complex and several different approaches have been implemented at Ekati. These are largely driven by the internal lithological complexity of the kimberlite but take into consideration the minimum size of the selected mining unit (block) for which a confident tonnage forecast is required. For kimberlite lithologies that are relatively homogeneous (e.g. mudstones, siltstones, sandstones, volcaniclastic varieties of uniform olivine content, and magmatic kimberlite) mean densities are typically based on a minimum of 50 declustered samples within the domain.

Burial and compaction of volcaniclastic kimberlite results in a systematic and significant increase in density with depth in the pipe (Fig. 6). Thus, where a geological domain extends over a wide depth interval, it is necessary to subdivide it further into appropriate horizontal density domains. The use of geostatistics in providing local density estimates is currently being investigated.

5. GRADE MODELING

A number of different grade estimation approaches have been followed at Ekati. For any specific kimberlite ore body, the method of grade estimation is chosen based on the amount and spatial distribution of sampling information, statistical and geostatistical characteristics of the available grade data and the geology of the kimberlite / domain being evaluated. As mentioned above, the RC samples used for grade estimation are relatively small and generally result in a high intrinsic nugget effect. In addition, most geological domains display a high degree of local variability. Where this variability reflects the presence of discrete lithological units with distinctly different grade characteristics, the potential for interpolation of local grade data is limited, particularly where the dimensions of these units are not well constrained (i.e. not resolved by geological modeling). In these situations, estimation of local grades requires a high horizontal sample density and / or a narrow sampling interval (to provide improved vertical resolution).
is not available, and where variography indicates an absence of spatial structure in the grade data, global grade estimates are generally applied.

5.1 Global grade estimation methods

Estimators that have been used to derive global grades for kimberlite domains include the mean, geometric mean, Sichel's t-estimate and the median of the relevant RC sample grades. The choice of estimator is primarily a function of the statistical distribution of RC grade values. In cases where RC grades are approximately normally distributed (e.g. Beartooth, Fig. 7), the mean of the sample grades is expected to provide the most reliable estimate of global domain grade. More commonly, RC grade values are positively to strongly positively skewed. In these cases, either the geometric mean or Sichel's t-estimate are used. For grade distributions indicating multiple populations that cannot be separated into spatially coherent groups (i.e. geological units represented by grade populations occur on a scale that is too small to be resolved by the RC or delineation drilling), parametric statistics such as arithmetic and geometric means are not considered appropriate and the median grade value is used as the best approximation (least potential bias) of the overall domain grade.

5.2 Local grade estimation methods

Where sampling density is sufficient and spatial structure is apparent in the grade data (e.g. Misery, Fig. 8), local estimation methods are employed. Interpolation of sample grade values is generally carried out by ordinary kriging. However, for kimberlite domains with apparent multiple sample grade populations (Fig. 9), indicator kriging methods may be more appropriate than ordinary kriging and application of such methods to resource grades in similar domains of other pipes is currently being investigated. Interpolated grade values are represented in block models that are configured based on the geological factors and grade distribution characteristics.
5.3 Block modeling

Regardless of the estimation method used, all grade estimates are represented as numerical block models. Block dimensions of 30 x 30 x 30 m are generally used and are governed largely by RC sample length and drill hole spacing. Depending on the grade estimation approach taken, block grades are either initialized to global (domain) values or are kriged. Where geological phases have been delineated, these are incorporated as hard boundaries in the block model.

Variographic analysis of the grade data shows that, despite the relatively small sample size, reasonable spatial structures are generally obtained within geological domains. The nugget effect from RC samples ranges from 30% to 80% with the lower nugget effects apparent in the decline sampling (e.g. Panda, Fox). Variogram ranges are about 30 m to 120 m horizontally, and about 100 m to 150 m vertically.

The sample search radius for kriged models is typically equal to or slightly wider than the maximum variogram range. The influence of grade outliers may be mitigated by reducing the interpolation distance for these samples during kriging. Samples with highly anomalous grade values are investigated for impact of large stones. Block grade estimates are validated by analyzing the kriging error and efficiency, by comparing descriptive statistics for sample grades to those of block grades and by comparison of bench sample mean grade with the bench block mean grade.

The block models are re-blocked to dimensions appropriate for mine planning and optimization purposes, in most cases 15 x 15 x 15 m. All pertinent information is systematically documented as metadata to ensure repeatability of the resource estimate.
6. ASSESSMENT OF UNCERTAINTY OF RESOURCE ESTIMATES

Two approaches have been taken to assessing the risk / uncertainty of resource estimates for Ekati kimberlites. Firstly, uncertainty in the key resource variables, i.e. global ore value ($/tonne) and total resource value ($), is assessed using Monte Carlo simulation, a statistical approach that models uncertainty in the key output variables based on probability models constructed for the required input variables (i.e. grade, volume, bulk density and diamond value). The probability models for input variables are based on sample data (for grade and density), pipe modeling (for volume, see Pipe models section above) and, in the case of diamond value, on statistical modeling of value data for large diamond parcels (e.g. Panda-only production data).

In addition to the Monte Carlo approach, uncertainty in both local and global grade has been investigated using conditional simulation. Conditional Simulation (CS) is a geostatistical approach to modeling that attempts to reproduce the range of grades present in the sampling data as well as the spatial variability described by the variograms. Instead of producing a single, average case model, CS produces a number (typically 20 to 200) of equiprobable spatial grade models (Fig. 10), based on close-spaced nodes. The range displayed by the CS models gives a direct indication of grade uncertainty in a spatial context within the pipe, thus providing an ideal platform for assessing risk on a spatial basis and for defining forward work programs to address the risk.

6.1 UNCERTAINTY AND RESOURCE CHARACTERISTICS

The economic pipes at Ekati have undergone a phased approach to project development. Phased acquisition of resource data (in this case primarily by drilling) progressively reduces uncertainty and moves a speculative economic pipe from concept to pre-feasibility then feasibility, and
ultimately a decision to develop. As previously shown, the main sources of risk relate to
geological and associated grade factors and these are generally mitigated by increasing the spatial
density of delineation and RC drill holes. As a minimum, confident evaluation of the feasibility of
a kimberlite deposit requires that sampling of the deposit is spatially representative, that
delineation drilling provides a high degree of confidence that no significant unsampled domains
are present, and that a large enough diamond sample (generally several thousand carats) has been
obtained to provide reliable indication of average diamond value. Beyond this, the level of
information required to lower the resource risk to an acceptable level is dependent on the number
of domains present and their geological and grade complexity and, importantly, the relationship
between the ore value ($/tonne) distribution within each domain, as indicated by sampling, and
economic cut-offs specific to the deposit in question. This relationship between “resource
complexity” and the level of information required to establish feasibility of a deposit can be
qualitatively illustrated with reference to a number of specific scenarios at Ekati (illustrated
schematically in Fig. 11):

*Low resource complexity* (e.g. Panda, Koala North) – these are pipes in which the kimberlite
domains present either shows relatively uniform grade distribution or, in the case of internally
complex domains, show grade and value ranges that predominantly exceed economic cut-offs. In
these deposits, stockpiling low value kimberlite to avoid displacing higher value material is not
required, no waste domains of kimberlite or non-kimberlite are defined within the pipe and, while
minor proportions of mud rich and host rock xenolith material (i.e. diamond poor) are present,
they are accounted for as geological grade dilution and do not require delineation and separate
handling or treatment. The amount of information required to provide acceptable levels of risk in
tonnage, grade and value estimates is relatively low and, in most cases, local estimates are less
critical than in the case of more complex examples.
**Moderate resource complexity** (e.g. Lynx, Sable, Misery) – these pipes exhibit some form of grade or geological complexity within the deposit that inhibits using a single domain model for grade estimation. Geological grade complexity has contributed to downgrading the confidence in a portion of the resource available but significant volumes of kimberlite waste (below grade cut-off) or marginal grade (stockpiled) kimberlite are not present. The variance in tonnage, grade and value has been reflected in the level of confidence in the estimation and, in general a higher level of information is required to take them to feasibility level than is the case for the pipes of low complexity described above.

**High complexity** (e.g. Pigeon, Koala, Fox) – these pipes exhibit one or more of the following geological and grade complexities discovered during evaluation that require forward work programs to lower the resource risk to an acceptable level. Deposit complexity has contributed to downgrading the confidence in a portion of the resource available. Either kimberlitic or non-kimberlitic waste domains are present within the pipe that require selective mining techniques and that are excluded from the resource. A portion of the deposit contains marginal value ore that may be stockpiled dependent on the value of the blended feed at the time of extraction. These are higher risk projects that require more extensive evaluation programs than those discussed above. If the risks are appropriately managed, however, these deposits are expected to deliver significant value.

**7. SUMMARY AND CONCLUSIONS**

Resource evaluation of diamondiferous kimberlite is typically initiated when a drill hole intercept is analyzed and significant microdiamonds and diamond-inclusion type minerals are recovered. If prospective, a kimberlite body is evaluated further using a staged exploration approach,
involving mostly drilling in the case of Ekati. The aim of this work is to obtain sufficient data to construct various models that appropriately define the deposit resource.

In order to adequately evaluate the diamond resource, reliable models are required for pipe volume, internal geology, density, diamond grade and diamond value. Uncertainty in these models is linked to a combination of geological complexity and the amount and quantity of data available. The level of uncertainty is reflected in the classification of the resource into appropriate categories (i.e. pre-resource, inferred, indicated and measured). In addition to appropriate classification of the resource, it is critical that the estimation approach taken for any given ore body or domain is appropriate for the level of information available and the geological character of the kimberlite being evaluated.

The geological characteristics (pipe morphology and internal geology) of kimberlites at Ekati are highly varied necessitating a range of resource estimation approaches. In addition, resource estimation methodology is typically constrained by the small size of available samples, their limited vertical spatial resolution and a relatively low sampling density. However, careful characterization of internal geology and thorough statistical and geostatistical analysis of available data (including risk analysis using Monte Carlo and conditional simulation methods) has permitted selection of appropriate resource estimation methods as well as a recognition of the degree of uncertainty associated with the estimate. The risk associated with a particular resource estimate reflects this uncertainty but also takes into consideration the relationship of estimated possible ore value ranges to economic cut-offs. Reducing risk to acceptable levels at the resource estimation stage is critical for identifying and realizing the maximum value of a deposit and forward work programs are carefully formulated to address key areas of uncertainty identified by risk analysis.
Evaluation work carried out at Ekati over the last decade has highlighted the difficulties associated with estimation of diamond resources in these complex ore bodies in a very challenging physical environment. It has also shown, however, that a pragmatic approach, based on a sound understanding of the geological characteristics of the ore bodies, an appreciation of sampling limitations, careful assessment of available data and application of appropriate estimation methods, can lead to highly effective evaluation of resources as well as identification of key risks to be addressed by forward work.

8. ACKNOWLEDGEMENTS

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9. REFERENCES


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Fig. 1. Cutaway view of a pipe illustrating RC drill hole horizontal spacing of 25 m with 30 m down hole sample spacing. Grade samples are represented by spheres scaled for grade.

Fig. 2. Five solid rendered wire frame models illustrating the variation of size and shape among the Ekati kimberlite pipes.
Fig. 3. Panda and Koala North pipes illustrating the smooth interpretation versus the rougher as-mined solid model.

Fig. 4. Idealized vertical sections illustrating the four generalized internal geological models of Ekati kimberlite pipes.
Fig. 5A. Down hole (-90°) normal scores continuity variogram calculated from Panda RC drill hole grade samples. Maximum range is 120 m.

Fig. 5B. Down hole (-7°, 020°) variogram calculated from Panda Decline grade samples. Maximum range is 28 m.
Fig. 6 Scatter plot of bulk density sample values plotted versus elevation within a pipe.

Fig. 7 Beartooth histogram of RC sample grades for carats per tonne; an example of a normal sample population distribution.
Fig. 8 Down hole omni directional normal scores variogram of Misery RC sample grades. Number of samples = 133. Lag distance 30m with intial offset of 5m. Nugget value of 0.090, first spherical model at 0.566 at a range of 125m second spherical model at increment of 0.344 at 240m.

Fig. 9 Panda histogram of RC sample grades for carats per tonne; an example of multiple sample populations.
Fig. 10 Six plan view levels through a pipe with 2.5 x 2.5 m nodes. Darker nodes indicate higher grade, with indistinct clustering of higher grades in half of the pipe. Each nodes is the average value of 25 conditional simulations chosen at random and plotted on a graph of grade with depth increasing to the right to quantify resource risk.
The individual simulations are more tightly clustered in the upper levels of the pipe, and become more scattered in depth, reflecting the decline in sample density.

Fig. 11 Schematic qualitative relationship between resource variability (complexity) and sampling (drilling) density. The smallest and least variable deposits have tolerable resource risk in terms of estimation of the in situ value. The larger and more variable a deposits require significantly more resource management to mitigate risk.