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GEOLOGY AND EVALUATION OF KIMBERLITE DYKES AT KOIDU, SIERRA LEONE

Moss* S[1], Nowicki T[1], Hetman C[2,3], Freeman L[2], Abedu B[2]

[1] Mineral Services Canada, Vancouver, Canada; [2] Koidu Holdings S.A., Freetown, Sierra Leone; [3]currently with Northern Superior Resources, Sudbury, Canada

INTRODUCTION

Kimberlite dykes are a common feature in kimberlite fields being mined for diamonds around the world. While the focus of most kimberlite exploration is on discovery and evaluation of more voluminous pipe systems, dykes can represent significant resources for diamonds and, in the right circumstances, can be profitably exploited. However, kimberlite dykes present a unique set of challenges in efforts to constrain resource volumes and diamond grades. The high surface area to volume ratio of dykes implies the requirement of significantly more drillholes (and, thus, cost) to define and constrain modelled volumes and tonnes using conventional methodologies. Moreover, many kimberlite dykes are geologically and structurally complex, and are not single sheets of uniform thickness, but occur as arrays of closely-spaced, bifurcating, or anastamosing segments with variable thicknesses or as locally discontinuous, en-echelon dyke segments.

Here we briefly describe the geology of kimberlite dykes at Koidu Kimberlite Project, Sierra Leone and discuss some of the challenges attending measurement of geological properties from kimberlite dykes for mining purposes. First, dyke thickness data collected from a series of kimberlite dyke “zones” at Koidu by means of surface mapping and from drillhole intersections are presented. Second, we discuss the potential implications of dyke geology properties on resource evaluation. We then suggest a three-component approach to modeling the location and volume of dykes, incorporating observations of dyke properties from surface mapping, drillhole intersections, and variography.

GEOLOGY OF KOIDU DYKES

The Koidu kimberlite field lies in eastern Sierra Leone, and is part of a Jurassic age province of kimberlites within the Man Craton, which extends from the 154 Ma Droubja

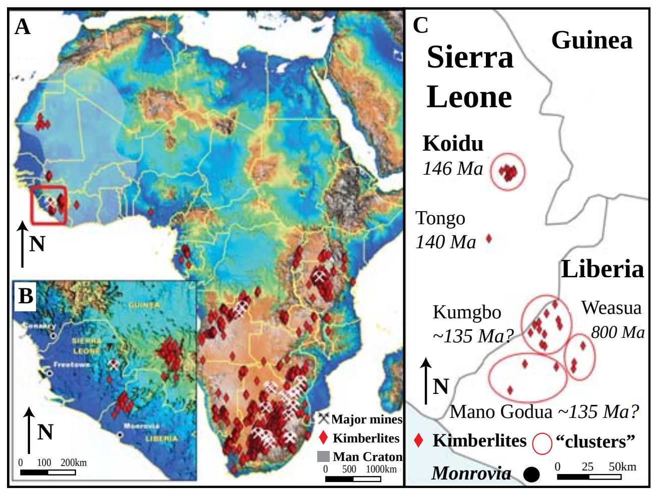

Figure 1: Regional maps showing location of Koidu kimberlite field: (A) map of Africa indicating continent-wide kimberlite occurrences; (B) map of west African nations with kimberlites; (C) map of Jurassic age kimberlites within the Man Craton (modified after Skinner et al., 2004)

kimberlite in southeast Guinea, includes the ±146 Ma bodies at Koidu, and then extends southwards to the ± 140 Ma bodies at Tongo, Sierra Leone (Skinner et al., 2004; Figure 1). The Koidu kimberlite field comprises two main kimberlite pipes, K1 and K2, and a series of sub-parallel, vertical dykes and adjoining blows (Figure 2a). For the purposes of geological modelling, 4 main dyke zones are identified at Koidu (DZA, DZB-W, DZB-E, DZC). These are defined as near-vertical complex dyke structures consisting of one or more parallel sheets in relatively close proximity (i.e. within 10 m across strike). The dyke zones collectively have an overall NE strike (058 to 075) and are modelled as extending ~ 2.4 km along strike but are known to extend up to 10 km in length. The dyke zone drillhole intersection data and geology model properties are provided in Table 1, and the distribution of drillholes indicated in Figure 2b. Each dyke zone consists of one or more sub-parallel kimberlite sheets of variable width (< 10 cm to

10 m) and interstitial country rock content (mostly granite) (Figure 2c). Separate segments are modelled for sections of

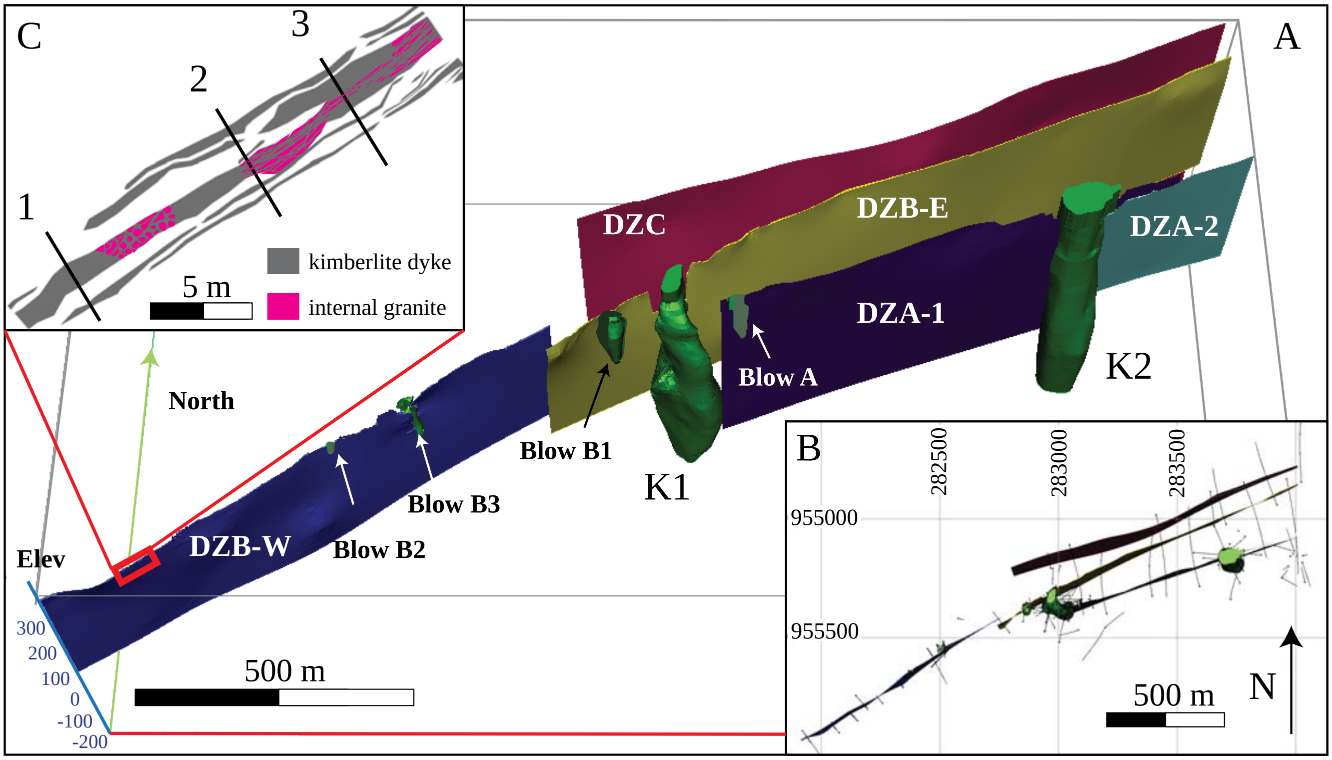

Figure 2: 3-D geological models of Koidu kimberlite bodies: (A) Inclined view from above facing north, showing the main kimberlite pipes K1 and K2, blows A, B1 and B3, and dyke zones DZA-1, DZA-2, DZB-W, DZB-E, and DZC; (B) Plan view of Koidu dykes, pipes and blows, showing distribution of drillholes used to delineate geological models; (C) Plan view of a segment of trench mapping of DZB-W, showing multiple kimberlite dykes and stringers, with local zones of abundant internal granite. Three cross-sections (1,2,3) are indicated to highlight local differences in i) individual dyke thicknesses, ii) the number of dyke intersections, iii) the amount of internal granite, and iv) the thickness of minable width through the dyke zone at a local scale.

the dyke zones that appear to form part of the same intrusive event (i.e. similar orientation, intrusive "style" and kimberlite characteristics) but are either slightly offset, or are not conclusively connected (e.g. DZB-E, DZB-W, DZA-1, DZA-2). The main dyke zones are offset from each other by ~40 to ~175 m, and are generally continuous at surface, with only local displacement or discontinuity. Modelled dyke zone segments vary from 280 (DZA-2) to 1,310 m (DZB-East) in length. The true thickness of the thickest sheet in each dyke zone intersection (referred to as the "main dyke") ranges from 0.03 to 3.08 m, and the number of individual sheets across-strike ranges from 1 to 13. Trench mapping shows individual sheets to be generally horizontally continuous (Figure 2c), locally comprising multiple separate intrusions (Figure 3), with minor dis-continuities and complexities in the kimberlite sheets apparently associated with fractures and cross-cutting diabase dykes present in the adjoining country rock. Dyke zones are commonly cross-cut by the blows and pipes at Koidu, but in certain cases they also intrude these bodies indicating complex temporal relationships. Macroscopic textures observed in hand samples, field outcrops and pit exposures show that there is significant internal variability with respect to olivine content, specifically the size and proportions of olivine crystals larger than 1 mm (Figure 3d). Thin section petrography reveals minimal variation in groundmass mineralogy and texture within each dyke zone. The different dykes zones are also petrographically very similar, although subtle variations in the relative abundances, sizes, crystal habits and textures of groundmass carbonate, phlogopite and spinel are evident. Internal country rock dilution within the majority of sheets is generally low (<5 %) but can be locally variable, and in situ country rock between dyke sheets within a typical minimum minable stope width (~0.80 m) can be much higher (> 60 %).

Table 1: Summary of drillhole intersections and model properties of Koidu kimberlite dykes

Dyke Zone	Mean dyke azimuth	Mean dyke dip	Strike length (m)	Depth (m)	Drillhole intersections	Mean dykes per intersection	Mean true thickness of main dyke
DZA - 1	72.1	85.5	775	500	9	6	0.57
DZA - 2	69	86.5	280	355	3	3	0.76
DZB-E	63.3	86.8	980	325	12	3	0.89
DZB-W	53.5	83.4	1310	370	24	6	1.2
DZC	64.4	87	1260	555	8	1	0.64
Total for Koidu dykes					56	4	0.74

RESOURCES ESTIMATION CHALLENGES

To estimate a resource from diamondiferous kimberlite bodies, it is necessary to develop reasonably confident

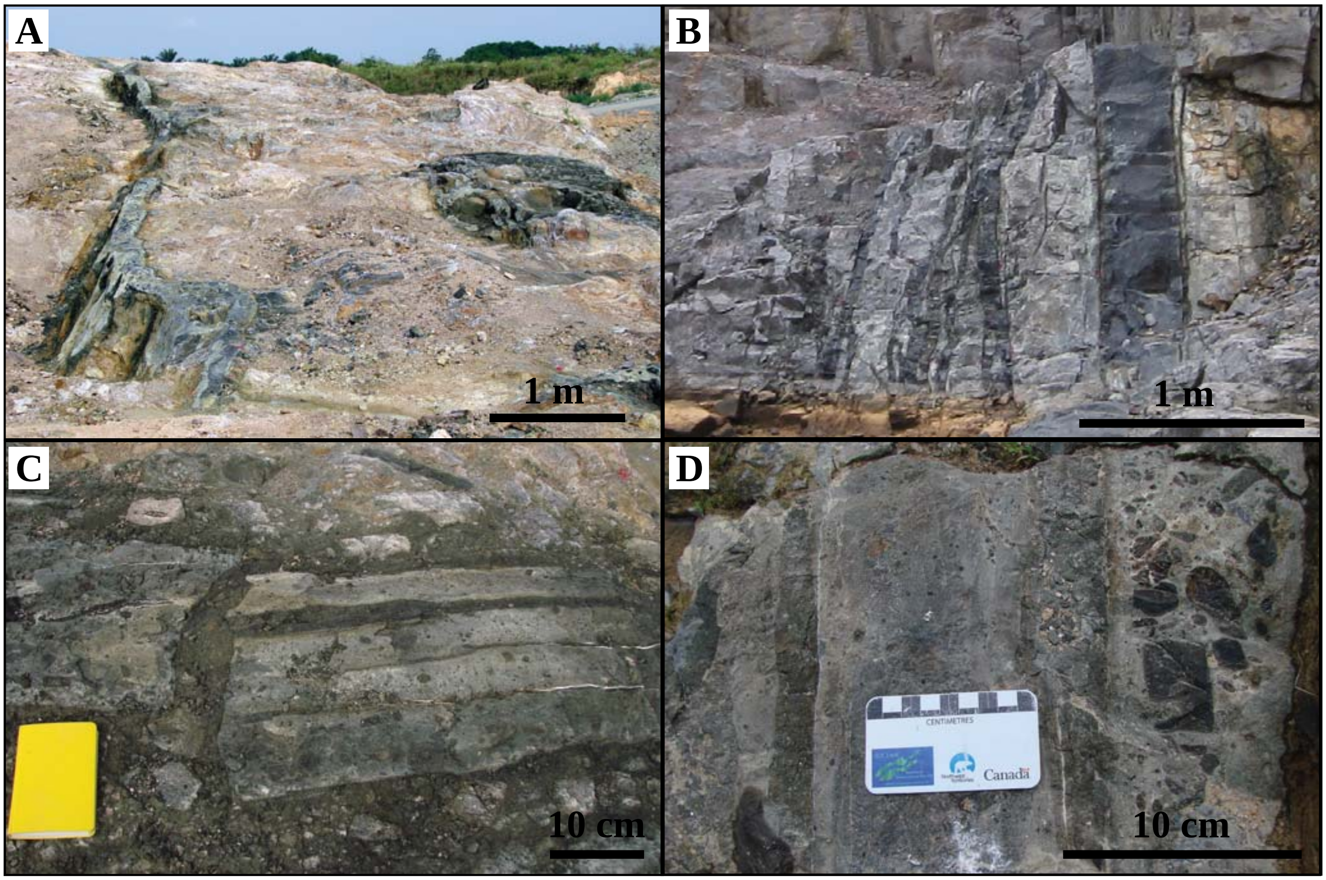

Figure 3: Photographs showing aspects of the geology of Koidu kimberlite dykes: (A) view facing southwest along DZB-E, showing variable dip and position of dyke, and adjacent Blow B2; (B) main kimberlite dyke and adjacent anastomosing stringers; (C) complex dyke comprising multiple, cross-cutting kimberlite intrusions, and country rock-rich margins; (D) internal complexity of a single dyke, comprising multiple intrusions with variable amounts of mantle-derived olivine and other xenocrysts and xenoliths.

estimates of the volume of kimberlite, diamond grade (typically in carats/tonne), and rock density. The variability in observations described above results in significant challenges in estimating the location and mineable thickness of kimberlite dyke material over an area of interest for the volume component of resource estimation. There are several aspects to this. First, the local discontinuity of the sheets within dyke zones and observed variations in strike and dip over small scales (e.g. Figure 3a) limit the confidence of projections of the dyke surface away from known points (drillhole intersections and surface exposures). Second, variations in the thickness of the main dyke as well as the number of peripheral sheets that could (e.g., Figures 2b, 3b) potentially be included in an economically viable mining width, limit the confidence in projections of dyke zones widths away from known points and complicate the definition of the width of mineable resource at any given point. Moreover, distinguishing between internal dilution and country rock in-between two or more sheets of kimberlite can be difficult based on drill core, and assumptions made on the basis of these interpretations can have significant implications for kimberlite volume estimates. Third, the internal geological variability within a single sheet (e.g., multiple intrusions, sorting of mantle load, country rock dilution; Figures 3c, 3d) can limit the confidence in geological and grade continuity between known intersections.

VOLUME ESTIMATION APPROACH

Given the implications of the above-described variability on assumptions of the extent, position, thickness or continuity for dyke projections, any approach to volume estimation for use in resource evaluation must take these factors into account. We suggest that observations of dyke properties from surface mapping, drillhole intersections, and variography can be used to aid in generating preliminary resource volumes and to identify areas of low confidence requiring further investigation for use in resource estimation of complex dyke arrays such as those observed at Koidu.

Below, we describe an approach to modeling a resource volume for dykes comprising three aspects: (1) modelling the spatial extent of the dyke zone; (2) estimating confidence levels for the exact location of the dyke zone; and (3) evaluating and estimating dyke thickness.

Spatial Extent

The first component comprises constructing a model surface to represent the best interpretation of the location and limits of the dyke using drillhole intersections and surface exposures as constraints. The model should take into consideration information on the character and continuity of the dyke based on surface mapping (if available) and possible controls that can be inferred from the structure of the host rocks. The model can also be spatially-constrained by evaluation of dyke continuity within and between known intersections by macroscopic drillcore logging, petrography and, if possible, indicator mineral data. This evaluation can help to define the spatial limits of a geologically-continuous dyke. The resulting model provides an indication of the surface area of the dyke segment being modelled and forms the basis of the resource estimate. Because of the effective 2-dimensional character and broad-scale continuity of many dyke systems, the surface area of the dyke system can generally be constrained at a reasonably high confidence level.

Dyke Zone Location

A second component is to estimate the degree of confidence that a model surface will represent the exact location of the dyke at any given point in space. In the absence of detailed surface / underground mapping data or an unusually uniform dyke system, it is not possible to precisely constrain the dyke location over the full extent of the area being estimated. The degree of uncertainty is dependent on a combination of the complexity of the dyke zone (e.g., variability in strike and dip, number and extent of off-sets, lengths of individual dyke segments, etc.) and the amount of information available. This uncertainty can be represented by modelling a zone around the "best-fit" dyke surface model within which the dyke is expected to occur with a high probability. In areas close to data, this zone will be narrow, but with distance from known intersections, it will broaden to reflect the interpreted uncertainty in the dyke location. Studies of mapped dyke segments, including geostatistical approaches, can help to constrain how the width of the "high-probability zone" should change with distance from known dyke intersections.

Dyke Thickness

The third component of the resource estimate involves evaluating and estimating dyke thickness. In combination with the surface model described above, this allows for calculation of the dyke volume and, based on measured bulk density, resource tonnage. Evaluating and estimating dyke thickness is multifaceted, and there are two aspects that need to be dealt with: a) how to model variations in dyke thickness across the extent of the dyke, and b) how to estimate optimal mining thickness where multiple kimberlite sheets are present in the dyke zone.

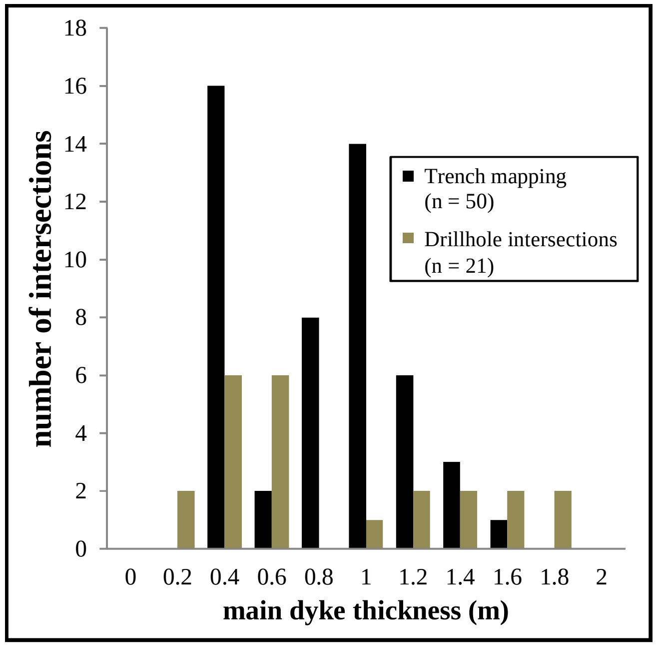

Figure 4: Histogram of the true thickness of main dyke based on trench mapping and drillcore intersections of DZB-W.

Dyke Thickness Modelling

The key question for modelling dyke thickness is how far can one confidently project dyke thickness information away from known intersection points, i.e. what are the constraints on interpolation of dyke thickness across the modelled dyke zone. Based on visual observation of dyke exposures (Figure 4), mapping and variography, the variability in dyke thickness at Koidu suggests that a given intersection point only provides constraints on dyke thickness over a maximum distance of approximately 25 m, beyond which, the thickness is not in any way constrained by the data point. This range can be used to identify areas requiring further work to improve the confidence in estimations of local dyke thickness. For example, applying a 25 m radius around every drillhole intersection and trenching area measured at surface for one of the Koidu dyke zones highlights the areas in the model of the main dyke thickness which require more thickness information (i.e., surface mapping and/or drilling) to achieve a moderate level of confidence (Figure 5). Dykes which have less variability than those observed at Koidu may have a greater range of continuity (e.g., 50 m range; Figure 5), and, thus, a larger domain of confidence with the same amount of data collected. However, it is most likely that even with relatively high dyke thickness continuity and a reasonably close-spaced drill pattern, only a small proportion of a given dyke segment can be considered to have locally constrained thickness (Figure 5). Thus, in general, we do not consider it viable to generate interpolated models of dyke thickness based on typical drill hole data and have used a "global"

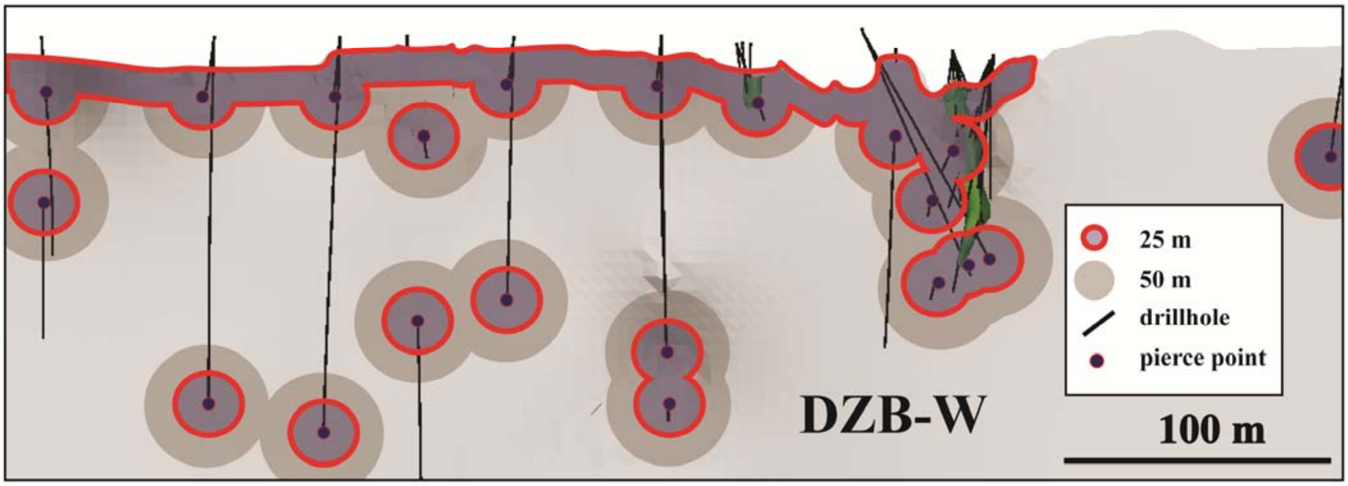

Figure 5: Profile view facing north of DZB-W 'confidence' model. Drillholes are shown as black lines, and circles of varying radii (25 m; 50 m) are superimposed over drillhole pierce points on the DZB-W 3-D model to highlight parts of the model which require further work to increase confidence in the volume estimate for resource calculation. The radius of the circles corresponds to the range beyond which there is no expected correlation with the point of known thickness. For DZB-W, the 25 m radius around 21 drillhole intersections and ~500 m of surface mapping includes ~11% of the model volume; a 50 m radius includes ~19% of the model. Areas with little no model confidence are light grey.

approach based on estimating average thickness of the "mineable kimberlite zone" over dyke segments, following statistical and spatial analysis of data to ensure no trends are present or bias introduced.

Optimal Mining Thickness

Determining the optimal mining width is complex and dependent on financial / mining criteria. Two approaches have been applied: a) definition of the mining zone based on simple criteria to maintain internal dilution below a certain cut-off (i.e. peripheral sheets only included in mining zone if the incorporation of the intervening wall-rock does not dilute the ore beyond a certain chosen threshold - e.g. 20 %); and b) algorithms can be set up based on key economic input parameters to sequentially add peripheral sheets to the mining zone up to the point where a minimum economic cut-off grade or rock value is reached. For initial dyke resource estimates at Koidu, the former approach was taken.

ESTIMATING DIAMOND GRADE

While not the main subject of this contribution, it is important to mention the significant challenges associated with estimation of diamond grade in dyke systems. Variation in diamond grade can arise from a number of factors including: the presence of multiple dyke sheets representing different kimberlite magmas with different diamond contents (Field et al., 2009; Scott Smith and Smith, 2009); and varying degrees of sorting, crystal-settling or filter-pressing within individual intrusions, leading to variations in the horizontal and vertical distributions of mantle minerals, including diamond (Dawson and Hawthorne, 1973; Field et al., 2009). In the absence of well distributed bulk sample data, which are difficult to generate for dyke systems, particularly in a vertical sense, demonstration of grade continuity in support of resource estimates for dykes can be very challenging. However, prudent use of data from drillcore logging, thin section petrography, indicator mineral studies and microdiamond analysis to evaluate geological and grade continuity, when combined with suitable bulk sampling data can in certain instances permit definition of inferred and indicated resource grades.

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