GEOLOGIC MODELLING OF COMPLEX OREBODIES: COMBINING DETERMINISTIC AND PROBABILISTIC MODELS

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ABSTRACT

In the context of mineral resource estimation, it is necessary to model the most important aspects of the deposit's geology to condition and constrain the estimation of its resources. It is unlikely that a resource model without geologic constraints would be reasonably accurate. There are many complex mineral deposits that evidence multiple geologic controls on mineralization. Birimian-type gold deposits, as well as those in the Brazilian shield, and in Nevada and in the Carolina Terrane in the United States, to name a few, often evidence a combination of structural, lithological, and/or alteration controls to mineralization, resulting in complex spatial distributions and patterns of gold grades.

Traditionally, only those controls that can be explicitly modelled are taken into account, either through interpretation on sections and plans of three dimensional shapes, as for example veins or structures, or through implicit modelling techniques of those same shapes, or of grade shells. These methods, called here deterministic, result in wireframes or solid models that are used to control the grade estimation process. But there are instances where those shapes do not encompass all of the mineralization, or consider all the mineralization controls described in the deposit, and thus what could be a significant fraction of the resource is estimated without controls, or not considered at all in the resource estimate. These controls, while difficult to model explicitly, can be represented probabilistically using geostatistical techniques.

A combination of deterministic (whenever possible) and probabilistic, or geostatistical modelling of geologic variables is proposed to improve the geologic modelling of complex gold deposits, and in doing to improve the corresponding resource estimate. An example is described from an unnamed West African gold deposit.

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INTRODUCTION

Any and all resource estimation efforts should be supported by a robust geologic model which should represent as faithfully as possible mineralization controls that have properly been identified during the exploration of the deposit. Geologic models are one of the three pillars of recoverable resource estimates (Bruna et al., 2014), and is mostly responsible for the correct estimation of mineralized tonnages. Geology is the fundamental part of any resource model and as such needs to include a high standard of data collection, interpretation and competence in geological modelling (Sterk and Reid, 2014; Bruna et al., 2014).

In some geologically complex deposits, it may be necessary to have a flexible approach to modelling, based on both traditional (wireframing or implicit modelling) and probabilistic approaches. This paper discusses the methodology and provides a successful example of such an instance.

The Birimian is characterized by the rocks to the southern part of the West African Craton and is present through Côte d'Ivoire, Ghana, Guinea, Mali and Burkina Faso. The rocks of lower greenstone facies consist of mostly alkaline granites, and metamorphosed sedimentary and volcanic sequences. The Birimian was formed over 50 million years between 2.2Ga and 2.1Ga years ago (Boher et al, 2009).

Birimian-type deposits are considered geologically complex, with multiple examples of deposits within which mineralization occur because of different and spatially-superimposed controls. For example, Allibone et al. (2002) describe the Bogoso deposit as steep pitching, high-grade orebodies located in localized left-hand dilational jogs in the strike of the controlling faults. Mineralization is hosted in graphitic mylonite and in splays, with 80% of mined gold at Bogoso derived from the main crush zone and a further 15-18% from a further dense network of faults east of the main zone. In addition, Bogoso has five mineralogically distinct styles of gold mineralization, a further indication of the complex nature of gold deposits in the Birimian.

Another example of a structurally complex deposit is Kononogo, Ghana, where numerous 'skinny' wireframes have to be used to be geologically accurate (Sterk and Reid, 2014). This becomes time consuming and complex using common 3D modelling software. There is a tendency for modelling geologists to tighten up the wireframes in order to save time and because they want to be conservative, thus decreasing accuracy. Narrow wireframes are also more uncertain, as the projection of these bodies from one section to next is highly uncertain, and therefore also decreases the accuracy of the mineral estimation.

Therefore, the use of wireframes or implicit models do not always provide the complete solution to a robust geological model, and in some cases, either for practical or for geological reasons, do not encapsulate the entire mineralized volumes that exist in the deposit. In these circumstances, it is necessary to consider hybrid geological models, partly deterministic and partly probabilistic.

METHODOLOGY

Mineral deposition is governed by complex processes, the structure of mineral deposits being partly deterministic and partly stochastic. One of two basic approaches could be used to develop a geologic model: a) a deterministic model that estimates the geological category at each location, or b) a model that provides a probability of each category at each location.

The first approach is the most common, usually modelling large-scale geological controls explicitly using triangulations or implicit modelling. The traditional and simplest method is based on two-dimensional interpretation, generally done on cross sections. Then, the resulting polygons representing the interpreted shapes are refined on a second set of longitudinal sections. Finally, the model can be refined on plan views, from which the full three-dimensional shape is built.

As an alternative, implicit modelling techniques have been in use in the mining industry for the past decade or so, although the petroleum industry has used them since the late 1980's. An implicit modeller builds a deterministic model, an alternative to wireframing, usually on the basis of being a more agile process. In all cases and regardless of the tools used, geologic modelling with extensive interpretation is always recommended, since the final geologic model will be a combination of quantitative and qualitative information, and thus requires trained professionals who understand a great deal about the geometry of the deposit.

Another approach to geologic modelling is to use a signed distance function (DF) that maps the location of boundaries and at the same time allows for an assessment of the uncertainty, in this sense being a probabilistic method. This uncertainty is represented spatially by a zone (or bandwidth) that is quantifiable and needs to be calibrated. The DF is calculated directly from individual drillhole samples coded with a distance, rather than a wireframe model. This approach is mostly applicable to binary geologic systems, with only two geologic domains, as in for example vein-type deposits.

The polygonal (or nearest-neighbour) technique assigns the geologic attribute to points or blocks in the three-dimensional space according to a fixed rule; for example, each block is assigned the geologic attribute from the drill hole data that is closest to its centroid (Stone and Dunn, 1994). It is similar to a geologist drawing the interpreted shapes, except that the computer will not use additional geologic knowledge or judgement to guide the assignment of geology in the three-dimensional space. Often, nearest-neighbour models are used to check the global volumes of interpreted models.

Indicator-based techniques describe the discrete distribution by assigning an indicator to each geologic attribute. The indicators can be kriged simultaneously (Multiple Indicator Kriging) or sequentially one at a time. In either case indicator kriging provides a probability of the geologic variable being present.

In the example shown below, a combination of deterministic (traditional wireframing techniques) and probabilistic models (Multiple Indicator Kriging) was deemed necessary to capture in the final geologic model all the mineralization controls described in the deposit. As it turned out, approximately 60% of the total Au is contained in the wireframes, with the remaining and approximately 40% in the probabilistic model, with various degrees of uncertainty.

A GOLD PROJECT EXAMPLE

The example shown here corresponds to a gold project that lies within a relatively small greenstone belt that lies within the belt of Birimian (Paleo-Proterozoic) greenstones that extend into Burkina Faso from Côte d'Ivoire. The rock types found in the district are for the most part mafic volcanic rocks with minor cherts, turbiditic meta-sediments and a fluviodeltaic formation. The volcano-sedimentary rocks were intruded by tonalite-trondhjemite-granodiorite (TTG) type plutonic rocks and undifferentiated granitoids. The greenstone belt was subjected to WNW/ESE-directed crustal shortening during the Eburnean Orogeny, but has a lower aspect ratio than similar belts in West

Africa (i.e. it is short and wide) which is consistent with its comparatively undeformed state, while a penetrative fabric is absent.

This orogenic lode-gold deposit is hosted by Early Proterozoic (Birimian) mafic volcanics (basalts), with granodiorite and mafic porphyry intrusions. The main granodiorite body occurs as a north-south trending subvertical mineralized intrusive sheet in the northern half of the deposit (Figures 1 and 2). The northern end of the deposit is unconformably overlain by an intra-Birimian basin filled with relatively un-mineralized volcano-sedimentary rocks. The basaltic volcanics are thought to be the equivalent of the middle portion of the Sefwi Group (Perrouty et al) of western Ghana which has an age of 2,174-2,154 Ma.

The deposit consists of a major north-south trending structure and a second mineralization core about 450 meters to the west of the major structure. The structure is a discrete relatively continuous zone with an average thickness of 14 meters, extending down to the east at a dip of 25 to 30°. The north-south trending zone to the west is a 500-meter-wide zone with arrays of quartz-carbonate veining and discrete structures extending down to the east at a dip of 30°. The best mineralization in this wide zone is where the structures cut a north-south trending granodiorite stock.

Geologic Controls: Stratigraphy, Intrusions, and Structures

In the southern part of the deposit the geology is dominated by mafic volcanics, much of which is pillow basalts, with lesser mafic porphyry bodies. Some of the massive basalt is possibly intrusive as sills into the pillow basalts. Volcaniclastic and mafic lapilli tuff layers occur within the basalts.

The granodiorite stock occurs in the northern half of western zone. It is sub-vertical and extends for a total of 1000 meters (750 meters at surface) with a N-S trend. This granodiorite body is altered and well mineralized with an array of mineralized quartz-carbonate veins.

Porphyry bodies occur within the volcanic sequence below the major structure to the East. The porphyry bodies on the Western zone are thought to be the hypabyssal equivalents of the granodiorite plug and at least some are a series of offshoot dykes from the granodiorite stock. Whilst some porphyry carries gold, there are numerous examples where the host basalt at porphyry contacts is altered and veined and carries significant gold values.

Gold mineralization was formed during Late Eburnian transpression and is overprinted only by minor kinking and by late brittle faulting. An Eburnian structure of particular importance is an arcuate, NE-trending regional compressional fault which was reactivated as a dextral strike-slip structure at a late stage in the Eburnian orogeny. Dextral motion along the east-north-east-trending segment of the regional fault generated a north-to-north-east-trending sigmoidal lens. The east-dipping structures observed in drill holes (Figure 2) suggest that the N–S fault branch passing through the gold deposit experienced transpressive movement.

The network of mineralized faults and fractures which host the gold deposit are located immediately south of the corner of a 10 km-scale intra-Birimian basin filled with volcano-sedimentary rocks distinct from the basaltic rocks which host most of the deposit.

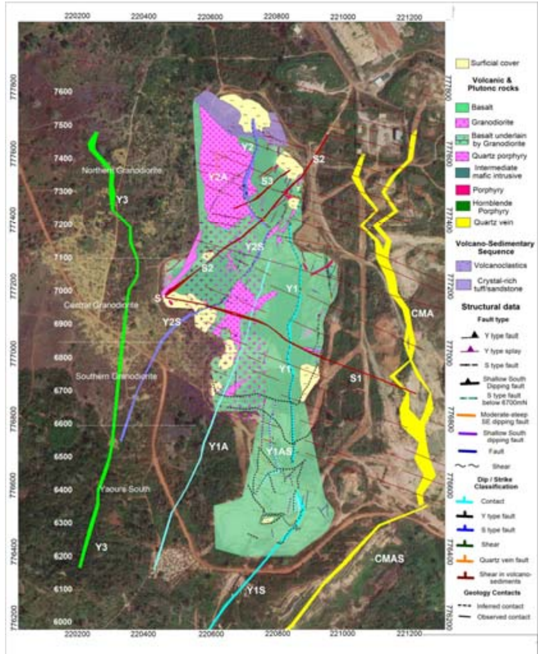

Figure 1: Map of gold-bearing structures

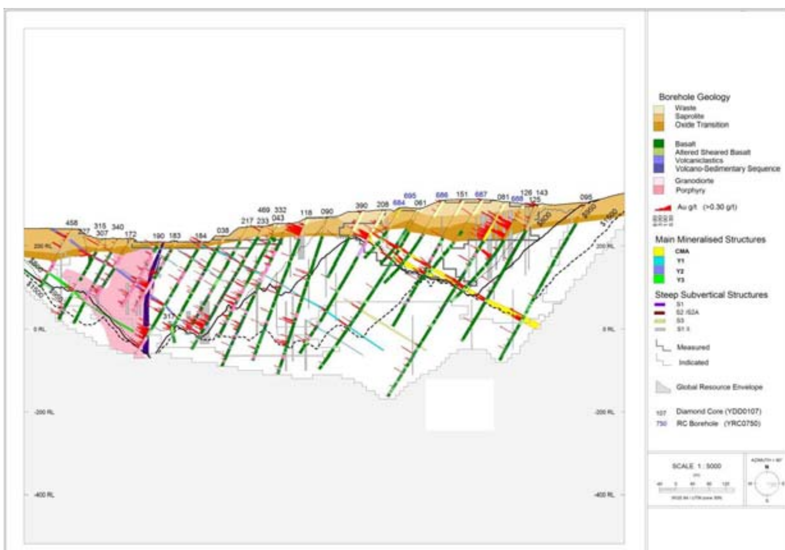

Figure 2: Example Drill Section

Geologic Data and Geologic Model

Only a handful of structures within this deposit were volumetrically significant and also continuous enough to be modelled deterministically, using wireframes derived from correlating the features from one section to the next.

Other geologic variables cannot be interpreted and modelled across cross sections with any confidence. However, they are deemed important controls of gold mineralization as indicated by geologic knowledge and statistical analysis of the correlations between gold grade and lithologic codes. These were estimated into the block model using categorical multiple indicator kriging.

The final geologic model is a combination of interpreted, deterministic solids, and a probabilistic estimation for those variables that are not continuous enough to be modelled.

Previous geologic work resulted in the definition of 145 lithologic codes. This level of detail, while perhaps appropriate for exploration, is incompatible and impractical for developing a geologic model that would support resource estimation.

Project geologists filtered and rationalized the coding system, resulting in 11 domains which are major groupings and classes derived from the original 145 codes. In addition to geologic knowledge, various statistical analyses were run to better understand the relationship between each code and its corresponding gold grade distribution and further grouped the domains into a set of 6 geologic domains that could not be modelled using wireframes. Table 1 shows the domains that resulted in the geologic model that supports the resource model.

Table Error! No text of specified style in document.**1**: Final Geologic Domains in Support of Resource Estimation

FINAL CODE	Character Code	Description	Type of Model
1	Oxides	Surface that separates the oxidized from fresh mineralization	Wireframe
2	Dumps	Old Mine Dumps	Wireframe
3	CMA	Structure	Wireframe
4	Y1	Structure	Wireframe
5	S1	Structure	Wireframe
6	Y3	Structure	Wireframe
7	QV OUT	Quartz Vein	MIK
8	CV OUT + OTH + EXT	Carbonate Veins and Extrusives	MIK
9	SH OUT+AC+FR OUT+INT	Sheared; Carbonate Alteration; Fractured Rock; Intrusives	MIK
10	AL+ALSH	Altered and Altered and Sheared	MIK
11	ALFR	Altered and Fractured	MIK

The summary of the units that support and condition the Resource Model is:

- An envelope that is used to constrain extrapolation. This envelope is a simple shape that was interpreted by the geologists on site and is intended as a limit to mineralization. All geologic domains described below exist within this envelope.
- A surface that separates Oxides from Fresh rock. Additionally, two solids representing the old mine waste dumps were used to separate a near-surface sub-unit, which are these barren dumps.
- A three-dimensional solid representing the main structure (Domain 3). This zone is very consistent across many sections, and is the most significant single structure present. Also, three other three-dimensional solids representing structures Y1, Y3, and S1. These structures are narrow, and have variable gold grades. Regardless of their gold content, these structures contribute positively to the overall geologic model by increasing the understanding of the deposit, as well as constraining grades during the estimation process.
- The remaining volume described by Domain Codes 7 through 11 in Table 1 could not be modelled explicitly, as they do not correlate well from one section to the next. MIK was first used to populate the resource block model, providing an estimate of the proportion of

domains 7 through 11 within each block. The wireframes were then used to overprint the block codes where they existed.

An example of the block model coded with the deterministic domains (codes 1 through 6) is shown in Figure 3.

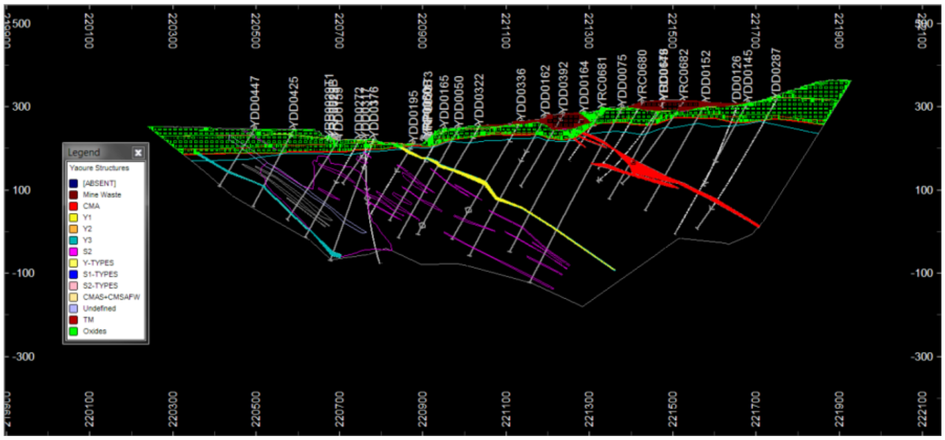

Figure 3: Cross Section showing deterministic geologic domains in the block model, including structures, weathering surfaces, and mine waste dumps

Multiple Indicator Kriging of Categorical Variables

The indicator kriging-based estimation methods are non-parametric in the sense that they do not make any prior assumption about the distribution being estimated. The objective of the method is not to estimate parameters of an assumed distribution, but directly estimate the distribution itself.

The MIK approach to estimating categorical variables provides spatial models for discrete classes or domains, such as in the case of geologic models (Rossi and Deutsch, 2014). Consider K mutually exclusive categories s_k, $k=1,\ldots,K$ within a stationary domain. These classes are exhaustive, that is, any location **u** has one and only one of these K categories assigned to it.

Consider defining an indicator for the presence ($i(\mathbf{u};\, s_k)=1$) or absence ($i(\mathbf{u};\, s_k)=0$) of any class k for each location **u**, then the kriging estimate of the indicators provides a probability of s_k occurring at that location:

$$Prob^*\{I(u;s_k)=1\,|\,(n)\} = p_k + \sum_{\alpha=1}^{n} \lambda_\alpha \left[I(u_\alpha;s_k) - p_k \right]$$

where p_k is the expected value of class k, inferred for example from the declustered data for the entire domain. The weights λ_α are solved using the indicator covariance for s_k in a simple or ordinary kriging system, which would use local averages, instead of the global mean for the entire domain, to obtain a proportion more representative of the neighborhood of location **u**.

The K categories can be defined in any order; the local conditional cumulative distribution function (ccdf) obtained from indicator kriging provides a cumulative distribution function-type (cdf) ordered set of the probability interval [0,1] discretized in K intervals. The ordering of the K categories is arbitrary and does not affect the final model.

Using MIK, the probabilistic model for domains 7 through 11 was obtained, which combined with the determinist models (wireframes) for domains 1 through 6, consisted of the full geologic model and domains for the estimation of gold resources.

RESULTS AND DISCUSSION

Geologically complex gold deposits, such as those of the Birimian belt, require some out-of-the-box thinking when it comes to modelling. Short of using some more sophisticated techniques to simulate the deposit's geology, it is necessary to use of a combination of deterministic and probabilistic geologic models in order to capture the full suite of mineralization controls, as described by project geologists. This allows for robust grade estimation, and a better quantification of the project's resources.

In all cases, it is always preferable to develop models based on geologic interpretation and the geologist's knowledge and criteria at the time of modelling. However, there are instances where a number of important controls cannot be explicitly modelled, and any deterministic model (wireframe) will either take too long (in practical terms) to develop, by highly uncertain as to the characteristics of the domain it pretends to model, or outright impossible to develop.

While the approach is not novel, combining deterministic and probabilistic models has not been used in industry as much as it should have. This is a shortcoming that this paper attempts to address, by providing an example where obvious benefits have been obtained.

Figure 4 shows a cross section of Au grades estimated within the geological model developed. Note the multiple orientations of these domains and corresponding grade estimates. Without the combination of the deterministic model (wireframes describing the Easterly dipping structures) and the probabilistic model (more steeply mineralized zones), the resource estimate would be lacking; compare to Figure 3, which shows only the structures, and thus where grade would only exist within the wireframes shown. In this particular case, the amount of gold outside the deterministic model is about 40% of total, which has a significant impact on project economics.

CONCLUSIONS

This paper has discussed the limitations that the traditional methodologies for developing geologic models have in some instances. For deposits that are geologically complex, such as many of the Birimian-type, it is nearly impossible and usually impractical to represent in a model all mineralization controls observed in the deposit. Deterministic models can under-represent the total amount of contained metal, in some cases significantly.

The main conclusions drawn from the work described are:

- Always model the mineralization controls observed deterministically (through wireframing or implicit modelling), developing the interpretations and three-dimensional solids as is traditional;

- When a number of the mineralization controls or geologic features cannot be modelled, consider the use of a probabilistic model; the model needs to be based on sound geologic data, and they need to be properly validated, most importantly, they need to reflect the spatial distribution of the attributes modelled. This may not be an easy task to accomplish, but sound geologic work in data handling and interpretation can ensure a consistent model;

- In the example described, the addition of a probabilistic model resulted in a +40% increase in resource ounces that otherwise would not have been accounted for when evaluating project economics.

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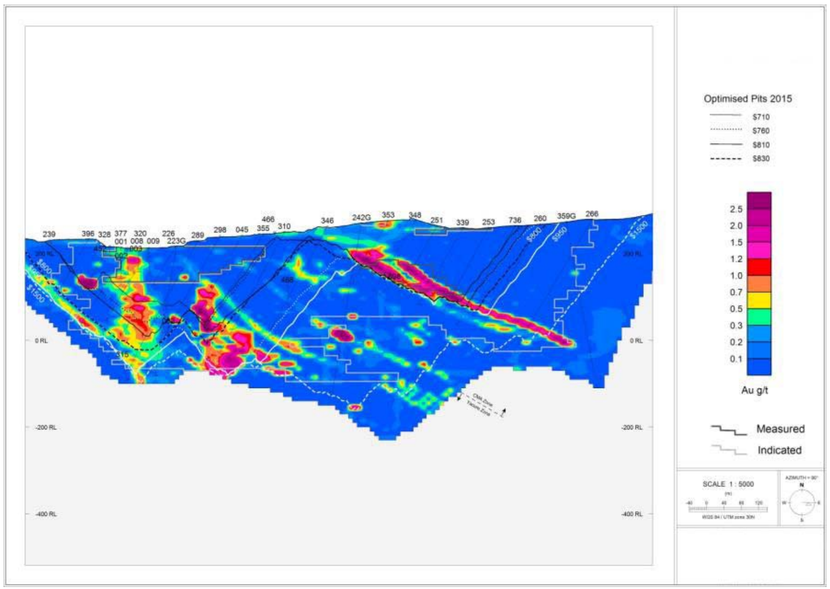

Figure 4: Cross Section showing Au estimated grades

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