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3D Block Modeling and Reserve Estimation of a Garnet Deposit

by

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A Non-thesis Project Report submitted in partial fulfillment of the requirements for the degree of

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Abstract

The purpose of this project is to develop a three-dimensional block model for a garnet deposit in the Alder Gulch, Madison County, Montana. Garnets occur in pre-Cambrian metamorphic Red Wash gneiss and similar rocks in the vicinity. This project seeks to model the percentage of garnet in a deposit called the Section 25 deposit using the Surpac software. Data available for this work are drillhole, trench and grab sample data obtained from previous exploration of the deposit. The creation of the block model involves validating the data, creating composites of assayed garnet percentages and conducting basic statistics on composites using Surpac statistical tools. Variogram analysis will be conducted on composites to quantify the continuity of the garnet mineralization. A three-dimensional block model will be created and filled with estimates of garnet percentage using different methods of reserve estimation and the results compared.

Acknowledgements

I would like to acknowledge my academic advisor, Pete Knudsen for his support and guidance throughout the course of this work. I would also like to acknowledge my committee members Chris Gammons and Diane Wolfgram for their insightful inputs and critiques. I would like to thank Pete Rossiter (Mine Engineer, GarnetUSA) for the opportunity to do this work on their active project.

Table of Contents

1. Introduction

1.1. Background

Garnet is a large group of rock-forming minerals with a general chemical composition of $A_3B_2 (SiO_4)_3$. In its composition, A can be either Ca^{2+}, Mg^{2+}, Fe^{2+} or Mn^{2+} whilst B is $Al^{3+,}$, Cr^{3+}, Fe^{3+}, Mn^{3+} or V^{3+}. Garnet mostly forms during regional metamorphism of shale into gneiss and schist, but can be found in rocks of metamorphosed basalt, contact metamorphism, subsurface magma chambers, deep source volcanic eruptions and residual soil from weathered garnet-bearing rock. In Montana, alluvial deposits of garnet are located along the Ruby River in Madison County. The rocks in this area are mostly highly metamorphosed and Archean in age.

Aside gemstone garnet, the industrial type garnet is valuable mainly because of its hardness and has a variety of uses such as water jet cutting, abrasive blasting, water filtration and for the production of many abrasive powders. According to the U.S. Geological Survey website, refined industrial garnet sells for $150 to $450 per ton and accounted for a 1994 production value of $14 million in the United States against a $233,000 production value of gem garnet in the same year. It also noted that while many deposits in the US produce fine gem-quality garnet, only a few deposits are mined for industrial garnet.

In the stages leading to the development of any deposit, an acquired mineral prospect is expected to yield areas of mineralization when subjected to geological investigation techniques. Good estimation of this mineralization is the first step in assessing the economic merit of the venture and becomes the basis for mine planning during early years of production.

1.2. Project Objectives

This project seeks to use all available information obtained from mapping, sampling, testing and geologic observation to outline and estimate garnet tonnage and grade of the deposit using

Surpac software. The original plan was to estimate block grades by the Ordinary Kriging method since it is the most common method of estimation and is widely regarded for its ability to produce good estimates with very low variance of errors. The complex interaction of ore and waste in the deposit prompted the use of the Indicator Kriging method to estimate the grade distribution of blocks in an attempt to model waste zones better.

Another key objective of this project is to create a robust Surpac block model which will be a database for the storage of all block properties and estimated values. This model will provide graphical three-dimensional visualization of ore properties for easy analyses. Information can be extracted as sections for mine planning decision making.

1.3. Project Overview

The garnet mine is located in the Ruby Valley of Madison County, Montana and develops a hard rock deposit in the Alder Gulch area. Alder Gulch is historically significant for the mining of placer gold through the 18th and 19th century, a time when alluvial garnet crystals were considered a “nuisance” because they plugged the sluice boxes of the historic gold miners and interfered with their recovery (Gevock, 2009).

The specific project site is a portion of the Red Wash Hard Rock Mine Permit area called Section 25 (red quadrangle in Figure 1.1), located just north of the Baldy Mountains and a few miles south-east of Alder in southwestern Montana.

The development of this deposit is expected to yield over $2 million per year in local and state taxes, increasing in future years with production and project growth. Tens of millions of dollars for the county and state are expected for the entire life of mine (Jackson, 2014).

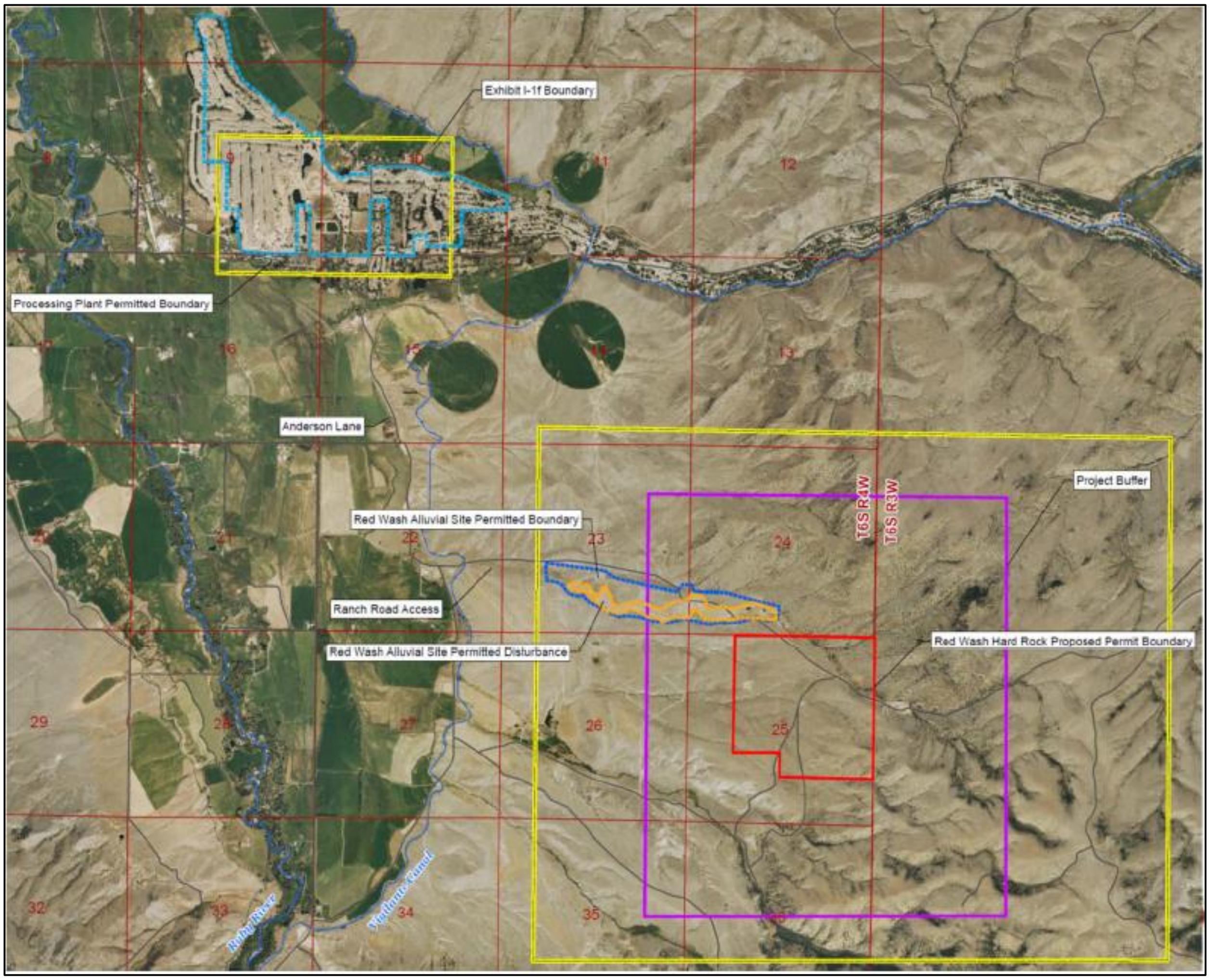

Figure 1.1 Project Overview Locations (Jackson, 2014)

1.4. Geology

The rocks in the Alder Gulch area are mostly Archean gneiss and schist. To the east of the deposit, in the Virginia City area, the Archean rocks are unconformably overlain by Tertiary volcanics, mainly andesite and basalts (Kellog and Williams, 2006). Garnets in the Red Wash Hard Rock deposit occur in garnet biotite gneiss and mafic garnet gneiss geologic units.

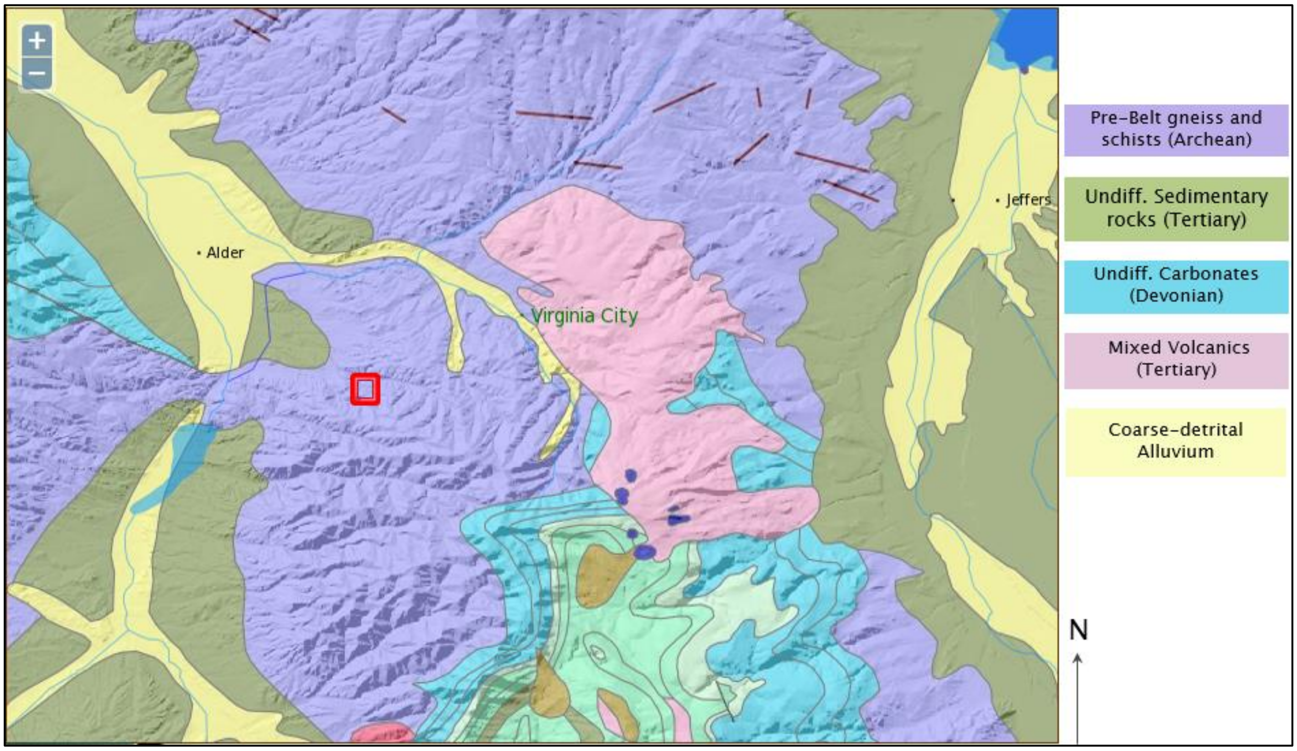

Figure 1.2 Geological setting of the region (from http://mrdata.usgs.gov/sgmc/mt.html)

The garnet biotite gneiss has a matrix composed of quartz, feldspar, biotite and sillimanite. The mafic garnet gneiss is dominated by amphiboles and pyroxenes. Unlike the garnet biotite gneiss, which is mostly garnet – rich, the mafic garnet gneiss may be garnet-rich or totally barren. Biotite and aluminosilicate schist also occur in the area and generally do not have any significant garnet content. Other barren units in the deposit are mostly biotite gneiss and schist. Quartz-dominant rocks on the property like the quartzofeldspathic gneiss, quartzite and quartz-biotite gneiss, are known to be generally garnet poor. The geology of the Section 25 area is shown in Figure 1.3.

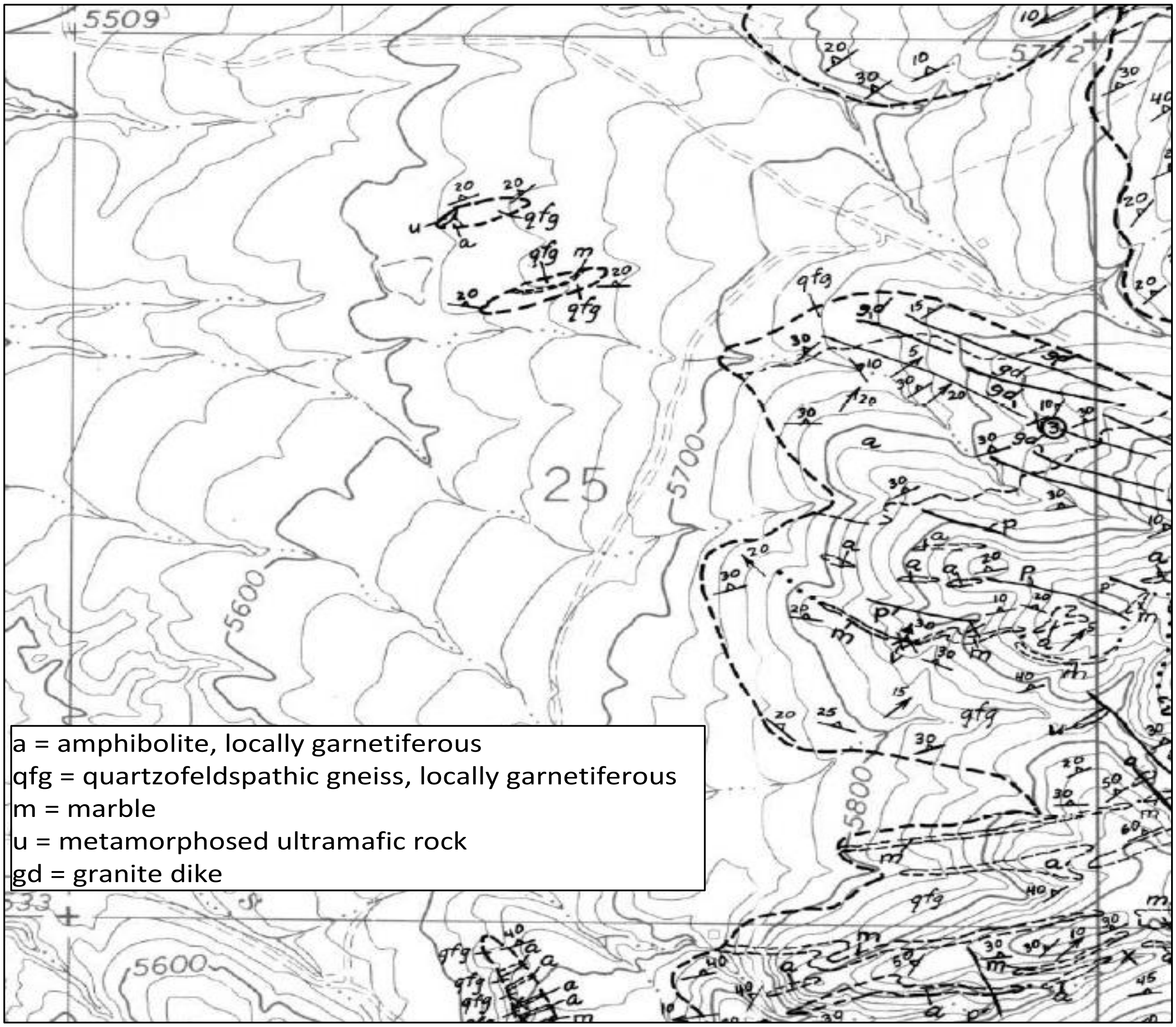

Figure 1.3 Geology of the "Section 25" area. From Wier (1982)

The average strike of the deposit on the eastern portion is 256 degrees while on the western side the strike averages 243 degrees. The metamorphic foliation dips shallowly at angles around 32 degrees in a general north direction. Two major fault systems trending N-S and E-W have been mapped in the area. These fault zones are clay-rich with some commonly occurring slickensides.

2. Literature Review

The true value of a mineral deposit is not known until the shape, size and other critical characteristics are determined. Before the use of modeling software like Surpac and Vulcan, orebody shape and size determination was a very complicated, time-consuming and error-prone task. Technological advancement in this area has provided more reliable computational methods capable of developing models more accurate to true representation in relatively shorter timeframes. Nonetheless, the basis for accurate modeling still remains dependent on the quality of the data and a good understanding and interpretation by the modeler.

Geostatistical methods are used to determine unknown values of variables (grade, thickness, ore quality etc.) at all other points in the deposit using known values at known points (drillhole data) in the deposit. Geostatistics can be defined simply as data analysis and spatial continuity modeling (Journel, 1989).The basic concept of geostatistics is regional variability of parameters (Matheron 1971, 1963; Krige, 1984). Geostatistical calculations combine deterministic and descriptive methods with probability and statistics (Mallet, 2002).

According to Zhang (2011), the goal of geostatistics is to predict the spatial distribution of a property using two basic forms: estimation and simulation. Estimation produces a single “best” estimate of the spatial occurrence based on sample data and modeling a variogram which represents the spatial correlation of the data at hand (Figure 2.1). This estimate is usually produced by kriging.

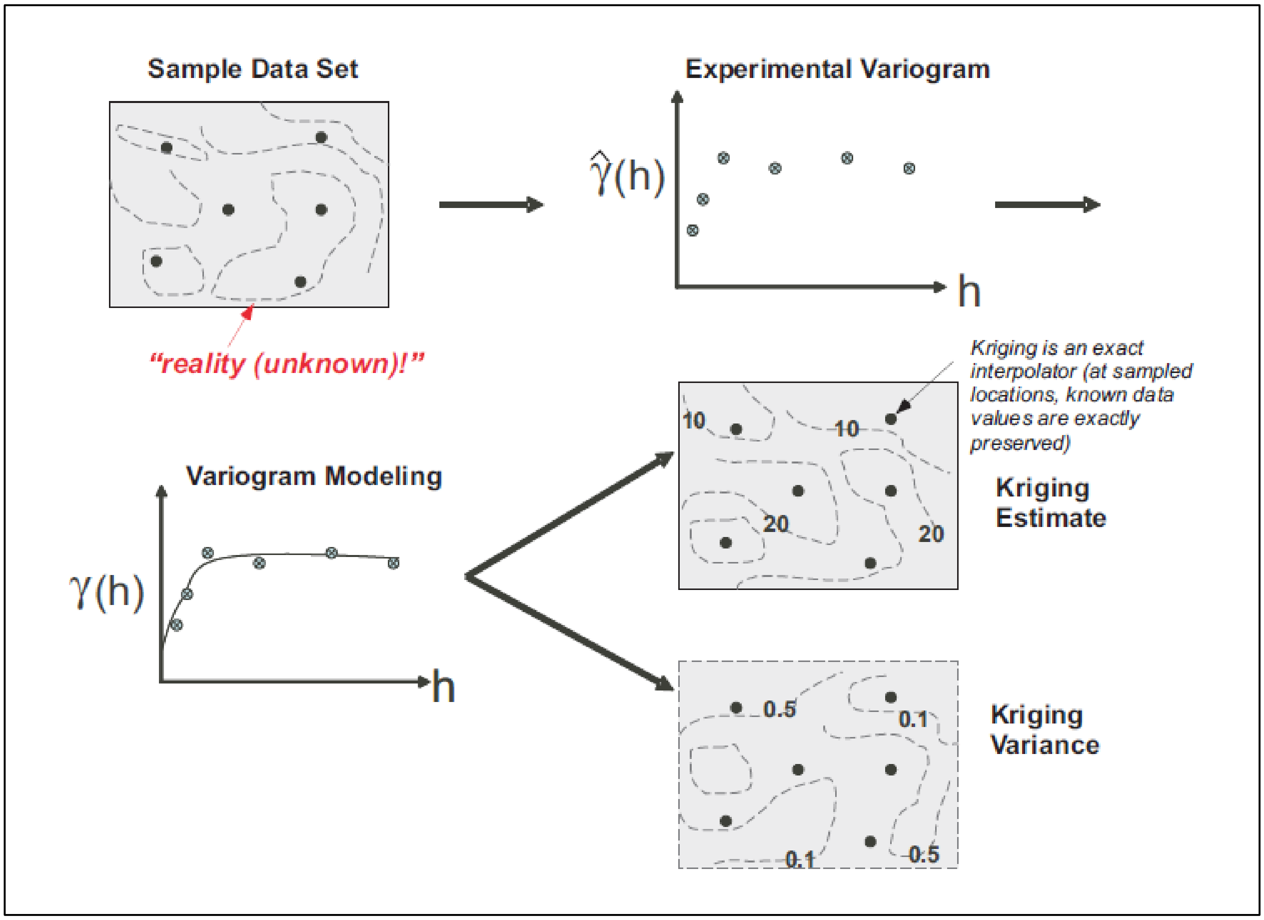

Figure 2.1 Geostatistical estimation workflow (Zhang, 2011)

The concept of modeling a variogram is based on Tobler's first law of geography which states that "Everything is related to everything else, but near things are more related than distant things". A variogram is usually a graph (Fig 2.2) that shows how a measure differs with respect to distance between all pairs of sampled locations. The variogram is key to building a mathematical model which describes how the measure varies with location. Modeling the relationship between the sample locations to show how the measure varies with respect to the distance of separation between these locations is called Variogram modeling.

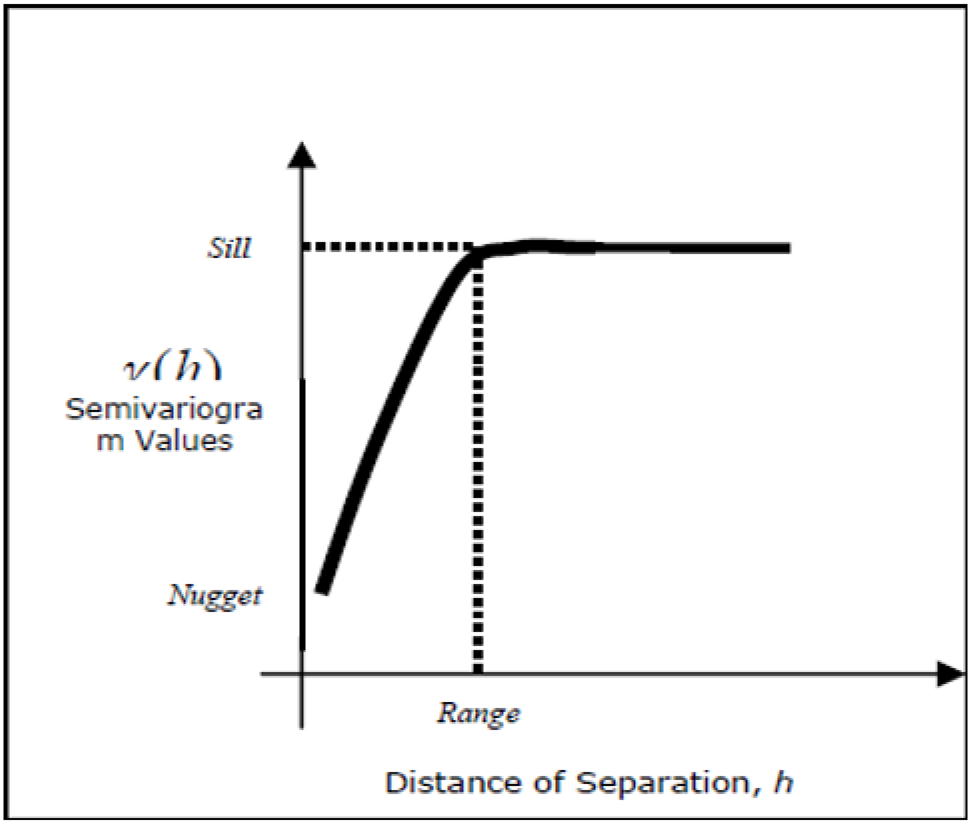

Figure 2.2 A spherical variogram model

Figure 2.2 shows that pairs of samples with a smaller distance of separation (h) between them have a smaller variance γ (h). As the separation distance increases, the variance increases until a point is reached where no correlation can be established between the samples. This threshold distance is called a range. The variance becomes independent of distance and stays constant beyond the range for any given pair. Thus, the inverse of the range can be used as a measure of variability. The maximum variance for the variogram is the Sill and the Nugget effect is the variance at zero distance of separation. Though the nugget is expected to be zero when the distance of separation between two samples is zero, this is never the case for samples at locations close to each other due to factors like sampling errors. Variogram modeling is used in the prediction of a measure at an unknown location by a method called Kriging. The nugget, sill and range values from a fitted variogram determine the weights used in the Kriging process.

Kriging is a group of geostatistical methods for the interpolation of the different regional variables' value at an unobserved location from observations of its value at nearby locations, which consist of ordinary kriging, indicator kriging, co-kriging and others (Bayraktar and Turalioglu 2005; Emery 2005; Hormozi et al. 2012). The choice of the proper method to use depends on the particulars of the data and the spatial model type desired. Of the several kriging methods, the most commonly used method is Ordinary Kriging (Lefohn and Knudsen 2011). Ordinary kriging is a linear model based on local neighborhood structure (Tahmasebi and Hezarkhani 2010), only involves the variogram (Chiles and Delfiner 1999; Afzal et al. 2011) and works under the assumption of a stationary condition. According to Knudsen (1994), Ordinary Kriging is a linear estimator of the grade of a block, Z*(v) and has the form:

$$Z * (v) = \sum_{i=1}^{n} \lambda_i Z(x_i),$$

where n is the number of samples taken into account for the interpolation at locations, x_i. The weights, λ_i, are determined by solving the following set of simultaneous equations.

$$\sum_{j=1}^{n} \lambda_j \gamma(i,j) + \mu = \overline{\gamma(i,v)} \qquad \text{For i = 1 to n.}$$

$$\sum_{i=1}^{n} \lambda_i = 1.0$$

Once the weights are calculated, the estimate Z*(v) can be determined.

A user-defined neighborhood search rule is defined as either a circle with a search radius or an ellipse with major and minor axis orientation (as used in this project) to select sample values to be used in estimation. The neighborhood is expected to contain at least 3 samples for any meaningful estimation to be made (Savelieva, 2005).

Due to the complex interaction of ore and waste in the Red Wash Hard Rock deposit, Indicator Kriging was also used to estimate garnet grades in the deposit. This type of kriging estimates the distribution of grade values within a block rather than the mean grade of the block. The proportion of the block above cutoff and the grade of the block above cutoff can then be calculated as a result (Knudsen, 1994). Though developed by Switzer (1977), it was made useful to the mining industry by Journel (1983). Indicator Kriging is particularly suited for mineral deposits which are characterized by (Knudsen, 1989);

a) a low average concentration, high variance and a skewed distribution of assay values which tend to produce outliers
b) poor continuity of mineralization
c) complex intermingling of ore and waste and
d) difficulties in obtaining reliable samples.

Though very effective at solving the above problems, the importance of having good sampling data cannot be understated. This method relies on good samples to perform at its best, just like all other estimation methods.

According to Knudsen (1994), indicators (cutoff values) are set and indicator variables $i(x;z_c)$ are assigned a value of one if the sample $Z(x)$ is below the specified cutoff z_c and a value of zero if above.

$i(x;z_c) = 1$ if $Z(x) \leq z_c$ otherwise

$i(x;z_c) = 0$

The indicator variable is thus a function of the grade of the sample and the cutoff grade, indicating whether a sample is below a cutoff. The $i(x;z_c)$ notation used for the indicator, uses x to indicate the location of the sample $Z(x)$ and z_c as the cutoff value for this particular set of indicators. The indicator function is used to define indicator values for all samples in the deposit. Once defined the indicators become regionalized variables used for statistical computations. For a particular cutoff, the mean of the indicators calculated by the following equation gives the proportion of samples in the deposit below cutoff (Knudsen, 1994)

$$\bar{i}z_c = \frac{1}{n}\sum_{j=1}^{n} i(x; z_c)$$

Block estimates are stored in databases called block models. The Surpac software creates these databases as spatially referenced three dimensional models from point and interval data such as drill holes. The block model extents are defined in a model space by setting minimum and maximum values for Northing, Easting and Elevation. This set space is the total area of influence of the drill holes which will be used for the reserve estimation. A simple schematic to illustrate this is shown in Figure 2.3.

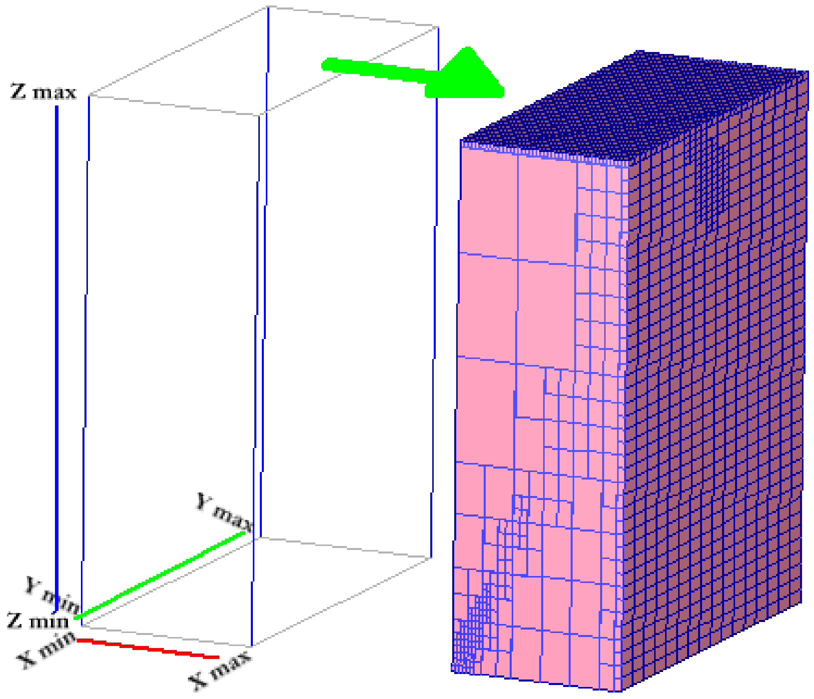

Figure 2.3 Block model extents in 3D coordinates (culled from Surpac manual)

The Surpac block model is created empty before it is filled with interpolated values of the property desired. At this stage, it becomes a database for storage which allows the user to rapidly make one or several combinations of a preferred analysis. Analyses made include but are not limited to estimation of volume, tonnage and the average grade of a deposit from sparse drillhole data. Some key terminology used in block modeling (as explained in the Surpac Manual) are:

Attributes: these are created to define the properties to be modeled. Each block is assigned these attributes. Attributes can contain numeric or character string values.

Constraints: a constraint is a logical combination of one or more spatial objects on selected blocks. Objects used in constraints are plane surfaces, digital terrain models (DTMs), solids, strings and block attribute values. Constraints are used to perform functions on block models. They can be saved to a file (with a .con extension) for rapid re-use.

The basic steps of building a block model and filling it by some estimation method in Surpac is outlined in the workflow (Figure 2.4).

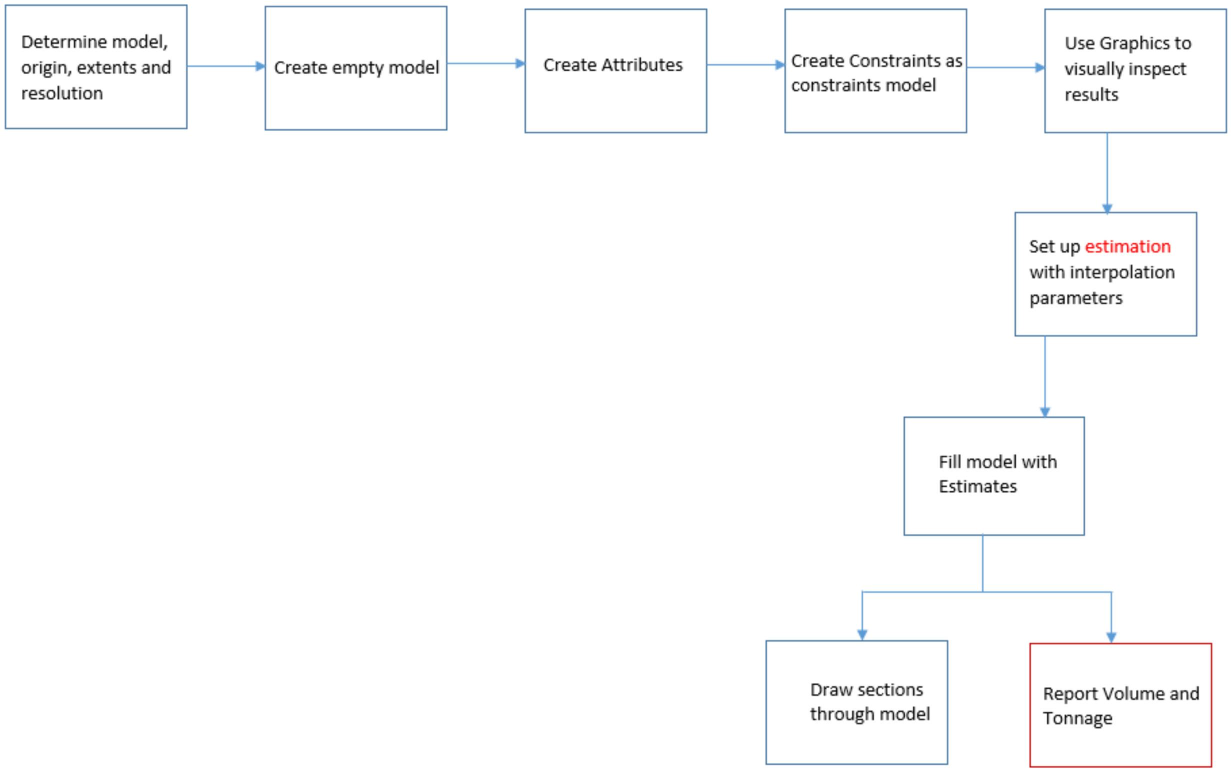

Figure 2.4 Simplified workflow of block model and estimation processes

3. Data and Methodology

3.1. Geological Database

The drillhole database for the deposit contains 32 drillholes, 28 trench samples and over 800 face and grab samples. The database is organized as a Surpac readable access file complete with logs of lithology, collar information and assay data from all sampled intervals. Drillhole and trench samples were used for the estimation of garnet content in the block model. Face and grab samples were excluded for the purpose of reducing sampling bias which is a source of error in geostatistical evaluation and grade estimation. The locations of drill hole and trench collars used for estimation are shown in Figure 3.1.

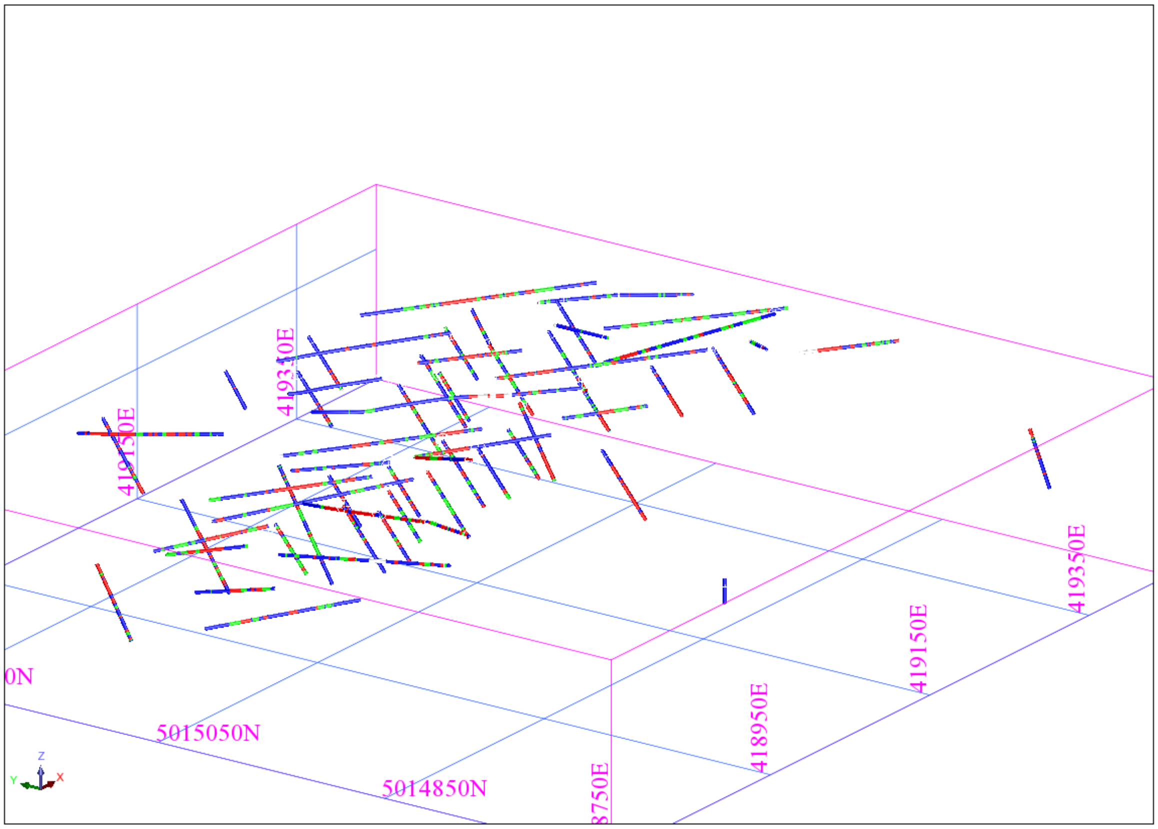

Figure 3.1 Drillhole and trench collars showing garnet intercepts

The figure below shows a section of drillholes highlighting garnet percentages and classification. The blue portion represents intercepts below the 8% garnet cutoff (=< 7.99% garnet) and are the waste zones. The ore zone is represented by the two other colors based on classification as either low or high grade garnet intercepts. Low grade zones (from 8% garnet content to 11.99%) are displayed in green while high grade garnet zones (greater than 12%) are shown in red. This color scheme will be used throughout this report.

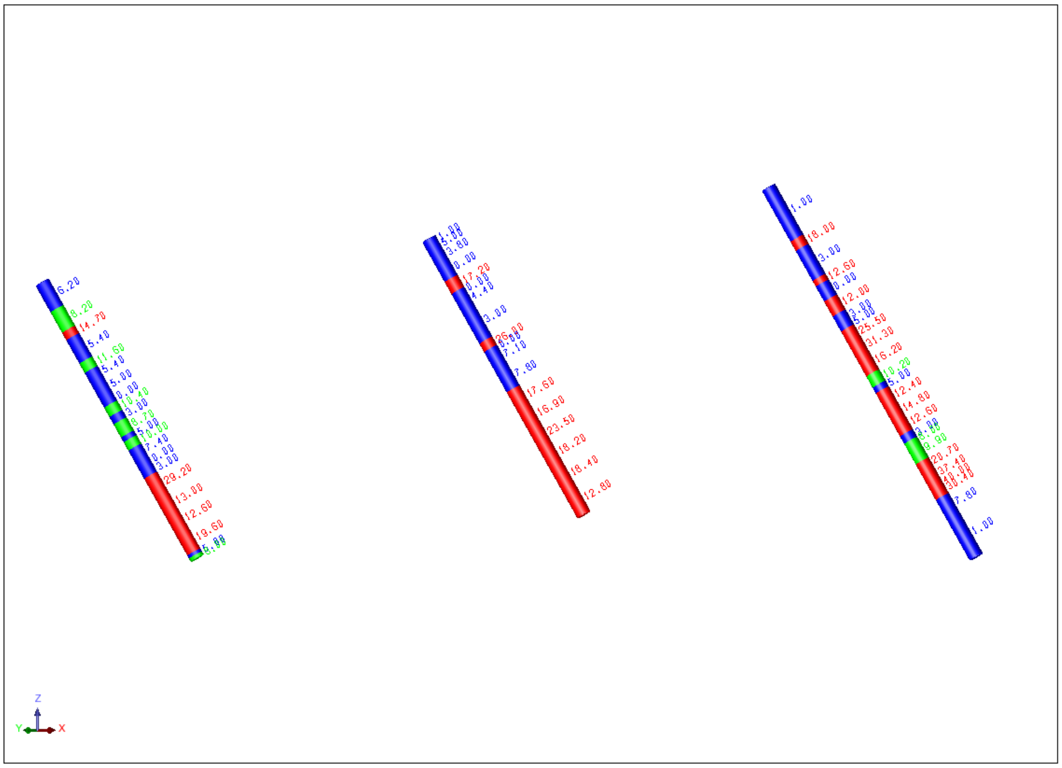

Figure 3.2 Drillhole display according to garnet percentages

Compositing a set of drillhole intervals to uniform sample lengths is required for geostatistical evaluation and grade estimation. It is a means of accounting for the relative importance of each sample through length weighting. Since original sampling of drill holes was done on 10ft samples, a set of 10ft (3.048m) composites was calculated resulting in a total of 1462 composites. No grade values were cut.

3.2. Methodology

3.2.1. Data Validation

The first step in estimation of a resource is the assessment of how reliable the exploration data is. Data validation, although a “small step” in the overall scheme of work, has the potential of revealing database errors which can be detrimental to the efficient reporting of resource tonnage, grade and classification.

A brief audit of the database was done to avoid the occurrence of unpleasant surprises when the processes of geostatistical estimation were started. The database of the Red Wash Hard Rock deposit was analyzed for inconsistencies such as duplication of collar data, erroneous entry of drillhole depth and assay values. No errors were detected thus providing a satisfactory basis for the use of this database in its original form for reserve estimation.

3.2.2. Basic Statistics

Determining the statistical properties of data to be used for geostatistical evaluation is as important as it is useful. The best means of statistically grouping data is graphical examination using histograms and box plots (Howarth 1984, Garrett 1989).Histograms are frequency distribution graphs of data which are useful in the detection of multi-modalism and outliers in the data; two characteristics that are potentially hazardous to any geostatistical evaluation. Multi-modalism refers to grouping of commonly occurring values which occur in different regions of the data set. This is shown as several “humps” on a histogram and is indicative of the existence of more than one population. It is absolutely important to detect and subsequently analyze these different populations individually.

Another important aspect is the computation of statistical measures (e.g. mean, mode, variance, standard deviation and skewness). These characteristics of the distribution ultimately indicate the spread and symmetry of the distribution.

Statistics of 10ft garnet composite values in the mineralized zone are shown in Table 3.1. A histogram showing the distribution is shown in Fig 3.3.

Table 3.1 Statistics of 10ft Garnet Composites

Number of samples	1462
Minimum value	0.00
Maximum value	47.12
Mean	8.63
Median	7.06
Variance	50.34
Standard Deviation	7.09
Coefficient of variation	0.82

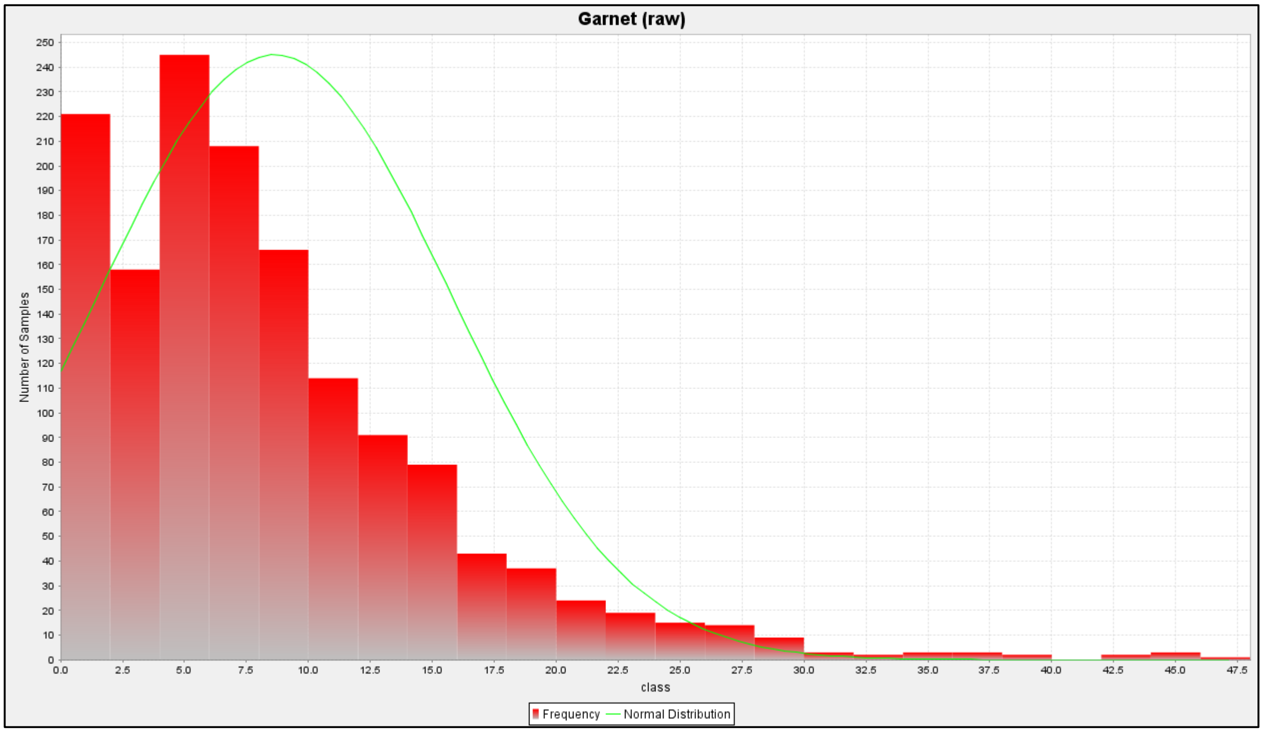

Figure 3.3 Histogram of 10ft Garnet percentage composites

Geostatistical methods are optimal when data are normally distributed with very minimal deviation from stationarity (minimal deviation of mean and variance in space). Clustering of composites at lower garnet percentage (below 9%) and the tail extending towards higher values suggest that the data does not perfectly fit a normal distribution, a very typical occurrence with geological data. It is common to find a large number of small values and a few large values which gives it the positive skew observed. The histogram plot is seen to show a single population and a co-efficient of variation of 0.82. The high number of “zeros” seen from the statistical analysis of the data is a key factor for the choice of the Indicator Kriging (IK) method of estimation. The high “zero” frequency suggests a possible complex interaction of ore and waste zones and IK has the capacity of handling these waste zones more efficiently, as discussed previously.

3.2.3. Variography

As discussed previously, the accurate determination of the continuity of the mineralization with respect to direction is done with variogram analysis. The variogram shown in Figure 3.4 is at an azimuth of 90° and a dip of 0°. Figure 3.5 shows a variogram at an azimuth of 0° and a dip of 27°. It was observed to have a slightly shorter range than the first variogram.

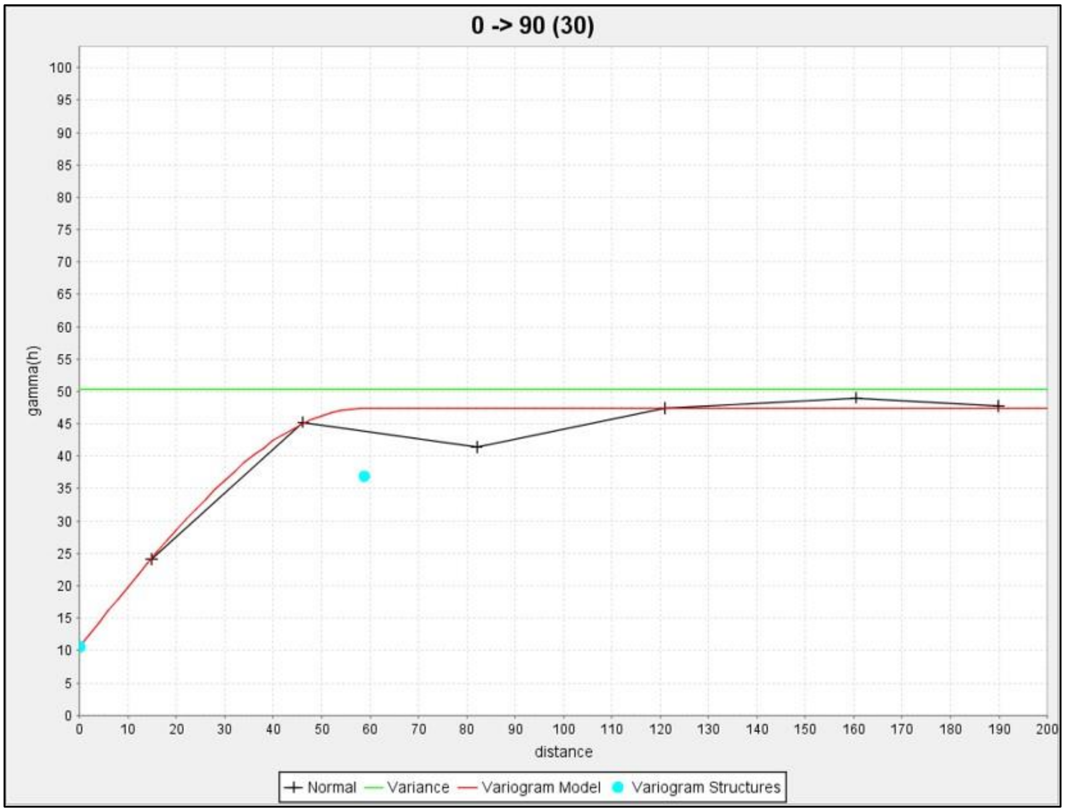

Figure 3.4 Garnet variogram major axis

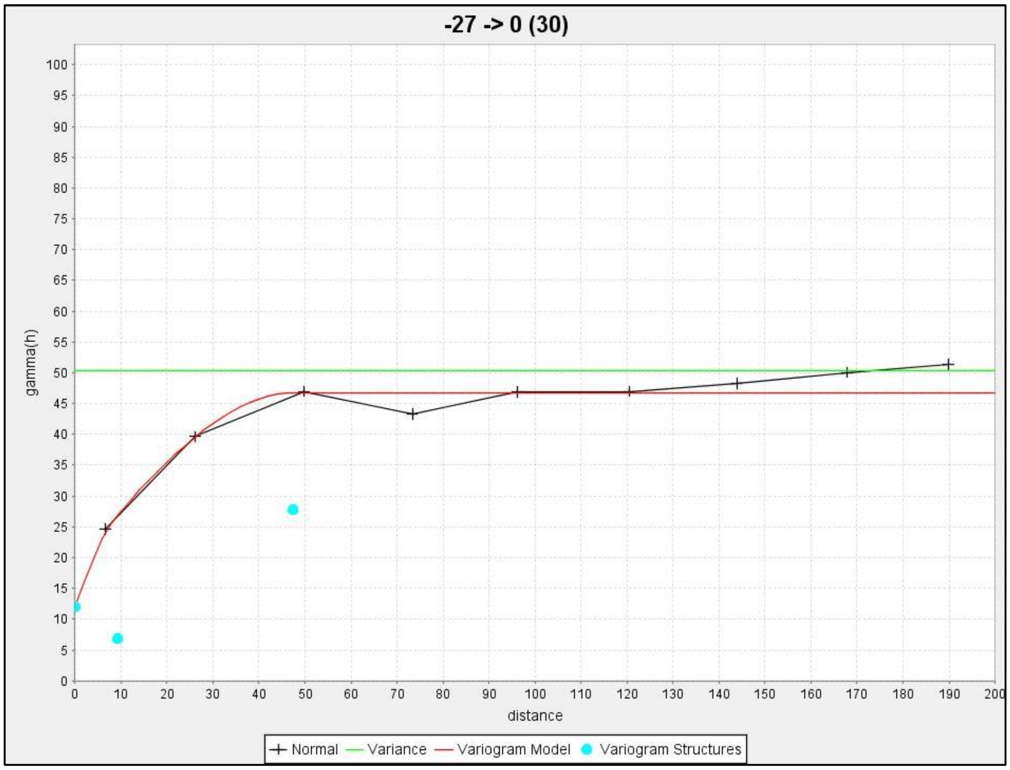

Figure 3.5 Garnet variogram semi-major axis

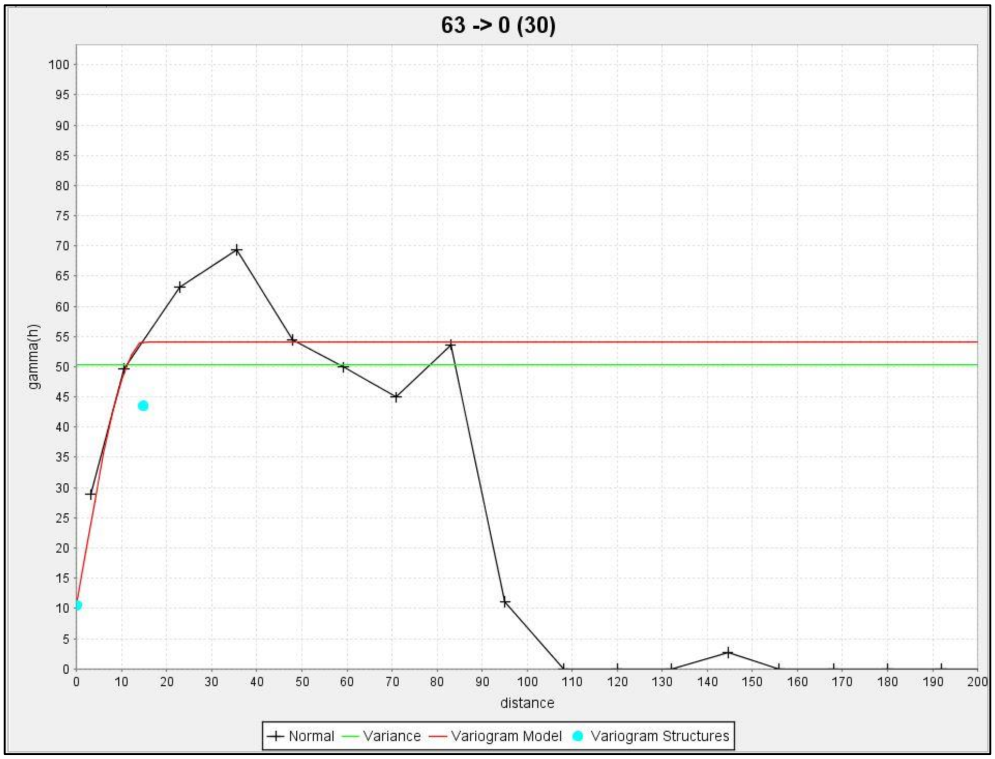

Figure 3.6 Garnet variogram minor axis

The variogram orthogonal to the first two directions is shown in Figure 3.6. It is observed to have a much shorter range of about 15m. The ratio of the range of the major axis (Figure 3.4) to that of the minor axis (Figure 3.6) is 3.92. The major/semi-major anisotropy ratio was calculated as 1.22. Thus, it can be seen that garnet is quite nearly isotropic in the plane that dips about 27° to North but shows a strong anisotropy in the orthogonal direction to this plane. This may be due to the minor axis variogram being perpendicular to foliation of the metamorphic rock.

The anisotropy factors calculated from the ratio of these ranges enables the calculation of anisotropic distance and the subsequent performance of estimations using three-dimensional anisotropy. Anisotropic distances calculated determine the weights given to sample values in the vicinity of the block being estimated. To perform estimations, Surpac builds an anisotropic ellipsoid (similar to Figure 3.7) around each block to be estimated using anisotropic ratios of the three mutually perpendicular axes.

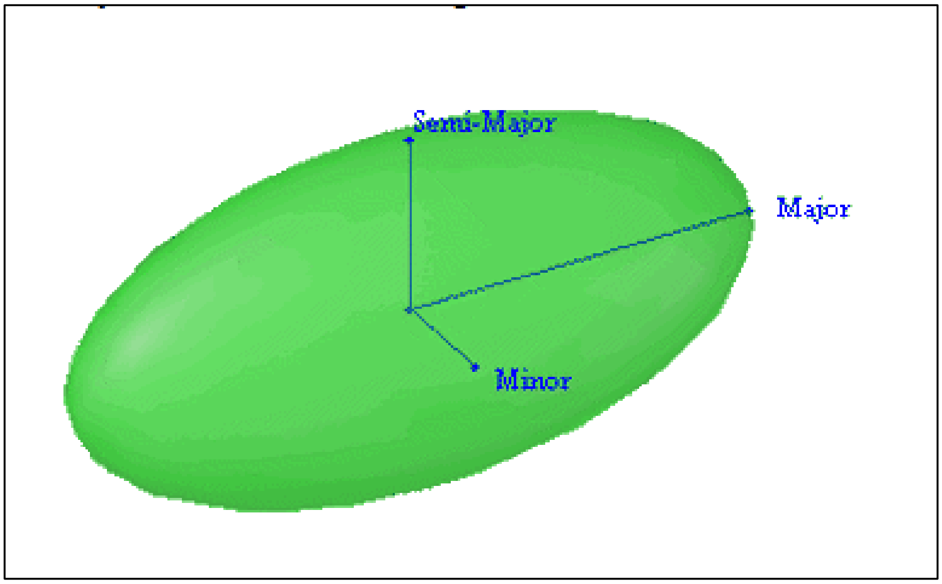

Figure 3.7 A Surpac anisotropic ellipsoid (from Surpac Manual)

The anisotropic distance from the centroid of the block to known sample values is calculated using the relation:

Actual Distance x Anisotropy Ratio = Anisotropic Distance.

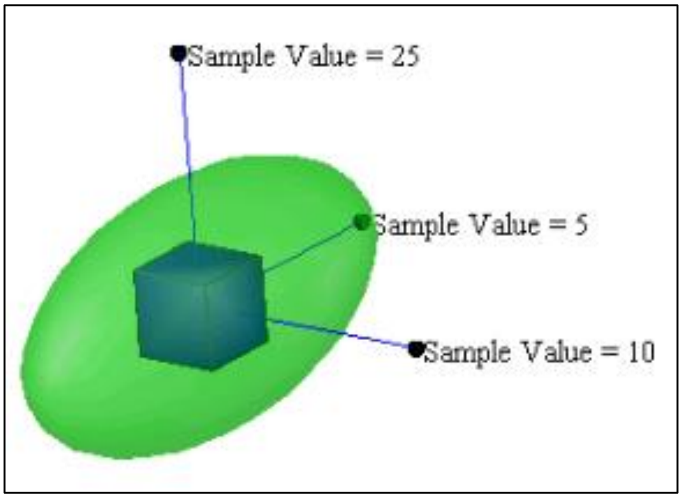

Figure 3.8 Ellipsoid and neighboring sample relation (from Surpac Manual)

This means that supposing three sample values are distributed around a block (such as in Figure 3.8) at an equal distance of 5 meters in all directions from the block, anisotropic distance calculations will be summarized as shown in Table 3.2.

Table 3.2 Anisotropic distance calculations (using assumed Actual distance values)

Axis	**Sample Value**	**Actual Distance (m)**	**Anisotropy Factor**	**Anisotropic Distance (m)**
Major	5	5	1	5
Semi-major	25	5	1.22	6.1
Minor	10	5	3.92	19.6

Weights to be assigned to the sample values are then calculated based on the anisotropic distance. This shows how anisotropy affects weighting of sample values in the calculation of block grade. It should be noted that weight values will differ for different geostatistical methods.

3.2.4. Block Model Geometry and Characterization

The three-dimensional coordinates used to define the model extents were specified in this step. The block size to be used for interpolation and reporting were also assigned. A 5m by 5m by 3m block was chosen for this model. This corresponds to approximately a 200 tonne block for a drill pattern of 50m spacing between drillholes in the ore zone. A practical rule of thumb suggests that a block size of ¼ to 1/3 of the drillhole spacing will maximize resolution of the model but the smaller 5m x 5m x 3m model is a convenient size for mine planning purposes. The block size, maximum and minimum coordinates used are summarized in Table 3.3.

Table 3.3 3D Coordinates and Block size of model

Type	Y	X	Z
Minimum Coordinates (m)	5014850	418700	1650
Maximum Coordinates (m)	5015400	419550	1851
User Block Size (m)	5	5	3
Min. Block Size (m)	5	5	3
Rotation (degrees)	0	0	0
Total Blocks	215080		

The model generated from these parameters is shown in Figure 3.9 below.

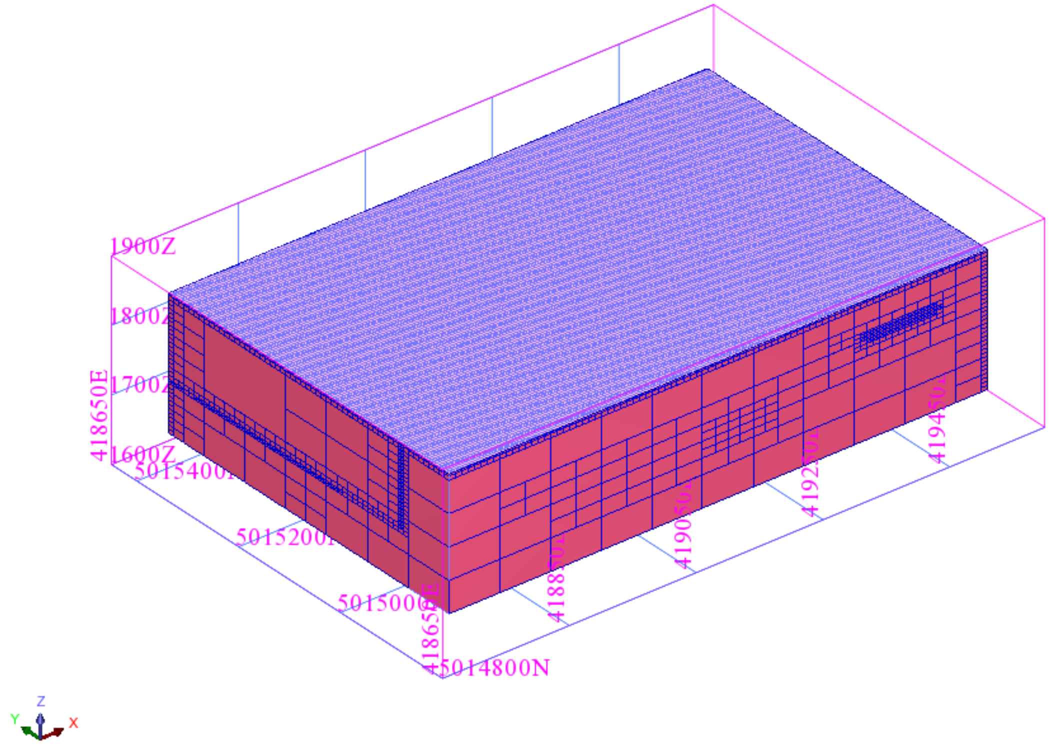

Figure 3.9 Display of generated 3D Block Model

The generated block model may be constrained graphically by topography to better represent the land form of the area. To do this, a combination constrain file named ‘*blockmod_constr.con*’ was created to show only blocks which lie below the topography as “rock” when applied. The result of adding the ‘*blockmod_constr.con*’ constraint to the generated block model is shown in Figure 3.10.

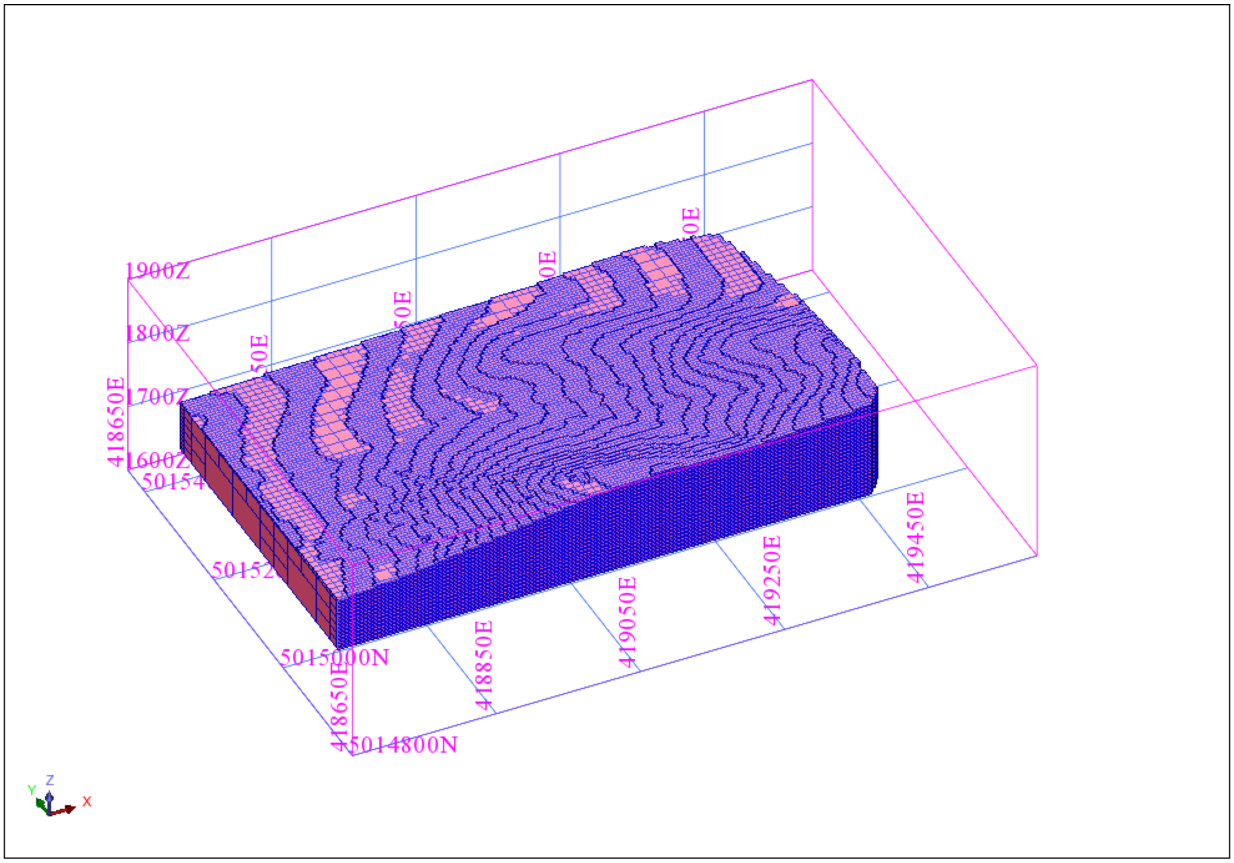

Figure 3.10 Display of constrained Block Model

After generating the block model, attributes were assigned to the blocks for each of the properties to be modeled and for known properties to be used for analysis such as material type and specific gravity of the mineral deposit. The ‘material’ type attribute was created and filled in as ‘rock’ or ‘air’ for blocks below or above topography respectively. An attribute for specific gravity was created and set to a value of 3.7 (the average specific gravity of garnet) for all ‘rock’ blocks. This attribute is used in grade-tonnage calculations when reserves are reported. The properties of attributes specified for this model are shown in Table 3.4.

Table 3.4 Attributes added to Block Model

Attribute Name	Type	Decimals	Background
ani_dist_nearest_samp	Float	3	-99
avg_dist	Float	3	-99
garnet_id1	Float	3	-99
garnet_nn	Float	3	-99
material	Character	-	rock
nsamp	Integer	-	0
sg	Float	2	-99

3.2.5. Estimation

After generating the model and specifying the attributes of the properties to be modeled, the blocks were filled with garnet estimates. The methods used to estimate the percentage garnet in each block were Ordinary Kriging (OK) and Indicator Kriging (IK). The variogram and interpolation parameters used for estimation by Ordinary Kriging are shown in Tables 3.5 and 3.6.

Table 3.5 Garnet variogram parameters

Variogram Model			
Model Type:		Spherical	
Nugget :		10.8	
Structure		Sill	Range
	1	35.5	58.9m
ANISOTROPY FACTORS			
Major Axis		Azimuth = 90°	Dip = 0°
Semi-major Axis		Azimuth = 0°	Dip = 27°
Minor Axis		Azimuth = 0°	Dip = 63°
Semi/major ratio		1.22	
Minor ratio		3.92	

Table 3.6 Garnet interpolation parameters

Max search distance of major axis	60m
Max vertical search distance	7m
Maximum number of informing samples	15
Minimum number of informing samples	3

Based on the quantity of garnet grades within percentile groups from the basic statistical analysis, 8 cutoff grades (indicators) were chosen for indicator variogram analysis and modeling. Modeled variogram parameters for these indicators are included in the Appendix A section of this report.

It was observed that the range of sample pairs were seen to decrease as indicator values increased. This was expected and is explained by the fact that a low grade population of sample values will be continuous over greater distances than a population of higher grades.

4. Results

Garnet reserves estimated by the OK and IK methods were reported by applying constraints to the block model such that only kriged blocks within the constrain file ‘blockmod_constr.con’ were taken into consideration during grade-tonnage calculations.

The reserves estimated by the OK and IK methods using calculated variogram and interpolation parameters are shown in the grade-tonnage curve in Figure 4.1 below. Actual tonnages above cutoff for the deposit were omitted from the graph due to proprietary restrictions. 3D models showing garnet reserves (garnet >= 0.01%) estimated with the OK and IK method are shown in Figures 4.2 and 4.3 respectively.

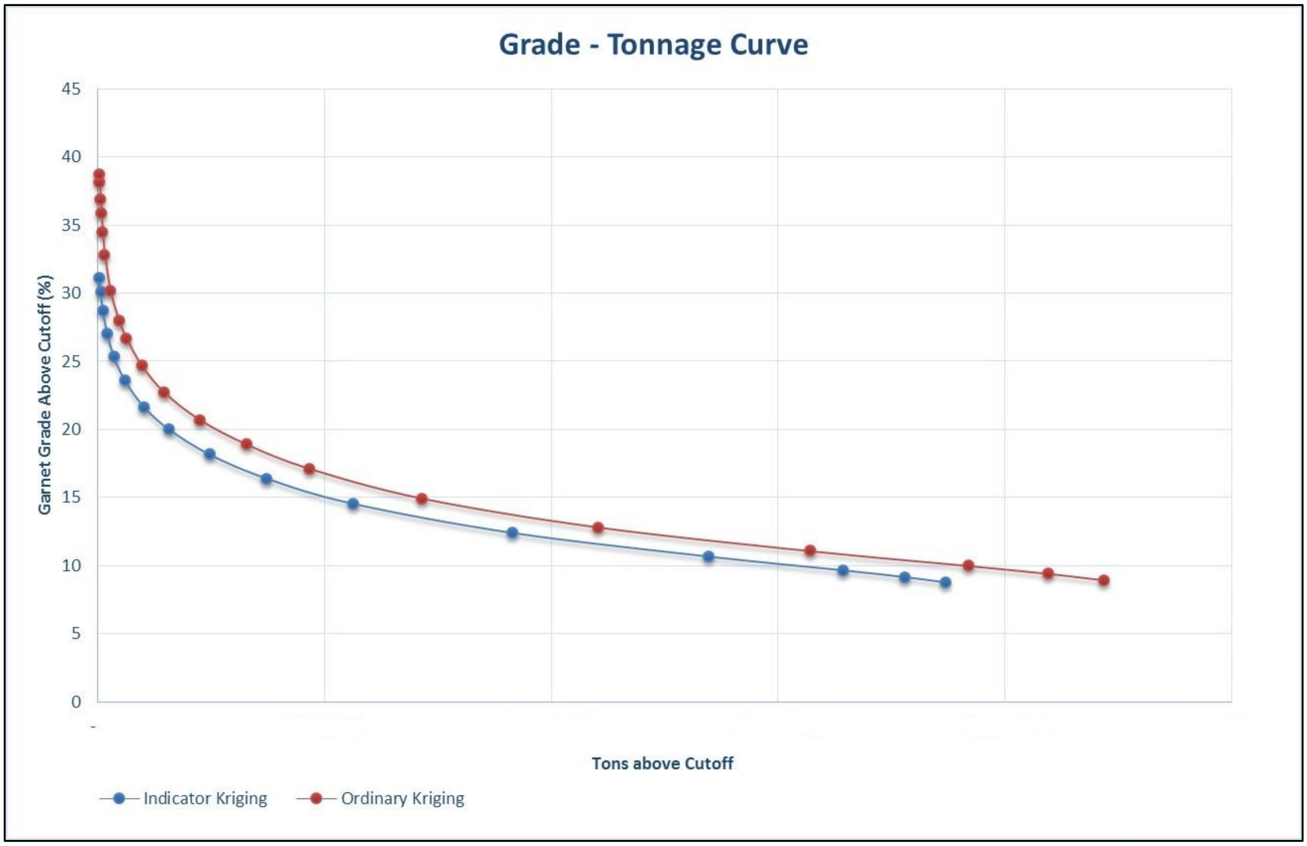

Figure 4.1. Grade-Tonnage curve of estimated garnet (Tonnages omitted due to proprietary restrictions)

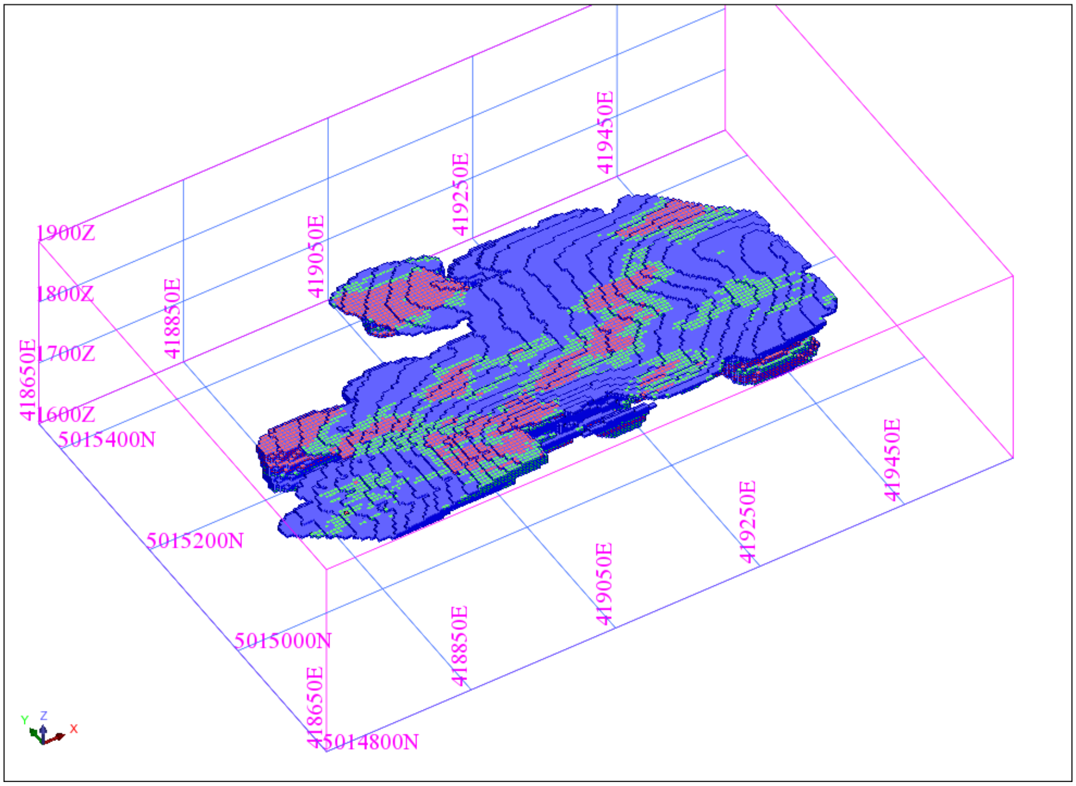

Figure 4.2 3D Model showing garnet estimates by OK

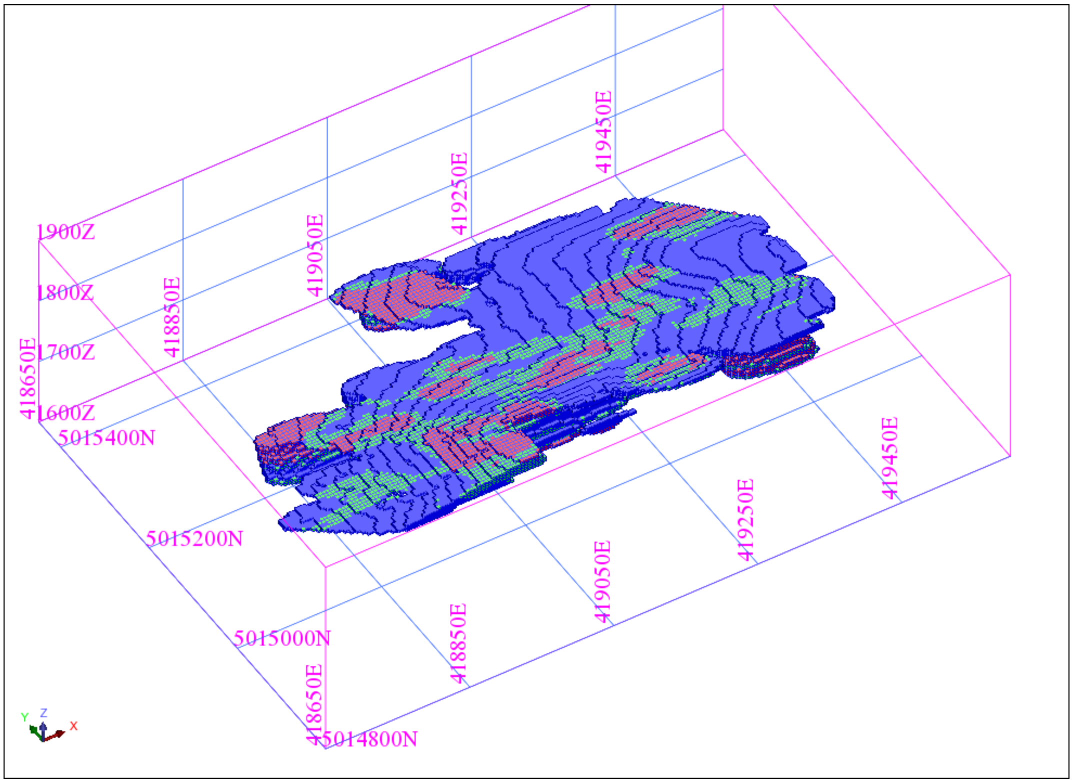

Figure 4.3 3D Model showing garnet estimates by IK

5. Conclusions and Recommendation

5.1. Conclusion

From the results of our estimation, exploration drilling and trenching in the Section 25 Block of the Red Wash Hard Rock site has identified a substantial garnet deposit at a good average grade.

5.2. Recommendation

It is recommended that more drilling and exploration be done in the Section 25 area to better define and improve confidence in the reserves estimated. Detailed geological mapping of rock units in the deposit is also recommended. An increase in geological data will allow relationships between garnet grades and lithology to be established. This correlation will be useful in enhancing selectivity of the deposit and for mine planning purposes.

References

Afzal, P., Fadakar, A. Y., Khakzad, A., Moarefvand, P., RashidnejadOmran, N. (2011). Delineation of mineralization zones in Porphyry Cu deposits by Fractal Concentration-Volume modeling. *Journal of Geochemical Exploration, Vol 108*, pp 220 – 232

Bayraktar H.,Turalioglu F.S. (2005). A kriging-based approach for locating a sampling site in the assessment of air quality. *Stochastic Environmental Research and Risk Assessment 19 (4)*, pp 301-305

Chiles,J.-P., Delfiner, P.(1999). *Geostatistics: Modeling Spatial Uncertainty*. John Wiley & Sons Inc. New York, p 695

Emery, X. (2005). Simple and ordinary kriging, multi-gaussian kriging for estimating recoverable reserves. *Mathematical Geology, v. 37*, pp 295-319

Gevock, N. (2009, June 14). Miner putting creek together while extracting valuable garnets, *The Montana Standard*, Retrieved from

http://mtstandard.com/news/local/miner-putting-creek-back-together-while-extracting-valuable-garnets/article_a21f3e23-4dd7-5450-8779-73e55a81e1b3.html

Hormozi, H., Hormozi, E., Rahiminohoogi, N. (2012). The classification of the applicable machine learning methods in robot manipulators. *International Journal of Machine Learning and Computing, Vol 2*, pp 560-563

Howarth, R. J. (1984). Statistical applications in geochemical prospecting: A survey of recent developments. *Journal of Geochemical Exploration, v 21*, pp 41-61

Jackson, B.D. (2014). Permitting and Developing the Garnet USA Mine and Plant and the Butte Highlands Mine. *2014 Mine Design Operations and Closure Conference-Fairmont Hot Springs, Montana*

Journel, A.G. (1983). Nonparametric estimation of spatial distributions. *Mathematical Geology, Vol 45*, pp 445 - 468

Journel, A.G. (1989). *Fundamentals of Geostatistics in Five Lessons, Vol. 8*, Short course in Geology, Washington, D.C., American Geophysical Union.

Kellog, K.S., Williams, V.S. (2006). *Geologic map pf the Ennis 30' X 60' quadrangle, Madison and Gallatin Counties, Montana, and Park County, Wyoming.* MBMG Open File 529

Knudsen, H. P., Fritz, C. B. (1989). Using IK to determine pod boundaries in a karst lignite deposit. *Proceedings of the 21st APCOM Symposium*. New York Society of Mining Engineers of the American Inst. Of Mining, Metallurgical and Petroleum Engineers.

Knudsen, H. P. (1994). *A short course on Indicator Kriging*. Geostatistics course lecture notes, Montana Tech (unpublished), p 34

Krige, D.G. (1984). Geostatistics and the definition of uncertainty, *Trans. Inst. Min. Metall. Section A v. 93*, pp 41-47

Lefohn, A.S., Knudsen, H.P. (2011). Using ordinary kriging to estimate the April-September 24-hour W126 and N100 ozone exposure metrics for 2010 for the United States, Retrieved from : http://webcam.srs.fs.fed.us/ozone/spatial/2010/contractor_2010.pdf

Mallet,J-L. (2002). Geomodelling. *Applied Geostatistics Series*, Oxford University Press New York, 2002, 624 p.

Matheron, G. (1963). Principles of geostatistics. *Economic Geology, Vol. 58*, pp 1246 – 1266

Matheron, G. (1971). The theory of regionalized variables and its applications. *Cahiers du Centre de Morphologie Mathematique, Fasc. N^o 5*, ENSMP, Paris.

Savelieva, E. (2005). Using ordinary kriging to model radioactive contamination data. *Applied GIS, Vol 1 N^o 2*, 2005, pp 10-01 to 10-10, doi:10.2o14/ag050010

Switzer, P. (1977). Estimating of spatial distribitions from point sources with application to air pollution measurement. *Bulletin of International Statistical Inst., XLVII (2)*, pp 122-137

Tahmasebi,P., Herzarkhani, A. (2010). Application of adaptive neuro-fuzzy interference system for grade estimation – case study, Sarcheshmesh porphyry copper deposit, Kerman, Iran. *Australian Journal of Basic and Applied Sciences, Vol 4*, pp 408 – 420 ISSN 1991-817

Wier, K. L. (1982). Maps showing geology and outcrops of part of the Virginia City and Alder quadrangles, Madison County, Montana. *U.S. Geological Survey, Miscellaneous Field Studies Map*, MF-1490.

Zhang Y. (2011). *Introduction to Geostatistics*, Course Lecture Notes, University of Wyoming (Unpublished), pp 1- 36 Retrieved from http://geofaculty.uwyo.edu/yzhang/files/Geosta1.pdf

Appendix A: Indicator Kriging Variogram Parameters

```
CUTOFF 0.100000
VARIOGRAM MODEL = Spherical
    Cumulative sill    0.806377
    Nugget effect      0.016000

    MODEL    C VALUE     RANGE    AZIMUTH    PLUNGE       DIP     SEMI_MAJOR_RATIO   MINOR_RATIO
       1       0.790377    136.530    135.760    -21.150        -22.230          1.336        3.298



------------------------------------------------------------------------
CUTOFF 2.000000
VARIOGRAM MODEL = Spherical
    Cumulative sill    0.881404
    Nugget effect      0.576000

    MODEL    C VALUE     RANGE    AZIMUTH    PLUNGE       DIP     SEMI_MAJOR_RATIO   MINOR_RATIO
       1       0.305404    125.010     91.251      -8.747       45.592          1.582           1.806



------------------------------------------------------------------------
CUTOFF 5.000000
VARIOGRAM MODEL = Spherical
    Cumulative sill    0.979178
    Nugget effect      0.462000

    MODEL    C VALUE     RANGE    AZIMUTH    PLUNGE       DIP     SEMI_MAJOR_RATIO   MINOR_RATIO
       1        0.517178     89.513     91.251      -8.747         45.592         1.119           4.137



------------------------------------------------------------------------
CUTOFF 8.000000
VARIOGRAM MODEL = Spherical
    Cumulative sill    0.971137
    Nugget effect      0.698000

    MODEL    C VALUE     RANGE    AZIMUTH    PLUNGE       DIP     SEMI_MAJOR_RATIO   MINOR_RATIO
       1      0.273137    77.989    91.251        -8.747       45.592          1.119          4.011




------------------------------------------------------------------------
```

```
CUTOFF=12.000000
VARIOGRAM MODEL = Spherical
    Cumulative sill    1.000287
    Nugget effect      0.710000

    MODEL   C VALUE    RANGE   AZIMUTH    PLUNGE      DIP    SEMI_MAJOR_RATIO   MINOR_RATIO
      1      0.290287   66.925   91.251      -8.747     45.592        1.204            4.127



----------------------------------------------------------------------
CUTOFF=15.000000
VARIOGRAM MODEL = Spherical
    Cumulative sill    1.039554
    Nugget effect      0.816000

    MODEL   C VALUE    RANGE   AZIMUTH    PLUNGE      DIP    SEMI_MAJOR_RATIO   MINOR_RATIO
      1     0.223554    47.103   91.251     -8.747     45.592        1.132            3.973




----------------------------------------------------------------------

CUTOFF=17.000000

VARIOGRAM MODEL = Spherical
    Cumulative sill    1.060316
    Nugget effect      0.648000

    MODEL   C VALUE    RANGE   AZIMUTH    PLUNGE      DIP    SEMI_MAJOR_RATIO   MINOR_RATIO
      1      0.412316   42.033   91.251       -8.747   45.592       1.523            3.976



----------------------------------------------------------------------
CUTOFF=25.000000
VARIOGRAM MODEL = Spherical
    Cumulative sill    0.983597
    Nugget effect      0.127000

    MODEL   C VALUE    RANGE   AZIMUTH    PLUNGE      DIP   SEMI_MAJOR_RATIO   MINOR_RATIO
      1     0.856597    40.189   91.251     -8.747     45.592        1.503            3.996
```