Peñasquito Breccia, Mexico - Silver OK Estimation
Math 586 Final Report

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Introduction

This report represents an initial evaluation of drill hole silver assay data from the Peñasquito mine, Mexico. Our investigation includes a comparison of variograms generated by R coding versus a standard mining industry modeling and statistical software (Leapfrog Edge) and includes an ordinary kriging estimation using R within the Peñasquito breccia domain.

The Peñasquito mine is a polymetallic ore deposit containing economically recoverable Ag, Pb, Zn and Au. From ounces produced on an annual basis, Peñasquito is the fifth largest silver mine in the world and the largest in Mexico. The mine is located in the Zacatecas district, Mexico and started operation in 2010.

The drill hole database is currently under confidentiality with an Information Sharing Agreement between Newmont Mining Corp. and NMT (2021). For this investigation, drill hole data within the Peñasquito 'Breccia' only will be evaluated. This that consists of 74,761 samples, which represents a fraction of the total data set provided by Newmont (383,015 samples).

The evaluation involves the following parameters:

- Exploration data analysis, generation of semi variograms and kriging estimation (Ordinary kriging and simply kriging).
- R coding was used to performed this project.
- 3D variogram generation and kriging estimation was challenged to complete in R, because a proper package was not found.
- A decision to complete the variograms and estimation using 2D depth slices was assumed.

Log Normal data was used to generated variograms. A brief comparison of the variograms generated in R versus variograms generated in Leapfrog Edge show similar shapes as well as nugget, range and sill. Simple Kriging and Ordinary Kriging results show very similar outcomes. Only Ordinary kriging mean maps and standard deviation are presented in this report.

Figure 1. Location of Peñasquito and air view of the actual mine

Objectives

1) Find a method to estimate the 3D Ag data from the Peñasquito mine using R coding. This is a large data set that can be a challenge to work, without a specialized mining software.
2) Is R software capable of performing a 3D variogram and estimation in this capacity?
3) Estimate the Ag grades (ppm) within the host Breccia body in the Peñasquito mine using ordinary kriging and simple kriging. After obtaining a reasonable variogram, try to estimate using kriging techniques in 2D or, if possible, in 3D.
4) Compare the variograms completed by R with Leapfrog Edge mine modeling software.

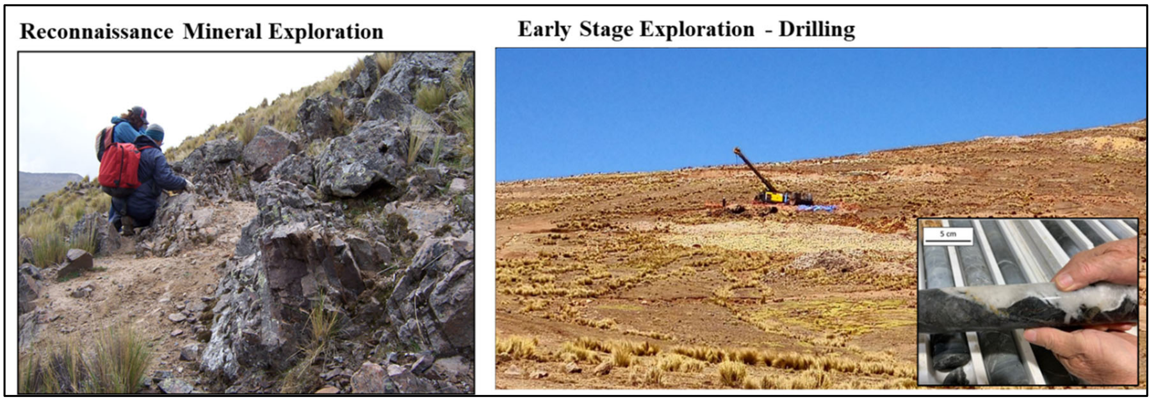
Background

Before going into the discussion of the Peñasquito drill hole data, the following is a summary of the mining project stages (Figures 1 to 5) in order to put into perspective how drill hole data is generated.

1- Reconnaissance Mineral Exploration; geologists are looking for evidence of cohesive zones of mineralization to determine the potential of a future project. Mapping rock along with mineralized outcroppings, and mineral claim staking or leasing a property are important in this stage.

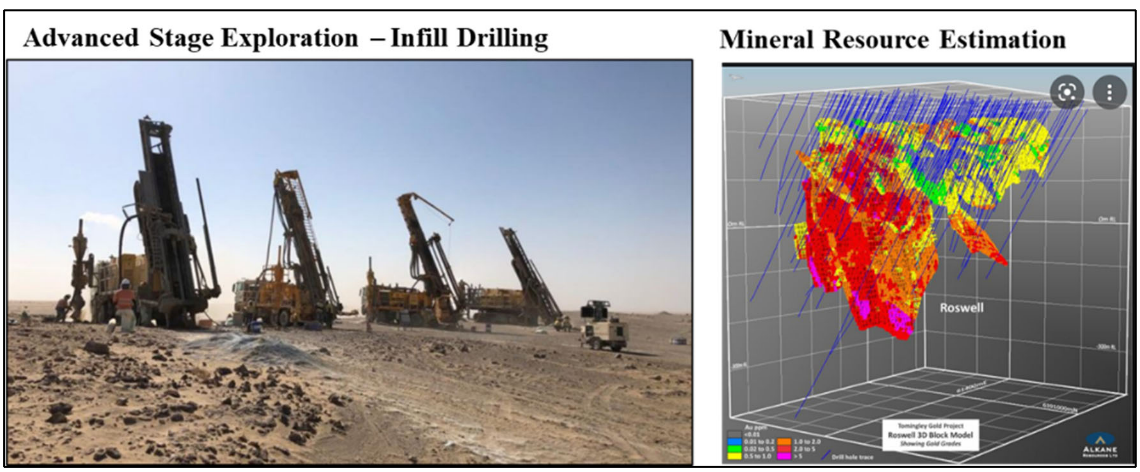
2- Early-Stage Exploration; historical and new generated surface data is used as vector. Collecting new information and increasing confidence in a project's viability is achieved by surface mapping, sampling in the field, geophysics and evaluation of historical data.

   i. Drilling; With diamond core drilling, a pipe fused with industrial diamonds is used to drill through rock layers. A "core" cylinder of rock is left in the center of the pipe, which is then recovered as a sample. This core can then be analyzed to determine more about its composition as well as the relationship between rock layers. Drill holes can be hundreds of meters to over a kilometer deep. Each hole extracts a small diameter (~ 2 ¾ inches) of rock (referred to as ‘core’) from the earth. Core samples are sent to the lab for elemental analyses such as Au, Ag, Pb, Zn in the rock.



Figures 1 and 2. Reconnaissance and early exploration drilling.

3- Discovery – once a discovery is made, then the question becomes: “is this discovery economic”? This stage focuses in understanding the dimensions to which cohesive 3D mineralization extends and at what grade concentration (grade). After discovery, a typical drilling program may consist of 100’s to + 1000 drill holes eventually included in a resource estimate (geostatistics analysis).



Figures 3 and 4. Advanced stage drilling, 3D modeling and resource estimation.

4- Early to advanced development; focuses on project de-risking by collecting more data, including engineering design and planning which yields a more precise 3D understanding and leads to a final ‘yes-no’ decision to advance the project to a mine. Reconnaissance stage exploration to final decision for mine construction ranges from 8 to 15 years.

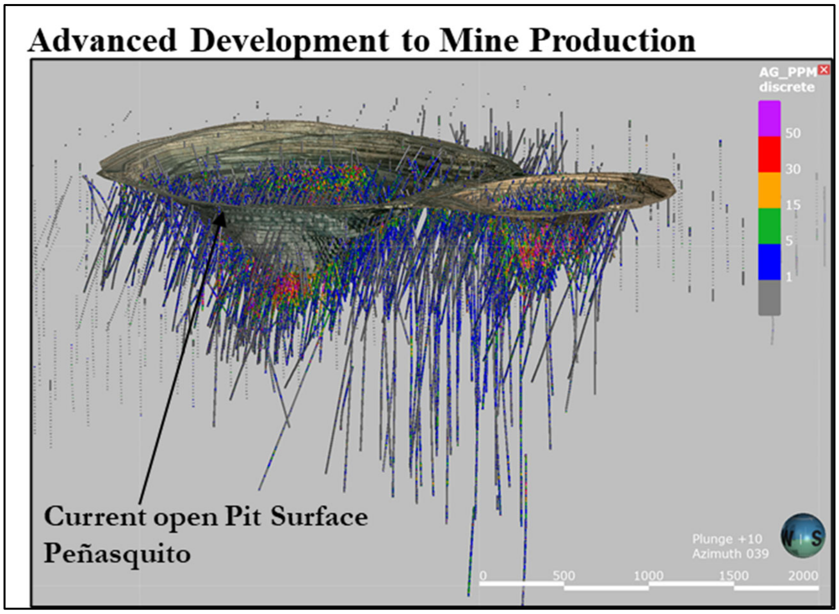
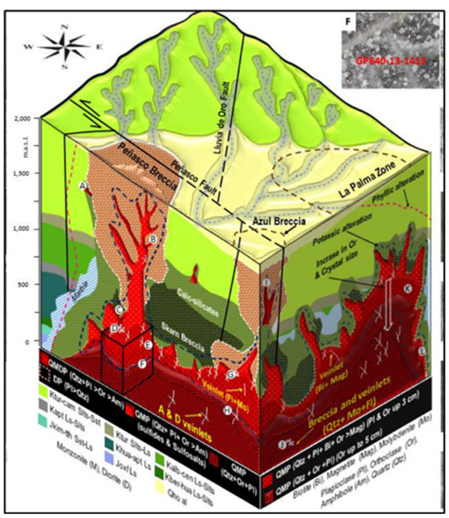


Figure 5. Peñasquito 3D view looking ENE of the open pit mine along with drill hole traces showing Ag assays.

The Peñasquito geology consists of 2 diatremes explosive breccias (Peñasco and Azul) that intruded sediments from the Caracol formation during the late Cretaceous (Figure 6). The mineralization is hosted mainly in the diatreme breccias. The Peñasquito breccia dimensions are 900m x 800m x 1200m(depth). See Figure 7.



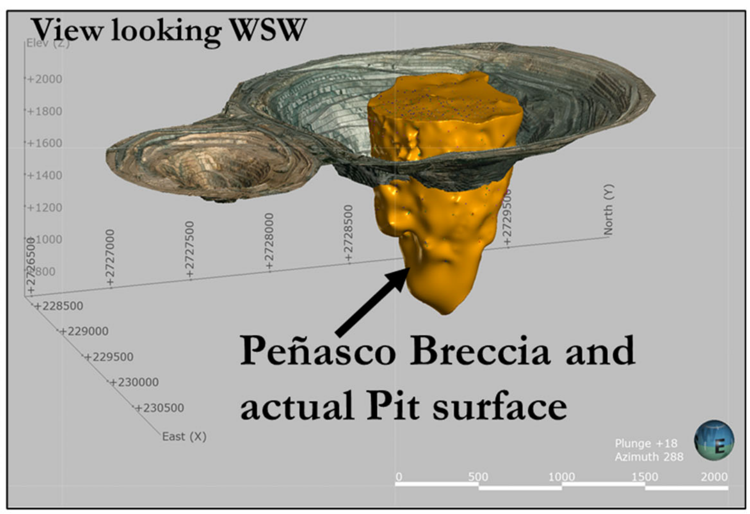
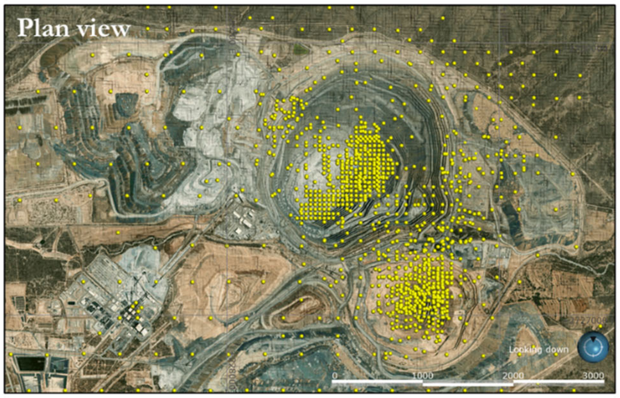


Figure 6, 3D geology of the Peñasquito mine. In orange is shown the Peñasco and Azul breccias. Figure 7, Peñasco breccia 3D model and actual open pit.

Peñasquito Data Set

The original data was presented in excel format, a total of 74,761 samples from 386 drill holes (Figure 8). Samples within the Peñasquito breccia were filtered and then composite to 4m intervals. A total of 37,830 samples (Figure 9) was obtained, then imported into R. The mid-point of each composite consists of a UTM coordinate (Easting, Northing and Elevation) and average silver value in ppm (grams/metric ton). For the purpose of this evaluation, only data within the Peñasquito breccia was selected in order to avoid a large data set that could result in data analysis issues with the version of R software that was used.



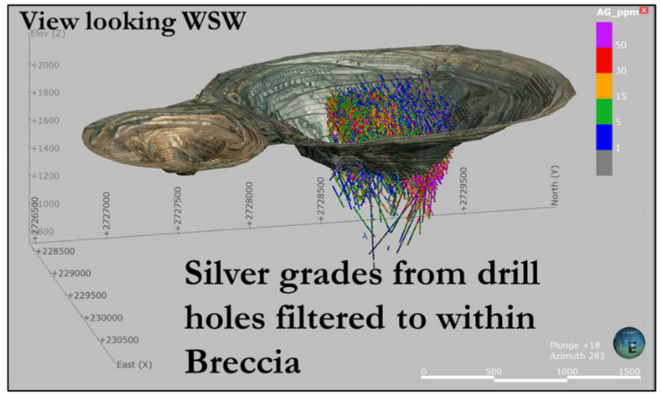


Figure 8, Plan view of 386 drill holes collars. Figure 9, Data used for the kriging estimation.

The data shows a favorable log normal distribution all within the breccia domain. The sample distance ranges from 35 to 60m on average.
Exploration Data Analysis (EDA) includes histograms of composited data (Figure 10), log normal data and 3D scatter plots.
The silver composite data is positively skewed. After transforming the data to log normal it was evident the log normality of this data.

Table 1; Ag ppm values (4m composites) within Intrusive Breccia

Name	Count	Mean	Standard deviation	Coefficient of variation	Variance	Minimum	Lower quartile	Median	Upper quartile	Maximum
AG_ppm	37628	21.71	50.10	2.308	2510.29	0.10	4.00	10.00	24.00	4155

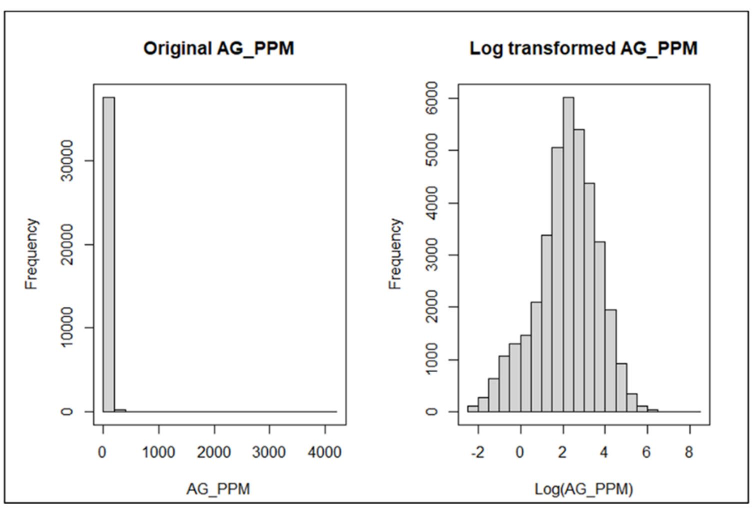


Figure 10, histograms of composite data and log Normal transformation.

From the scatter plot of depth and silver concentration, we observed that there might be a slightly negative trend or correlation as the depth increased. We have checked this correlation between depth and silver concentration and found the value as −0.10. (Figure 11)
Below is the tabulation representation of the 10 data split using some key statistical values (Table 2).

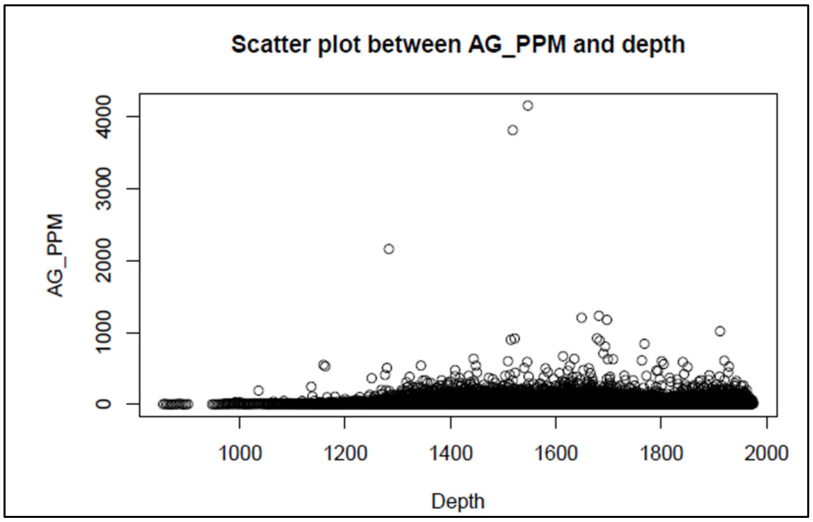


Figure 11

Table 2

Depth Slice number	Sample Size	Mean	Depth (From)	Depth (To)
stat_splt1	3796	27.19	854.57	1413.38
stat_splt2	3797	31.3	1413.38	1504.43
stat_splt3	3796	30.43	1504.44	1582.85
stat_splt4	3797	24.69	1582.86	1651.34
stat_splt5	3795	22.33	1651.35	1711.89
stat_splt6	3796	16.58	1711.93	1766.76
stat_splt7	3793	16.24	1766.77	1818.46
stat_splt8	3793	15.99	1818.46	1867.83
stat_splt9	3792	15.84	1867.84	1912.57
stat_splt10	3675	16.58	1912.57	1974.46

The impact of the extreme outliers can be assumed due to the unusual results obtained in some of the slices. Pending to evaluate is the impact of the outliers.

Methodology follows to generate variograms and then kriging estimation

1. Created the histogram of original data and log-transformed data.
2. Attempted to see the correlation between depth and silver concentration in the deposit AG_PPM.
3. Subdivided the entire data set into 10 separate depth sliced intervals (Table 2) and completed the same comparable analysis on each depth sliced data set.
4. Observed the variogram in both directions (x and y).

5. For each depth sliced data set we completed Simple kriging and Ordinary kriging. The data shown in the mean map are log-transformed. We can use the exponent of the number to convert in our original scale.

Variograms

In this case the variograms represent a measure of geologic distance identifying silver mineralization trends within the Peñasquito Breccia. The variogram results in R and Leapfrog Edge show clear anisotropy within the Peñasquito Breccia for silver values.
As was mentioned the outliers were not investigated, but it is assumed they are impacted the robustness of the final variograms, especially within the depth slices, where these outliers are clearly identified. Capping extreme outliers is a common practice in the mining industry not only during the variogram modeling, but also in the final kriging estimation.
Pending to determine is the best anisotropy directions, not multiple directions, as this investigation was looking to determine.
Spherical variograms are the most common variograms shapes used in mining industry estimation modeling, as well as the use of nested structures. Even some variograms can be a sum of the spherical variogram and exponential variogram to explain the remaining variance.

Type = Spherical

$$\gamma(h) = \begin{cases} C_0\left[\frac{3}{2}\frac{h}{a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] & for\ h \le a \\ C_0 & for\ h > a \end{cases}$$

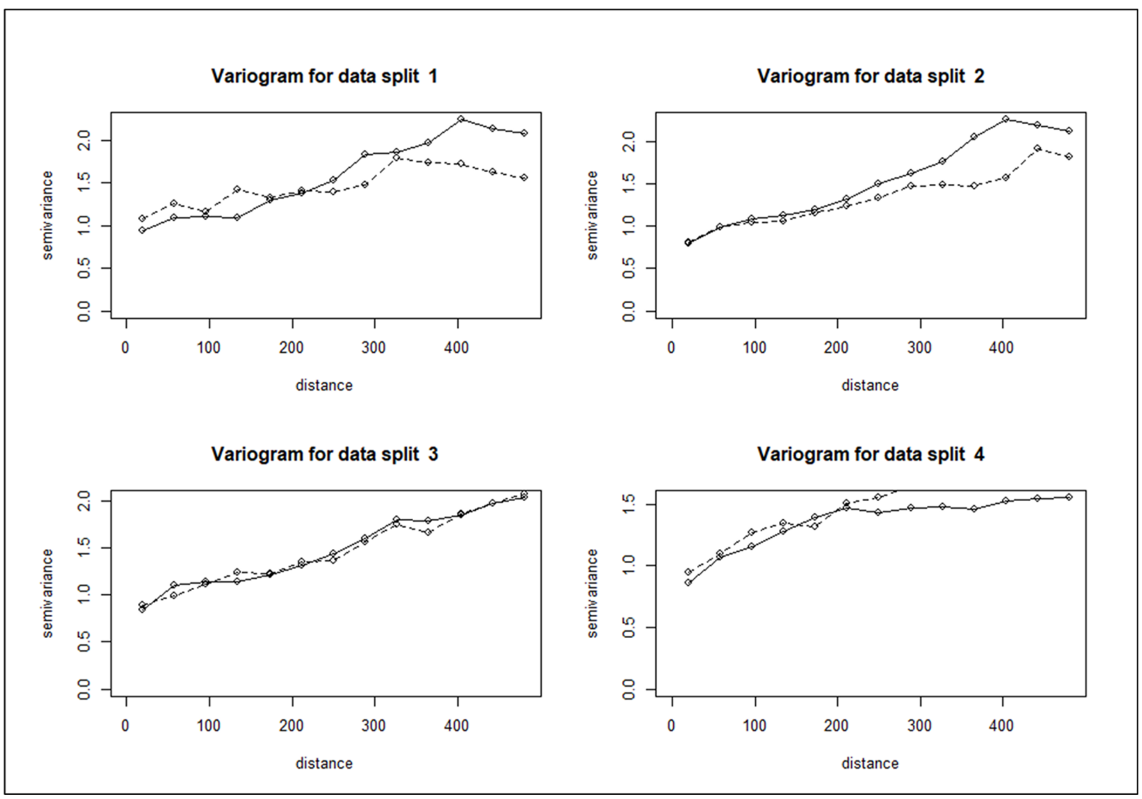


Figure 12, Log Normal empirical variograms (depth slices 1 to 4) completed in R.

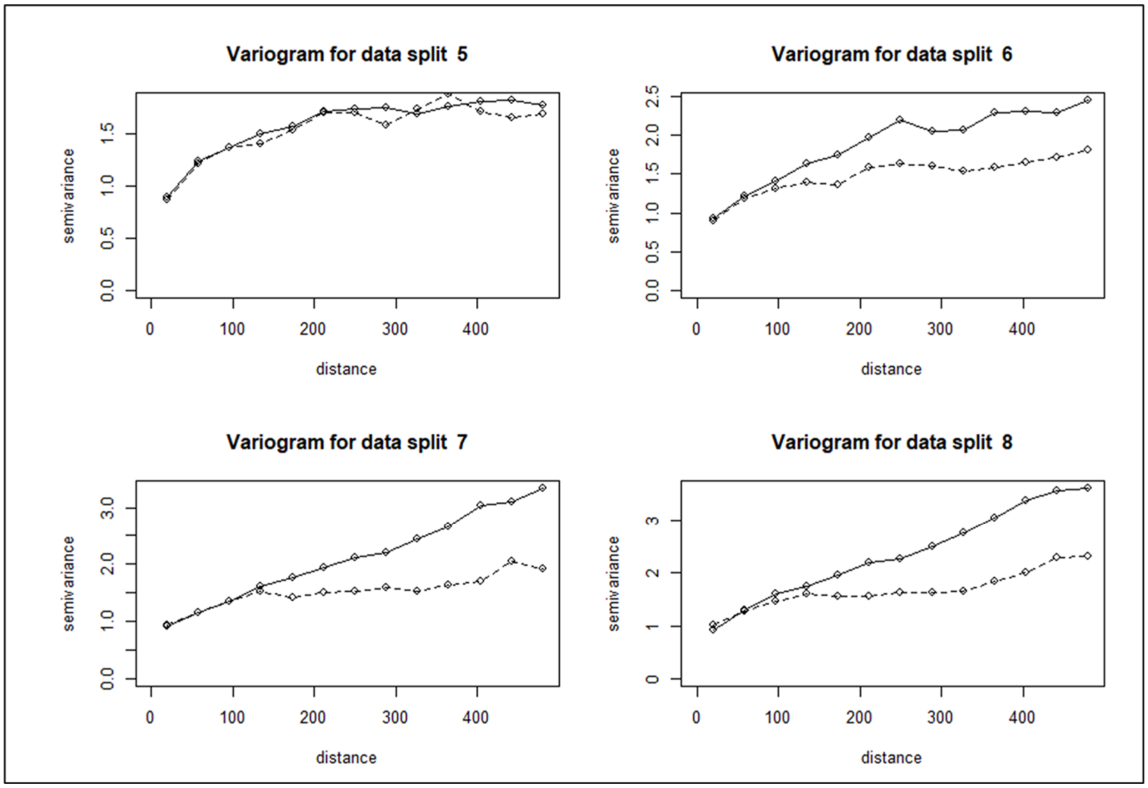


Figure 13, Log Normal empirical variograms (depth slices 5 to 8) completed in R.

A visual variogram comparison of R with Leapfrog Edge shows very similar shapes, sills and ranges.

Leapfrog Edge 3D variograms assumptions

Main direction variogram is 62° azimuth
Log Normal data
Spherical variogram model
Nugget; ~20% of the total sill
Total sill was 2.073
2 nested structures

Table 3; Leapfrog Edge variogram information

[Variogram Parameters]							
Structure	**Sill**	**Normalised Sill**	**Model**	**Alpha**	**Major Range**	**Semi-Major Range**	**Minor Range**
Nugget	0.475	0.229					
Structure 1	0.390	0.188	Spherical	-	67.68	42.66	20
Structure 2	1.208	0.583	Spherical	-	500	300	200
Total Sill:	2.073	1.000					

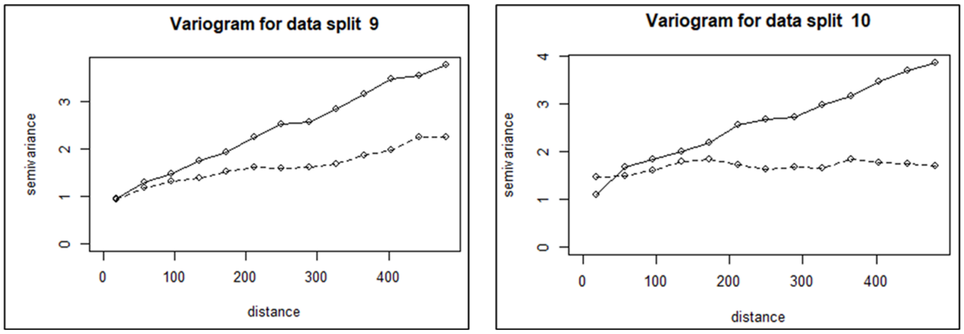


Figure14; empirical variograms generated in R for depth slices 9 and 10.

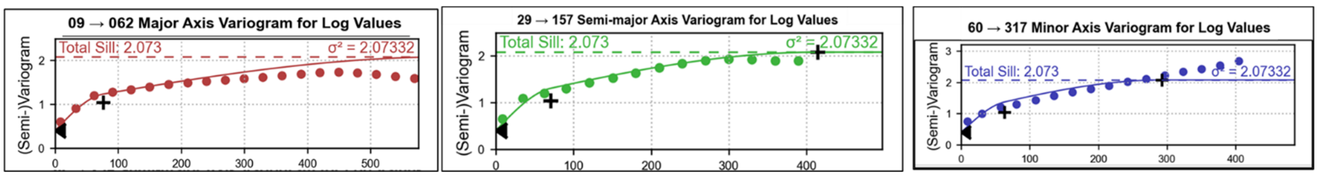


Figure15; empirical variograms and spherical models generated in Leapfrog Edge for the 3D data in each ellipsoid range: Major, Semi-Major and Minor.

	Nugget	Sill	Scale
splt1	0.8106289	5.1918508	2509.7178
splt2	0.6919255	6.0775100	2695.5858
splt3	0.8290546	4.9443998	2851.1500
splt4	0.8187377	0.6799453	270.9232
splt5	0.8944577	0.8689709	272.1335
splt6	0.9670379	1.3606835	428.9092
splt7	0.8503774	311.4649234	91469.8257
splt8	0.9275918	228.4077780	59439.2394
splt9	0.8860701	6.2258913	1487.5566
splt10	1.2805438	134.0764598	37683.3355

Spherical variogram parameters in R

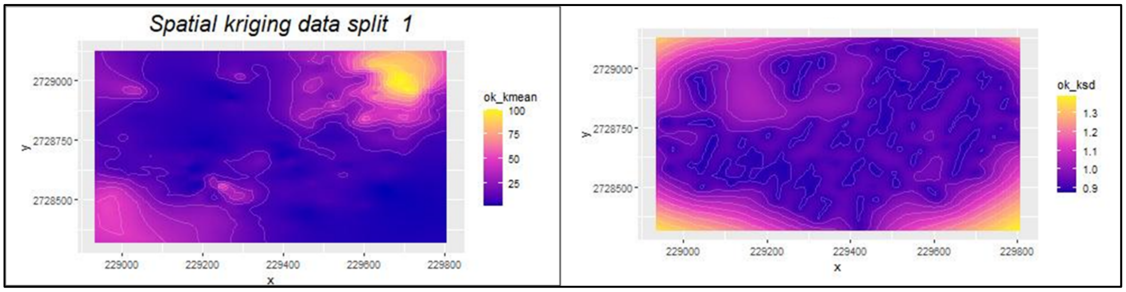
Ordinary Kriging

The main foundation of the kriging estimate is to compute the weights that minimize a probable error variance. Contrary to SK, OK does not make any previous assumption about the mean. Ordinary kriging limits the sum of weights to be 1. As a consequence, the mean does not need to be known. For this reason, Ordinary kriging is widely used within the mining industry. Block kriging instead of point kriging is used in the mining industry in order to account for the simple reality that points are too small to be accurately mined.

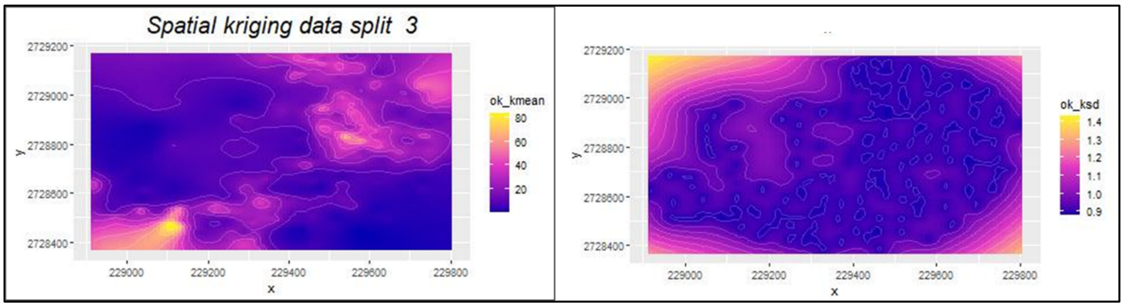
WLS estimates of Nugget, Sill and Scale

In the mining industry universally, the most common variogram model used is the spherical model. We observed from the Leapfrog Edge software that our variogram plots were very close to the Spherical model. We considered two different dimensions and found almost similar types of shape of the semi-variogram for both directions. Other than 2/3 splits all the data sets follow similar structures in terms of the semi-variogram.

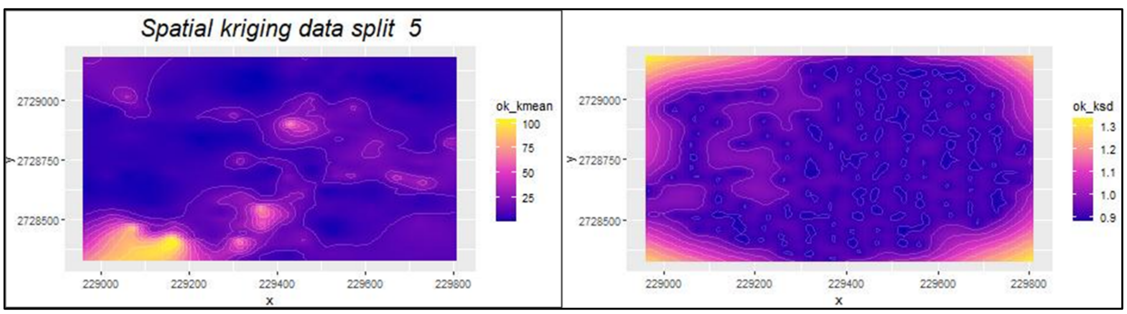
Point ordinary kriging was estimated within the Peñasquito breccia using R coding.
See below OK mean and standard deviation maps for some depth slices.



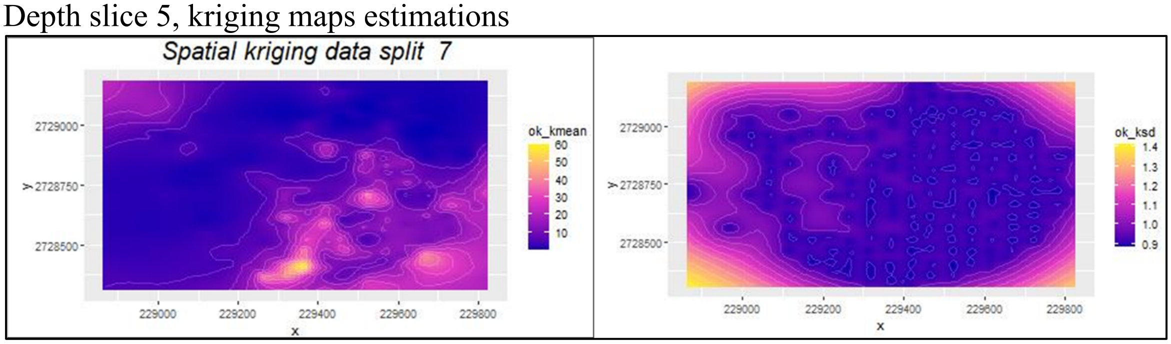
Depth slice 1, kriging maps estimations



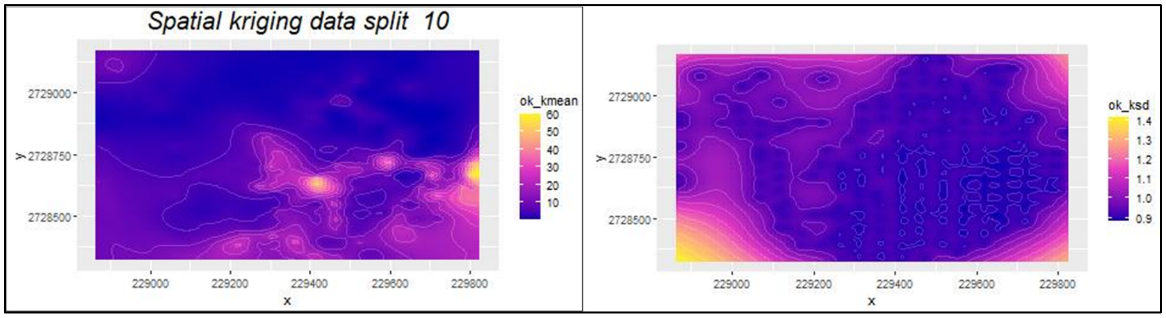
Depth slice 3, kriging maps estimations



Depth slice 5, kriging maps estimations



Depth slice 7, kriging maps estimations



Depth slice 10, kriging maps estimations

Conclusions

- A large RAM computer, with greater than 32 GB is necessary to work with a large database in R.
- It is difficult to find a proper x-y-z 3D coding for variograms and kriging estimates in R.
- There is anisotropy shown in the variograms generated in R and leapfrog. Pending, is to determine the best anisotropy direction.
- Outliers would have an impact on the final estimate. This remains to be verified.
- The estimate maps of OK and SK are very similar.
- Point kriging estimation was completed.
- Pending is to complete a block kriging estimate.

References

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