REPORT: GEOSTATISTICAL ANALYSIS OF CO-NI DEPOSIT USING KRIGING

Submitted as a requirement for Geomodelling course

by

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1. Exploratory Data Analysis on Co-Ni deposit data:

A statistical data analysis has been performed for the given Cobalt (Co) and Nickel (Ni) concentrations at the location's "x" and "y" as per the data. Data visualization of the Co and Ni would provide more insights into the distribution, relationships, and potential geological anomalies.

1.1.1. Analysis based on properties of data:

1. Identifying unusual properties:
    a. There are some outliers apart from the uniform grid.
    b. The "Co" concentration is represented as point size, which falsely implied as a fault.
    c. There are overlays present due to neighborhood of higher concentrations.

1.1.2. Histogram (Co and Ni)/Skewness:

From the histograms of Co and Ni, it is evident that both distributions are very close to normal/gaussian distribution, despite slight left-skewness's and long tailed. Q-Q plot also confirms this, showing a positive correlation of the data with respect to theoretical quantiles of normal distribution.

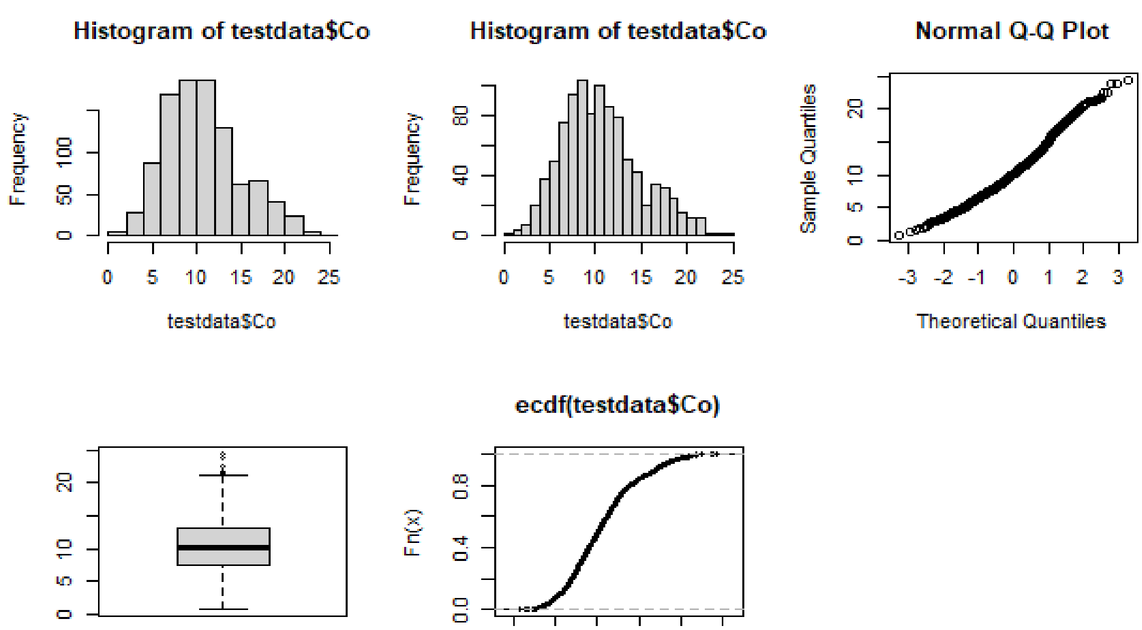

Figure 1: Graphical visualizations of histogram, bar plot and Q-Q plot for the data on 'Co' concentration

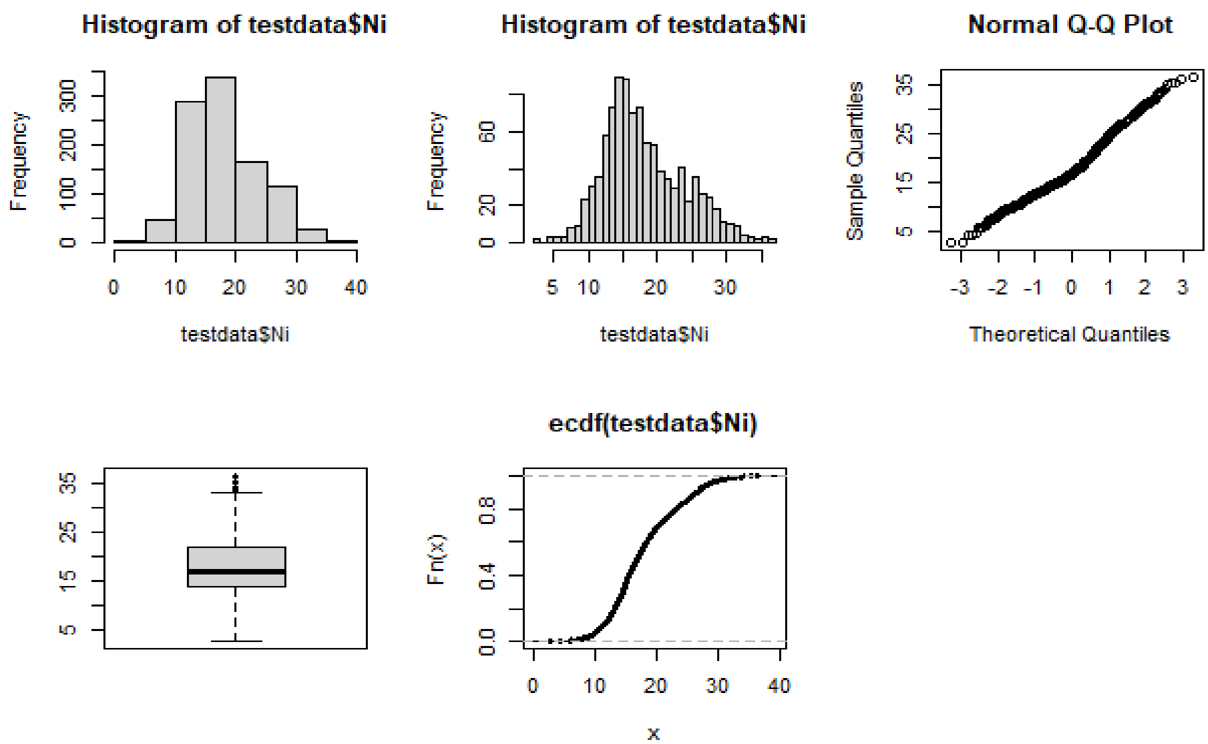

Figure 2: Graphical visualizations of histogram, bar plot and Q-Q plot for the data on 'Ni' concentration.

1.1.3. Outliers Identified from Boxplots:

From boxplots of Fig1 and Fig2, both Co and Ni exhibit outliers at higher concentrations. The location of the outliers can be identified in Fig3 represented by a cross symbol.

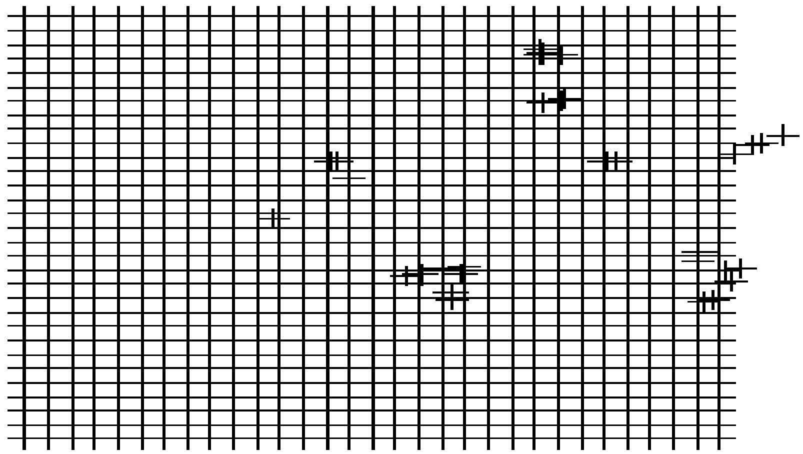

Figure 3: Grid indicating measurement locations (x, y) for the data points with outliers.

1.1.4. Optical impressions in spatial maps and bindings:

Since, the concentration of Co and Ni were represented with marker size. overlapping of the neighboring high concentrations might imply misinterpretation of actual variation in the data.

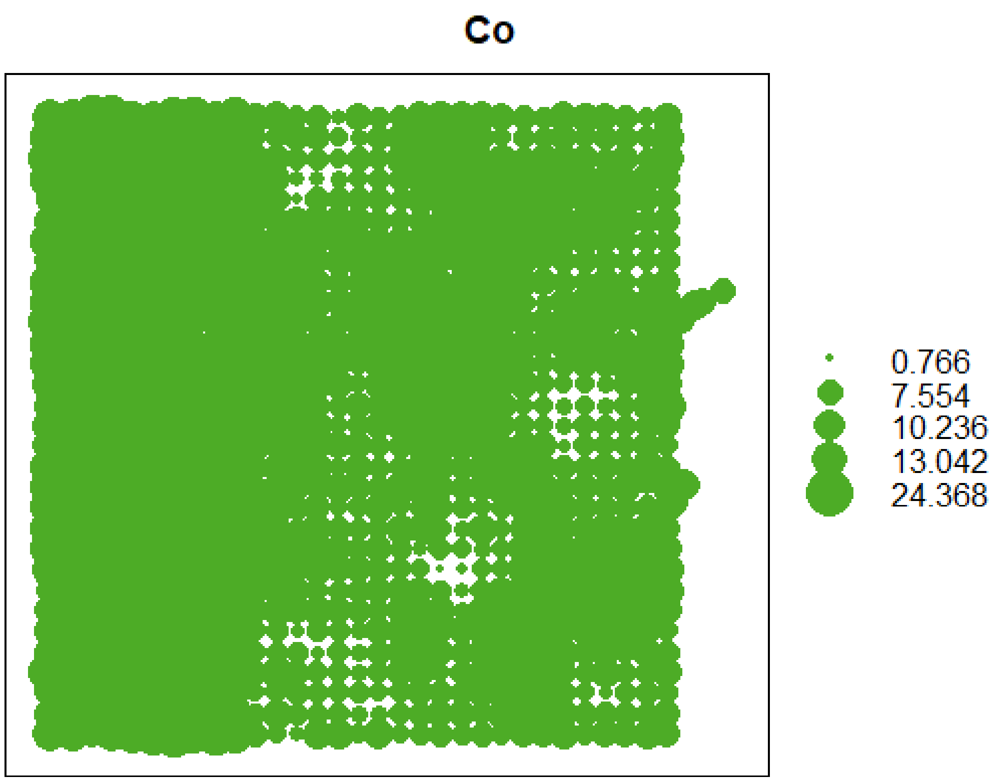

Figure 4: Visualization of 'Co' concentration by marker size

There is visible evidence of Overlays in both Co and Ni. This could be due to binding/rounding errors while measuring the data.

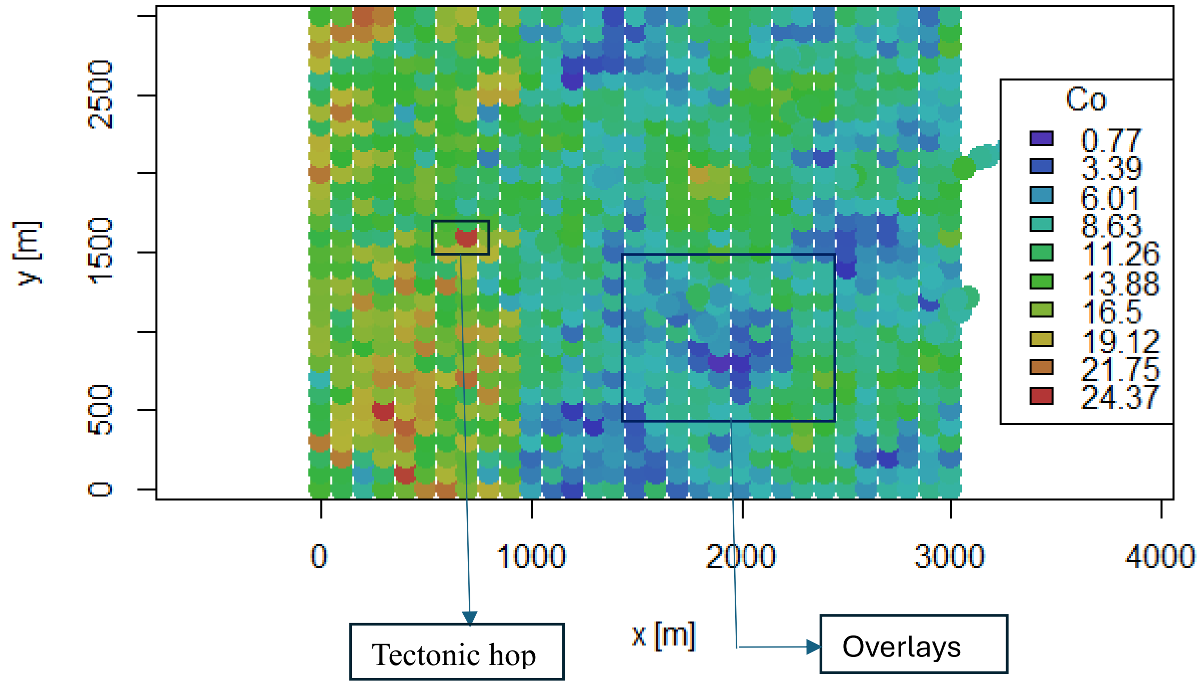

Figure 5: Visualization of 'Co' concentration by color indicating faults due to optical impression.

1.2. In general, most of the high concentrated Co lie on the left side and low concentrated Co lie on the right side.

1.1.5. Tectonic faults or hops: There are observable discontinuities in concentration of both Co and Ni, suggesting tectonic faults.

1.1.6. Correlation / Dependencies

1. The concentrations of Co and Ni are moderately positively correlated with linear correlation of 0.519

2. Similarly, horizontal location("x") is moderately negatively correlated with Co and Ni at -0.534 and -0.68 respectively. On the other hand, the Co and Ni concentrations are almost linearly correlated longitudinally.

	X	x	y	Co	Ni
X	1.00000000	0.132573864	0.487331023	-0.04336849	-0.07545011
x	0.13257386	1.000000000	0.008204151	-0.53736541	-0.68002821
y	0.48733102	0.008204151	1.000000000	0.02671672	-0.04970914
Co	-0.04336849	-0.537365407	0.026716722	1.00000000	0.51870446
Ni	-0.07545011	-0.680028214	-0.049709141	0.51870446	1.00000000

Table 1: Table of correlation between locations and concentrations of Co and Ni.

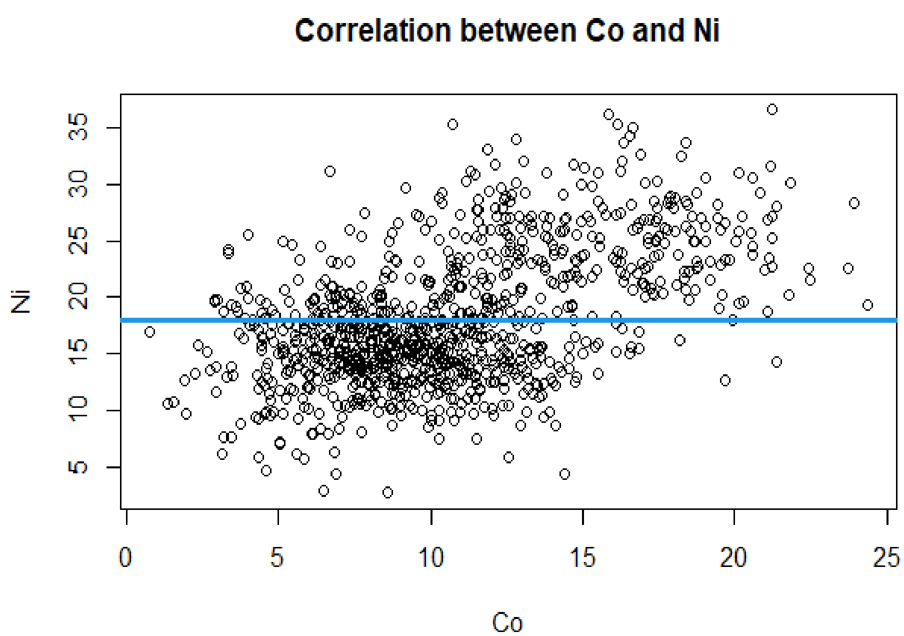

Figure 6: Correlation between concentrations of Co and Ni

1.1.7. Observations vs. Expectations

The weaker correlation between Co and Ni may suggest differential mobility during geochemical processes.

The outliers apart from the uniform location of data points were not expected. These outliers' concentration might be responsible for deviation of Co, Ni histograms with their ideal gaussian distributions.

1.1.8. Other Problems

While grid is uniform, there are anomalies at high values   These could be the measuring or rounding errors.

1.2 Variogram Analysis on Co-Ni:

1.2.1. Variogram cloud

a. From the variogram cloud, there are some outliers/extreme values of semi variances at long distances (as it reaches 1500m)

b. From visual inspection, pairs are frequently observed below 1000m.

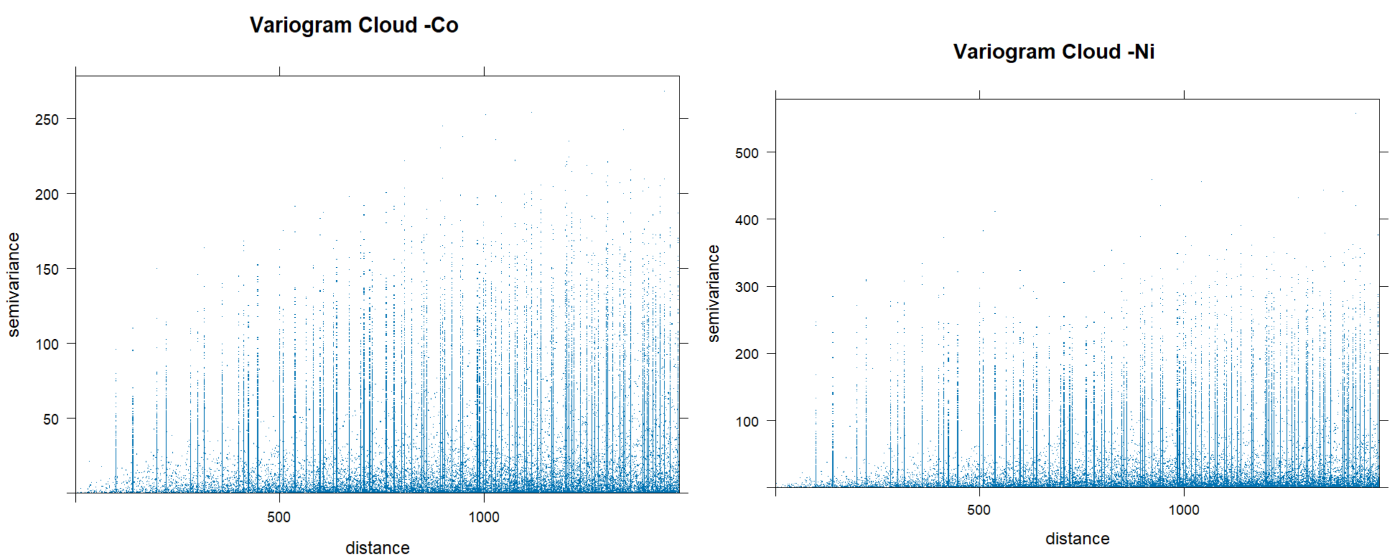

Figure 7:Variogram clouds for Co and Ni

1.2.2. Check for anisotropy:

a. The Variogram maps of both Co and Ni reveal anisotropy:

The variogram maps of Co and Ni, as shown below, don't follow symmetric distribution of variance concentrations along x and y.

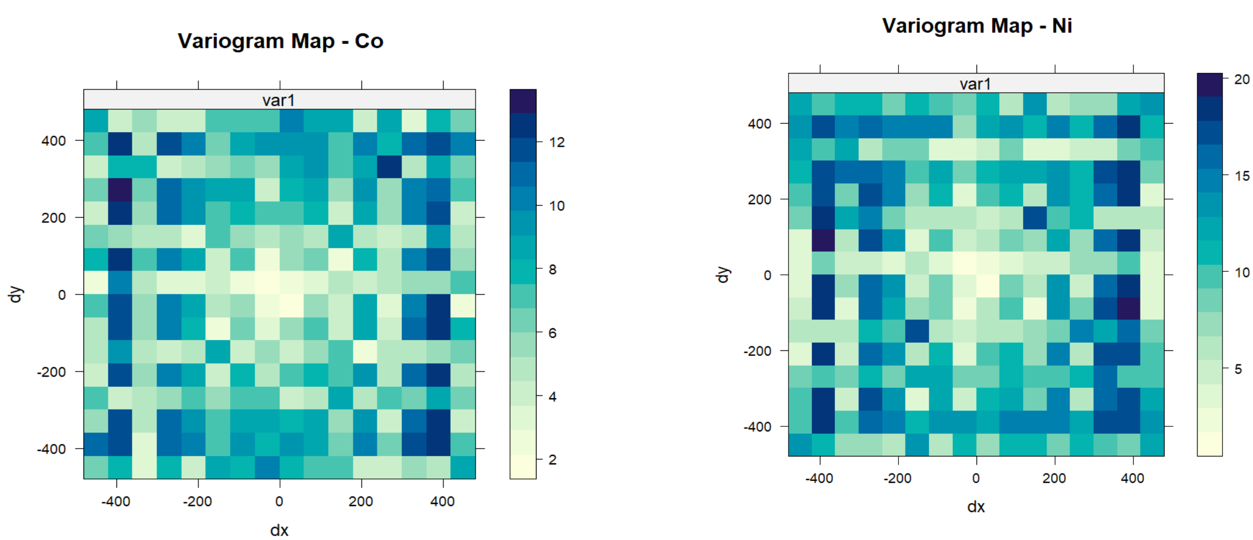

Figure 8: Variogram maps for Co and Ni

1.2.3. Fit for Variogram model:

Initially, a reasonable fit was achieved with an exponential variogram for Co and spherical variogram for Ni, as shown in Figure10.

The essential parameters for defining an exponential variogram for Co:

2.1.5. Semivariance increases and stabilizes around range of 1250m
2.1.6. The sill is considered approx.18
2.1.7. Nugget is considered approx.2.

The essential parameters for defining exponential variogram for Ni:

i. Semi variance increases and stabilizes around range of 1400m

ii. The sill is considered approx.30

iii. Nugget is considered approx.2

But, because of the anisotropy of Co and Ni concentrations from the variogram maps above, exponential variogram model for Co and spherical variogram model for Ni doesn’t fit the data at 0,45,90,135,180 degrees.

From figure 9, though a reasonable fit has been observed at 135 degrees for Co and 45 degrees for Ni. The model doesn’t fit at other angles. This confirms the presence of anisotropy along different angles.

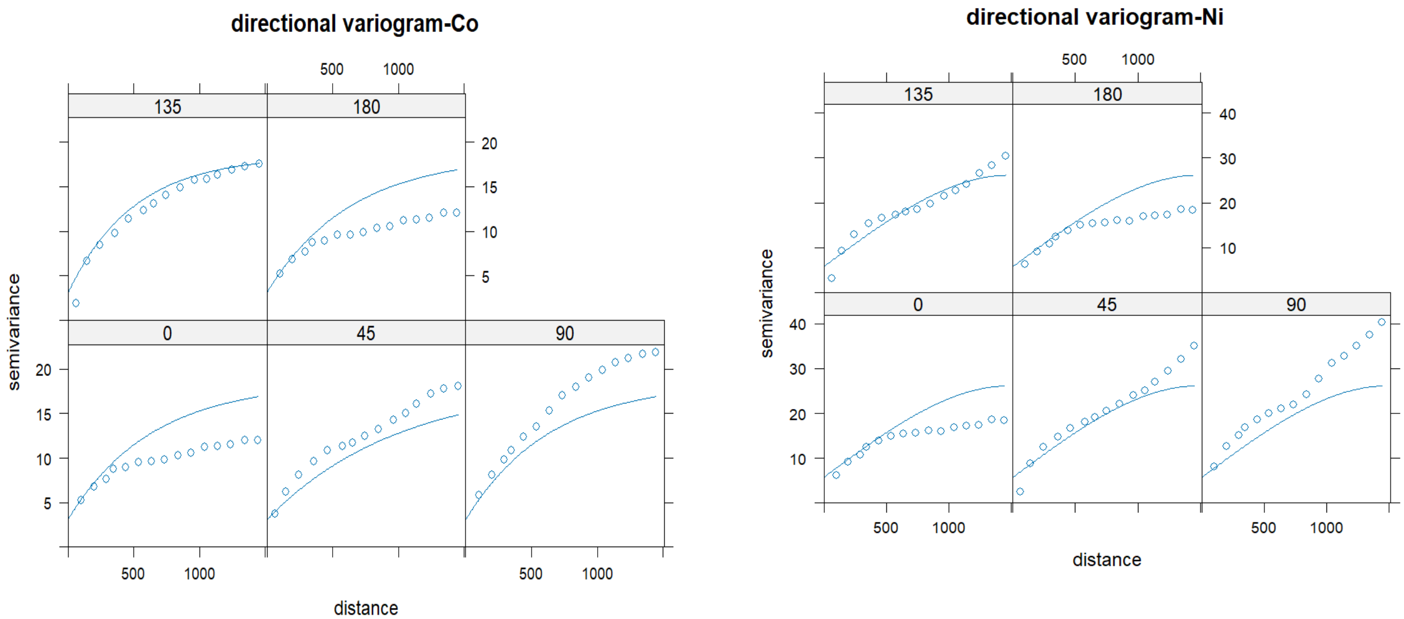

Figure 9: Directional fit of the exponential model for Co and spherical model for Ni at 0,45,90,135 and 180 degrees.

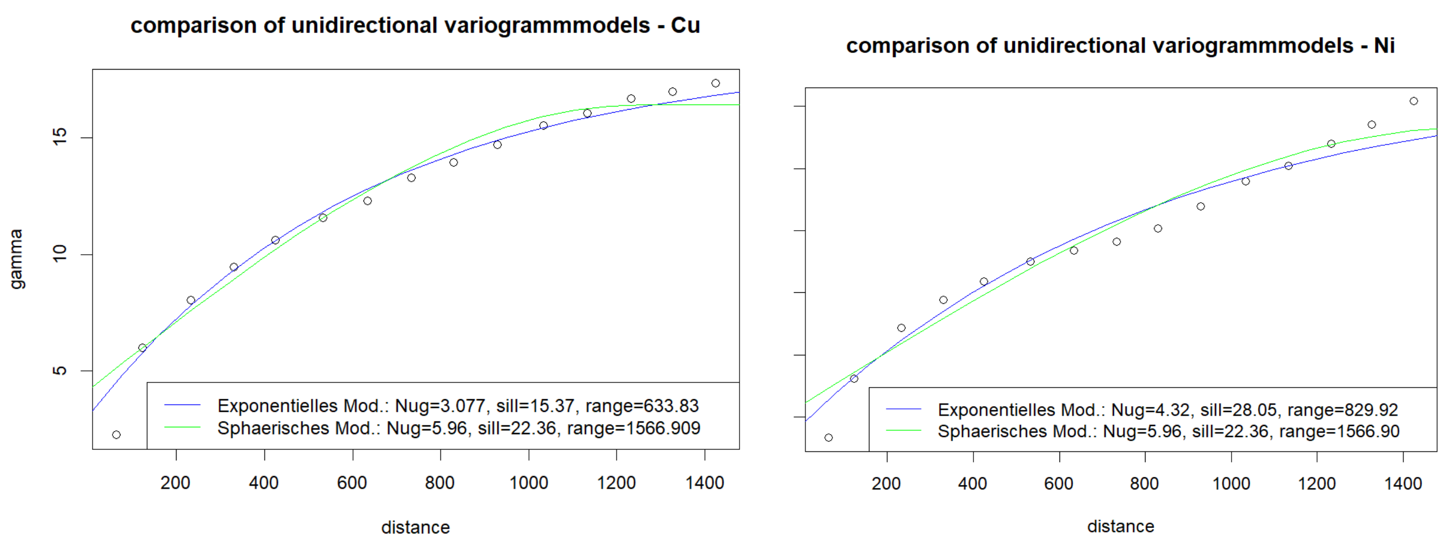

Figure 10: Comparison of exponential and spherical variogram models for Co and Ni, indicating nugget, sill and range.

1.3. Kriging

Before applying kriging, a regular grid of points (with 10-unit spacing) is created resulting in spatial grid. The same grid is used for estimation of both Co and Ni concentrations.

The data exploration analysis and check for anisotropic suggested that there is no deterministic trend in the coordinates and no external global is known. Therefore, ordinary kriging is preferred to estimate uncertainty locations across the grid. Ordinary kriging estimates at an unknown point by considering means of neighborhood.

The 'Co' and 'Ni' concentrations are predicted across the grid with respect to known certainty which are referred to as var1.pred and var1.var in Figure11 and Figure12 respectively.

var1.pred: Kriging estimate of Co or Ni across the grid area.

var1.var: Kriging variance —i.e., how confident the model is at each grid cell.

It can be observed from Figure 11 and 12 that the variance of the predicted Co or Ni concentrations is relatively low. This indicates the models —exponential model for Co and spherical model for Ni —are relatively more confident about the predictions.

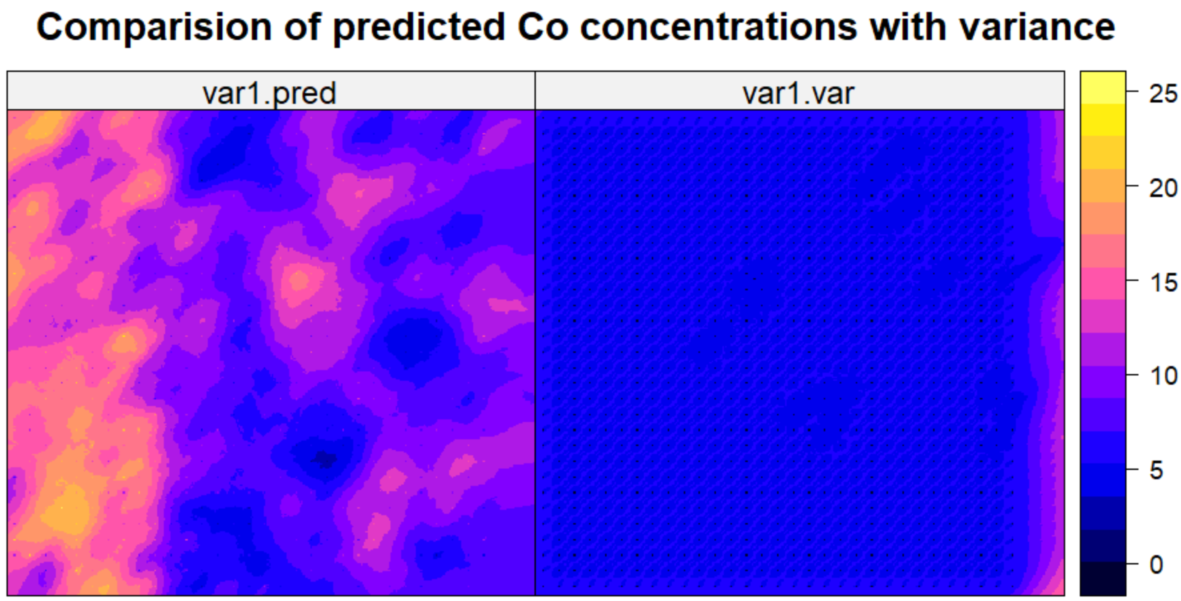

Figure 11: Predicted 'Co' concentrations with their variance across the grid using ordinary kriging.

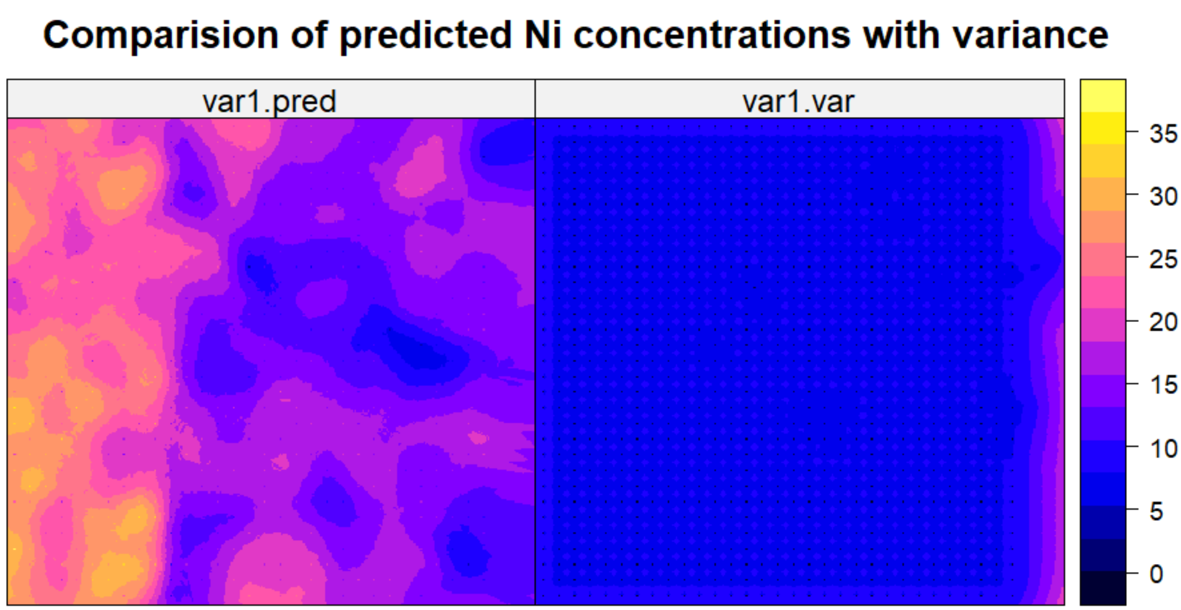

Figure 12: Predicted 'Ni' concentrations with their variance across the grid using ordinary kriging.

1.4. Cross Validation: Evaluation of Kriging analysis

To validate the predictions, a leave one out strategy is employed. During this leave one out strategy, concentration of a Co/Ni is predicted with trained variogram model after removing each sample from the data.

```
> summary(mcv_co)
Object of class SpatialPointsDataFrame
Coordinates:
  min  max
x   0 3271
y   0 3000
Is projected: NA
proj4string : [NA]
Number of points: 994
Data attributes:
   var1.pred          var1.var         observed          residual            zscore               fold      
 Min.   : 3.791   Min.   :4.236   Min.   : 0.766   Min.   :-9.199412   Min.   :-3.927809   Min.   :  1.0  
 1st Qu.: 7.922   1st Qu.:5.486   1st Qu.: 7.554   1st Qu.:-1.477840   1st Qu.:-0.621461   1st Qu.:249.2  
 Median :10.010   Median :5.486   Median :10.236   Median : 0.052062   Median : 0.022228   Median :497.5  
 Mean   :10.655   Mean   :5.505   Mean   :10.655   Mean   :-0.000647   Mean   :-0.000253   Mean   :497.5  
 3rd Qu.:13.249   3rd Qu.:5.486   3rd Qu.:13.042   3rd Qu.: 1.448652   3rd Qu.: 0.618334   3rd Qu.:745.8  
 Max.   :20.524   Max.   :8.578   Max.   :24.368   Max.   : 8.571795   Max.   : 3.658954   Max.   :994.0  
```

Figure 12: Summary of cross validation metrics for Co using exponential model

```
> sd_co <- sd(mcv_co$residual)
> sd_co
[1] 2.40918
```

Figure 13: Standard deviation of residuals for Co using exponential model

It is observed that the standard deviation of residuals is 2.409, which is reasonably small as its 10% of the total range 0.7566 to 24.368. Also, the mean of the residuals is almost 0. As a result, the exponential model used for estimation of Co concentrations can be relied upon and resemble the actual Co data.

Similarly, from Figure 14 and 15, we could infer that standard deviation of Ni residuals is 2.78, which is even smaller than Co as the range of observed values is from 2.73 to 36.55. Also, the mean of residuals is almost 0.

```
> summary(mcv_ni)
Object of class SpatialPointsDataFrame
Coordinates:
  min  max
x   0 3271
y   0 3000
Is projected: NA
proj4string : [NA]
Number of points: 994
Data attributes:
    var1.pred          var1.var          observed
 Min.   : 7.535   Min.   : 7.426   Min.   : 2.731
 1st Qu.:14.440   1st Qu.: 8.454   1st Qu.:13.978
 Median :16.747   Median : 8.456   Median :17.022
 Mean   :18.040   Mean   : 8.498   Mean   :18.038
 3rd Qu.:22.277   3rd Qu.: 8.456   3rd Qu.:21.820
 Max.   :29.644   Max.   :12.225   Max.   :36.554
    residual             zscore               fold
 Min.   :-11.158883   Min.   :-3.709717   Min.   :  1.0
 1st Qu.: -1.567512   1st Qu.:-0.538676   1st Qu.:249.2
 Median :  0.009555   Median : 0.003286   Median :497.5
 Mean   : -0.002721   Mean   :-0.000744   Mean   :497.5
 3rd Qu.:  1.560976   3rd Qu.: 0.535242   3rd Qu.:745.8
 Max.   : 10.773700   Max.   : 3.705054   Max.   :994.0
```

Figure 14: Cross validation results summary for Ni

```
> sd_ni<- sd(mcv_ni$residual)
> sd_ni
[1] 2.781768
```

Figure 15: Standard deviation of Ni using spherical variogram model

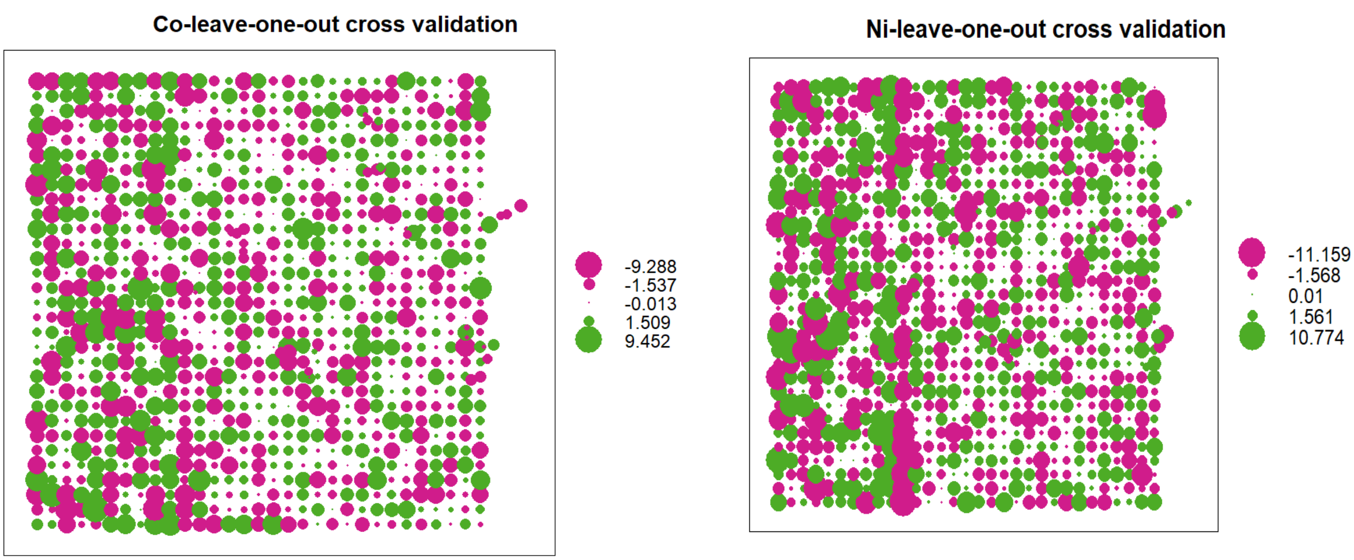

Figure 16: Bubble plot indicating the size of residuals for Co an Ni.

2. Variogram and analysis based on sub regions of high concentrations and low concentrations

2.1. Comparison of subregions kriging a with Overall-Area Results

As identified in the exploratory data analysis Figure5, there is a high concentration of Co and Ni at x<1000m and low concentration at x>1000m. So, they are separated into 2 datasets. As before, kriging analysis is performed on both the datasets.

It can be observed from Table2 that, the standard deviations for kriging during cross validation for x<1000m is higher than the standard deviations during cross validation for x>1000m. This is due to the presence of high concentrations of Co and Ni on the left side(x<1000m), which led to big residuals.

Analysis	Overall area		x<1000m		x>1000m	
	Co	Ni	Co	Ni	Co	Ni
Check for anisotropy	Present	Present	Mosty isotropic	Mostly isotropic	Mostly isotropic	Mostly isotropic
Variogram model	Exponential model	Spherical model	Exponential model	Spherical model	Exponential model	Spherical model
Variogram Parameters	Range:1250m Nugget:2 Sill:18	Range:1400m Nugget:2 Sill :30	Range: 1250 Nugget:2 Sill :18	Range:1400 m Nugget:2 Sill :30	Range: 1250 Nugget:2 Sill :18	Range:1400 m Nugget:2 Sill :30
Fit with the data	Fit not achieved at all angles	Fit not achieved at all angles	Good fit achieved	Good fit achieved	Good fit achieved	Good fit achieved
Kriging type	Ordinary kriging	Ordinary kriging	Ordinary kriging	Ordinary kriging	Ordinary kriging	Ordinary kriging
Standard deviation of kriging cross-validation	2.409	2.781	3.157	3.415	1.970	2.052

Table 2: Summary of kriging analysis results on comparision with x<1000m and x>1000m with overall area.

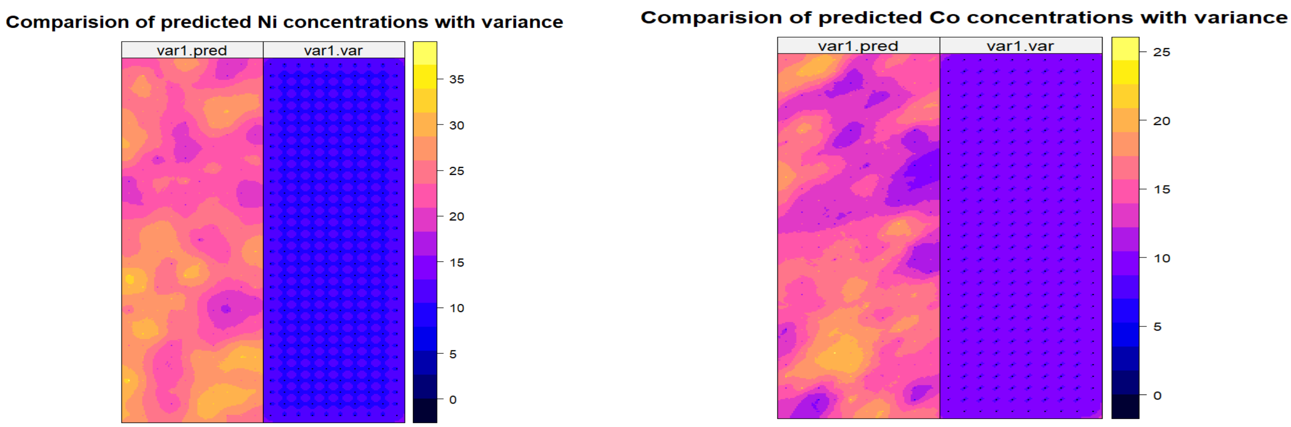

Figure 17: Kriging prediction of Co and Ni concentrations with its variance for x<1000m data

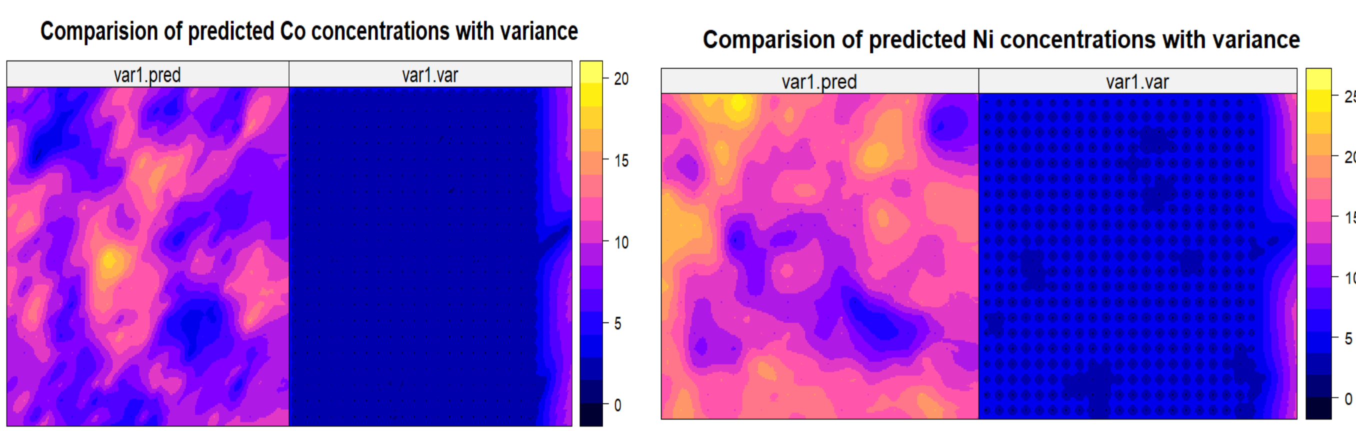

Figure 18:Comparision of Co and Ni predictions with its variance for x>1000m data.

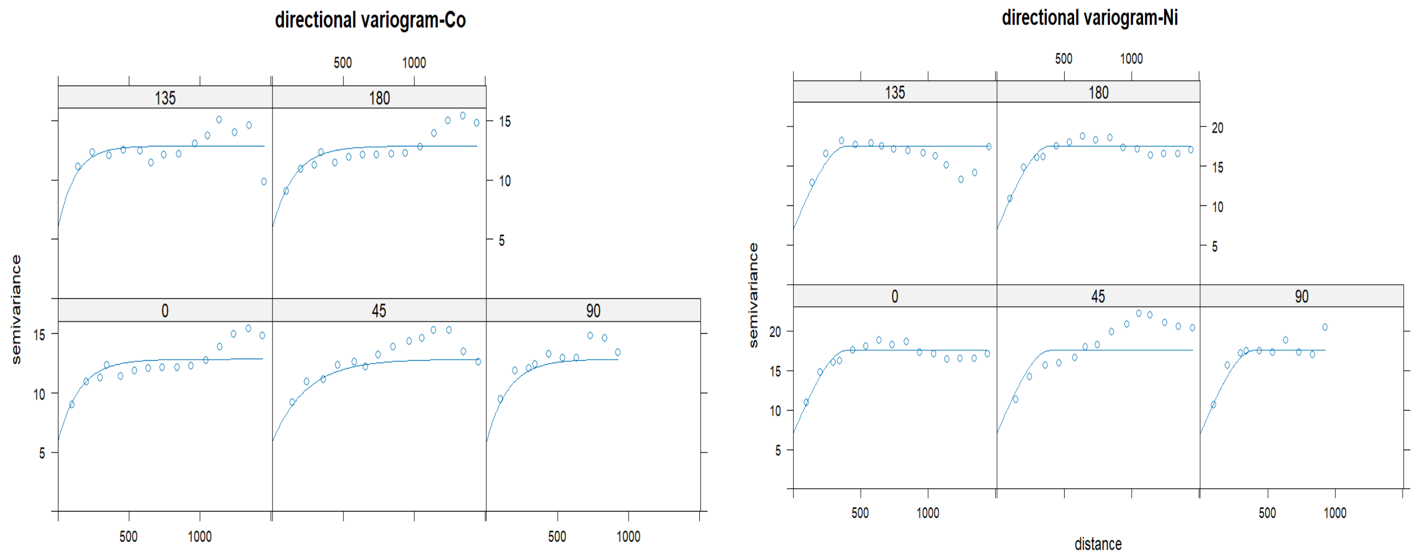

Figure 19: Directional variogram of Co and Ni concentrations for x<1000 data

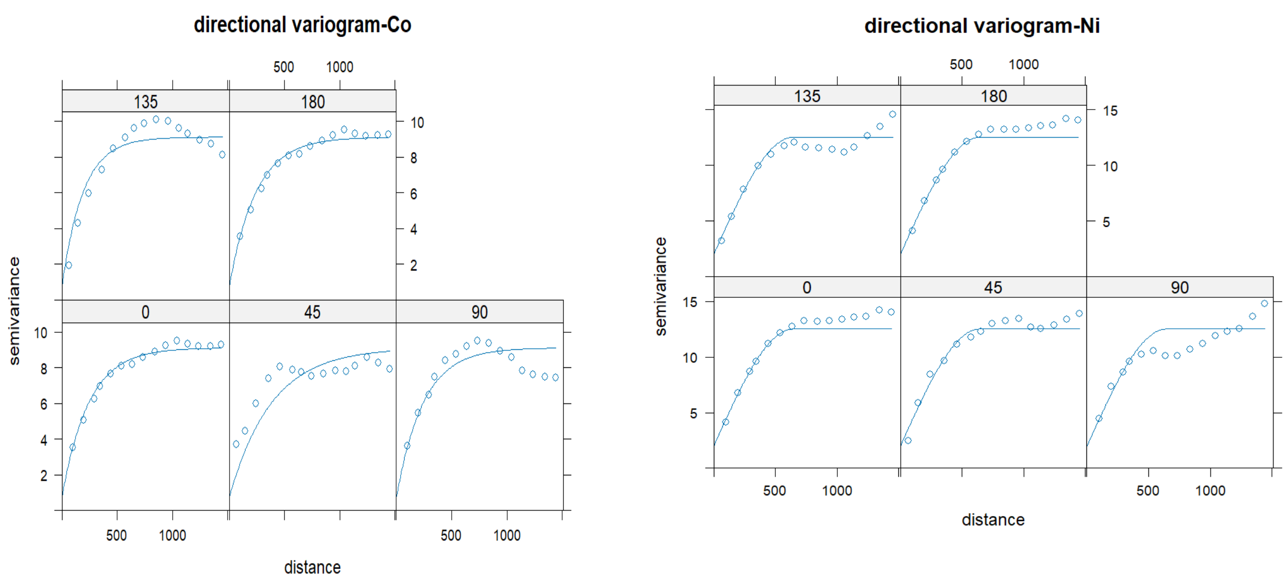

Figure 20: Directional variogram of Co and Ni concentrations for x>1000m data