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Correlations of SiO_2, Al_2O_3 and Other Elements in the Dam of an Iron Mine: Contributions to the Circular Economy

Vidal Félix Navarro Torres[1], Eduardo Da Rosa Aquino[1], Carlos Arroyo[2], Romulo Ferraz[3], Carlos Dalmiro[3], Ana Sampaio[3]

[1]Instituto Tecnológico Vale-Mineração, Santa Luzia, Brazil
[2]Departamento de Engenharia de Minas, Universidade Federal de Ouro Preto, Ouro Preto, Brazil
[3]Vale S.A., Parauapebas, Brazil

Email: vidal.torres@itv.org, eduardo.aquino@itv.org, carroyo@ufop.edu.br, romulo.ferraz@vale.com, carlos.dalmiro@vale.com, ana.sampaio@vale.com

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Abstract

Iron deposits are the main sources of raw material for the steel industry. These deposits are predominantly formed by iron oxide minerals, such as hematite, magnetite and goethite. The economic viability and metallurgical quality of the deposits depend not only on the iron content but also on the presence of undesirable contaminants, such as phosphorus, silica, and alumina. The presence of these contaminants directly impacts the beneficiation process and the performance of the final product in various processes, such as in blast furnaces, sintering, pelletizing and direct reduction. In this study, the influence and behavior of the contaminants associated with iron sediments deposited in a tailings dam are evaluated. A model based on ordinary kriging (OK) estimation was used, which included the contents of iron, silica, phosphorus, alumina, manganese, calcium oxide, magnesium oxide, and titanium dioxide and the loss on ignition. This model was used to evaluate the contents of the analytes via correlation analyses. The generated scatter plots revealed correlations between iron and silica, iron and alumina, and silica and alumina.

Keywords

Tailings Dam, Ordinary Kriging, Contaminants, Correlation

1. Introduction

Tailings dams are structures that are constructed to store the discarded material from mineral processing that cannot be recovered through physicochemical concentration processes. Many of the materials deposited in these dams have extremely fine particle sizes and high concentrations of ore, as prior mineral processing technologies did not allow the recovery of the finer fraction of the ore. In recent years, with the development of new technologies, these materials have found various applications (Ferrante, 2014). As a result, mining companies have exhibited interest in recovering and using the materials from tailings dams and integrating the recovered products into the industrial chain.

The interest of mining companies and the increasing number of recovery projects in tailings dams are associated with the principles of the circular economy, as stated by Kefeni et al. (2017). Reuse of tailings is extremely important because it extends the life cycle of mining processes and allows the recovery of precious and economically profitable elements. In addition, in line with the circular economy, Hunt et al. (2014) reported that the development, application and standardization of new technologies are important to integrate mineral production with the reuse of tailings and to promote sustainability.

According to Mochizuki and Tsubouchi (2019), the progressive depletion of high-quality iron ore reserves, combined with the increasing demand for steel, indicates a growing need for the use of low-quality ores, such as limonite, which is rich in goethite and gangue components (Si, Al and P). However, the higher impurity content and the presence of water reduce its performance in blast furnaces, increasing slag generation, coke consumption, energy expenditure, CO_2 emissions and production costs and reducing the metal yield. In this context, the development of efficient processing technologies aimed at reducing gangue components while increasing the iron content is essential for the sustainability of the steel industry.

Couto et al. (2010) reported that high levels of phosphorus are detrimental to the steelmaking process because phosphorus results in brittle and fractured materials, reducing the market value of iron ore. Briefly, aluminum oxides contribute to the formation of brittle sinters, altering the composition of slag in the blast furnace and consequently compromising its operation.

According to Svoboda (1994), iron ore used as a raw material in the steel industry, when it contains high levels of silica and alumina, can negatively affect the production of pig iron and steel. Rath et al. (2014) reported that when these contaminants are present in large quantities, highly viscous slag is formed in blast furnaces in large quantities, which requires the use of a greater amount of flux.

Additionally, Singh et al. (2024) reported a critical threshold for the phosphorus content in iron ore; high levels of phosphorus cause cold shortness, resulting in more brittle steel with low toughness. The treatment of iron ore with high levels of phosphorus requires more complex metallurgical approaches and higher energy consumption, which leads to high operational costs. Ofoegbu (2019) emphasized that to keep the price of steel competitive, technically and economically viable technologies are needed in the steel industry.

Lu et al. (2007) and Hessien et al. (2008) reported that an increase in the alumina content in the sinter can negatively impact its permeability to gases and liquids and its reducibility in the lower part of the blast furnace. In addition, it can lead to increased slag production and coke consumption. Hou et al. (2024) reported that the physicochemical and metallurgical properties of sinter with a high alumina content directly influence the operational stability of the blast furnace.

In the context of the tailings dams of iron ores, evaluating the economic viability of tailings reuse requires a detailed characterization of not only the content and quality of the iron present in the sediments but also the spatial distribution of the main contaminants, such as silica, alumina and phosphorus. These parameters must be determined to ensure the continuity and efficiency of the production chain, including mining planning and sequencing, mineral processing, and the generation of products that strictly meet the specifications of the consumer market. In addition, the control of contaminants is related to the principles of circular economy. High levels of these deleterious elements increase energy consumption, slag generation, coke use, and fluxes and carbon emissions in the blast furnace. On the other hand, reducing the levels of these contaminants through appropriate processing methods increases metallurgical efficiency, reduces emissions and strengthens the recirculation of materials, thereby improving the sustainability and circular characteristics of the steel industry.

In this study, a statistical and spatial evaluation of the distribution of iron and its contaminants in the sediments of an iron ore tailings dam is conducted. The objective is to evaluate the influence and behavior of the contaminants associated with iron in the reprocessing of the tailings. A more comprehensive characterization of these materials improves the metal recovery potential, operational costs and processing requirements. In addition, this in-depth understanding contributes to the development of strategies aligned with the principles of circular economy by promoting the reintegration of tailings in the production chain, thereby reducing the need for new mines and minimizing environmental impacts associated with the disposal of these materials.

2. Database

The database consists of an estimated block model that contains Fe (iron), SiO_2 (silica), P (phosphorus), Al_2O_3 (alumina), Mn (manganese), CaO (calcium oxide), MgO (magnesium oxide), TiO_2 (titanium dioxide) and loss on ignition (LOI). Detailed information regarding drill hole samples, variographic analysis, and the estimation strategy employed is described in Aquino et al. (2025). For a better visualization of the estimates, plan views of the estimated models for the analytes Fe, SiO_2, P and Al_2O_3 are illustrated in **Figures 1-4**, respectively.

The estimates were validated by comparing the global mean estimates of the ordinary kriging (OK) model with the estimates obtained by the nearest neighbor (NN) method. The means of the variables differed by 0% to 6.25%, with the OK model sometimes providing estimates that were too smooth or levels that were overestimated relative to the estimates obtained by the NN method. These values were considered consistent and within the acceptable limit, with less than a 10% difference in the means obtained by the two methods. The means for Fe and all the estimated contaminants are given in **Table 1**.

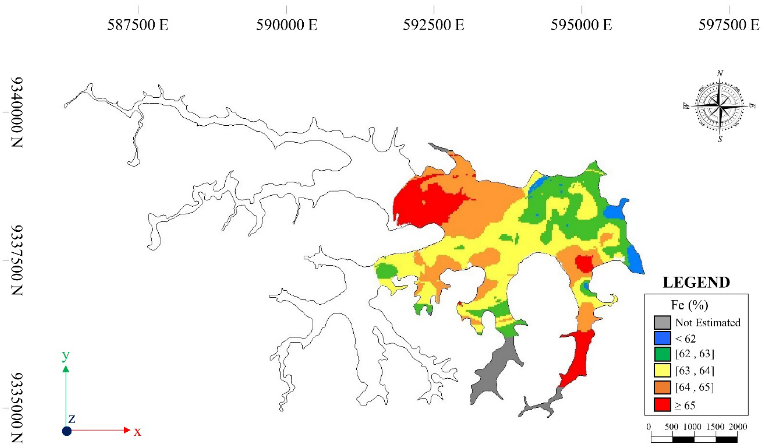

Figure 1. Plan view of the block model estimated for Fe (iron).

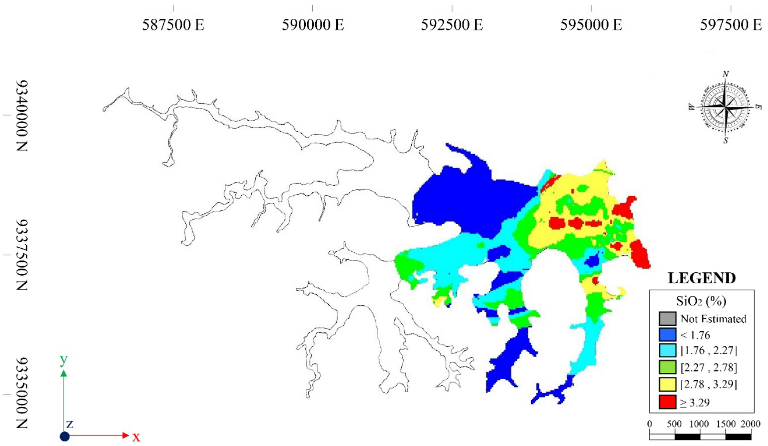

Figure 2. Plan view of the block model estimated for SiO_2 (silica).

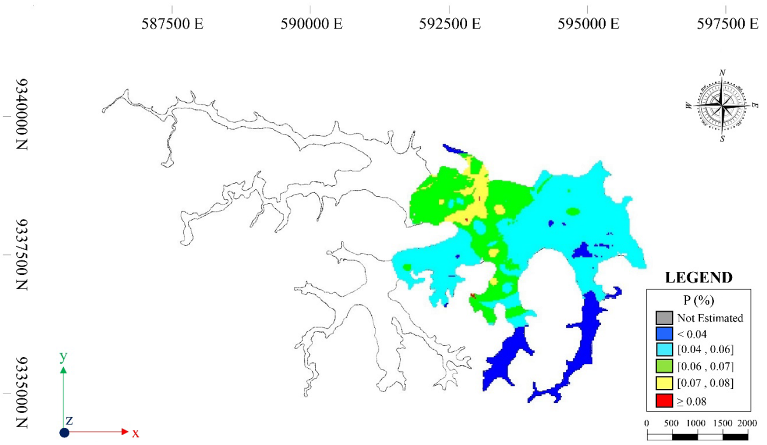

Figure 3. Plan view of the block model estimated for P (phosphorus).

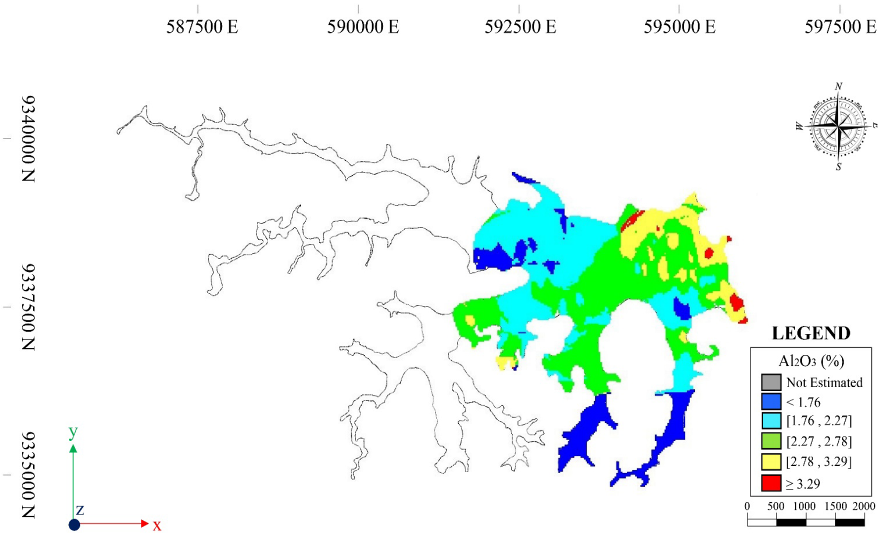

Figure 4. Plan view of the block model estimated for Al_2O_3 (alumina).

Table 1. Comparison of the means obtained by the OK and NN methods for Fe and the contaminants.

Variable	Mean-OK method (%)	Mean-NN method (%)	Difference (%)
Fe	63.89	63.84	0.08
SiO_2	2.06	2.09	−1.46
P	0.06	0.06	0
Al_2O_3	2.31	2.33	−0.87
Mn	0.83	0.84	−1.2
CaO	0.016	0.015	6.25
MgO	0.06	0.06	0
TiO_2	0.16	0.17	−6.25
LOI	2.95	3.03	−2.71

In addition, the results were validated through swath plots, which allow the local bias of the estimation method to be evaluated, i.e., whether the mean of the estimated values follows the trend of the data. The means of the estimates obtained by the OK method can be compared with the means of the samples or the means of the estimates obtained by the NN method. These analyses were performed along ranges or slices previously defined in the estimated model. Then, local deviations, bias and imprecision in the model estimates were identified. The validated swath plots for Fe, SiO_2, P and Al_2O_3 are shown in **Figures 5-8**, respectively, and the results reveal the consistency of the estimates.

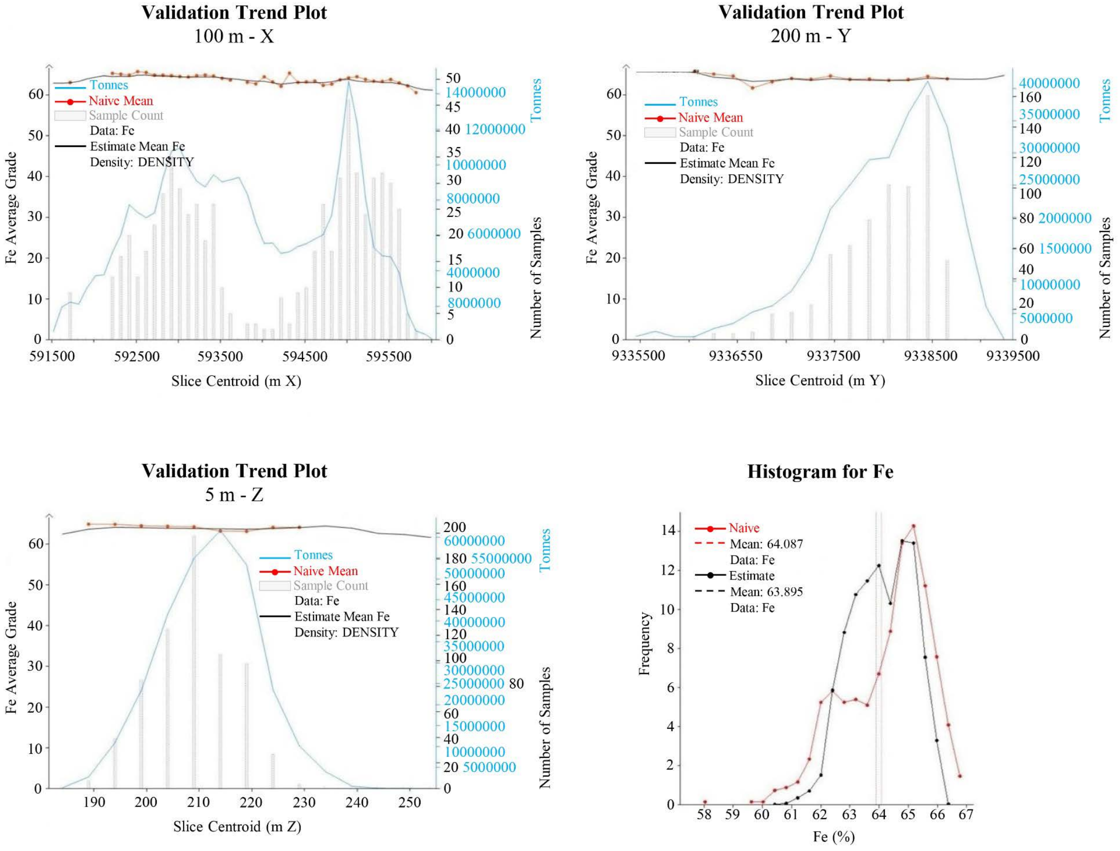

Figure 5. Swath plots for Fe on the *X*, *Y* and *Z* axes.

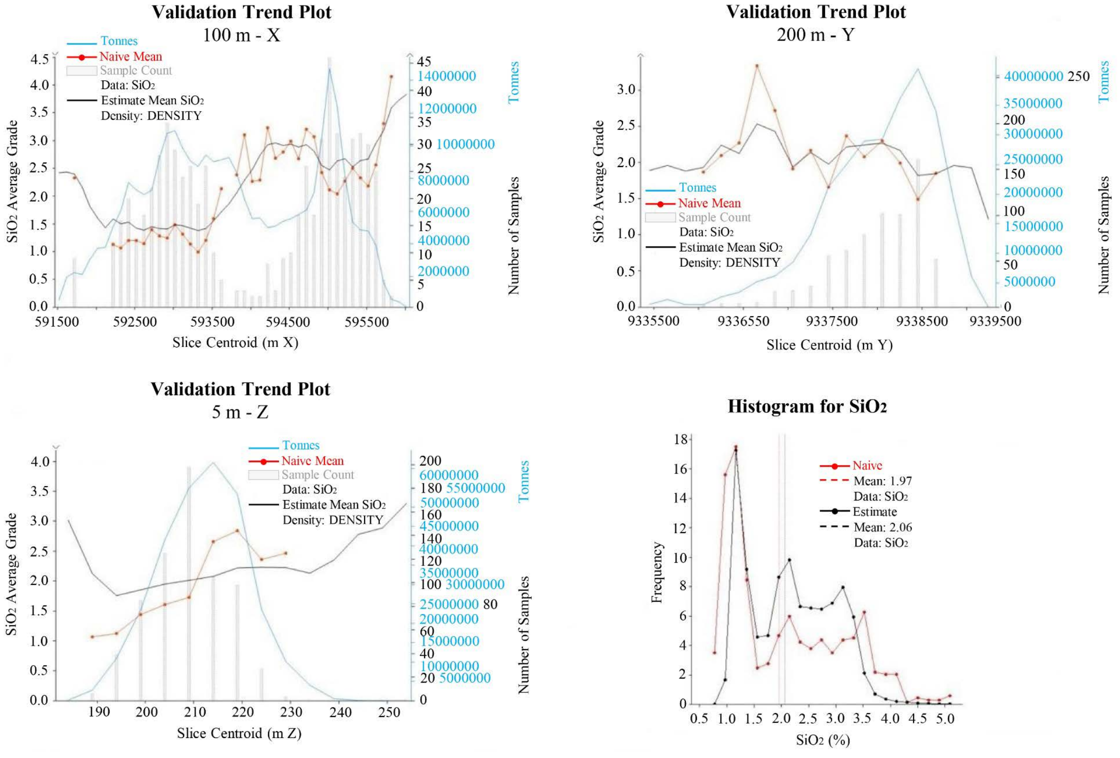

Figure 6. Swath plots for SiO_2 on the *X*, *Y* and *Z* axes.

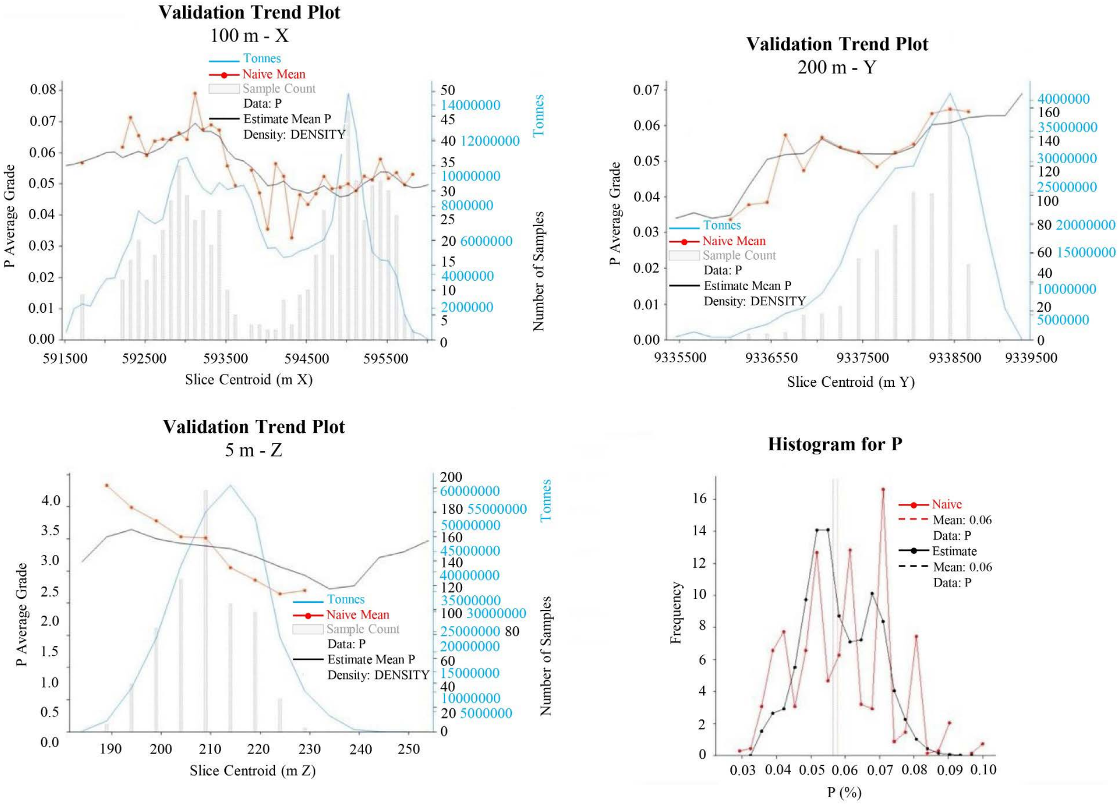

Figure 7. Swath plots for P on the *X*, *Y* and *Z* axes.

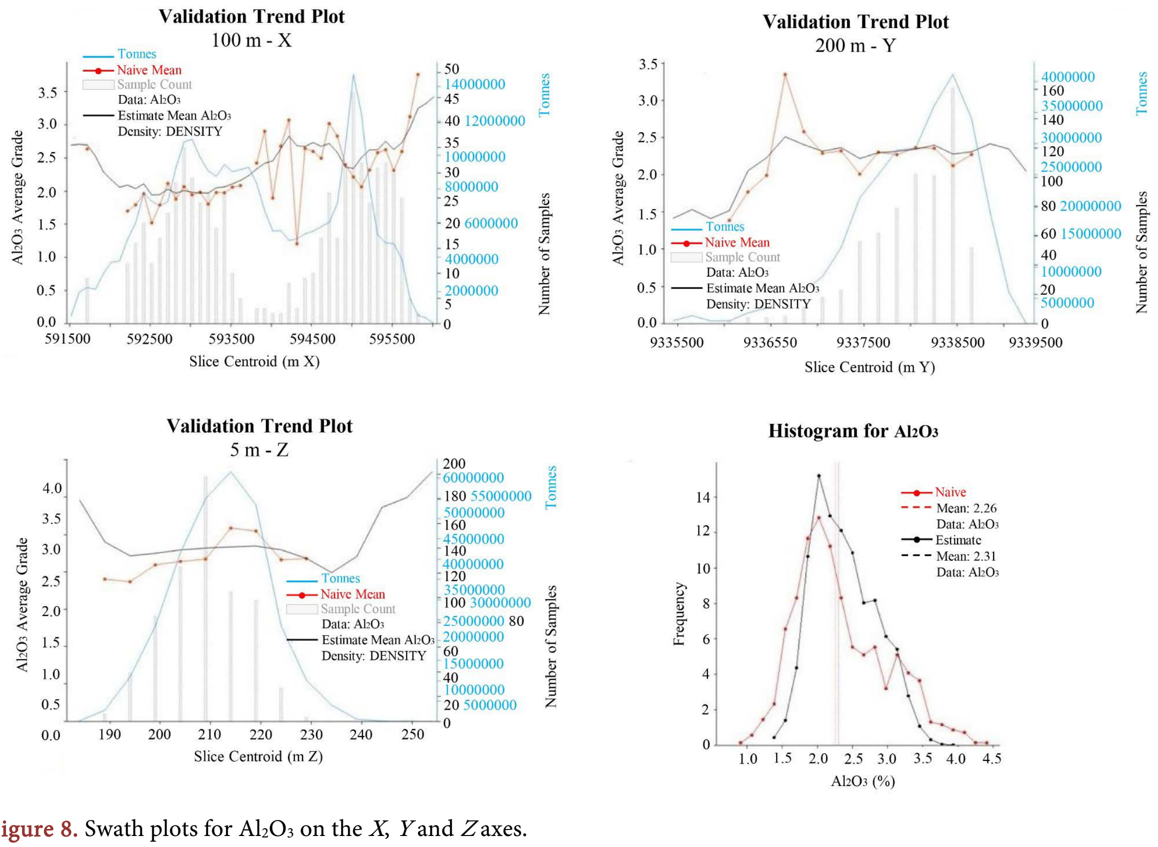

Figure 8. Swath plots for Al_2O_3 on the *X*, *Y* and *Z* axes.

3. Materials and Methods

The aim of the proposed methodology is to statistically evaluate the contents of the contaminants present in the tailings sediments of a dam of an iron mine on the basis of a model estimated by the OK method. Through correlation analysis, the behavior of the contaminants was evaluated in relation to the element, Fe, to verify the distribution of these contaminants and their influence on the planning stages, mining operation and ore treatment when the tailings are reused. A flowchart of the steps of the methodology is given in **Figure 9**.

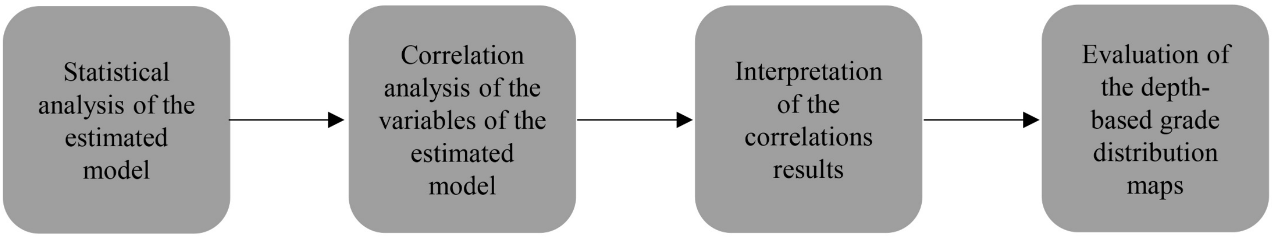

Figure 9. Flowchart of the proposed methodology.

3.1. Statistical Analysis of the Estimated Model

The block model estimated by the OK method provides the contents of the analytes Fe, SiO_2, P, Al_2O_3, Mn, CaO, MgO, and TiO_2 and information on the LOI. To better understand how the contents are distributed, the main statistics of all the variables were evaluated. A summary of the statistical results for each analyte in the estimated model is given in **Table 2**.

Table 2. Summary of the statistical results for all the analytes in the estimated model.

Variable	Mean (%)	Standard Deviation (%)	Minimum (%)	p_{10} (%)	Median (%)	p_{90} (%)	Maximum (%)
Fe	63.86	1.04	60.06	62.50	63.89	65.23	66.12
SiO_2	2.12	0.77	0.70	1.06	2.08	3.12	7.43
P	0.06	0.01	0.03	0.04	0.05	0.07	0.10
Al_2O_3	2.32	0.45	1.25	1.78	2.28	2.93	3.80
Mn	0.82	0.17	0.39	0.59	0.84	1.02	1.77
CaO	0.02	0.00	0.01	0.01	0.02	0.02	0.06
MgO	0.06	0.01	0.04	0.05	0.06	0.07	0.14
TiO_2	0.16	0.03	0.08	0.13	0.16	0.19	0.25
LOI	2.92	0.38	1.73	2.25	3.04	3.25	3.75

The statistical results of the estimated model presented in **Table 2** are fundamental for the iron ore production chain. In accordance with the quality specifications of the ore to be fed into the treatment plant, the planning strategy determines the sequence of the mining operation and ensures that the objectives of the plant are satisfied. The performance of the ore treatment plant directly determines the content of iron and the contaminants, as well as the granulometric consistency of the final product, which is important for the iron ore to meet the quality specifications required by steel contracts.

In accordance with the Specifications Guide-Global Iron Ore (S & P Global Inc., 2026), published in January 2026, the Platts specifications are used to evaluate various iron ore products worldwide. The document mainly specifies the quality of the iron ore traded between the mineral and steel industries. The market price of iron ore products is determined by product quality specifications regarding the content of iron and the associated contaminants. Essentially, product quality is based on certain content limits, with a minimum value for the Fe percentage and maximum values for the percentages of various contaminants. For the tailings in the dam, the products can be classified as "fine" or "pellet".

Iron ore fines products such as "IODEX CFR China" and "TSI Iron Ore Fines CFR China" are characterized by content limits of 61% Fe, 4.5% SiO_2, 2.5% Al_2O_3, 0.1% P, 0.02% S and 8.0% moisture. "Iron Ore Fines 65% Fe CFR China" has content limits of 65% Fe, 2.0% SiO_2, 1.4% Al_2O_3, 0.065% P and 8.5% moisture. "Iron Ore Fines 58% Fe CFR China" has content limits of 58% Fe, 6.0% SiO_2, 2.9% Al_2O_3, 0.06% P and 8.0% moisture.

The iron ore pellet product "Iron Ore Spot Blast Furnace Pellet Premium 65% CFR China" has content limits of 65% Fe, 5.0% SiO_2, 0.35% Al_2O_3, 0.02% P, and 0.003% S, as well as Cold Crushing Strength (CCS) of 250. Iron ore pellet products such as "Iron Ore Spot Blast Furnace Pellet Premium 63% CFR China" and "Iron Ore Spot Blast Furnace Pellet 63% CFR China" have content limits of 63% Fe, 4.0% SiO_2, 3.5% Al_2O_3, 0.07% P, and 0.008% S and a Cold Crushing Strength (CCS) of 230.

The market also provides penalties in the sale price of the products if the percentages of the contaminants do not meet the maximum limits. Typically, penalties are applied for every 1.0% above the maximum limit for silica and alumina and every 0.01% above the maximum limit for phosphorus. Additionally, the sale price of the products typically increases as the Fe percentage increases. Usually, premiums are applied for every 1.0% above the minimum iron content in the product.

As shown in **Table 2**, the statistical distribution of the analytes based on the estimates obtained from the model indicates that the levels of Fe and the main contaminants (SiO_2, Al_2O_2, and P) are generally comparable to those of iron ore products that meet the Platts specifications, with the iron content ranging from 61% to 63%, depending on the central (median) values and typical operation scenarios. For products with 65% Fe, the requirements are met only under the most favorable distribution scenarios (p_{90} and maximum values); thus, the processing plant must demonstrate more robust performance and greater contaminant rejection efficiency. Thus, the final distribution profile of the products depends on the operational strategy adopted by the company and the quality specifications required by the market and end customers.

3.2. Analysis and Interpretation of the Correlations between Variables in the Estimated Model

To evaluate the behavior of the analytes with respect to each other, the linear Pearson correlations analyses were initially performed based on the estimated grades for each block of the model. No comparison was carried out with the relationships observed in the sample data. The objective of this integrated analysis is to increase the understanding of how the analytes behave in the dam, thereby supporting the planning and strategic sequencing operations of the mine. In addition, this analysis aims to predict the performance of the processing plant given the quality requirements of the steel market. The correlation coefficients between each analyte are given in Table 3.

Table 3. Pearson's linear correlation coefficients between the analytes in the kriging model.

	SiO_2	P	Al_2O_3	Mn	CaO	MgO	TiO_2	LOI
Fe	−0.89	0.34	−0.96	−0.27	−0.56	−0.53	−0.78	−0.50
SiO_2		−0.64	0.85	−0.07	0.63	0.33	0.59	0.22
P			−0.27	0.36	−0.42	0.21	−0.03	0.29
Al_2O_3				0.15	0.58	0.56	0.79	0.47
Mn					−0.12	0.25	0.35	0.56
CaO						0.46	0.43	0.07
MgO							0.61	0.57
TiO_2								0.64

Based on a correlation coefficient threshold of 0.80 (positive or negative), the results reveal strong correlations between Fe and SiO_2, Fe and Al_2O_2, and SiO_2 and Al_2O_2. Scatter plots illustrating the Pearson correlations between these analytes, along with the linear regression trend line and the 99% prediction intervals, are presented in Figures 10-12, respectively.

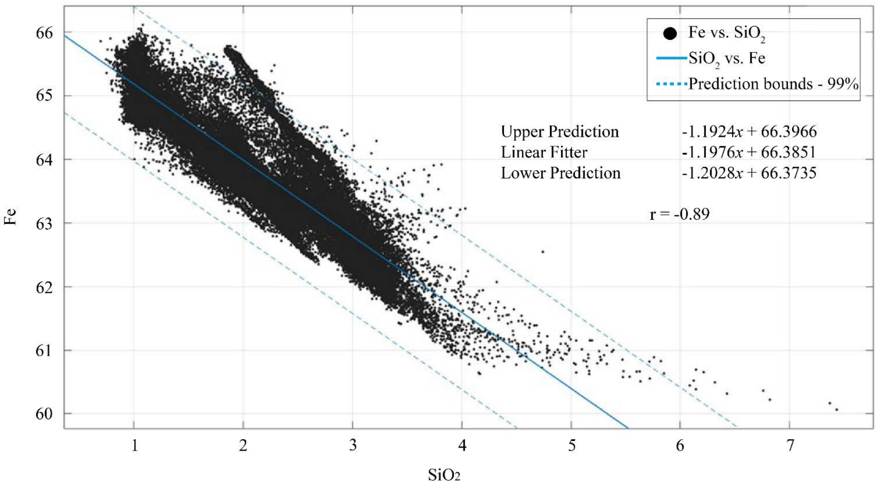

Figure 10. Correlations between SiO_2 and Fe.

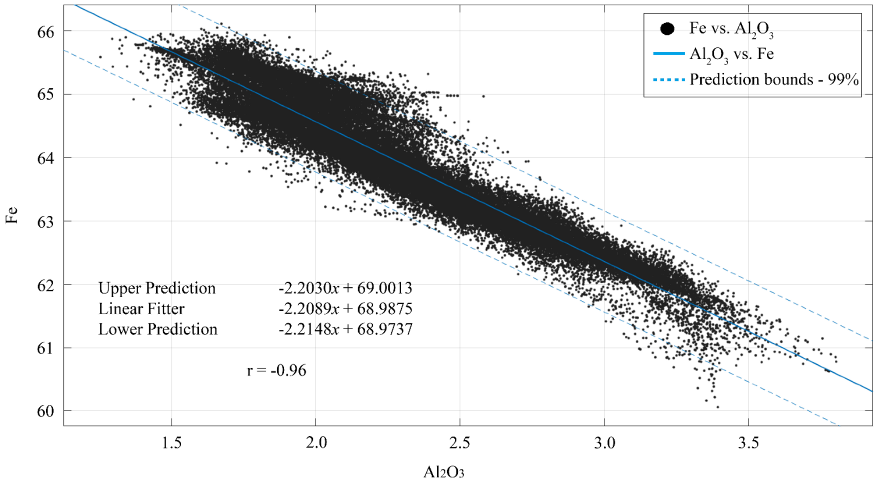

Figure 11. Correlations between Al_2O_3 and Fe.

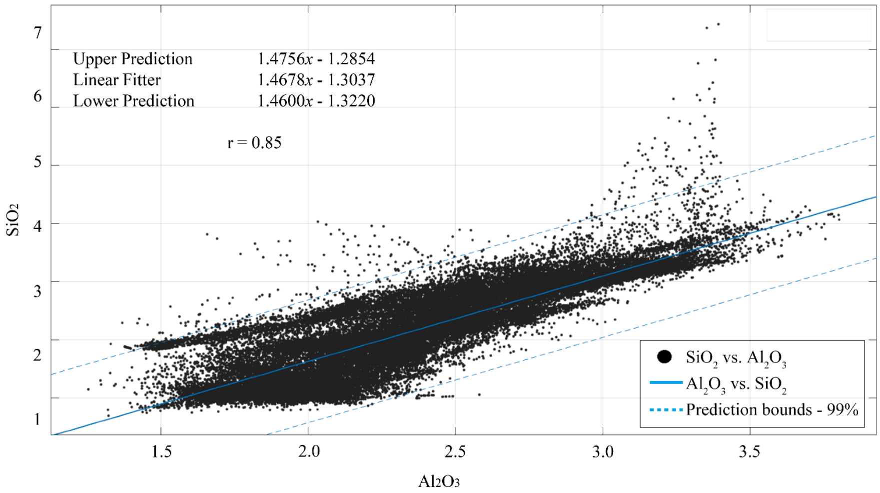

Figure 12. Correlations between Al_2O_3 and SiO_2.

Figure 10 and **Figure 11** reveal an inverse correlation between the analytes; when the iron content is high, the silica and alumina contents are low. Additionally, as the iron content decreases, the silica and alumina contents increase. This observation reflects the antagonistic effect of the iron content on the silica and alumina contents. In addition, the mineralogical behavior is consistent with that of iron ore deposits, in which iron enrichment occurs as silica and alumina contents decrease.

In contrast, **Figure 12** reveals a direct correlation; i.e., in regions with higher alumina content, the silica content is high, and in regions with low alumina content, the silica content is low. These findings indicate that these contaminants tend to appear together in iron sediments, reinforcing the importance of analyzing these contaminants together to develop better mining and processing strategies.

4. Results and Discussion

Initially, a statistical and graphical evaluation was performed to identify possible correlations between the main analytes, and scatterplots were constructed from the data obtained from the estimated model. A spatial analysis was subsequently performed using depth maps to evaluate the distribution of different grades of the analytes. These maps for depths of 229.5 m, 224.5 m, 219.5 m and 214.5 m are given in **Figures 13-16**, respectively.

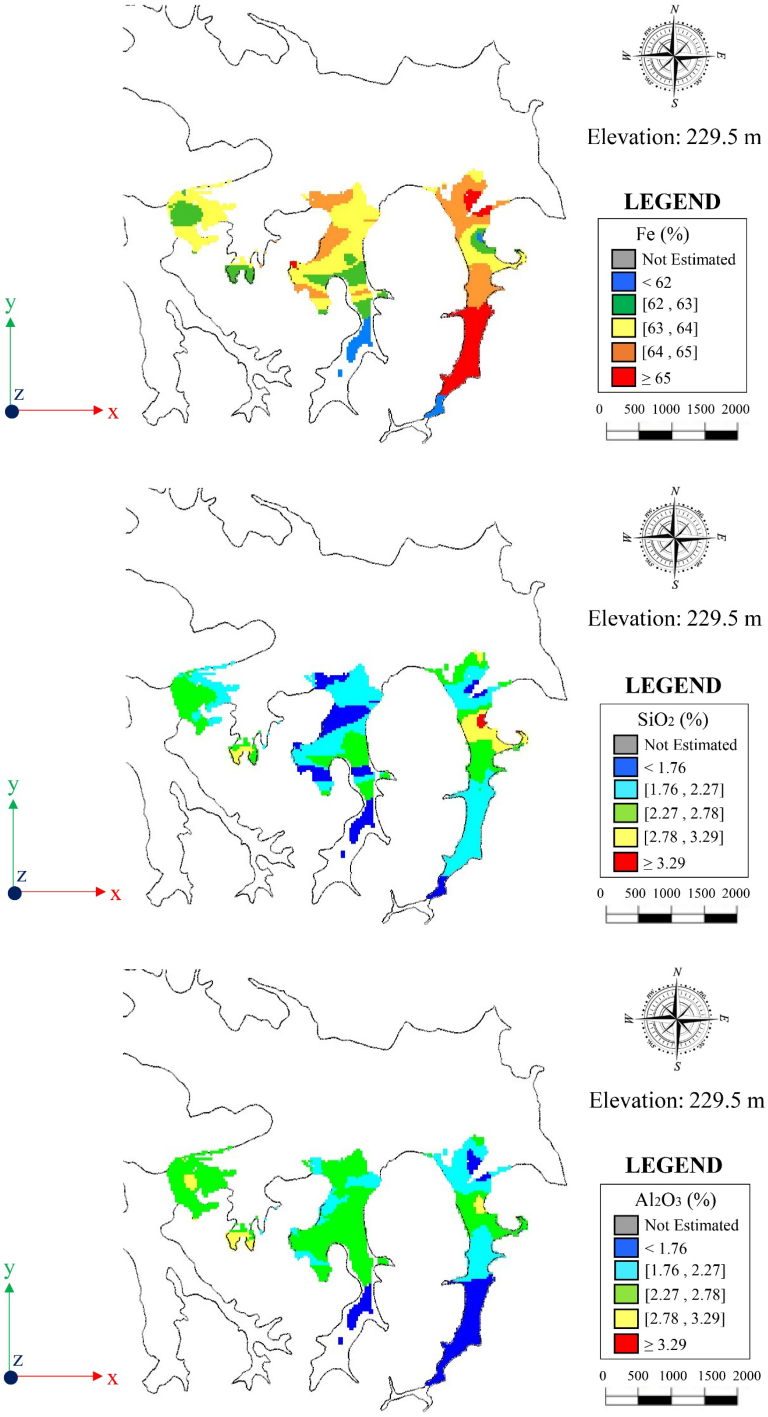

Figure 13. Spatial distribution of different Fe, SiO_2, and Al_2O_3 grades at an elevation of 229.5 m.

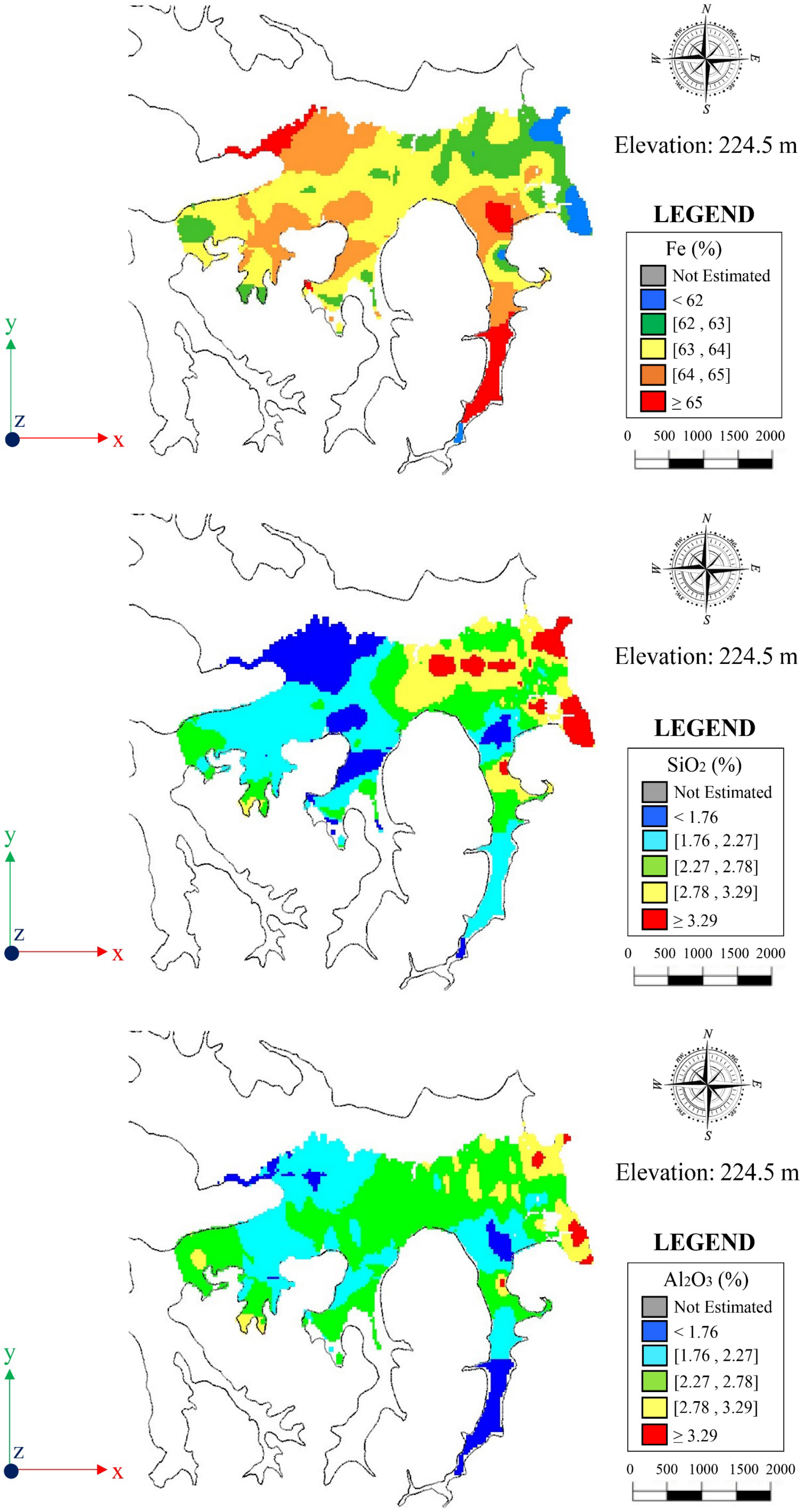

Figure 14. Spatial distribution of different Fe, SiO_2, and Al_2O_3 grades at an elevation of 224.5 m.

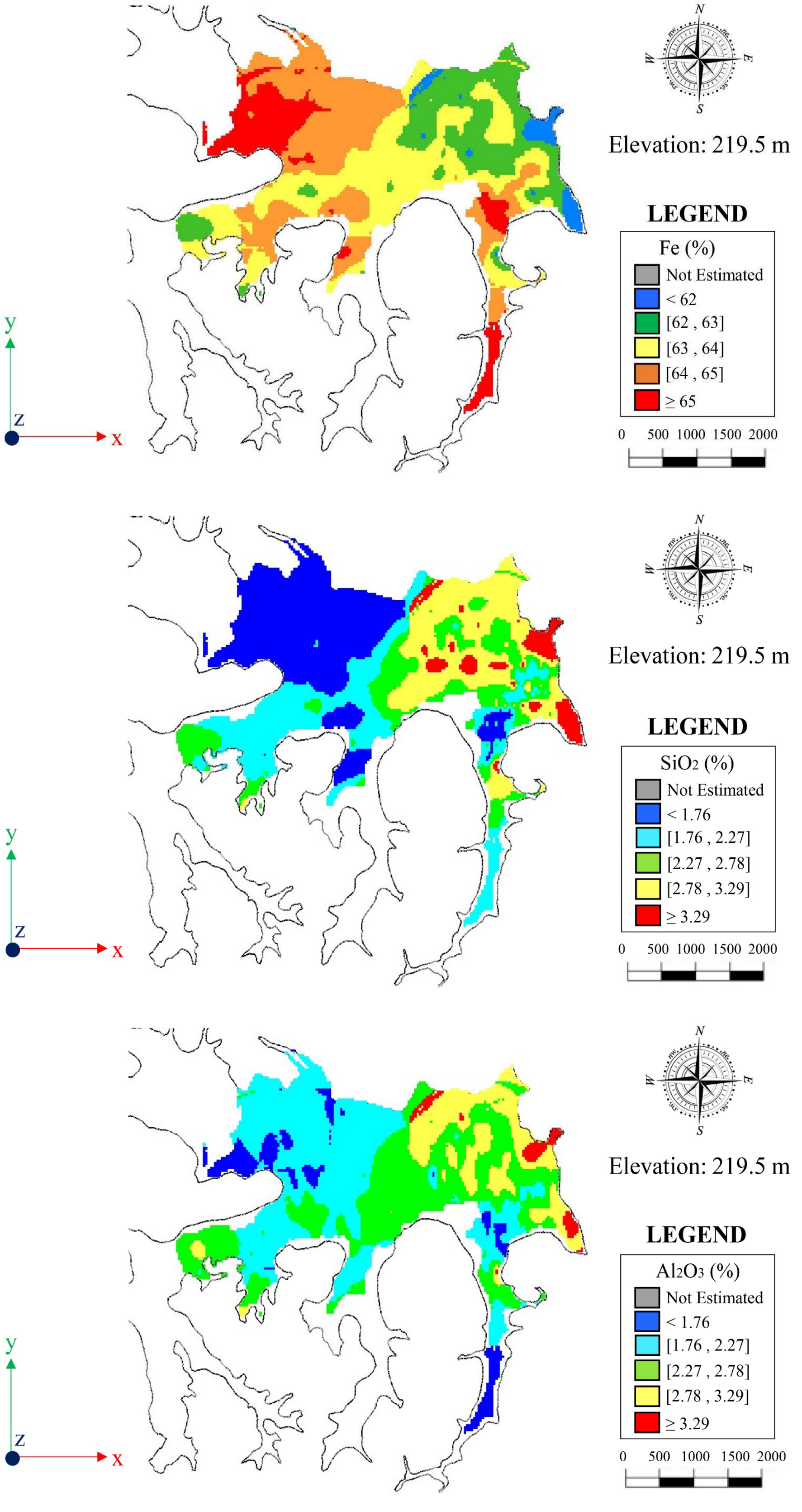

Figure 15. Spatial distribution of different Fe, SiO_2, and Al_2O_3 grades at an elevation of 219.5 m.

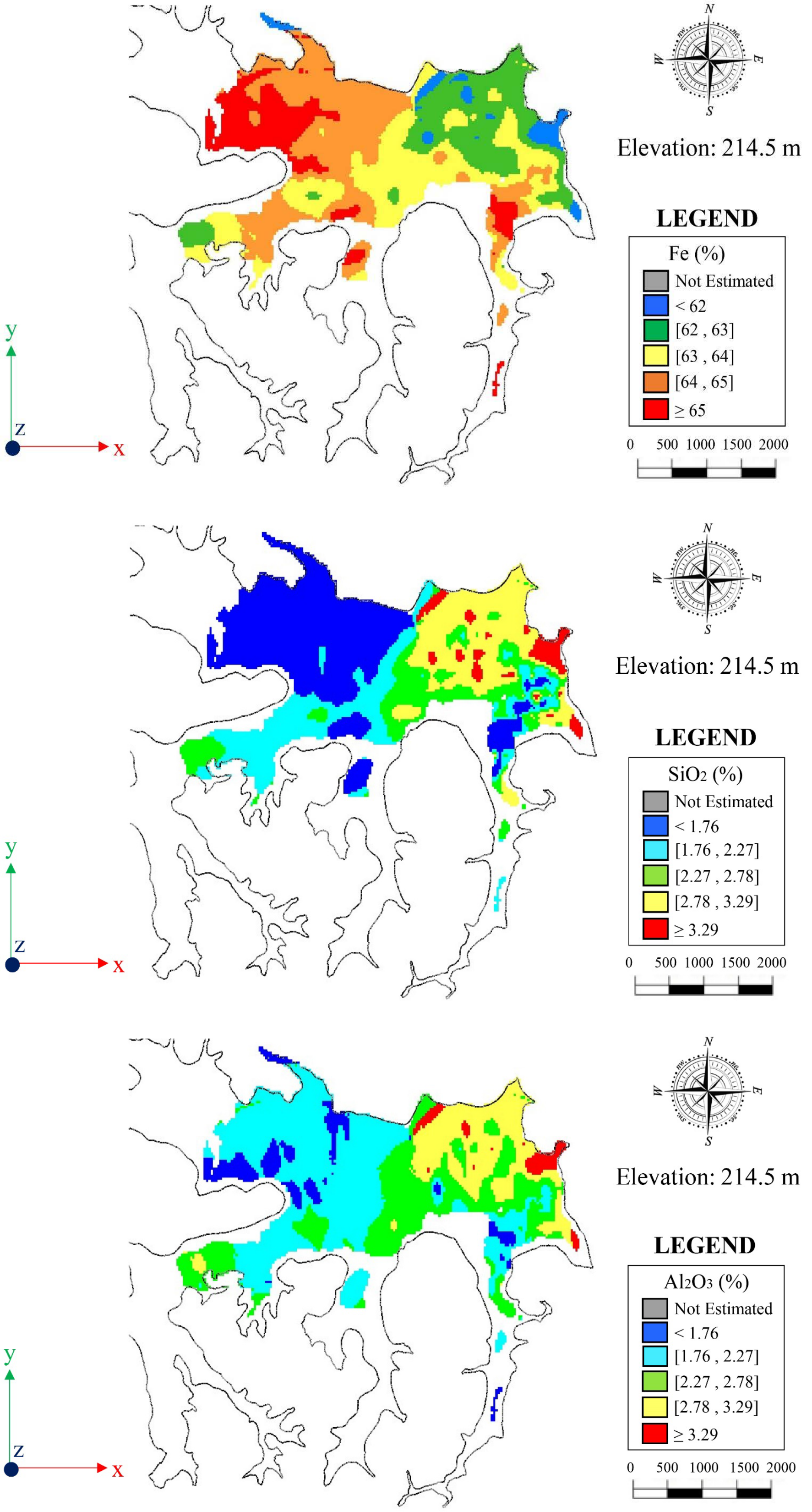

Figure 16. Spatial distribution of different Fe, SiO_2, and Al_2O_3 grades at an elevation of 214.5 m.

The maps in **Figures 13-16** were used to assess the spatial continuity and vertical variability of different grades of the analytes in the dam and provide three-dimensional views of the sediment deposits. The Fe maps exhibit zones with higher Fe contents (warm colors), which are generally associated with lower SiO_2 and Al_2O_2 contents (cold colors); these results are consistent with the correlations seen in the scatterplots. In contrast, regions with high levels of contaminants tend to have lower Fe values, indicating that these areas may require greater processing efforts or specific blending strategies.

Fe contents ≥ 65% are observed in the western region, with the Fe content gradually decreasing toward the east, reaching values between 56% and 62%. In the extreme southern part of the dam, the grade increases from 63% to 65%. In contrast, SiO_2 contents < 1.76% and Al_2O_2 contents < 1.76% are observed in the western region, with the contents increasing towards the east and exceeding 3.29% at the extreme east. In the southernmost region of the dam, the SiO_2 and Al_2O_2 levels decrease from 3.29% to 1.76% and even lower.

The depth analysis also revealed possible vertical trends, with certain layers exhibiting geochemical behavior more favorable for the production of products with higher iron contents, whereas other layers demonstrated suitability for the production of feeding products with lower specifications or blends that meet the maximum limits of the contaminants.

The correlation analysis between the analytes and the spatial depth models provides direct support for the planning and strategic sequencing of the mining process of the sediments deposited in the dam. The identification of spatial domains characterized by higher levels of Fe and lower levels of SiO_2 and Al_2O_2 allows increased selectivity and the possibility of directly improving the metallurgical performance of the plant, resulting in the production of more valuable mineral products. On the other hand, zones with less favorable compositions can be mined in a controlled manner, with the goal of producing blends or processing the materials with specific approaches. This approach contributes to reducing variability in the plant feed, increasing operational predictability and ensuring consistent compliance with market specifications, such as products in the range of 61% - 63% Fe or, in more favorable scenarios, with levels close to 65% Fe.

5. Conclusion

The geochemical variability among Fe, SiO_2 and Al_2O_2 demonstrates that when these analytes are assessed in an integrated manner through depth maps, consistent technical support can be provided, thereby enabling the role of tailings in the production system to be redefined. The correlations among these analytes indicate that relevant portions of the material traditionally classified as tailing have chemical characteristics that are compatible with the minimum specifications of the steel market, especially when appropriate blending and processing strategies are considered. This finding counters the conventional view of tailings as a liability, repositioning tailings as a potential input in the context of the iron ore chain.

The reuse of tailings as a marketable product reinforces the principles of circular economy by promoting the more efficient use of extracted mineral resources. The spatial identification of zones with greater metal recovery potential allows alignment among short-, medium- and long-term mining strategies, thereby reducing the generation of new tailings and maximizing the use of previously disposed materials. This approach contributes to reducing the environmental impacts associated with tailings dams while improving the economic value of mining enterprises.

Additionally, the positive effects on the performance of the treatment plant indicate that the reuse of tailings can be integrated into the production flow in a sustainable manner, provided that adequate operational and metallurgical control strategies are implemented. The possibility of converting tailings into products with specifications compatible with the steel market reinforces the transition from a linear production model to a circular production model in which losses are minimized and the life cycle of the ore is extended. Thus, the results of this study reveal that circular economy is not limited to environmental concepts but can be used to develop viable technical and economic strategies for iron ore mining.

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Conflicts of Interest

The authors declare that there are no potential conflicts of interest with respect to the research, authorship and/or publication of this paper.

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