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Statistical, Geostatistical and Spatial Analysis of Technology-Critical Elements in the Trepça Mine

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Berat Sinani[1], Blazo Boev[1], Arianit Reka[2,3], Bahri Sinani[4], Ivan Boev[1]*

[1] *Department of Petrology, Mineralogy and Geochemistry, Faculty of Natural and Technical Science, University "Goce Delchev", 2000 Stip, North Macedonia.*

[2] *Department of Chemistry, Faculty of Natural Sciences and Mathematics, University of Tetova, 1200 Tetovo, North Macedonia.*

[3] *Albanian Unit of Nanoscience and Nanotechnology, NanoAlb, Academy of Sciences of Albania, Fan Noli Square, 1000 Tirana, Albania.*

[4] *Department of Environmental Engineering, Faculty of Natural and Technical Science, University "Goce Delchev", 2000 Shtip, North Macedonia.*

Abstract

This study investigates the presence, concentration, and spatial distribution of Technology-Critical Elements (TCEs) in the Trepça Mine, focusing on ore body horizons VIII-XI. During research in the relevant archives (Trepça, ICMM, GSK), it was noted that no statistical, geostatistical or spatial studies have been conducted in the Trepça Mine for Technology-Critical Elements. Mineralizations in Trepça mainly occur as vein structures known as ore bodies. In this study, all existing ore bodies from horizons VIII-XI, were sampled. Representative samples were collected from each active ore body and analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to quantify elements including Bi, Co, Ge, V, W, Li, Ga, In, Te, and Nb. Statistical and geostatistical analyses were performed using Microsoft Excel, R Studio, and Golden Software Surfer to assess variability, correlations, and spatial trends. The highest concentrations were observed for Bi (avg. 98.81 ppm; max. 610.4 ppm), W (avg. 28.68 ppm), and Co (avg. 28.47 ppm), with significant variability across horizons. Correlation analyses revealed strong positive relationships between several elements, such as W–V (r = 0.70), W–Ge (r = 0.65), and Bi–W (r = 0.60), suggesting possible common geological origins. These findings highlight the potential for the sustainable recovery of strategic elements from Trepça's polymetallic ore zones and underscore the mine's relevance, not only for traditional metals, but also for critical raw materials essential to low-carbon and high-tech industries.

Keywords:
Geostatistics; Spatial; Distribution; TCE; Trepça

1. Introduction

The evolution and rapid increase in modern technologies has led us to greater focus on another group of elements called Technology-Critical Elements (TCEs) (**Zendehbad et al., 2021**). These elements are the backbone for the development and advancement of technology, such as in electronics, renewable energy, transportation, agriculture, health, military, etc. These elements are called critical because of the risk of their supply. According to the latest report, about thirty elements and minerals are critical as defined by the European Commission (**Dang et al., 2021**). In addition to rare earth elements, Technology-Critical Elements also include the platinum group elements, as well as Te, Ge, Ga, In, Nb and Ta (**Ebeling et al., 2022**).

Although many researchers from all over the world have conducted numerous studies on the Trepça polymetallic deposit, the research of Technology-Critical Elements within the Trepça ore bodies remains unexamined. Elements such as Bi, Co, Ge, V, W, Li, Ga, In, Te and Nb have gained great importance due to their role in modern technologies. However, their presence and distribution in one of the most important polymetallic deposits in Southeast Europe have not been systematically documented. Existing research and studies mainly focus on Pb, Zn, and Ag, but not to the appropriate extent on the presence, distribution, and interrelation of these elements in the ore bodies of the Trepça Mine, then the areas with the potential for their highest concentration, creating a spatial analysis of their distribution. A review of the available literature and studies revealed no studies linking the distribution of these elements with statistical, geostatistical and spatial analyses. The lack of such studies limits the identification of the presence of Technology-Critical Elements, their concentration and the geochemical relationship between them. With the increasing

* Corresponding author: Ivan Boev
e-mail address: ivan.boev@ugd.edu.mk
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Table 1: Application of Technology-Critical Elements in modern technology

Elements	Application in
Li	Batteries for modern devices and EVs; military and nuclear industries; light alloy; thermonuclear (Neves et al., 2024).
Bi	Refinery, Medicine, Cosmetics, Paint industry, Metal industry (Liu & Handschuh-Wang, 2025).
Co	Batteries, Superalloys, Chemical and Ceramics, Cemented Carbides, Steels, Magnets (Graedel & Miatto, 2022).
Ge	Semiconductors; IR lenses/optics; fiber optics; PET catalyst; thermal detection (Abdou et al., 2023).
V	Steel, Aviation, Catalysts, Pigments and photosensitive materials (Storm, 1994).
W	Steel alloys, Lamp filaments, Electronics, Pigments, Lubricants, Catalysts, Radiation protection, Medical, Dental films (Christian et al., 2011).
Li	Batteries for modern devices and EVs; military/nuclear industry; light alloy; thermonuclear power (Neves et al., 2024).
Ga	MRI contrast agent; uses in glass, ceramics, glazes; nuclear applications (Abdou et al., 2023).
In	Electronics and displays; base metal sulphide deposits; solar cells (Abdou et al., 2023).
Te	Semiconductors; CdTe for solar panels; thermoelectric (Abdou et al., 2023).
Nb	Technology, Mobile Phones, MRI (Abdou et al., 2023).

global demand for critical minerals, studying their occurrence in the Trepça deposit has become essential, the reason for such a study is related to the study of Technology-Critical Elements in Pb-Zn polymetallic deposits around the world and comparison with them. Polymetallic hydrothermal deposits are a significant source of TCEs elements, such as Nanmushu Pb-Zn polymetallic deposit, China (**Wu et al., 2023**), Hehuashan Pb-Zn polymetallic deposit (**Liu et al., 2024**), Chipu Pb-Zn deposit, China (**Tan et al., 2025**), Badovc Pb-Zn deposit, Kosovo (**Mederski et al., 2024**), Zhugongtang Pb-Zn deposit, China (**Song et al., 2023**), Yangtze Pb-Zn polymetallic deposit, China, Pb-Zn deposit, Guangxi, (**Yu et al., 2023**), Pb-Zn hydrothermal deposit, Aerhada, China (**Li et al., 2023**), Pb-Zn hydrothermal deposit, Zhenzigou, Diannan, Xiquegou and Erdao in Qingchengzi (**Duan et al., 2024**).

Considering that Trepça currently has all active exploration and exploitation in horizons VIII to XI, our study is also focused on these horizons. This study aims to provide a general assessment of the Technology-Critical Elements in the Trepça Mine by presenting these through statistical, geostatistical and spatial methods. This study aims to:

1. Identify the presence,
2. Assess the concentration and variability
3. Examine correlation and PCA
4. Model spatial distribution.

After this, a clear study will be presented regarding the presence and distribution of Technology-Critical Elements in these horizons that are currently active. This study, based on the first literature related to statistical, geostatistical and spatial methods, is a systematic assessment of these Technology-Critical Elements in the polymetallic deposit in Trepça. Also, through the aforementioned analyses, we see the interconnection and distribution of these elements, the areas with higher and lower concentrations, the direction and orientation of the distribution of these elements, which will then pave the way for the Trepça Geological Service and the Mines for concrete actions in their utilization and the transition from the use of traditional metals to Technology-Critical Elements.

Table 1 presents some of the Technology-Critical Elements identified in this study and their use in modern technologies.

This study represents a shift in research perspective toward the investigation of critical elements and their spatial distribution. It expands the mining focus of the Trepça Mine-traditionally centered on Pb-Zn, Au, and Ag - into a new and promising field: the study of critical elements, their identification, analysis, and spatial distribution.

2. Methods

The Trepça Mine is an underground mine operation developed across horizons, each separated by approximately 60 m vertically. At present, mining activities occur only within horizons VIII–XI. Some ore bodies have been fully exploited, others remain active, while several have not started yet. Sampling has been conducted in all ore bodies that are active.

The main objective of this study is to determine the spatial distribution patterns of these elements within horizons VIII-XI, which contain the largest geological reserves. Golden Software Surfer was used to visualize spatial variations and identify zones with elevated concentration of technology-critical elements (Bi, Co, Ge, V, W, Li, Ga, In, Te and Nb).

Furthermore, the analysis of these chemical elements was performed using contemporary methods such as ICP-MS, supported by data processing and visualization tools including Microsoft Excel, R Studio, and Golden Software Surfer. These methods ensure a detailed and accurate representation of the distribution of Technology-Critical Elements.

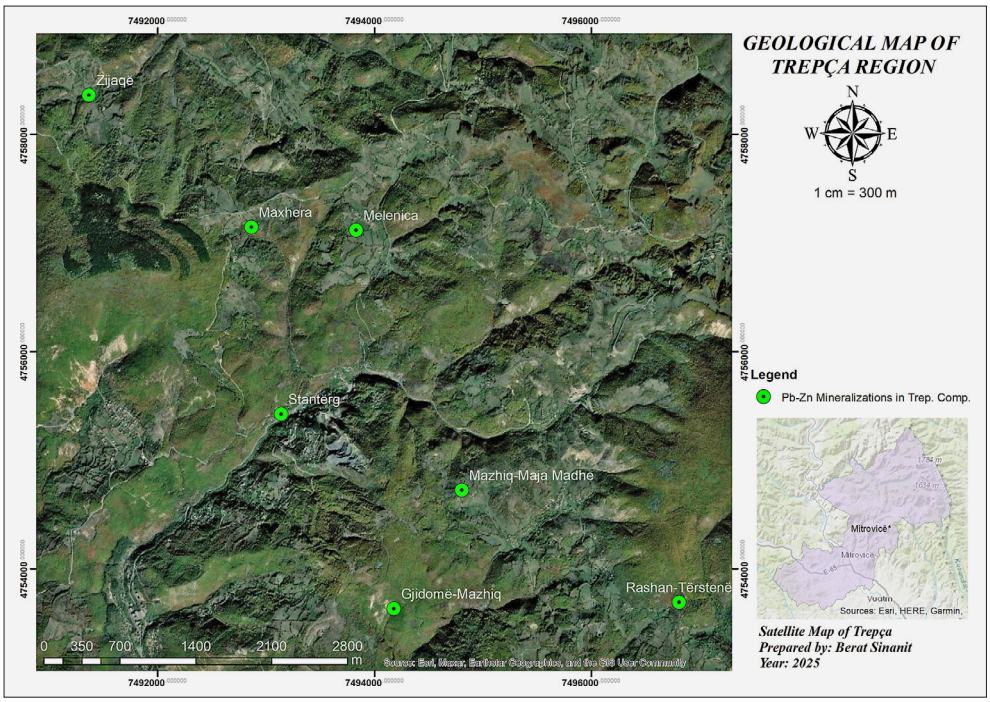


Figure 1: Satellite map of the study area

Efficient extraction of metals and metalloids requires understanding their geochemical behaviour, mineralogy, and precipitation (**Wanhainen et al., 2017**). The process of their precipitation is with particular emphasis on sulfur oxides where there may be concentrations of trace elements (**Webster et al., 1998**). Pb-Zn sulfide minerals are very particularly sensitive to oxidation, which may result in the enrichment Technology-Critical Elements.

Since antiquity times, minerals have been used for various purposes (**Paçarizi et al., 2024**). These minerals are extracted in millions of tons of ore every year, and this arises as a need for technological uses (**Falagán et al., 2017**). If the concentration of rare minerals is high, they can be reprocessed and extracted (**Antonijević et al., 2008; Cook et al., 2009; Yin et al., 2018**). The most important Pb-Zn-Ag deposits are in the Stan Terg, Artana, Hajvalia, Kizhnica, Belo Brdo, Crnac, and Drazhnje (**Mederski et al., 2021**). Pb-Zn mineral deposits especially sphalerite can accumulate or contain various critical metals (**Mederski et al., 2024**). For a long time, various studies have been on the distribution of Au, Ag, Pb and Zn in the Trepça Mine, but very few studies have focused on the spatial analysis of Technology-Critical Elements (**Sinani et al., 2023**). **Figure 1** presents the Satellite map of the Trepça Mine complex.

The Shala e Bajgorës region lies in northern and northeastern part of Kosovo, covering over 400km^2 (**Kelmendi et al., 2024**). The Trepça Mine is situated approximately 10 km northeast of Mitrovica and one of the largest Pb-Zn mineral deposits in the south-eastern Balkans, where exploitation began in medieval times (**Kołodziejczyk et al., 2016**). In this area, at a distance of over 10km from the city of Mitrovica in the direction of Shala e Bajgorës, the Trepça Mine is located (**Zeqiri et al., 2022**). The Trepça Mine is characterized by large reserves and a known source of Pb-Zn and Ag, but based on the knowledge of geology of Trepça Mine, the presence of Technology-Critical Elements should also be investigated. Therefore, this study was conducted on the distribution of Bi, Co, Ge, V, W, Li, Ga, In, Te and Nb in the Trepça Mine. This region is part of the Serbian-Kosovo-Macedonian metallogenic province. This area is located in the Vardar zone (**Elezaj & Kodra, 2007**).

These deposits, like Trepça, offer opportunities to revisit previously exploited ores using modern analytical tools and sustainable extraction frameworks. Such an approach aligns with global trends toward low-impact mining and circular material flows.

Mitrovica, located in the northern part of Kosovo, has a long history of lead and zinc mining. The history of lead and zinc mining is directly linked to the history of the entire country of Kosovo. Until recent decades, Trepça was known for its high exploitation of lead and zinc, for which it is still known today (**Hyseni et al., 2010**). The name "Trepça" was first mentioned in 1303 in some documents in the Archives of Dubrovnik in Croatia. The development of mining in this area dates back to Illyrian and Roman times, while the greatest development is known in the 13th century (**Shala, 2014**). Kosovo is known for its variety of complex geological formations (**Peci et al., 2014**). In recent decades, Trepça was known as one of the most successful companies in the former Yugoslavia (**Hetemi & Kastrati, 2008**). In 1926, the British bought the concessions and on September 9, 1927 they formed the company under the name "Trepça Mines Limited", which functioned until the end of World War II (**Nikolić et al., 2017**).

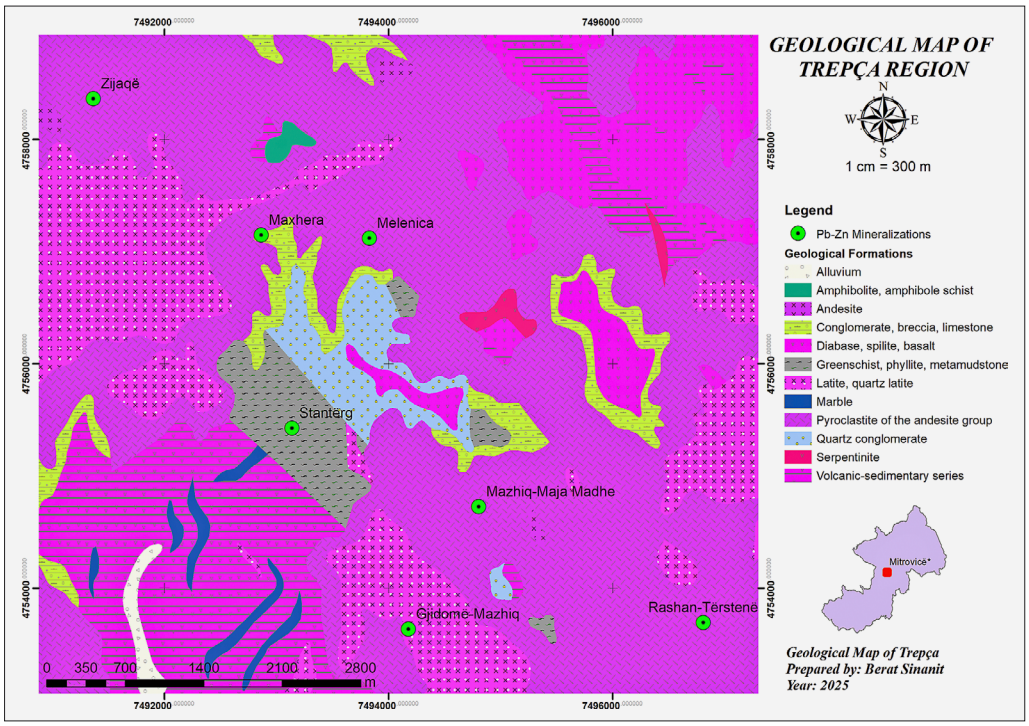


Figure 2: Geological map of the study area

Table 2: Mineral Reserves of Trepça Mine and concentration of Pb, Zn, and Ag (**Hetemi & Kastrati, 2008**)

Nr	Mines	Tones of Reserves	Concentration (%)			Reserves (t)		
			Pb	Zn	Ag (g/t)	Pb	Zn	Ag(kg)
1.	Stantërg	20,754,000	4.02	4.02	76.0	834,311	674,505	1,577,304
2.	Melenica	2,552,000	5.80	5.80	85.0	148,016	107,184	216,920
3.	Maxhera	600,000	3.80	3.80	72.0	22,800	18,000	43,200
4.	Mazhiq-Maja Madhe	1,500,000	3.30	3.30	60.0	49,500	42,000	90,000
5.	Gjidomë-Mazhiq	2,000,000	3.30	3.30	60.0	66,000	56,000	120,000
6.	Rashan-Tërstenë	2,500,000	3.30	3.30	60.0	82,500	70,000	150,000
7.	Zijaqë	5,175,000	2.83	2.83	16.0	146,453	112,815	82,800
8.	Total	35,081,000	3.85	3.85	65.0	1,349,579	1,080,504	2,280,224

2.1. Geological characteristics of study area

The geological structure of 'Trepça' consists of volcanic rocks and sedimentary formations that control mineralization. The ore bodies of the Trepça Mine mainly consist of:

A) in contact with limestone and breccia's and

B) in contact with limestone and shales as shown in geological map of the study area in **Figure 2**.

Most of the ore bodies are created between green shales and limestones in the Trepça Mine (**Hetemi & Kastrati, 2008**). Two main mineral groups are present:

[1]. Skarn group - Epidote, Garnet, Actinolite, Hedenbergite and Ilvaite

[2]. Hydrothermal group - Pyrrhotite, Pyrite, Galena, Sphalerite, Arsenopyrite, Rhodochrosite, Aragonite, Calcite, Gypsum, Quartz and others (**Hetemi & Kastrati, 2008**).

Table 2 presents mineral reserves of Trepça Mine and concentration of Pb, Zn and Ag.

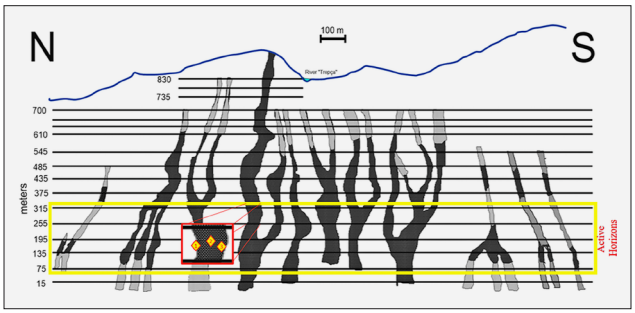


Figure 3: Spatial distribution of ore bodies within the Trepça Mine and the sampling location

The Trepça Mine mineral deposit has a hydrothermal origin; the mineralization is developed mainly in contact between schists and limestone within mineralization veins. Sampling was carried out for all bodies (three samples for each ore body) to analyze Technology-Critical Elements in the Trepça Mine. **Figure 3** presents Trepça ore mine bodies and sampling for each ore body.

Table 3: Analytical parameters for selected elements analyzing in NexION 300D

Element	LOD_ppt	LOQ_ppt	Standards	Calibration	Recovery	Analytical Error
Bi	5-10	15-30	Multi-element; CRM	4-6 points; IS: In/Bi	90-105	RSD 1-3%; ±5-10%
Co	2-5	6-15	Multi-element; CRM	4-6 points; IS: Sc/Rh	95-105	RSD 1-2%; ±5%
Ge	10-20	30-60	Multi-element + individual	4-6 points; IS: Rh/In	85-110	RSD 2-4%; ±10%
V	20-40	60-120	Multi-element	4-6 points; IS: Sc	90-105	RSD 3-5%; ±10%
W	5-10	15-30	Multi-element	4-6 points; IS: Re/Bi	90-110	RSD 2-4%; ±10%
Li	<1	2-3	Multi-element	4-6 points; IS: Sc	95-105	RSD 1-2%; ±5%
Ga	5-10	15-30	Multi-element	4-6 points; IS: Ge/In	90-105	RSD 1-3%; ±5-10%
In	1-3	3-9	Multi-element	4-6 points; IS: Rh	95-105	RSD 1-2%; ±5%
Te	20-40	60-120	Individual standard	4-6 points; IS: Bi/Rh	80-110	RSD 3-5%; ±10%
Nb	10-20	30-60	Multi-element	4-6 points; IS: Rh/In	85-105	RSD 2-4%; ±10%

2.2. *Sampling and analysis methodology*

To ensure the safety and reliability of the results obtained for the Technology-Critical Elements, a rigorous QA/QC protocol was applied, including sample blanks, duplicates, calibration verification and instrument performance monitoring. Duplicate analyses improve data reliability, especially for Bi, W and Co.

2.2.1. Analytical Quality Control

Quality control has also been increased by analyzing duplicate samples, and their comparison, using statistical methods and analyzing the standard deviation, making us have the most reliable results, with special emphasis on Bi, W and Co that indicate geological anomalies of some ore bodies. Thus, they have contributed to the maximum increase in data quality.

Table 3 presents the operating and performance conditions of the ICP-MS device in analyzing technology-critical elements.

2.2.2. Sampling in the Trepça Mine

Sampling at the Trepça Mine was carried out in a structured and representative manner, covering all active ore bodies in horizons VIII-XI. For each ore body, 3 samples were taken (in the left, central and right parts of the ore body), to ensure sample homogeneity and local variations. Samples were collected with accurate data for each ore body, to enable the use of geostatistical and spatial analyses.

To carry out this study, the procedure as shown in **Figure 4** was followed as below:

Sampling was done in each ore body, the samples were described and placed in bags for processing in the laboratory, where the following steps were carried out in the laboratory:

- Drying the samples for 24 hours at 105°C, the samples were ground and dried for 24 hours at a temperature of 105°C (**Sinani et al., 2023**), after which the samples were ground in the primary and secondary mills.
- Grinding in the Primary Mill
- Grinding in the Secondary Mill
- Digestion of samples and
- Analysis with ICP-MS (PerkinElmer NexION 300D), one of the most advanced techniques in the identification of technology-critical elements at very low levels. Analyses were conducted using a Perkin Elmer NexION 300D ICP-MS instrument. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is a powerful analytical method that allows for the fast, accurate, and highly sensitive determination of a broad spectrum of elements in both solid and liquid matrices. Utilizing ICP-MS technology, up to 76 elements can be measured simultaneously at extremely low concentrations, ranging from nanograms to picograms per liter. The system enables the detection of approximately 35 elements within a single sample in as little as three minutes.

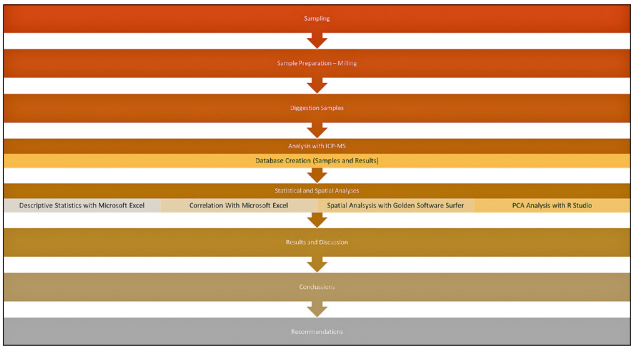


Figure 4: Flowchart of realization of this study

The instrument operates by generating a high-energy plasma using argon gas, into which the prepared liquid sample is introduced. This process atomizes and ionizes the elements present in the sample. The resulting positively charged ions are then accurately detected by a mass spectrometer, enabling precise elemental analysis of the solution. The focus of this study is:

v The elements taken in the study are Bi, Co, Ge, V, W, Li, Ga, In, Te and Nb. In many studies and research works in Pb-Zn deposits, the concentration of these elements have been studied, therefore these elements have been selected.

- Processing and creation of the database obtained from laboratory analyses.
- Initially, descriptive statistics such as Minimum, Median, Maximum, Mean and Standard Deviation are presented, were used to assess variability.
- Correlation – were used to identify geochemical relationships between these elements.
- PCA analysis were used to identify grouping of elements and
- Spatial Analysis was performed using Golden Software Surfer which is used to present the distribution of each Technology-Critical Element, Interpolation was carried out using the Kriging method. Where, the value of X represents the concentration of the element), the areas with the highest concentration of certain elements and the direction of distribution by presenting it for each horizon.

The limitations of this work are mainly as a factor of the exploitation of the uppermost horizons, as well as the access to the 12th horizon, which is not yet open or active.

Samples were taken only in ore bodies that are active or that have not started to be exploited and the studies are oriented only in the ore bodies and not in the surrounding rocks.

After performing the laboratory analyses and obtaining the chemical results, we used software for specific purposes:

- Microsoft Excel for Descriptive Statistics which were used from Data Analysis ToolPak and Correlations also to present distribution correlation between Technology-Critical Elements.
- Golden Software Surfer is used for spatial distribution of Technology-Critical Elements. In Surfer, the 3-dimensional representation method is used where the Z value represents the concentration of specific chemical element, this indicates that at points where we have a higher concentration the colors will be more pronounced.
- R Studio for PCA analysis for PCA analysis. We used the software packages (”FactoMineR”) and (”factoextra”) of the R Studio language to calculate and present the PCA analysis.

Geostatistics introduces geological modelling by providing advanced tools for representing the variability of both geological formations and their spatial distribution (**Hosseini et al., 2019**). Also, geostatistical analysis shows spatial variability and clear spatial correlation between studied variables (**Shao, 2024**). Digital transformation” describes the transformation process of any mine industry or business model to the implementation of digital technologies (**Barnewold & Lottermoser, 2020**). Golden Software Surfer has a powerful tools and function for interpreting geochemical data (**Valls, 2019**). The first two columns in both cases are the X and Y coordinates, and the next columns are the corresponding parameter Z (**Ali, 2024**). The following section presents a breakdown of Technology-Critical Elements using Microsoft Excel and Golden Software Surfer was used to present the spatial distribution of each Technology-Critical Element for each horizon in the Trepça Mine. By applying statistical and geostatistical methods, we can delineate the spatial distribution and potential origins of the chemical elements (**Schiavo et al., 2024**). To reduce the amount of data with minimum loss of important information (**Taşan et al., 2022**) we have used Principal Component Analysis (PCA). Classical PCA was used to identify covarying elements associated with different compositions and generations of minerals.

Thus, a combination of statistical, geostatistical and spatial analysis of the Technology-Critical Elements distributions, provides a clear understanding of distribution patterns of Technology-Critical Elements. Upon completing the statistical, geostatistical, and spatial analyses, we obtained a clear picture of the distribution of some Technology-Critical Elements in the Trepça Mine.

3. Results

3.1. Statistical and geostatistical analysis of Technology-Critical Elements in Trepça Mine

Descriptive statistics are tools that summarize the structure and variability of the obtained results (**Dong, 2023**). The parameters presented in this study are the minimum, median, maximum, mean, and standard deviation for the selected elements, as shown in **Table 4**.

Table 4 illustrates the statistical analysis of the concentrations of the selected elements in the analyzed samples, including minimum, median, maximum, means and standard deviations for the selected elements.

The values of Bi show high variability, with a mean concentration of 98.81 ppm (SD = 181.74) and a maximum value of 610.4 ppm, indicating an uneven distribution of this element.

Co has a smaller spread of values, with a mean of 28.47 ppm (SD = 21.12) and a maximum value of concentration of 81.64 ppm. The median value (22.02 ppm) indicates a relatively symmetrical distribution of Co.

The Ge concentrations show low variability, with a mean of 0.32 ppm (SD = 0.25) and a maximum value of 0.96 ppm, suggesting that this element is found in low and stable concentrations in the samples. A similar situation is observed for Nb (Niobium), with a mean of 0.41 ppm (SD = 0.25). W exhibits considerable variability, with a maximum value of 308.82 ppm and a high standard deviation (SD = 66.56) which may be related to specific mineralogical phases and will be examined through

Table 4: Descriptive statistics of the selected elements (ppm)

	Minimum	Median	Maximum	Average	Standard Deviation
Bi(ppm)	3.15	18.58	610.4	98.81	181.74
Co(ppm)	8.5	22.02	81.64	28.47	21.12
Ge(ppm)	0.01	0.22	0.96	0.32	0.25
V(ppm)	5.59	13.29	39.2	14.74	8.82
W(ppm)	2.08	14.8	308.82	28.68	66.56
Li(ppm)	0.27	0.65	21.12	2.67	5.38
Ga(ppm)	0.17	1.47	6.94	2.18	2.06
In(ppm)	0.1	1.16	12.08	2.38	3.46
Te(ppm)	0.02	0.25	41.8	2.68	9.28
Nb(ppm)	0.07	0.41	0.93	0.41	0.25

correlation analysis. For other elements, such as V, Ga and In, the means and standard deviations suggest a different distribution of these elements with low concentration within these horizons. Graphical representations allow researchers to show correlations and the distribution of data (**Alabi & Bukola, 2023**), where through visual representation, the distribution and direction of the spread of these data can be presented. The distribution and concentration of Technology-Critical Elements are shown by histograms in **Figure 5**.

Figure 5 illustrates the histograms for the distribution of the investigated Technology-Critical Elements. Trepça is a highly heterogeneous mineral complex, and his heterogeneity is reflected in the distribution of these elements. The elements Bi, W and Co present the greatest variability, which is reflected in the histograms presented above which present geochemical anomalies. Bi shows right-skewed distribution, which confirms the high mean and the very large variation. W presents two different groups suggesting two mineralogical phases in different geochemical environments.

While other elements such as Ge, Ga, Nb and Li, although in low concentration, have given more balanced histograms with a uniform presence and absence of different geochemical anomalies. Ge and Nb show similar intervals suggesting a homogeneous distribution. While Te and In have given some high results showing geochemical anomalies in some samples which indicate the localization of mineralization in certain areas. In general, just as the Trepça Mine is characterized by a fairly large geological complex, the distribution of these is also quite complex and characterized by large anomalies.

The relationships between the variables are illustrated by the scatter plot shown in **Figure 6**.

The distribution of Technology-Critical Elements in this diagram shows a considerable variability in both concentration and spatial pattern, suggesting formation under distinct geochemical and mineralogical conditions. To examine the relationships between these elements in more detail, a correlation analysis was performed.

Correlation analysis is a statistical method used to evaluate relationships between two or more variables (**Liu et al., 2025**). The correlation coefficient is one of the most important statistical parameters that represents the similarity and relation between two given variables (**Balabanova et al., 2010**), thus the correlation matrix will present the relation of each element with each other element. While now the correlation of the selected elements are presented, the correlation matrix presents the relationship between selected elements and their distribution within horizons 8, 9, 10 and 11. **Table 5** shows the correlation matrix which presents the interrelationship of each analyzed chemical element.

The correlation matrix shows the following relationships between selected elements:

Vanadium (V) and Tungsten (W) show a strong positive correlation (r = 0.70) suggesting a common geological source or similar formation processes.

Germanium (Ge) and Tungsten (W) with a correlation coefficient (r = 0.65) indicates a possible relationship between the mineralization of these elements.

Tungsten (W) and Bismuth (Bi) with a correlation coefficient (r = 0.60), this shows a strong positive correlation between these two elements. Same also for Vanadium (V) and Germanium (Ge) with a correlation coefficient (r = 0.58). Niobium (Nb) with Tungsten (W) and Vanadium (V) with a correlation coefficient (r = 0.54) between Nb and W, and (r = 0.56) for Nb and V presents a strong correlation between them.

Tellurium (Te) and Cobalt (Co) show a weak negative correlation (r = −0.10), while Indium (In) and Cobalt (Co) exhibit a stronger negative correlation (r = −0.38), suggesting different geological formation processes.

3.2. Spatial Distribution of the selected elements in four horizons

Before presenting the distribution of technology-critical elements, it is important to note that the ore bodies are mainly hydrothermal deposits, formed in contacts mainly between limestones and schists. Also, some northern ore bodies are built in cracks in limestones. **Figure 7** illustrates the location of ore bodies in horizons VIII-XI and geological formation contact with them.

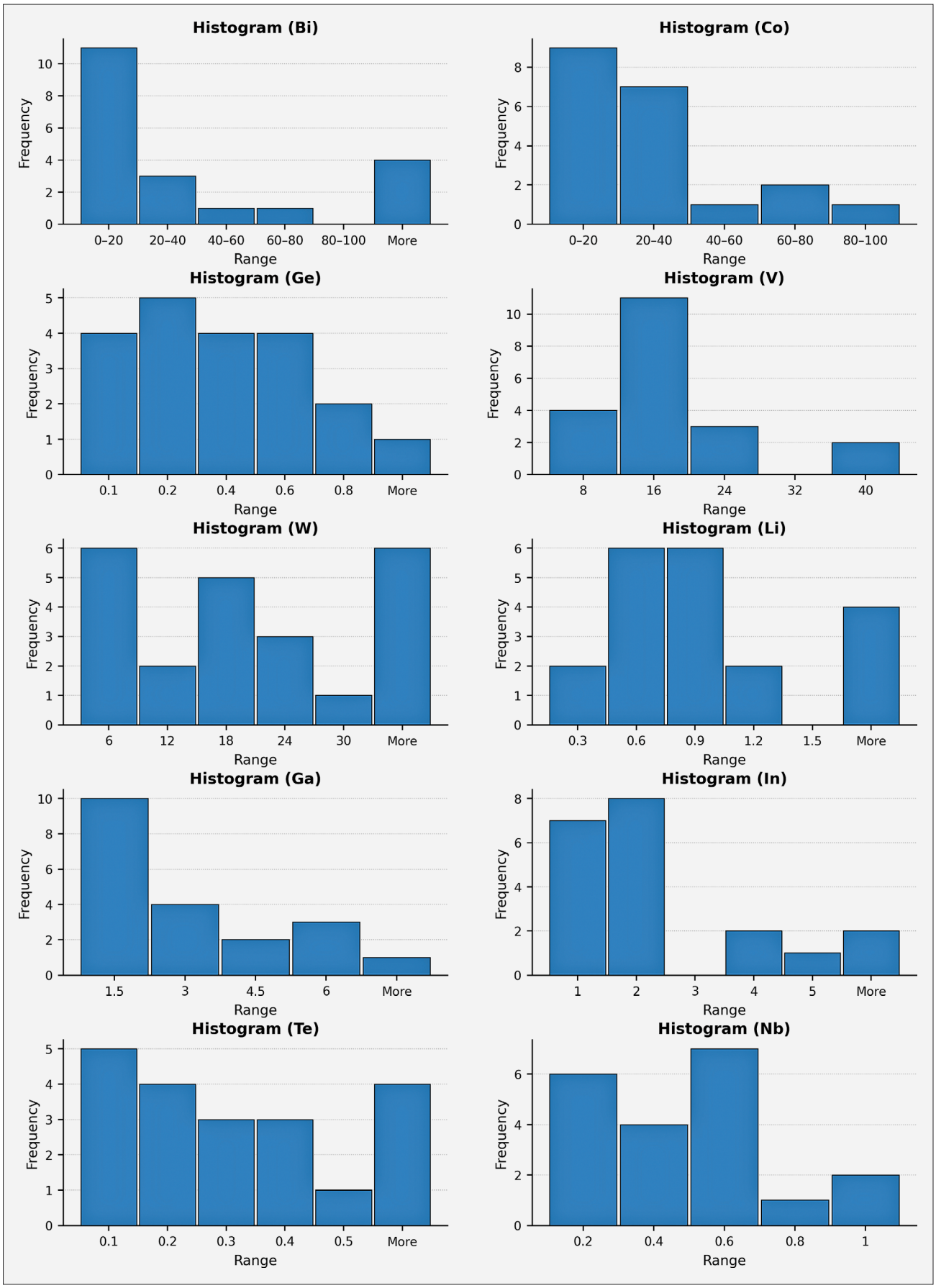


Figure 5: Distribution histograms of selected Technology-Critical Elements concentrations

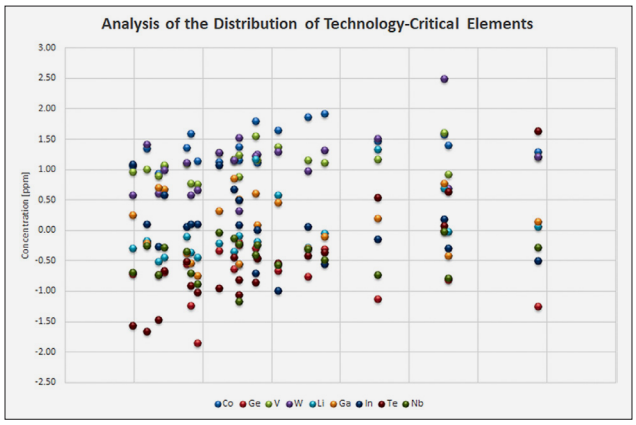


Figure 6: Scatter Plot diagram and relation of Technology-Critical Elements

Figures 8 – 13 illustrate the spatial distribution of Technology-Critical Elements and their horizontal concentration in ore bodies and horizons VIII - XI is presented.

Distribution of Bi in horizons VIII – XI

Figure 8 illustrates the distribution of Bi in four horizons studied in the Trepça Mine, where, for each horizon in which directions this element is most concentrated, as well as the degree of its concentration in the direction of depth.

Figure 8 shows the distribution of Bi in four horizons in active ore bodies. Bi is mainly concentrated in the southern ore bodies, although its distribution expands toward northern bodies with increasing depth. The figure shows that the highest concentrations are in ore bodies 127, 136, 146, and 156.

Distribution of W in horizons VIII – XI

In **Figure 9** we will see spatial distribution of W in horizons 8, 9, 10 and 11 in the Trepça Mine, where we will see for each horizon in which directions this element is most concentrated, as well as the degree of its concentration in the direction of depth.

Figure 9 shows the distribution of W in active ore bodies in horizons 8, 9, 10 and 11. W is more widely distributed than Bi, although its highest concentration remains localized in the southern ore bodies, but even this is distributed only in the southern ore bodies, while in horizon 9 it has given a distribution also in the southern bodies up to horizon 11. But with increasing depth, W begins to decrease in concentration values.

Distribution of Co in horizons VIII – XI

In **Figure 10** we will present the distribution of Co, in horizons 8, 9, 10 and 11, where we will see for each horizon in which directions this element is most concentrated, as well as the degree of its concentration in the direction of depth.

Figure 10 shows the distribution of Co, in active ore bodies in horizons 8, 9, 10 and 11. Laboratory analyses show that Co, occurs in both southern and northern ore bodies. The highest concentration was observed in Horizon IX within the northern bodies, whereas in Horizon XI a higher concentration was detected in the southern bodies, with significantly lower levels in the northern ones.

Distribution of Li in horizons VIII – XI

In **Figure 11**, we will present the distribution of Li in four horizons studied in the Trepça Mine, where we will see for each horizon in which directions this element is most concentrated, as well as the degree of its concentration in the direction of depth.

Figure 11 shows the distribution of lithium (Li) in active ore bodies from horizons VIII to XI. Li exhibits pronounced anomalies, particularly in Horizon IX, where a strong concentration peak is observed in ore body 136.

Distribution of Te in horizons VIII – XI

In **Figure 12**, we will see spatial distribution of Te in horizons 8, 9, 10 and 11 in the Trepça Mine, where we will see for each horizon in which directions this ele-

Table 5: Correlation Matrix of selected elements

	Bi (ppm)	Co (ppm)	Ge (ppm)	V (ppm)	W (ppm)	Li (ppm)	Ga (ppm)	In (ppm)	Te (ppm)	Nb (ppm)
Bi (ppm)	1									
Co (ppm)	0.08	1								
Ge (ppm)	0.19	0.16	1							
V (ppm)	0.34	0.35	0.58	1						
W (ppm)	0.60	0.10	0.65	0.70	1					
Li (ppm)	0.16	0.26	-0.01	0.45	0.16	1				
Ga (ppm)	0.06	-0.18	0.25	0.52	0.41	0.12	1			
In (ppm)	-0.23	-0.38	0.03	-0.10	-0.08	-0.22	0.10	1		
Te (ppm)	0.32	-0.10	-0.27	0.02	-0.03	-0.01	-0.11	-0.17	1	
Nb (ppm)	0.14	-0.08	0.51	0.56	0.54	-0.13	0.49	0.26	0.07	1

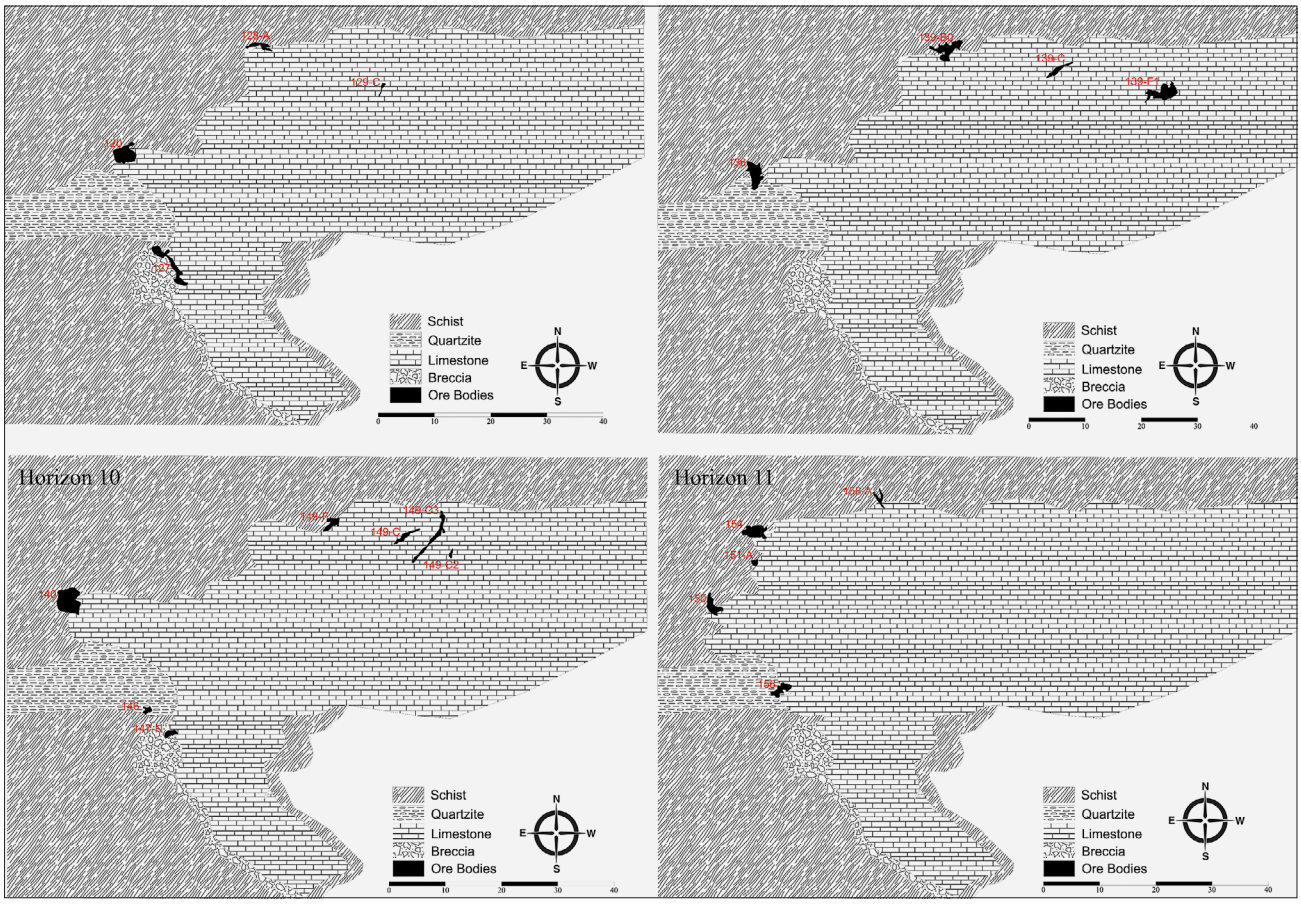


Figure 7: Ore bodies, geological formations and their location

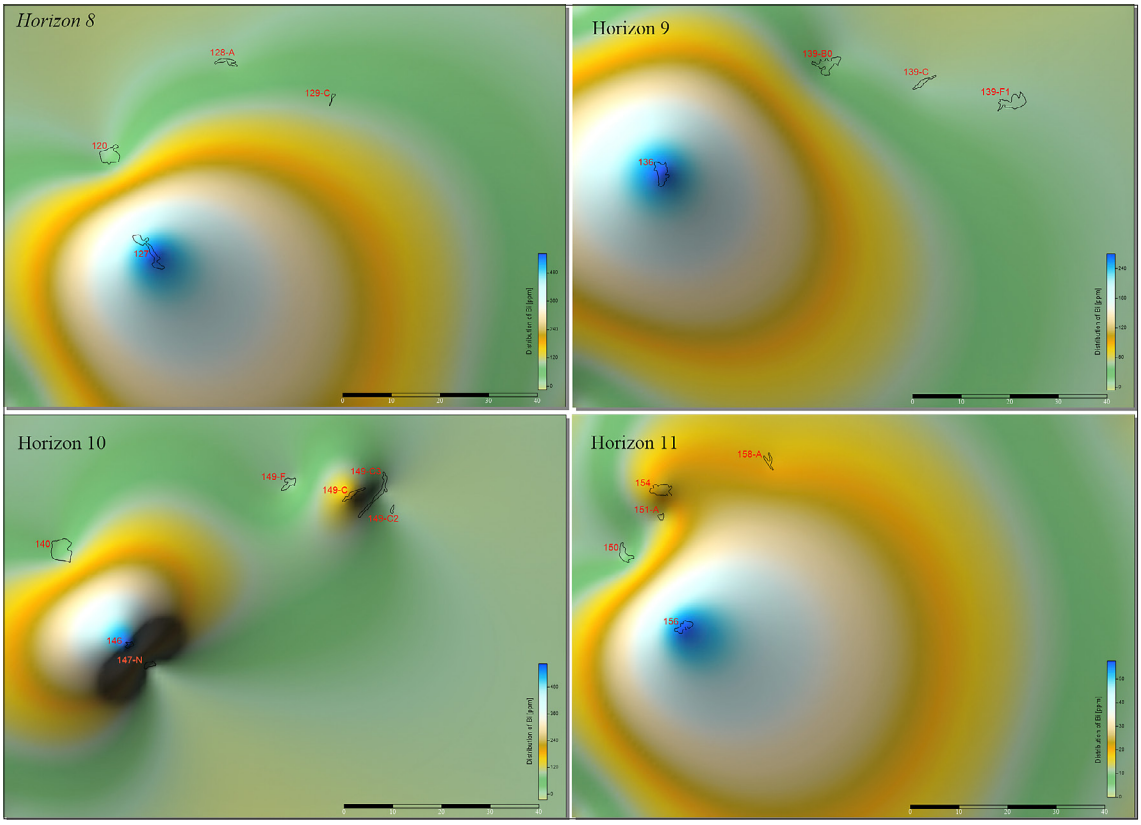


Figure 8: Distribution of Bi in horizons 8 – 11

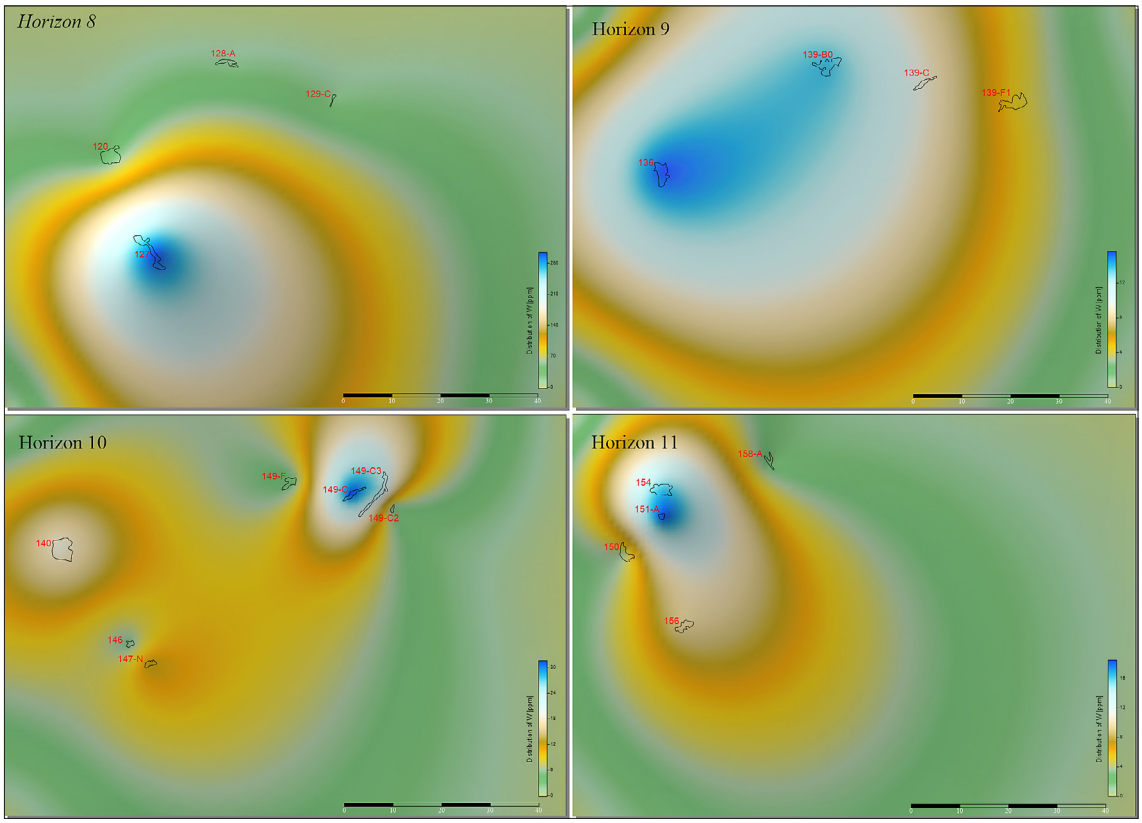


Figure 9: The vertical distribution of W, as a function of depth

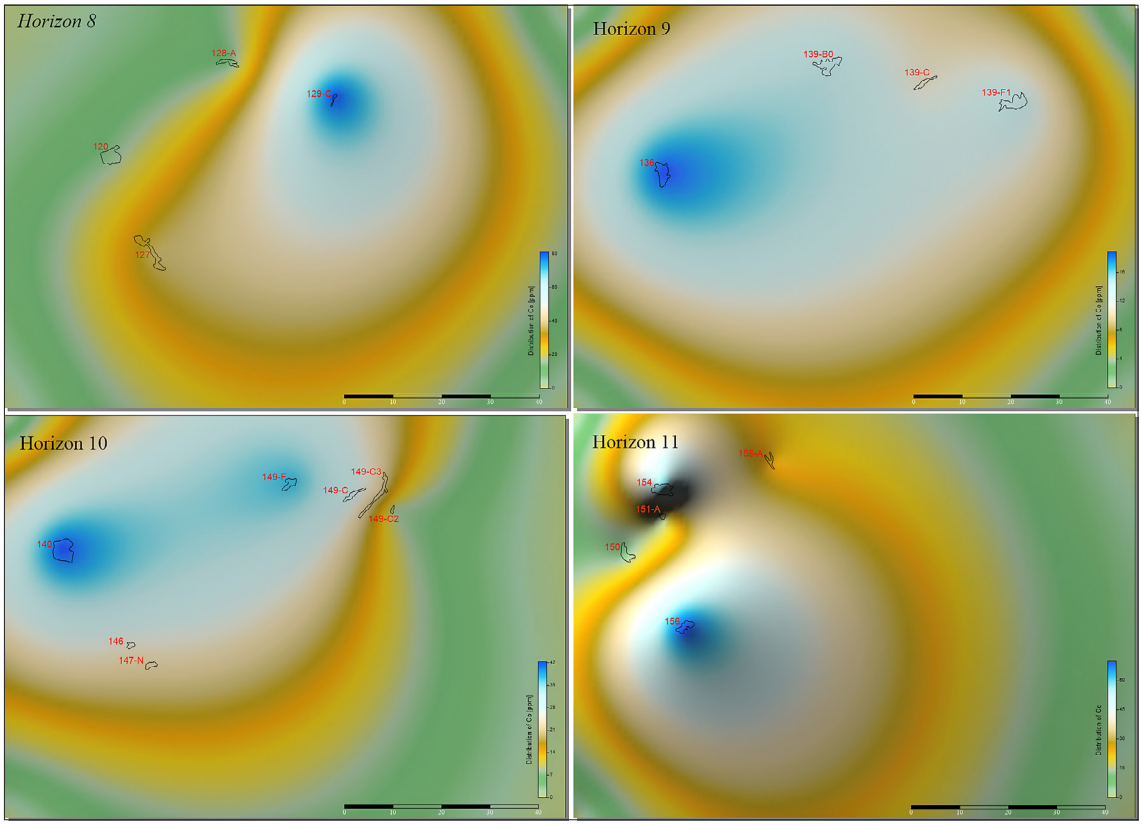


Figure 10: The vertical distribution of Co as a function of depth

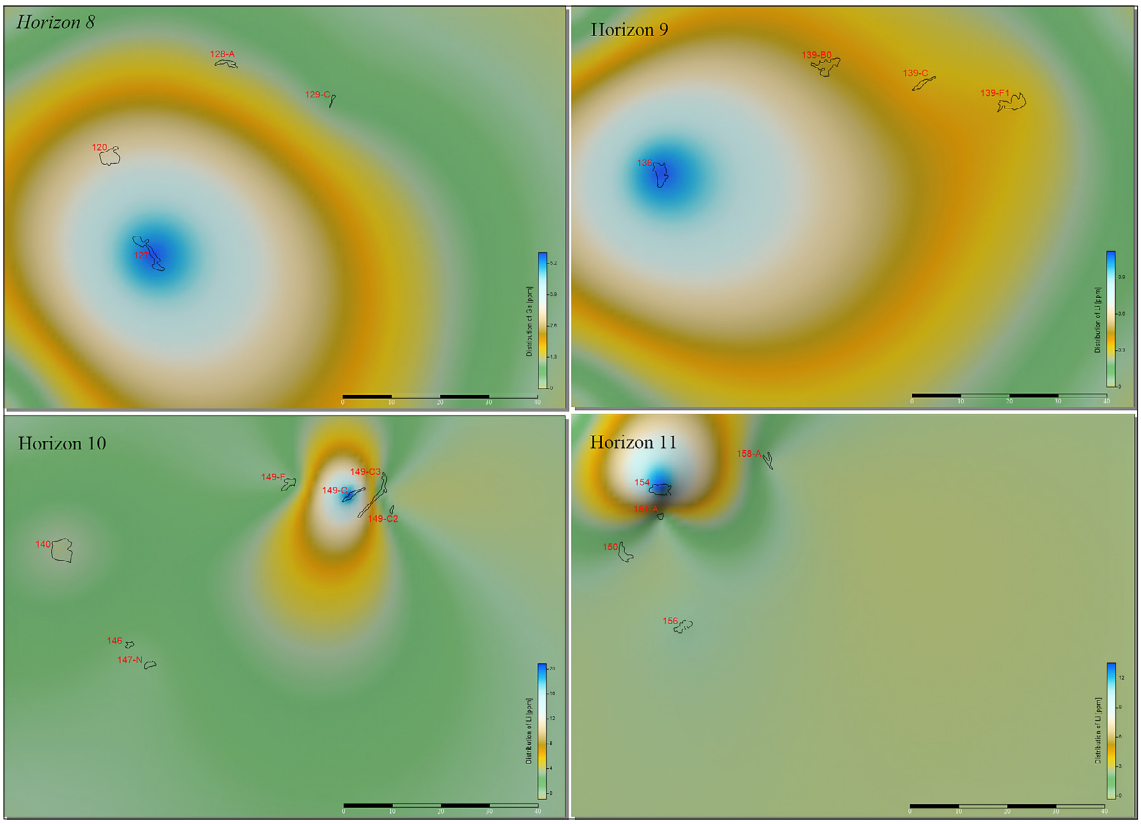


Figure 11: Distribution of Li in horizons 8 - 11

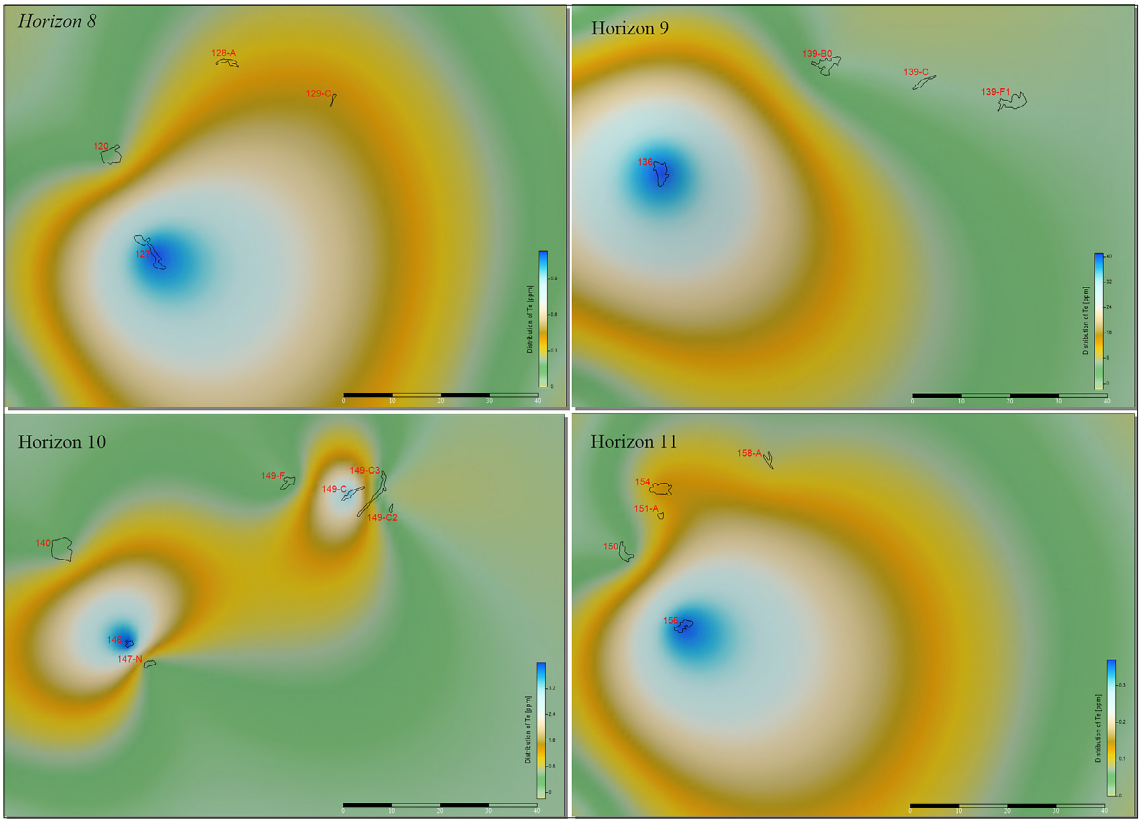


Figure 12: Distribution of Te in horizons 8 - 11

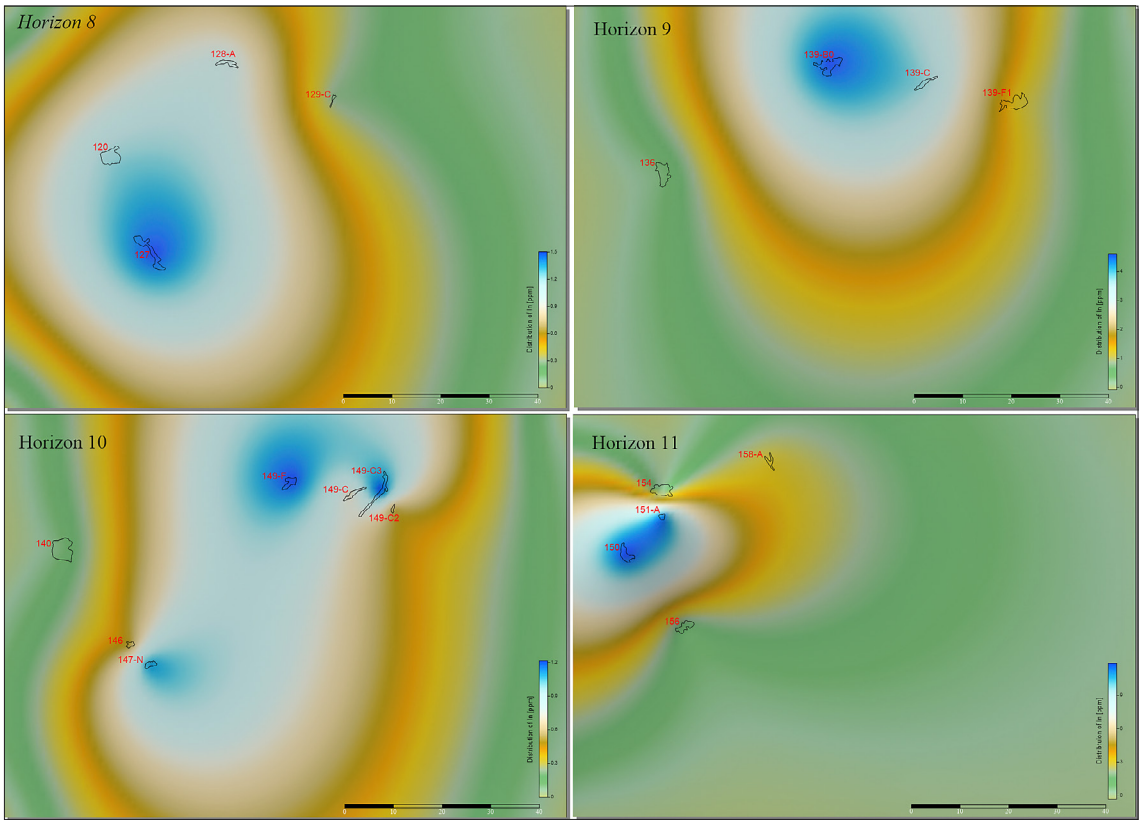


Figure 13: Distribution of In in horizons VIII - XI

ment is most concentrated, as well as the degree of its concentration in the direction of depth.

Figure 12 shows the heterogeneous distribution of Te across horizons VIII - XI, with higher concentrations consistently observed in the southern ore bodies 127, 136, 146 and 156 respectively. Te shows consistently higher concentration in the southern bodies, indicating a localized mineralization.

Distribution of In in horizons VIII – XI

In **Figure 13** we will present the distribution of In in four horizons studied in the Trepça Mine, where we will see for each horizon in which directions this element is most concentrated, as well as the degree of its concentration in the direction of depth.

Figure 13 illustrates the heterogeneous distribution of In across horizons VIII - XI. In, as in the correlation analysis that did not give a good correlation with any other element, In shows increasing concentration with depth, particularly within the central ore bodies, but decreases their concentration in southern and northern ore bodies.

3.3. PCA Analysis of Technology-Critical Elements

PCA was used to identify how Technology-Critical Elements group according to geological processes in the Trepça Mine. The groups of elements that appear in the PCA space represent potential mineralogical associations that can serve as indicators for prospecting and

Table 6: PCA Eigenvalues and Explained Variance Table for Technology-Critical Elements

PC	Eigenvalue	Percent_ variance	Cumulative_ percent
PC1	3.180	31.780	31.780
PC2	2.130	21.250	53.030
PC3	1.780	17.820	70.850
PC4	1.000	9.980	80.830
PC5	0.680	6.800	87.630
PC6	0.550	5.510	93.150
PC7	0.300	3.040	96.190
PC8	0.260	2.570	98.760
PC9	0.120	1.170	99.930
PC10	0.010	0.070	100.000

geochemical modelling. Variables in the PPCA analysis were standardized prior to PCA. The 2D graph presents the projection of variables (elements) into the first two principal components (Dim1 explains 31.8% of the variance and DIM2 explains 21.3% of the variance, DIM3 17.8% of the variance), which together account for 70.8% of the total variance of the data.

Te and Bi appear oriented mainly towards the positive axis of Dim2, with a high and close loading between them, suggesting a strong correlative relationship and perhaps a similar source or mineralization process especially

Table 7: Loading matrix for Technology-Critical Elements

Variable	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5
Bi	0.010	0.971	0.194	-0.062	0.054
Co	0.195	0.046	-0.762	-0.333	0.268
Ge	0.765	-0.228	-0.001	-0.412	0.006
V	0.899	0.163	-0.214	0.125	0.138
W	0.848	0.108	0.004	-0.136	-0.117
Li	0.259	0.129	-0.596	0.636	0.254
Ga	0.635	-0.083	0.270	0.490	-0.347
In	0.002	-0.374	0.659	0.140	0.606
Te	-0.110	0.961	0.207	-0.007	0.088
Nb	0.738	0.060	0.462	-0.128	0.110

in hydrothermal mineralization or skarn deposits like the Trepça Mine. **Table 6** presents the eigenvalues and loading matrix data for the technology-critical elements.

Table 6 presents the eigenvalues and the percentage of variance for each technology-critical element analysed through PCA in R Studio, this provides a clear overview of these elements by orientation and group. From the Eigenvalues table we see that the first component PC1 represents 31.78% of the variance and the component PC2 21.3%, showing that these two chemical processes dominate the variability of the samples. PC1 is dominated by V, W, Nb, Ge and Ga. While PC2 is dominated by Bi and Te, which are chemically related to hydrothermal mineralization, and PC3 is dominated by Li and Co. From this we see that we have three groups of Technology-Critical Elements. The loading matrix from the analysis is presented in **Table 7**.

Table 7 presents the variable loadings for the main components of the PCA analysis of technology-critical elements in the Trepça Mine, which indicate the contribution and direction of each chemical element in shaping the components. Positive or negative values reflect the strength and orientation that an element has an association with the component.

The loading matrix represents the chemical and geochemical direction of each component. Component PC1 shows a strong positive loading for V (0.899), W (0.848), Ge (0.765), Nb (0.738) and Ga (0.635), where these elements have strong positive loadings. In contrast, in PC2 we have very high loadings of Bi (0.971) and Te (0.961), where they are typical elements for hydrothermal phases. While the other elements present more complex but not dominant relationships in this group. Now, through the PCA plot, the grouping of Technology-Critical Elements will be graphically illustrated in **Figure 14**.

Figure 14 illustrates Principal Component Analysis plot for Technology-Critical Elements. The figure clearly separates the elements into three main groups:

(1) V-W-Nb-Ge-Ge (PC1)
(2) Bi-Te (PC2)
(3) Co-Li (PC3)

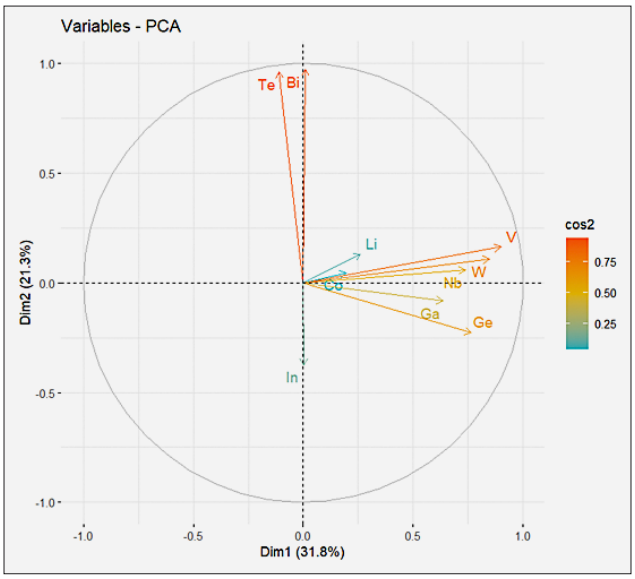


Figure 14: Principal Component Analysis Graph of TCE elements

4. Discussion

The spatial distribution of Technology-Critical Elements in Trepça shows notable similarities with several deposits worldwide regarding the concentration of these elements in hydrothermal systems. The elevated concentrations of Bi, W, and Co identified in several ore bodies of the Trepça deposit exhibit a strong resemblance to those observed in the Pyrenean hydrothermal deposit (**Cugerone et al., 2020**), where these elements are concentrated within the framework of sphalerite mineralization.

In this study, high concentrations of W, V, and Bi were also encountered. According to **Vikre et al. (2023)** such elements are found in significant amounts within sulfide mineralizations in the western United States, where their mobility is closely associated with hydrothermal processes.

Similarly, in the polymetallic deposit of Chamuhan, northeastern China (**Wu et al., 2025**), sulphide mineralization and hydrothermal processes exhibit a high presence of tungsten, showing a comparable pattern to horizons 8 and 9 of the Trepça Mine.

Through correlation analysis we have presented the correlation of the distribution of these elements. The statistical results are consistent with correlation matrix analysis, which confirms strong confirms positive relationships such as W-V (r = 0.70), W-Ge (r = 0.65) and W-Bi (r = 0.60).

Although Niobium (Nb) occurs at low concentrations, it shows significant correlations with several other elements as Niobium (Nb) with Germanium (Ge) has given a moderate positive correlation (r = 0.51), then Niobium (Nb) with Vanadium (V) has a moderate positive correlation (r = 0.56) and Niobium (Nb) with Tungsten (W) has a moderate positive correlation (r = 0.54).

While other elements present a weak positive correlation or we even have the case where we have a weak negative correlation, such as the case between Tellurium (Te) and Germanium (Ge), with a correlation (r = -0.27), we also have a weak negative correlation between Lithium (Li) and Indium (In) with a value of (r = -0.22). Other elements have not presented a significant correlation between them. So this presents that the highest concentration of Technology-Critical Elements is in horizons 8 and 9, but with increasing depth, the concentration of these elements decreases, as has been proven through spatial analysis with Golden Software Surfer.

The identification of high concentrations of Bi, W, and Co in specific ore bodies suggests the feasibility of selective recovery, which is a key principle of sustainable mining. Moreover, the association of TCEs with hydrothermal mineralization zones offers a path to refine exploration models for other regions, enhancing resource efficiency and reducing unnecessary environmental disturbance.

5. Conclusions

The findings indicate that Technology-Critical Elements in the Trepça Mine are heterogeneously distributed, particularly across horizons VIII-XI. Bi, W and Co show the highest concentration, with Bi averaging 98.81 ppm, W 28.68 ppm, and Co 28.47ppm, all exhibiting high variability. Despite this Ge, Ga, Nb and Li present a very low concentration but also with limited variability, so generally the four above-mentioned horizons can be characterized by the presence of Bi, W and Co in larger quantities.

Chemical analyses performed using the ICP-MS and spatial analysis have shown that Bi, W and partly Co exhibit high concentrations in horizons VIII and IX of the analysed ore bodies. In horizon IX, the concentrations are similar, but some anomalies appear like the Bi concentration, while with increasing depth in the X and XI horizons, respectively, elements such as Bi, W, Ga, Te and In display significantly lower concentrations.

These results are supported by the correlation analysis, which shows correlation among W, V, Ge and Bi indicating that their concentrations decrease consistently with depth.

Overall, both the chemical and correlation analyses suggest that the studied elements can be grouped into three groups and this is confirmed also by PCA analysis:

(1) Bi and Te,

(2) W, V, Ge, Ga, Nb and

(2) Co and Li which tend to show slightly higher concentration at greater depths. This behaviour is also supported by correlations such as V-W (r=0.70), and W-Ge (r=0.65). Co, in other hand, shows negative correlation with most elements, suggesting a different origin and mineralogical phases.

So, from this we can conclude that the Trepça Mine is a mine as a strategic object not only for traditional metallurgy and the exploitation of Pb and Zn, but also for modern technologies with the presence of these Technology-Critical Elements and their importance.

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SAŽETAK

Statistička, geostatistička i prostorna analiza tehnološki kritičnih elemenata u rudniku Trepča

Ova studija istražuje prisutnost, koncentraciju i prostornu raspodjelu tehnološki kritičnih elemenata (TKE) u rudniku Trepča s fokusom na horizonte rudnih tijela VIII-XI. Tijekom istraživanja relevantnih arhiva (Trepča, ICMM, GSK), uočeno je da u rudniku Trepča nisu provedene statističke, geostatističke ili prostorne studije tehnološki kritičnih elemenata. Mineralizacije u Trepči uglavnom se javljaju kao žilne strukture poznate kao rudna tijela. U ovoj studiji uzorkovana su sva postojeća rudna tijela iz horizonata VIII-XI. Reprezentativni uzorci prikupljeni su iz svakog aktivnog rudnog tijela i analizirani pomoću spektrometrije masa uz induktivno spregnutu plazmu (ICP-MS) kako bi se kvantificirali elementi, uključujući Bi, Co, Ge, V, W, Li, Ga, In, Te i Nb. Statističke i geostatističke analize provedene su pomoću softvera Microsoft Excel, R Studio i Golden Software Surfera u svrhu procjene varijabilnosti, korelacija i prostornih trendova. Najviše koncentracije uočene su za Bi (prosječno 98,81 mg/l; maksimalno 610,4 mg/l), W (prosječno 28,68 mg/l) i Co (prosječno 28,47 mg/l), sa znatnom varijabilnosti kroz horizonte. Korelacijska analiza otkrila je snažne pozitivne odnose između nekoliko elemenata, kao što su W–V (r = 0,70), W–Ge (r = 0,65) i Bi–W (r = 0,60), što upućuje na moguće zajedničko geološko podrijetlo. Rezultati istraživanja ističu potencijal za održivi oporavak strateških elemenata iz Trepčinih polimetalnih rudnih zona i naglašavaju važnost rudnika ne samo za tradicionalne metale već i za kritične sirovine bitne za niskougljične i visokotehnološke industrije.

Ključne riječi:
statistika, geostatistika, prostorno, raspodjela, TKE, Trepča, rudnik

Author's contribution

Berat Sinani (PhD Cand.): conceptualization; software; investigation; methodology; writing – original draft. **Blazo Boev** (Prof. Dr.): investigation; methodology; review and editing the paper. **Arianit Reka** (Prof. Dr.): data curation; validation; writing - review & editing. **Bahri Sinani** (PhD Cand.): investigation, software, visualization; **Ivan Boev** (Prof. Dr.): conceptualization; supervision; validation; writing, reviewing and editing the paper.