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# Geostatistical Studies and Anomalous Elements Detection, Bardaskan Area, Iran

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## Abstract

The aim of this study is geostatistical analysis and detection of anomalous elements in the Bardaskan area (in geological map of Bardaskan on scale 1:100,000 which is provided by the GSI organization). The study area is located in Khorasan province of Iran. Due to the availability of lithogeochemical regular data in the region as well as the importance of exploration of metal minerals in order to simplify and summarize the geochemical map, geostatistical methods were used to identify the mineralization potential of the region. Initially, using single-variable and multivariate statistical methods, anomalous elements were separated. Then, the thresholds (various communities) for the titanium element that was most likely to be anomalous were identified. Using these limits, the discriminant analysis was applied to the elements. Titanium, iron and magnesium elements were identified as the main mineral elements in the region. These elements indicate mineralization in the mafic bed rocks. Finally the map of the concentration of titanium element was mapped across the region with Kriging interpolation method. As a result, two anomalies of the titanium element in the region were identified.

## Keywords

Geostatistics, Geochemical Exploration, Discriminant Analysis, Titanium

## 1. Introduction

The statistics are a vast array of maths that study ways to collect, summarize, and conclude data. This science applies to a wide range of academic sciences from physics and social sciences to anthropology, as well as business, government, and industry. Statistics is the science and practice of human development through the use of experimental data. Statistics are based on the theory of statistics, which is a branch of applied mathematics. In statistical theory, random events and uncertainty are modeled by probability theory. In this science, studying and judging on various subjects is done on the basis of a society and judgment about a particular person is not at all questionable [1]. In other words, statistics should be the knowledge and practice of extracting, expanding and developing empirical human knowledge using methods of collecting, regulating, developing, and analyzing experimental data (from measurement and testing). More recent computing areas, such as machine learning, and machine exploration in data, are, in fact, the extension and spread of extensive knowledge of the statistics [2].

The geostatistics, which is the most important statistical theory based on the field concept of the place, is the theory of regional variables. The regional variable is defined as any environment property whose numerical values are distributed in one-, two-, or three-dimensional sampling space. The spatial variations of a regional variable have two structural and random components. One of the main goals of spatial statistics is to provide an appropriate model for describing the regional variable by taking into account the structural and random variability components. This section of spatial statistics is called geostatistics [3].

Identification and recognition of anomalies from background is an essential issue in geochemical exploration [4]. The aim of this study is to identify the anomalous elements in the Bardaskan area. In order to identify these elements, methods such as discriminant analysis and hierarchical clustering were used. The results on this scale can indicate regions susceptible to detailed explorations [5].

## 2. Data and Analytical Procedures

### 2.1. Regional Geological Setting

The Bardaskan area is in the geological map on scale 1:100,000 is one of the rectangular sheets of Kashmar map which is on scale 1:250,000. The study area is in geographical coordinates 57˚00' - 57˚30' eastern longitude and 35˚00' - 35˚30' northern latitude. The range of the Bardaskan sheet is among the cities of Khorasan Razavi province of Iran. Major geological subdivisions of Iran and geology map of Bardaskan area are shown in **Figure 1**. Khorasan province has a good position regarding the capacity and diversity of mineral reserves due to its special location, which is the location of the major geological phenomena. The vast reserves of oil and gas in the north of the province are abundant. Also, deposits of coal, copper, iron, manganese, fire clay, magnesite, white clay, various types of building stones such as marble, travertine, iron ore and gypsum are found in this province. The most important minerals in Khorasan Razavi province that have economic mines include:

- Magnesite.
- Fluorite.
- Bauxite.

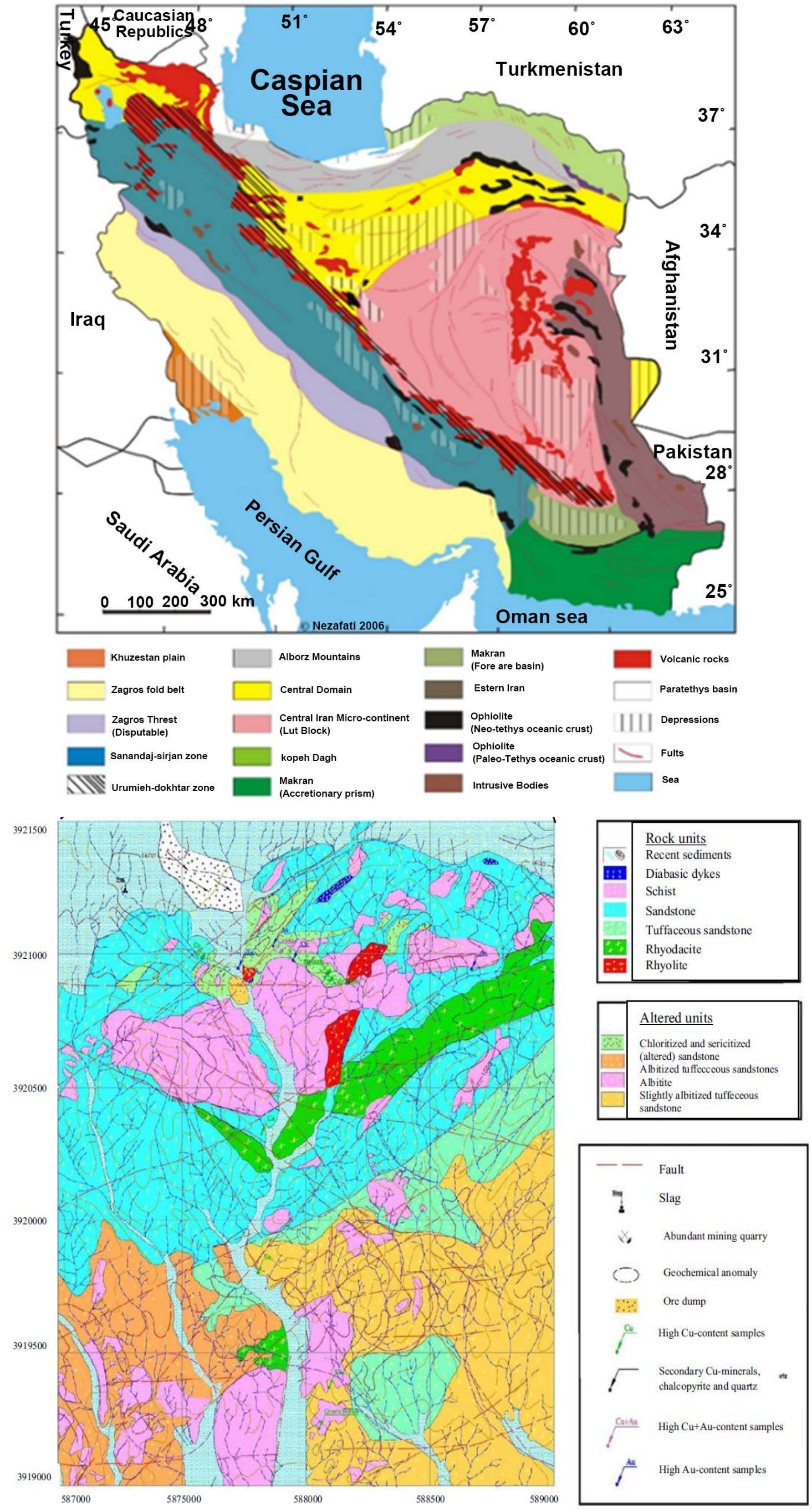


**Figure 1.** Major geological subdivisions of Iran [6] and geology map of Bardaskan area [4].

- Chromite.
- Copper.
- Turquoise.
- Coal.
- Iron.

Considering the existence of different economic mines in Khorasan Razavi province, the Bardaskan region, which is one of the most susceptible areas in the province, was selected to investigate exploratory geochemistry by applying statistical methods.

- **Geomorphology:**

From the morphological viewpoint, the Bards can area can be studied in two separate parts which are distinguished from each other by the Daroone fault. The part of the area located above the fault is a mountain range with a wide variety. But the southern part of the mentioned fault, except for the southeast hills, is a continuation of the outcrops of the Uzbak mountain range, with an average elevation of 850 meters above sea level, which occurs at a vast surface of quaternary units such as alluvial terraces, alluvial fans, clay and salt formations [7].

- **Stratigraphy:**

  **Precambrian**: This section is located south of Takanar main fault. The wedge form of this section, which is located between the Daroone and Taknar faults. Based on the existence of outcrops from the Taknar-Precambrian formation, and the covering of the Paleozoic and Mesozoic rocks it has been designated as an erosional window indicating the uplift of Precambrian Paleozoic basement rock of the Iran central tectonic zone in the Tertiary Age [8].

  **Taknar formation**: The Taknar formation consists of a thick sequence of schists, tuffs, green schists, and quartzite sandstones that have undergone a mild metamorphism in the sub-greenschist facies. In this sequence there are massive metamorphic rhyolites and rhyodacites. One of the important features of this formation is its contact with two intrusive masses. One Intrusive Mass of Precambrian that includes granite and granitoid, and another mass of granite whose time of influence is Eocene-Oligocene [9] [10].

### 2.2. Sampling

The type of sampling is lithogeochemical and is performed according to a regular network. A total of 483 lithogeochemical samples were collected from the area. Samples have been analyzed using ICP-AES method. Sampling network location is shown in **Figure 2**.

### 2.3. Correlation Analysis

Correlation is used to test relationships between quantitative variables or categorical variables. In other words, it's a measure of how things are related. The study of how variables are correlated is called correlation analysis [11].

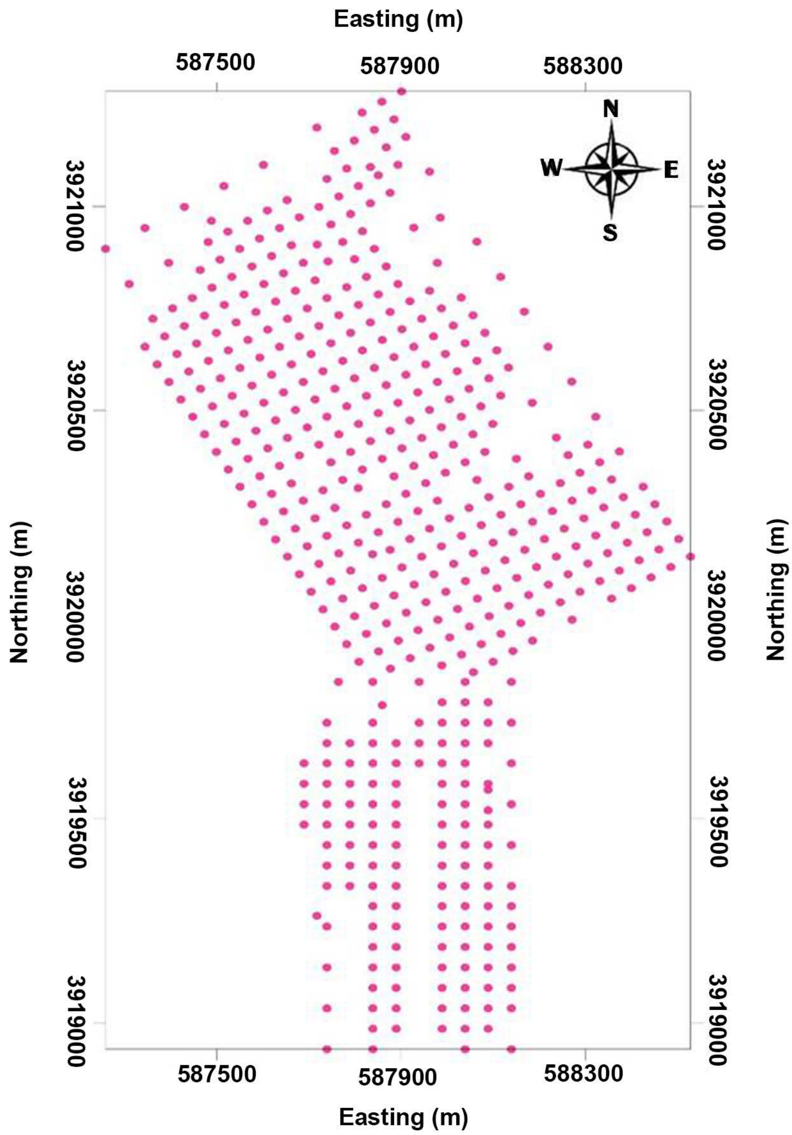


Figure 2. Sampling network location in Bardaskan area.

Correlations are useful because if you can find out what relationship variables have, you can make predictions about future behavior [12]. Correlation analysis in geochemical data is very important. One of the valuable results of the investigation of the correlation between chemical elements is the identification of the mineralization and geochemical behavior of the region [13].

## 2.4. Hierarchical Clustering

In data mining and statistics, hierarchical clustering (also called hierarchical cluster analysis or HCA) is a method of cluster analysis which seeks to build a hierarchy of clusters. Strategies for hierarchical clustering generally fall into two types [14]:

- **Agglomerative Method**:

  This is a "bottom up" approach: each observation starts in its own cluster, and pairs of clusters are merged as one moves up the hierarchy.

- **Divisive Method**:

This is a "top down" approach: all observations start in one cluster, and splits are performed recursively as one moves down the hierarchy (see **Figure 3**).

### 2.5. Linear Discriminant Analysis (LDA)

Discriminant analysis is used as a tool for the separation of communities [15]. This method is described by the number of categories that is possessed by the dependent variable [16]. Linear discriminant analysis works under the simplifying assumption that $\Sigma_k = \Sigma$ for each class *k*. In other words, the classes share a common within-class covariance matrix. Since $x^{\Sigma}x$ term is constant across classes, this simplifies the discriminant function to a linear classifier, $\delta_k(x)$ are known as discriminant functions [17] [18]:

$$\delta_k(x) = -\mu_k \Sigma^{-1} x + \frac{1}{2}\mu_k \Sigma^{-1}\mu_k + \log(\pi_k)$$

you can see the steps in discriminant analysis method in **Figure 4**.

The following plot shows the linear classification boundaries that result when a sample data set of two variables is modelled using linear discriminant analysis (**Figure 5**).

## 3. Results and Discussion

### 3.1. Raw Data Analysis

The results of the samples analysis which were taken regularly from rock units were analyzed using single-variable statistics. Regarding the field limitations of the elements in the area as well as their measured value in the samples, Ti, Cu, Mo and Zn elements are known as anomalous elements in the region.The result of this study is presented in **Table 1**.

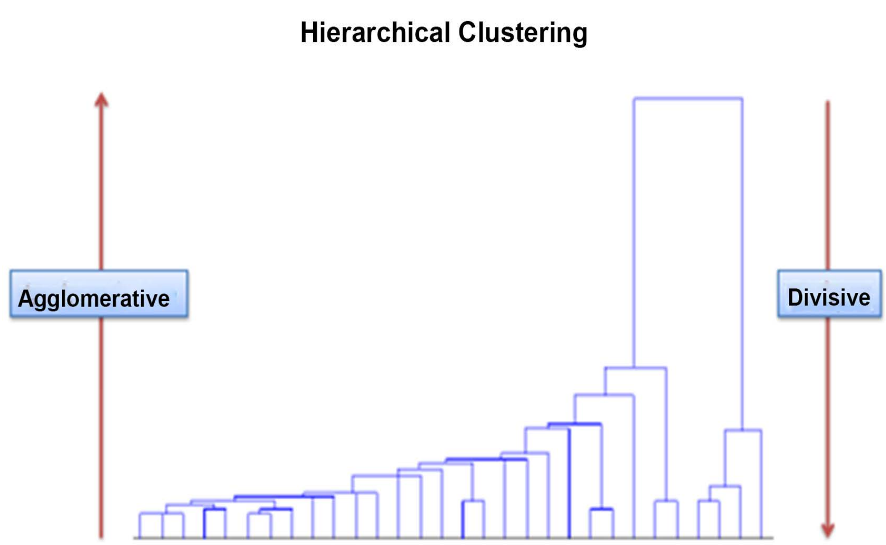


**Figure 3.** Hierarchical clustering strategies.

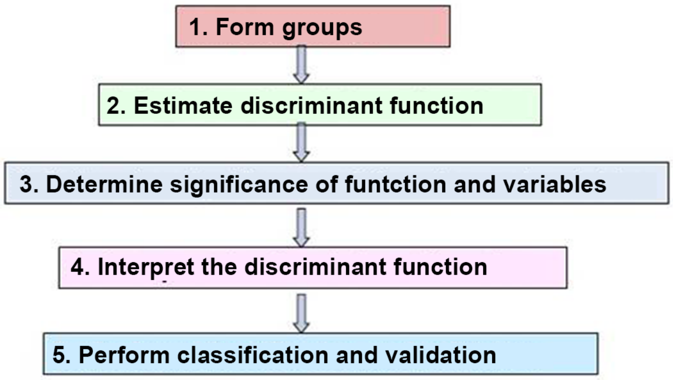


**Figure 4.** Steps in discriminant analysis.

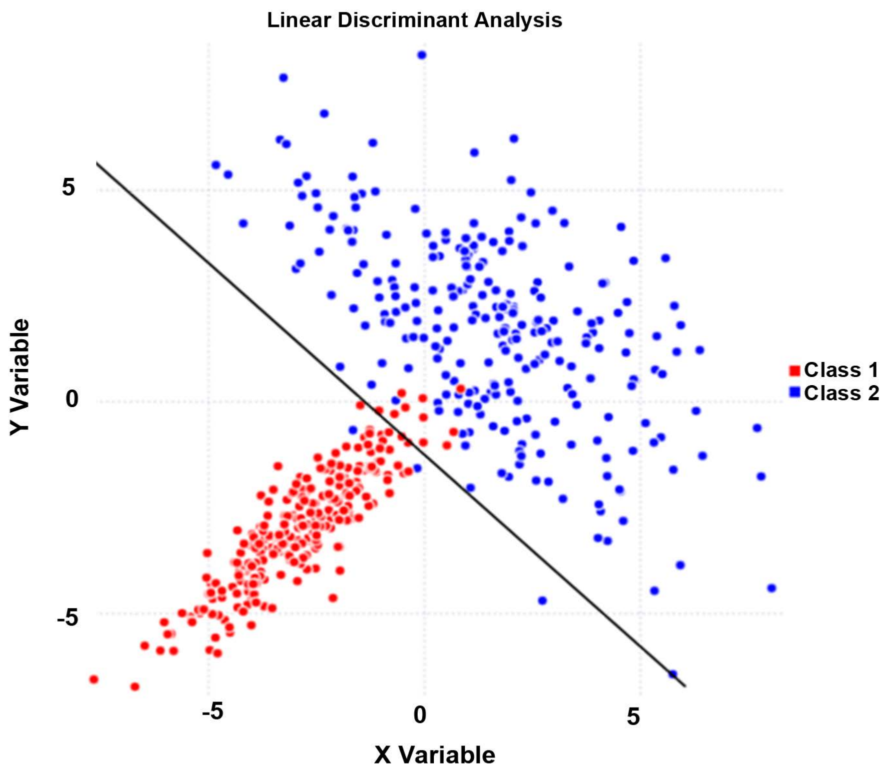


**Figure 5.** The separation of the two communities by the discriminant analysis.

## 3.2. Correlation Analysis

Using Spearman method, correlation coefficients among the elements in the region were investigated. Table 2 shows the correlation of the elements with each other.

## 3.3. Clustering

Considering the need for clustering and creating enough visibility to understand mineral elements and also the separation of these elements from the elements that have created the area's rocks, hierarchical cluster method was used (Figure 6). This clustering can be done by different methods. In this paper, the squared

Table 1. Descriptive statistics along with the limitations of the field and the detection of anomalous elements.

| Elements | Min | Max | Average | Std. Deviation | Variance | Skewness | Kurtosis | Median | Mode | Anomalous limit |
|---|---|---|---|---|---|---|---|---|---|---|
| Cr | 12 | 271 | 72 | 42 | 1788 | 2 | 5 | 59.000 | 47.0 | 100 |
| Mn | 27 | 3170 | 596 | 541 | 292,995 | 1 | 1 | 420.000 | 108.0 | 950 |
| Ni | 0 | 147 | 16 | 19 | 371 | 3 | 12 | 7.000 | 4.0 | 75 |
| Pb | 0 | 4000 | 40 | 234 | 54,811 | 12 | 182 | 5.800 | 0.0 | 12.5 |
| Ti | 156 | 19,900 | 3690 | 4027 | 16,218,242 | 2 | 3 | 2210.000 | 1020 | 5000 |
| Fe | 2120 | 143,000 | 39225 | 27,387 | 750,058,457 | 1 | 1 | 30,150.000 | 24,400 | - |
| Hg | 0 | 1 | 0 | 0 | 0 | 2 | 5 | 0.0000 | 0.00 | 0.08 |
| Ag | 0 | 28 | 1 | 2 | 4 | 10 | 113 | 0.8600 | 0.80 | 0.07 |
| Co | 0 | 331 | 12 | 24 | 576 | 9 | 101 | 5.650 | 0.8 | 25 |
| Cu | 2 | 43,100 | 437 | 3000 | 9,001,803 | 10 | 122 | 15.900 | 5.6 | 55 |
| Mo | 0 | 43 | 4 | 5 | 24 | 4 | 27 | 2.500 | 0.9 | 1.5 |
| Sb | 0 | 20 | 2 | 2 | 3 | 5 | 34 | 1.200 | 1.2 | 0.2 |
| Zn | 0 | 6200 | 119 | 374 | 140,037 | 12 | 167 | 47.800 | 138.0 | 70 |
| Sn | 0 | 37 | 3 | 3 | 9 | 7 | 62 | 3.000 | 2.0 | 2 |
| W | 0 | 19 | 7 | 3 | 11 | 0 | 0 | 7.100 | 6.0 | 1.5 |

Euclidean distance was used. Titanium, iron, and magnesium appear together, which reflects the mineralization in the mafic bed rock. In the correlation coefficient (Table 2), correlation of these elements was also observed.

### 3.4. Histogram and Probability Graph

Regarding the choice of the titanium element as target element, its histogram was drawn and the type of distribution of the statistical society of that, was detected as log-normal distribution (Figure 7). The cumulative probability curve for the titanium element is given below in Figure 8.

### 3.5. Separating Communities in the Probability Chart

The separation of communities from the titanium probability chart is considered to be an important point in determining the limits of the society and thus determining the geochemical threshold. For this purpose, a line is fitted to the probability diagram, and the fracture points of the diagram are investigated. Figure 9 illustrates the implications of this fit and determination of communities. Important communities are starting at 1000, 3000, and 9000 ppm which are considered as background, weak anomaly and strong anomaly of titanium in the region.

### 3.6. Linear Discriminant Analysis (LDA)

In this section, LDA was performed using the limits obtained in the previous section. Figure 10 shows the separated communities. In Figure 11, the identified

Table 2. Correlation coefficients of the analyzed elements relative to each other.

| | Au | Cr | Mn | Ni | Pb | Sr | Ba | Be | Ti | Fe | Hg | Ag | As | Bi | Co | Cu | Mo | Sb | Zn | Sn | W |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Au | 1 | | | | | | | | | | | | | | | | | | | | |
| Cr | 0.101 | 1 | | | | | | | | | | | | | | | | | | | |
| Mn | 0.022 | 0.423 | 1 | | | | | | | | | | | | | | | | | | |
| Ni | −0.035 | 0.637 | 0.618 | 1 | | | | | | | | | | | | | | | | | |
| Pb | 0.277 | 0.117 | 0.266 | 0.123 | 1 | | | | | | | | | | | | | | | | |
| Sr | −0.097 | 0.333 | 0.230 | 0.479 | −0.153 | 1 | | | | | | | | | | | | | | | |
| Ba | 0.127 | −0.189 | 0.089 | −0.172 | 0.381 | −0.323 | 1 | | | | | | | | | | | | | | |
| Be | 0.041 | −0.088 | 0.322 | 0.031 | 0.273 | −0.324 | 0.474 | 1 | | | | | | | | | | | | | |
| Ti | −0.060 | 0.383 | 0.779 | 0.680 | 0.100 | 0.421 | 0.090 | 0.302 | 1 | | | | | | | | | | | | |
| Fe | 0.099 | 0.559 | 0.791 | 0.727 | 0.252 | 0.327 | 0.010 | 0.228 | 0.780 | 1 | | | | | | | | | | | |
| Hg | 0.020 | −0.105 | −0.064 | 0.069 | 0.188 | −0.062 | 0.306 | 0.075 | 0.013 | −0.030 | 1 | | | | | | | | | | |
| Ag | 0.109 | −0.376 | −0.237 | −0.339 | 0.238 | −0.181 | 0.302 | 0.101 | −0.265 | −0.253 | 0.445 | 1 | | | | | | | | | |
| As | 0.298 | 0.275 | 0.302 | 0.221 | 0.376 | 0.036 | 0.273 | 0.189 | 0.271 | 0.439 | 0.014 | 0.056 | 1 | | | | | | | | |
| Bi | 0.317 | 0.247 | 0.363 | 0.149 | 0.466 | −0.169 | 0.211 | 0.321 | 0.202 | 0.425 | −0.055 | 0.053 | 0.614 | 1 | | | | | | | |
| Co | 0.005 | 0.554 | 0.648 | 0.697 | 0.179 | 0.356 | 0.020 | 0.128 | 0.675 | 0.775 | −0.058 | −0.298 | 0.480 | 0.435 | 1 | | | | | | |
| Cu | 0.200 | 0.456 | 0.543 | 0.442 | 0.461 | 0.100 | 0.164 | 0.198 | 0.445 | 0.618 | 0.108 | 0.037 | 0.485 | 0.626 | 0.523 | 1 | | | | | |
| Mo | 0.267 | 0.044 | −0.263 | −0.294 | 0.246 | −0.304 | 0.137 | −0.014 | −0.413 | −0.222 | 0.060 | 0.265 | 0.144 | 0.277 | −0.226 | 0.122 | 1 | | | | |
| Sb | 0.282 | 0.403 | 0.555 | 0.401 | 0.483 | 0.093 | 0.269 | 0.279 | 0.503 | 0.631 | −0.028 | −0.090 | 0.671 | 0.605 | 0.560 | 0.606 | 0.023 | 1 | | | |
| Zn | 0.165 | 0.412 | 0.815 | 0.544 | 0.495 | 0.086 | 0.177 | 0.440 | 0.681 | 0.747 | −0.059 | −0.104 | 0.452 | 0.523 | 0.590 | 0.640 | −0.106 | 0.653 | 1 | | |
| Sn | 0.053 | −0.375 | −0.113 | −0.341 | 0.210 | −0.428 | 0.520 | 0.457 | −0.066 | −0.162 | 0.159 | 0.255 | 0.006 | 0.078 | −0.229 | −0.050 | 0.146 | 0.073 | −0.024 | 1 | |
| W | 0.182 | −0.199 | −0.316 | −0.386 | 0.232 | −0.555 | 0.381 | 0.204 | −0.386 | −0.336 | 0.263 | 0.198 | 0.060 | 0.181 | −0.309 | −0.056 | 0.241 | −0.022 | −0.202 | 0.380 | 1 |

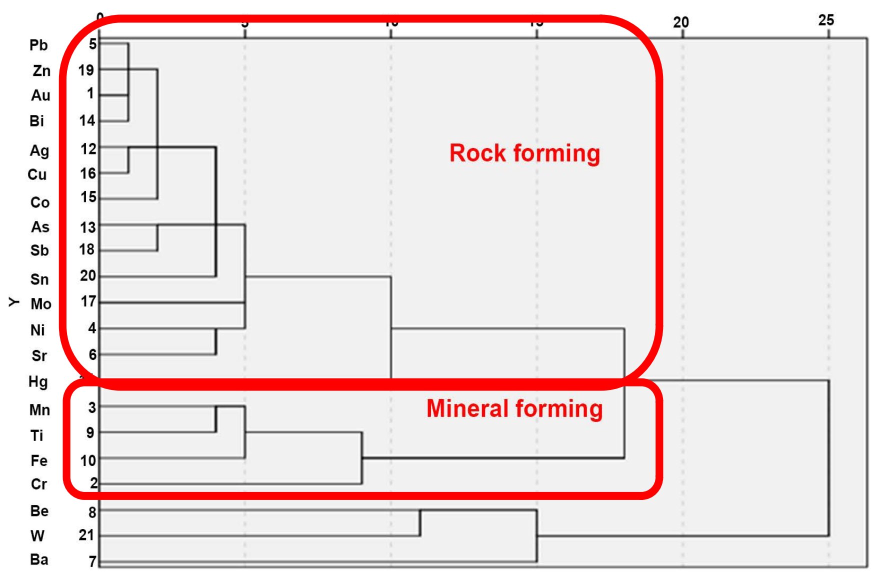


Figure 6. Elements clustering hierarchical chart.

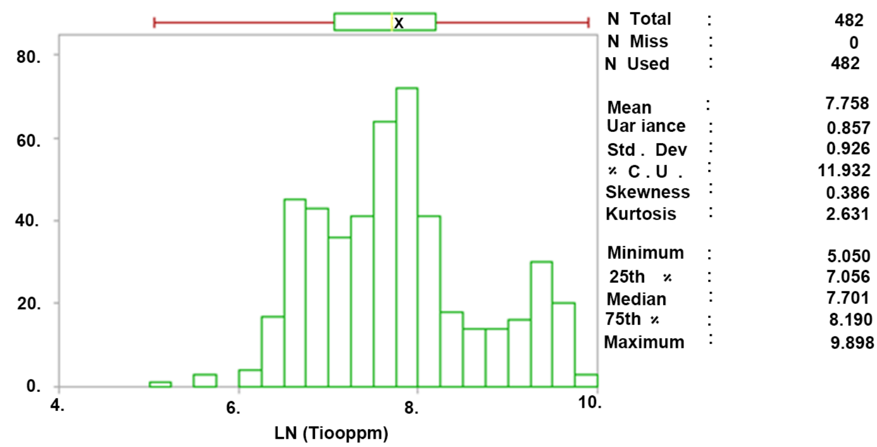


Figure 7. Histogram of titanium element in the Bardaskan region.

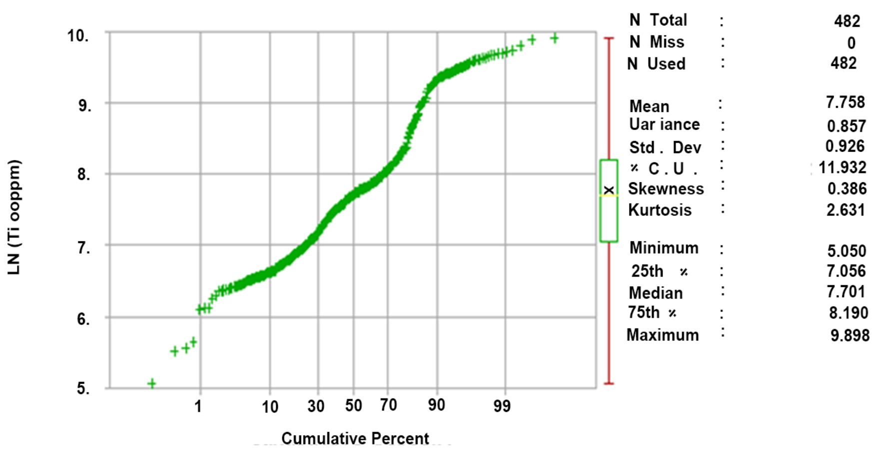


Figure 8. Cumulative probability curve for the titanium element in Bardaskan region.

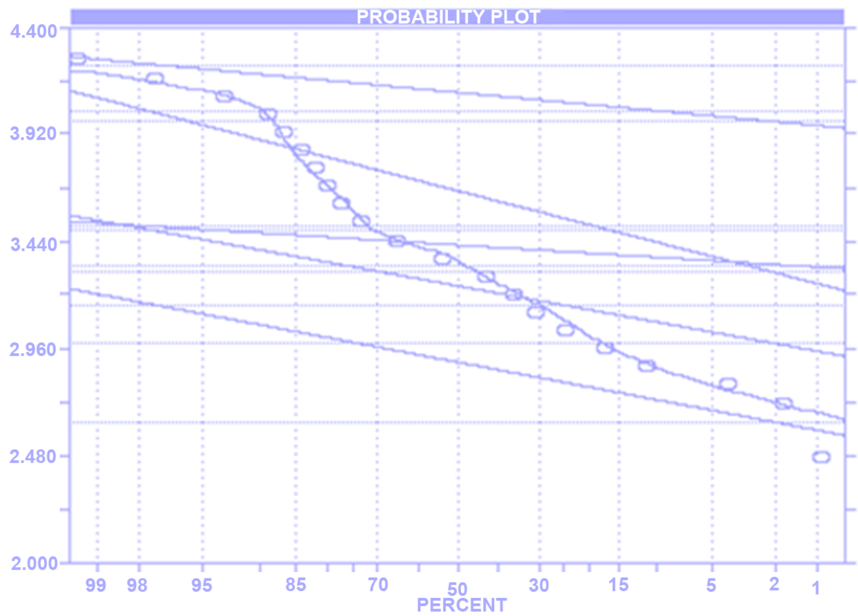


Figure 9. The probability chart along the lines of communities.

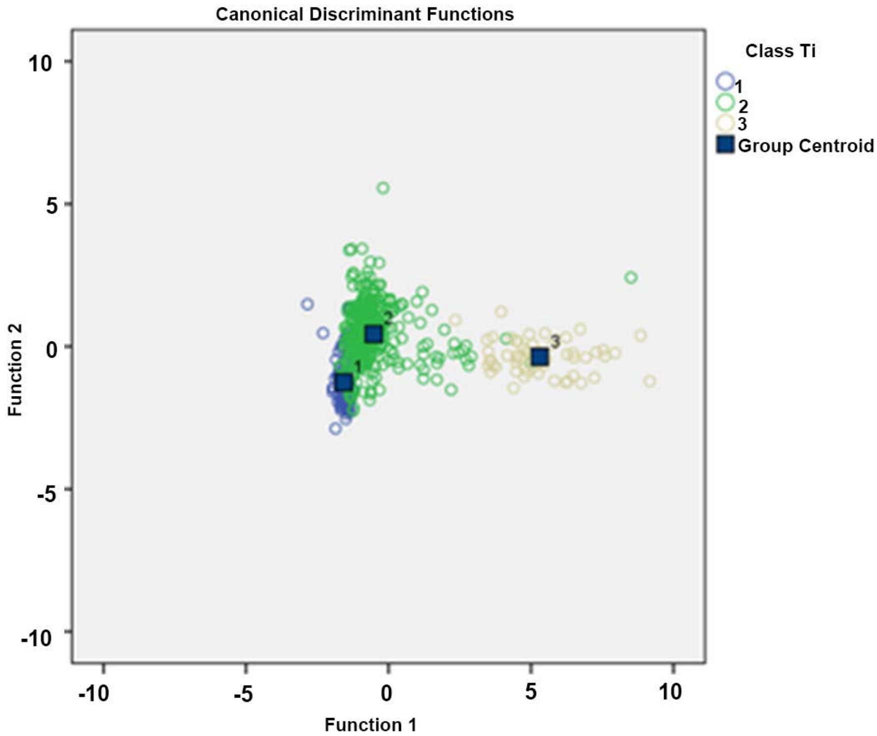


**Figure 10.** Three separated communities in LDA using geochemical limits.

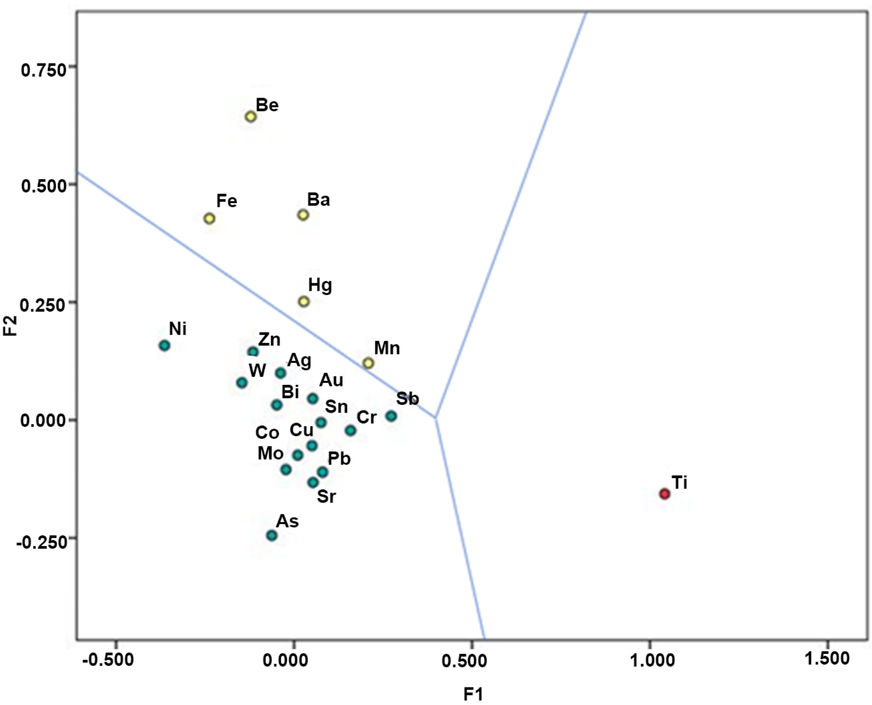


**Figure 11.** Three separated communities, based on elements in Bardaskan region.

communities are considered with consideration of all the elements and finally the accuracy of this separation is given in **Table 3**. In **Figure 10**, by applying the Linear Discriminant Analysis (LDA) method, three general communities are

Table 3. Validation of linear discriminant analysis (LDA).

| **Titanium** | | | **Group members predicted** | | | **Total** |
|---|---|---|---|---|---|---|
| | | | First | Second | Third | |
| **Cross Validation** | Counts | First | 81 | 14 | 0 | 95 |
| | | Second | 56 | 259 | 12 | 327 |
| | | Third | 0 | 1 | 59 | 60 |
| | **%** | First | **85.3** | 14.7 | 0.0 | 100.0 |
| | | Second | 17.1 | **79.2** | 3.7 | 100.0 |
| | | Third | 0.0 | 1.7 | **98.3** | 100.0 |

separated. In Figure 11, these communities are shown with details and members. The elements in these communities are as follows:

- 1st community: Ti.
- 2nd community: Be, Fe, Ba, Hg, Mn.
- 3rd community: Ni, Zn, W, Ag, Bi, Au, Sn, Cr, Pb, Sr, As, Mo, Cu, Co, Sb.

In Table 3, validation of each of the separated communities in the analysis of differentiation is shown in relation to the threshold values of the titanium element. According to this table, it has shown a high degree of accuracy for this grouping.

### 3.7. Anomaly Mapping

After performing various affairs and identifying the relationship between the elements and also recognizing the titanium element as important element in the region. Regarding the behavior of this element, which has been studied in different parts, in the form of anomalies, a map of the highest concentration limits in the region should be prepared. This map represents the best locations for detailed exploration and further exploration. The Kriging Interpolation method (with a variogram that was extracted from a radial survey) was used to prepare this map.

The map is shown in Figure 12. This map, from the blue (the lowest concentration of Ti) to the red (the highest concentration of Ti), is shown in the northern part of an anomaly and in the central part of a small anomaly. It should be noted that this map can be further investigated by changing the interpolation methods and analyzing the locations of the anomalies according to the geological map.

## 4. Conclusions

- The Bardaskan area, located in the Razavi Khorasan province of Iran, is one of the areas with metallic mineralization potential.
- Regarding the importance of geostatistical methods, at first lithogeochemical samples with single-variable methods were investigated. Correlation between elements was calculated. Then hierarchical clustering using squared Euclidean distance method was performed.

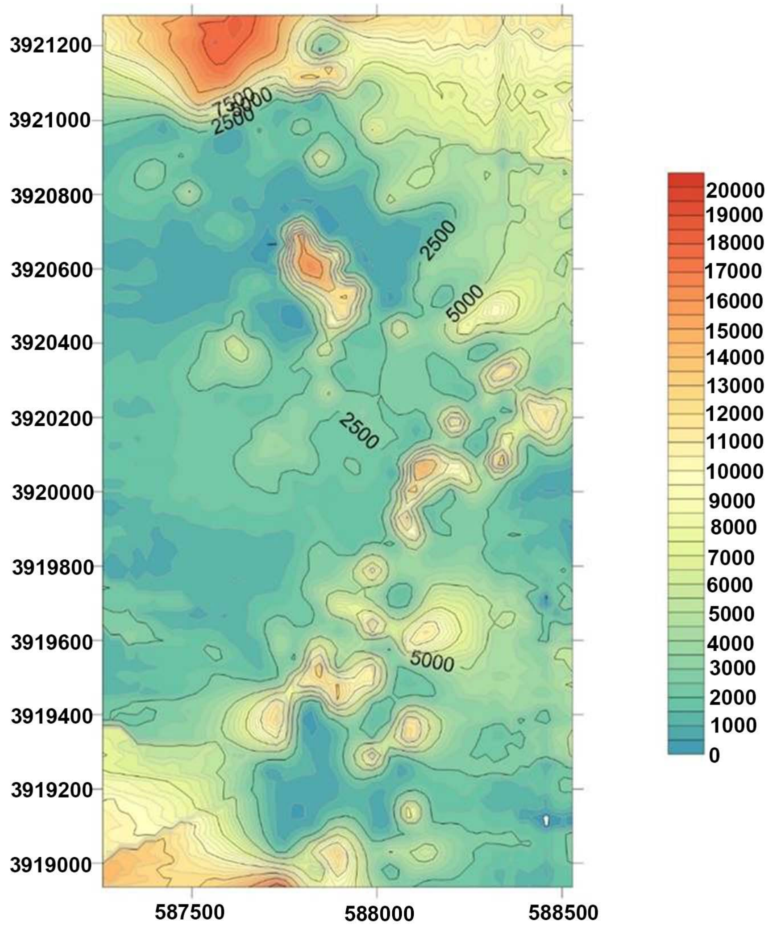


**Figure 12.** Titanium concentration map in the Bardaskan region using Kriging interpolation method.

- Hierarchical clustering, which according to the previous results identified the elements of titanium, iron, and magnesium as the mineralization phase, also showed the rock-forming phase.
- By carefully examining the histogram and cumulative probability diagram of the titanium, the log-normal distribution was determined for this element.
- By separating communities from the logarithmic probability diagram, the geochemical limits were determined 1000, 3000 and 9000 ppm for the titanium element, respectively.
- Due to the specified limits, the decision was made to carry out the Linear Discriminant Analysis (LDA). The results of this analysis were another proof of the phase of mineralization and rock-forming of the area and confirmation of the correct choice of titanium.
- Finally, in order to provide a better visibility of the titanium element distribution in the area, a map was prepared. The Kriging interpolation method was used to prepare this map.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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