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Review Article

Applications of Soil Geochemistry in Mineral Exploration

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ABSTRACT

Soil geochemistry is pivotal in mineral exploration, highlighting its significance and presenting key methods for evaluating data. Reasons for its indispensability include:

1. Identifying Anomalies: Soil, a natural filter, accumulates elements from buried deposits. Analyzing soil composition indirectly reveals hidden mineral deposits, aiding geologists in pinpointing areas for further exploration.
2. Defining Deposit Extent: After identifying anomalies, soil geochemistry helps determine deposit boundaries and size. Geologists map mineralization, assessing economic viability by analyzing spatial element distribution.
3. Understanding Mineralization Type: Analyzing specific element groups provides insights into underlying mineral deposit types. This guides geologists in focusing exploration efforts on valuable minerals, avoiding resource waste.
4. Cost-Effectiveness: Compared to drilling, soil geochemistry is cost-effective and non-invasive, covering large areas comprehensively and producing valuable data swiftly.

In conclusion, soil geochemistry is vital in mineral exploration, offering a cost-effective and informative means of detecting deposits. Accurate evaluation is crucial, and the study includes traditional statistical methods, multivariate statistics, and fractal/multifractal methods for this purpose.

Introduction

The element content and behavior in soils have captivated researchers for diverse purposes, evident in the plethora of studies conducted (e.g., [1]–[7]). Since the rise of environmental consciousness and sustainable development in the 1980s, investigations into soil quality, agricultural soil pollution, and heavy metal contamination have flourished (e.g., [8]–[11].). However, exploration geochemistry stands as the foundational and historically significant branch of soil geochemistry studies (e.g., [12]–[15]). These pivotal explorations resulted in the discovery and subsequent economic integration of numerous mineral deposits (e.g., [16], [17]). Contemporary research in soil geochemistry predominantly focuses on element enrichments in soils with natural or geological origins, such as hydrothermal alteration, weathering, and thermal springs (e.g., [18]–[20]). Additionally, a diverse array of analytical and statistical methods have been developed and implemented in soil geochemistry studies, further demonstrating the dynamic nature of this field (e.g., [7], [21], [30]–[32], [22]–[29]).

This study explains the contrasting behaviors and spatial patterns of elements within the soil. To differentiate and characterize these patterns, we employ a two-pronged approach. Firstly, classical statistical methods are utilized: mean ± 2 standard deviations, histograms, cumulative frequency curves, median ± 2 median absolute deviations, etc. These traditional tools provide a baseline understanding of element distributions. Secondly, we leverage novel concentration-area-numbers fractal/multifractal methods for calculating anomaly thresholds. This advanced approach delves deeper into the spatial complexity of element enrichments, allowing for more nuanced discrimination of anomalous versus background signatures. Finally, both single-element and multi-element halo methods are employed to construct comprehensive iso-concentration maps, visually representing the spatial variability of elements within the soil. This complementary utilization of established and cutting-edge methodologies aims to unveil a comprehensive and robust understanding of elemental behavior and distribution within the studied soil environment.

Material and methods

To conduct a soil geochemistry study for detecting element anomalies in the targeted region, it is first necessary to determine the sample size, sampling interval, and other relevant characteristics. Subsequently, soil samples are collected in the planned framework and appropriate quantities. Samples are collected from the B-horizon of the soil, and in the laboratory environment, natural moisture is removed, typically by drying at 60°C for 24 hours. Various approaches may be employed in sample preparation, but samples passing through a twin 80 mesh sieve are generally suitable for element analyses [14]. In mineral exploration, analyses of elements such as Cu, Pb, Zn, As, Mo, Sb, Ag, and Au are commonly performed. Previously, flame atomic absorption spectrometry was frequently used for the analyses of elements like Ag, As, Mo, Sb, Cu, Pb, and Zn, and graphite-furnace atomic absorption methods were employed for gold analysis. However, with the need for lower detection limits and advancements in technology, inductively coupled plasma atomic emission spectrometry (ICP-AES) and inductively coupled plasma mass spectrometry (ICP-MS), which allow for more sensitive and lower detection limits, are now widely used.

To ensure the accuracy and reliability of the analyses, it is crucial to use appropriate standards during the analysis process and conduct relevant accuracy and precision tests. Routine procedures can be seen on the [17]. Accuracy and sensitivity tests of sample analysis can be performed according to Skoog et al. [33].

Data analysis

In the first step of data, the descriptive statistics, such as mean, geometric mean, median, minimum, maximum, variance, etc., and the correlation coefficient and normality tests (Kolmogorov-Smirnov and Shapiro-Wilk tests) for elements in the soil samples, are also determined (Figure 1). Traditional statistical methods, particularly Exploratory Data Analysis (EDA), still hold significant advantages in mineral geochemistry studies and exploration geochemistry.

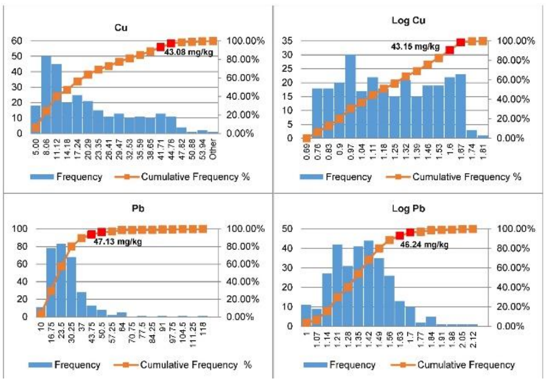

Figure 1. An example of class ranges frequency and cumulative frequency of some elements, as provided by Vural [34]

Factor analysis offers several key advantages in mineral exploration by helping unravel complexities in large geochemical datasets and making it easier to identify areas with potential mineral deposits. Here are some of the main benefits [6], [35], [36]:

1. Data reduction and simplification:

- Factor analysis condenses hundreds of measured element concentrations into a smaller number of "factors" representing underlying geochemical processes. This simplifies complex data, making it easier to visualize and interpret.

2. Identification of geochemical associations:

- Factors group elements with similar geochemical behavior, providing valuable insights into mineralizing processes. This helps identify pathfinder elements indicative of specific mineral deposits, guiding further exploration efforts.

3. Enhanced anomaly detection:

- Factor analysis can sharpen anomaly detection by highlighting areas where factor scores deviate significantly from background values. This helps prioritize areas for targeted exploration, reducing costs and focusing efforts on more promising locations.

4. Understanding geochemical zonation:

- Factor maps can reveal spatial patterns in geochemical associations, providing information about the zoning of mineral deposits. This knowledge can be used to predict the location of high-grade mineralization within a deposit.

5. Integrating geological and geochemical data:

- Factor analysis can be combined with geological information to generate more refined exploration models. This allows for a holistic understanding of the relationships between geology, geochemistry, and mineralization.

Overall, factor analysis provides a powerful tool for mineral exploration by:

- Reducing data complexity
- Identifying potential mineral deposits
- Guiding exploration efforts
- Understanding mineralization processes
- Improving exploration success rates

Examples:

- Identifying gold-bearing areas using factors associated with elements like As, Sb, and Au.
- Delineating copper-porphyry systems based on factors enriched in Cu, Mo, and K.
- Mapping the extent of rare earth element deposits using factors grouping relevant elements.

Factor analysis is not a standalone solution, but a valuable tool within a comprehensive exploration strategy. Its insights can be combined with other methods like geophysics, geological mapping, and remote sensing to refine exploration targets and increase the chances of discovering economic mineral deposits [16], [37]–[39].

The determination of realistic background values for elements is another important step in the evaluation of soil geochemistry data. There are many methods that can be used for this purpose. Some of these methods are quite simple, while others are very complex. The main methods are correlation analysis, factor analysis, cluster analysis, fractal, and multifractal methods. These methods are used directly and/or indirectly in the calculation of background values [27], [29], [47], [31], [40]–[46].

The methods used to determine the background values of elements in soil can be both geochemical and statistical, but statistical methods are more popular than geochemical ones. Because statistical methods reduce laboratory workload and are more economical [8], [35].

The most widely used method for calculating the threshold value is mean ±2standard deviation, and it has been used for almost 60 years. This method is suitable for data with normal distribution. If the data does not show normal distribution, then geometric mean or median±2standard deviation is used [48], [49].

Another method is to use percentiles [50]. In this method, the threshold value (Threshold) =Q3+(Q3-Q1)*1.5 is calculated. Here, Q3 and Q1 correspond to the 75th and 25th percentiles of the sample population, respectively.

Another conventional technique in threshold value calculation is the median ±2*Median Absolute Deviation (MAD). This method is used more often in right-skewed datasets. One of the most important advantages of the method is that it is minimally affected by outliers [51]–[53]. The MAD value is calculated using the following formula [36], [53], [54].

$$MAD = M_i\left(\left|X_i - M_j(X_j)\right|\right) \quad (1)$$

where M_i and M_j represent the medians of series i and j, respectively, X_i represents each observation in the population, and X_j represents the original population.

Physical and geological processes often behave in a fractal manner, rather than Euclidean geometry [55]. In the 1980s, researchers began to propose different fractal approaches to threshold value calculation, taking into account the fractal nature of physical and geological processes. The most common fractal approaches to threshold value calculation are Number-Size (N-S: [55]), Concentration-Number (C-N: [56]), Concentration-Area (C-A: [57]), Concentration-Distance (C-D: [58]), Power Spectrum-Volume (S-V: [59]) etc.

Each of these methods has its own advantages and disadvantages compared to the others [7], [16], [62], [63], [18], [23]–[25], [36], [46], [60], [61].

The most widely used fractal approach to threshold value calculation is the concentration-number (C-N) approach, which was proposed by Mandelbrot [55]. The C-N approach is also the simplest to implement, and it can be applied directly to raw data (Figure 2). The approach is modeled by the following formula:

$$N(\geq \rho) \propto \rho^{-\beta} \quad (2)$$

where $N(\geq \rho)$ represents the number of cumulative samples with element concentrations greater than or equal to ρ, the element concentration itself, and β denotes the fractal dimension. This model can also be rewritten as:

$$Log\ [N(\geq \rho)] = -\beta\, log\ (\rho) \quad (3)$$

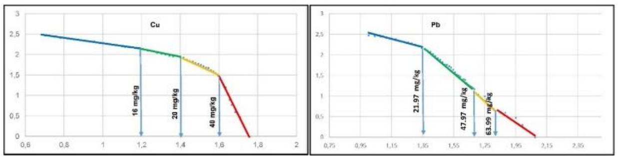

Figure 2. An example of C-N Log-log plots for elements Cu, Pb as provided by Vural [38]

The log-log plot of $N(\geq\rho)$ versus ρ reveals linear segments characterized by distinct slopes, denoted by $-\beta$ values, indicating various concentration ranges [56], [64].

In the evaluation of soil geochemistry data, it is as important to present the spatial distributions of the data with appropriate approaches as it is to find a realistic threshold value [65], [66]. The most common of these approaches are iso-concentration single-element mapping and multi-element halo mapping [60]. These techniques also have sub-techniques used according to the characteristics of the data. The most common of these techniques are kriging and inverse distance weighting [4]. In statistical studies, IBM SPSS software and/or Microsoft Excel modules may be employed, while for spatial statistical computations, software applications such as ArcGIS and QGIS can be utilized.

Discussion

Soil geochemistry studies are an important integral part of the exploration for natural resources, although they are not the whole process. In the exploration process, many studies such as general geology, structural geology, mineralogy, alteration geochemistry, geophysics and drilling are carried out in coordination with each other [67]. In the soil geochemistry study, which has an important place among these methods, it is especially important to evaluate the data in the most appropriate/correct way [43], [64]. Determining the threshold values of the elements in the soil and determining the element mobility characters and distribution patterns and plotting element distribution maps is an important step in the evaluation of soil geochemistry data [5], [10], [67]–[72]. New methods are always suggested, especially in estimating the threshold values of the elements in the soil [23], [28], [40], [41], [67], [73]–

[75]. Although very sophisticated statistical methods are used in soil geochemistry studies/exploration geochemistry, what is important is that the method works well. Therefore, it is the final result that the methods used are expected to be verifiable.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

Authors' Contributions

-Study conception and design: Dönmez

-Acquisition of data: Dönmez

-Analysis and interpretation of data: Dönmez

-Drafting of manuscript: Dönmez

-Critical revision: Dönmez

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