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# Should Geochemical Indicators Be Integrated to Produce Enhanced Signatures of Mineral Deposits? A Discussion with Regard to Exploration Scale

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***Abstract***

In this paper, we discuss the concepts behind dispersion patterns of geochemical anomalies when applied for prospecting mineral deposits in different exploration scales. The patterns vary from regional to local scale geochemical surveys, which is due to the differences in the corresponding underlying processes. Thus the ways for modelling the dispersion patterns and driving significant geochemical signatures should consider the variety when the area under study are delimited from regional to deposit scales exploration. Subsequently, this paper faces with two questions, namely (1) should various geochemical indicators be integrated in different exploration scales aiming at introducing stronger signatures of mineral deposits? and (2) how does the exploration scale affect dispersion patterns of geochemical indicator elements? We demonstrate that the exploration scale plays an important role on the reliability and usefulness of geochemical anomaly models. In this regard, although fusion may achieve reputable outcomes at regional scale exploration, we demonstrate that integration doesn't gain accurate results for exploration at local scale, which is due to the diversities of the elemental distributions in the two different scales. This achievement is approved by comparing two geochemical signatures, one obtained by integration of two different indicator factors and the other one that used a single factor. The former produces almost the whole studied area as prospective, while the later recognizes ~10% of the area for further exploration, which is closely related to the porphyry Cu mineralization and is verified by drilling results.

## 1. Introduction

Geochemical anomaly detection and mapping techniques are traditional and modern approaches aiding exploration geologists to prospect potentially economic mineral deposits [1-13]. The outcome of geochemical data analysis are commonly models of uni- and multi-variate dispersion patterns of indicator elements [14-22] representing the operation of syn-mineralization sub-systems of ore-forming processes [9, 23, 24] or exhumation post-mineralization sub-systems that distribute mineralized materials in the environments, various media [23, 24]. The two aforementioned geochemical processes, syn- and post-mineralization subsystems, differ in terms of the diversity of the processes operating during and after mineralization. The pre- and syn-mineralization processes operate as how as to make elemental enrichments in the trap sites, whilst post-mineralization exhuming processes, mainly weathering and erosion factors, act to distribute diluted amounts of the elements in the environments around mineral deposit sites. This means that the concepts behind dispersion patterns in regional/district scale and local/deposit scale are different due to the differences in the corresponding underlying processes. Thus, the ways for modelling the ensuing dispersion patterns and driving significant geochemical signatures

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should consider the variety when the area under study are delimited from regional to deposit scales exploration. Subsequently, two questions are flagged, that are (1) should various geochemical indicators be integrated in different exploration scales aiming at introducing stronger signatures of mineral deposits? and (2) how does the exploration scale affect dispersion patterns of geochemical indicator elements?

Intergradation of different geochemical indicators of a targeted mineral deposit is a common practice in geochemical anomaly modeling to produce stronger geochemical signatures, which reported mainly in regional scale geochemical surveys. This paper aims to face with the questions above through analysis of a deposit scale dataset of porphyry-cu mineralization in Isfahan province, Iran.

## 2. Studied Area and Dataset

The studied area is a small part of the Urumieh–Dokhtar magmatic arc (UDMA) of Iran. Geological setting of the area is investigated by the 1:1000 scale geological map prepared by the National Iranian Copper Industries Company (NICICO). Rock units in the area consist of sediment, intrusive and sub-volcanic units and dikes (Figure 1). Further information about the studied area could be found in [7, 8, 21, 25, 26].

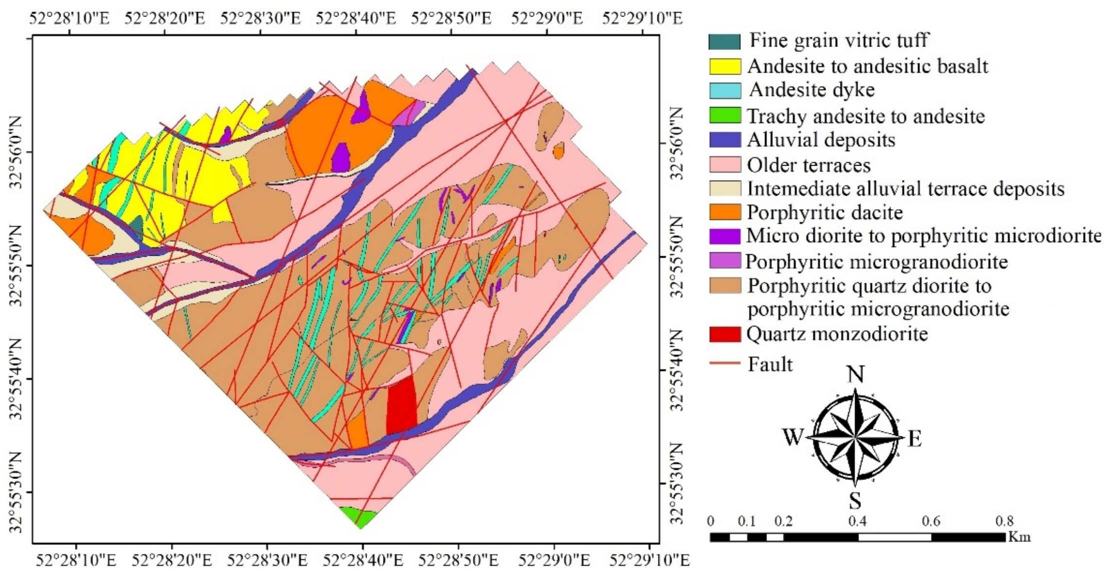


**Figure 1. Geological map of the studied area [26].**

Through an exploration program of Cu-Mo porphyry deposit, 945 residual soil samples were taken from the studied area by stratified randomized sampling method. Each of the samples involves 300 g of soil material taken form sampling cell with a 40 to 60 dimensions, which were analyzed for 43 elements including Ag, Al, As, Au, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, S, Sb, Sc, Sn, Sr, Te, Th, Ti, Tl, U, V, W, Y, Yb, Zn, and Zr. The employed analyzing technique for Au elements was flame atomic absorption, and for the rest of the elements was inductively coupled plasma. The detection limits for the elements were measured below the background value.

## 3. Methods and Results

### 3.1. Staged factor analysis

Recognizing significant multi-element geochemical signatures is an efficient practice one step forward undiscovered ore deposits [27, 28, 29, 30]. In this study, a staged factor analysis was performed for the enhanced recognition of multi-element anomalous signatures of the porphyry-Cu deposit. For this purpose, a fourth-stage factor analysis was used (Table 1). The general procedure of staged factor analysis includes two main phases, and both phases may consist of some sub-phases (hereafter referred to as stage), depending on the geochemical data and mineral deposit-type sought. The details of staged factor analysis are found in [15, 17].

**Table 1. Rotated factor matrix for a fourth-stage of staged factor analysis. Loadings in bold represent the selected elements based on threshold of 0.4 (the absolute threshold value) for each stage.**

| First main phase | | | | | | Second main phase | | | |
|---|---|---|---|---|---|---|---|---|---|
| First stage | | | Second stage | | | Third stage | | Fourth stage | |
| Element | F1 | F2 | Element | F1 | F2 | Element | F | Element | F |
| Zn | **0.875** | 0.028 | Zn | **0.879** | 0.063 | Zn | **0.872** | Cu | **0.901** |
| As | **0.815** | -0.276 | As | **0.827** | -0.242 | Pb | **0.814** | Mo | **0.743** |
| Pb | **0.811** | 0.127 | Pb | **0.810** | 0.150 | As | **0.811** | Au | **0.593** |
| Sb | **0.500** | 0.021 | Sb | **0.499** | 0.037 | Sb | **0.495** | Eigenvalue | 1.716 |
| Ag | 0.202 | 0.052 | Cu | 0.122 | **0.8657** | Eigenvalue | 2.326 | Var. | 57.198 |
| Cu | 0.150 | **0.856** | Mo | -0.263 | **0.772** | Var. | 58.155 | Cum. var. | 57.198 |
| Mo | -0.226 | **0.783** | Au | 0.415 | **0.504** | Cum. var. | 58.155 | | |
| Au | 0.425 | **0.485** | Eigenvalue | 2.619 | 1.685 | | | | |
| Eigenvalue | 2.634 | 1.677 | Var. | 37.410 | 24.074 | | | | |
| Var. | 32.925 | 20.965 | Cum. var. | 37.410 | 61.484 | | | | |
| Cum. var. | 32.925 | 53.890 | | | | | | | |

Regarding Table 1, the results of staged factor analysis disclose that there are two indicator factors reflecting the existence of a porphyry-cu deposit. These factors are Zn-As-Pb-Sb and Cu-Mo-Au associations in the third- and forth-stage factor analysis, respectively. Accordingly, the samples with high factor scores (FSs) values of these two factors could be utilized as indicator factors with affiliation to geochemical criteria to recognize interested area in the studied region.

Nevertheless, as depicted in Table 1, the factors in the third stage can be used as indicator factors [17] who demonstrated due to the mathematical basis of factor analysis, elements on a factor could have a negative influence on calculating FSs of other factors. Hence, to compute the reliable FSs for an optimal definition of exploration targets, the FSs should be computed for each factor individually [17, 28]. Figure 2 shows the spatial distributions of FSs (Zn-As-Pb-Sb association) and FSs (Cu-Mo-Au association), derived from the staged factor analysis.

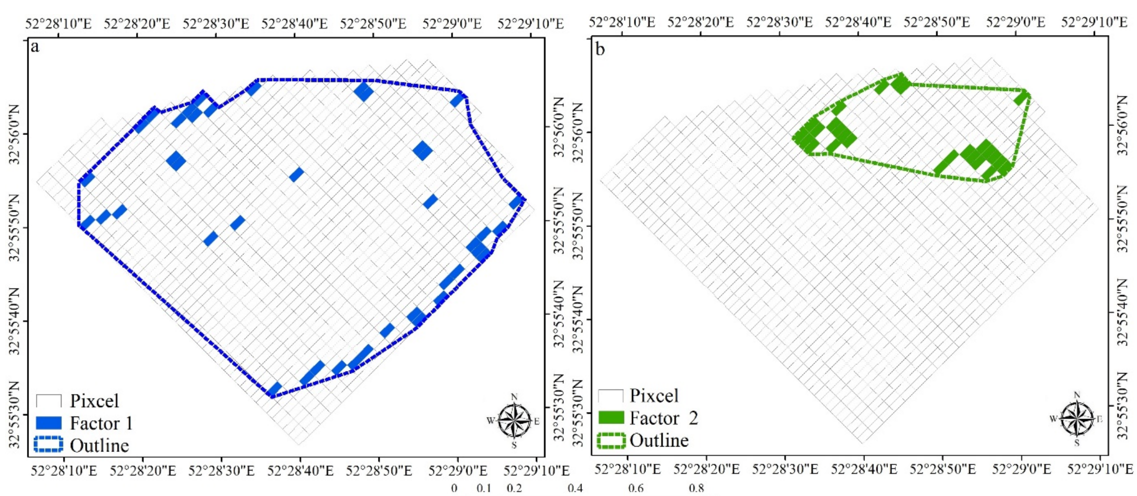


**Figure 2. Spatial distributions of two main factors derived from the staged factor analysis: Factor 1 (Zn-As-Pb-Sb association) (left) and Factor 2 (Cu-Mo-Au association) (right).**

## 3.2. Integration of multi-element geochemical signatures

The existence of different evidential data types would be more indicative for occurring of a mineral deposit in the vicinity [14]. As a result, when several different spatial evidence values are combined, a stronger multi-element signature is generated to prospect the deposit-type sought [14, 15, 16, 31, 32, 33, 34]. Thus, although each of the derived FSs, $FS_{Zn\text{-}As\text{-}Pb\text{-}Sb}$ and $FS_{Cu\text{-}Mo\text{-}Au}$ in Figure 3 could be an effective multi-element signature for porphyry-Cu mineralization, a stronger multi-element signature can be generated to prospect this type of mineralization via combination of values of the two indicator factors.

For this purpose, a logistic function [15, 17] was used to transform the unbounded FS values (resulted from staged factor analysis) into the 0-1 range. As a result, a weighted geochemical evidence layer known as the geochemical mineralization prospectivity index (GMPI) [15, 17] was generated for each of the two factors. Then, a fuzzy OR operator [14, 31] were used (Figure 4).

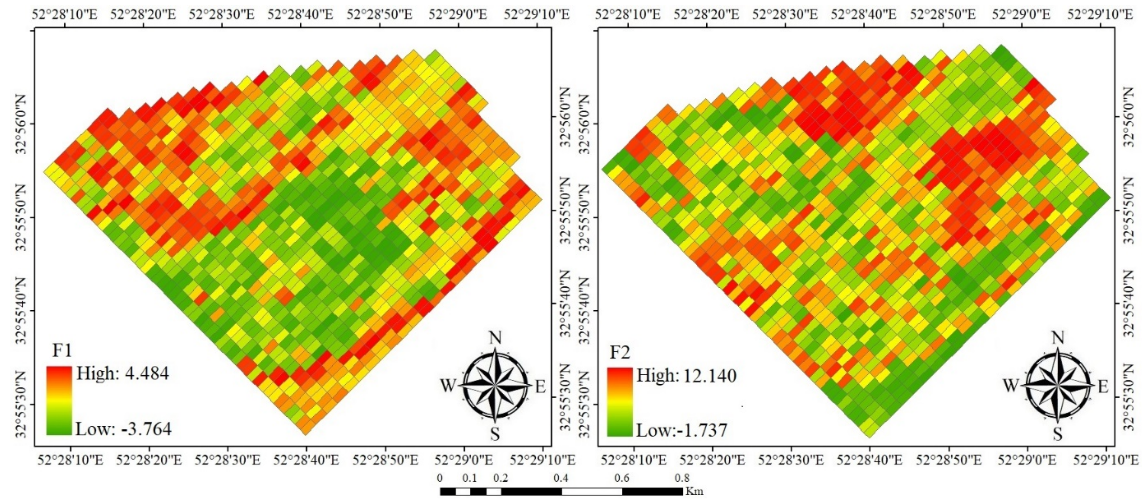


**Figure 3. Geochemical mineralization prospectivity index (GMPI) map of the factor $F_{1(Zn\text{-}As\text{-}Pb\text{-}Sb)}$ (left) and factor $F_{2\ (Cu\text{-}Mo\text{-}Au)}$ (right).**

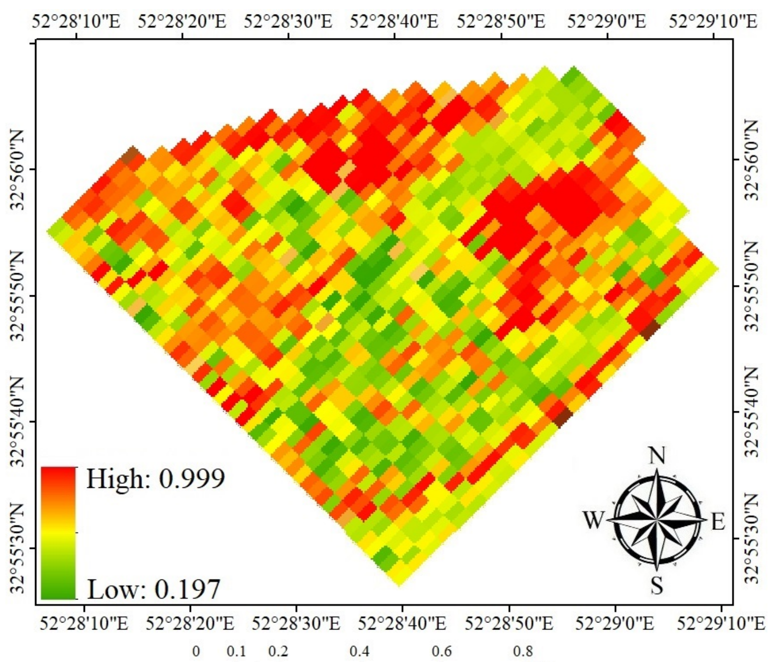


**Figure 4. Integrated map of $GMPI_{Zn\text{-}As\text{-}Pb\text{-}Sb}$ and $GMPI_{Cu\text{-}Mo\text{-}Au}$, using fuzzy OR operator.**

As it can be seen in the Figure 4, the whole studied area shows anomalous content of the derived signature that is correct and reasonable because the study is carried out on a deposit scale in an area that shows abnormal element concentrations. However, the main issue here is the delimitation of the anomalies to define first-round drilling sites. Thus at this local scale exploration, the integration does not gain the purpose of delimitation because the whole studied area is anomaly. In contrast, a model of zoning patterns of geochemical anomalies here outlines of F1 and F2 anomalies demonstrates zones where show higher potential of mineralization (Figure 5). According to Figure 5, anomaly areas of F2 show a high conformity with promising drilled boreholes. Comparison of the two geochemical signatures, one obtained by integration of two different indicator factors and the other one that used a single factor, demonstrated that the former produces almost the whole study area as prospective, while the later recognises only 10% of the area for further exploration, which is closely related to the porphyry Cu mineralization and is verified by drilling results.

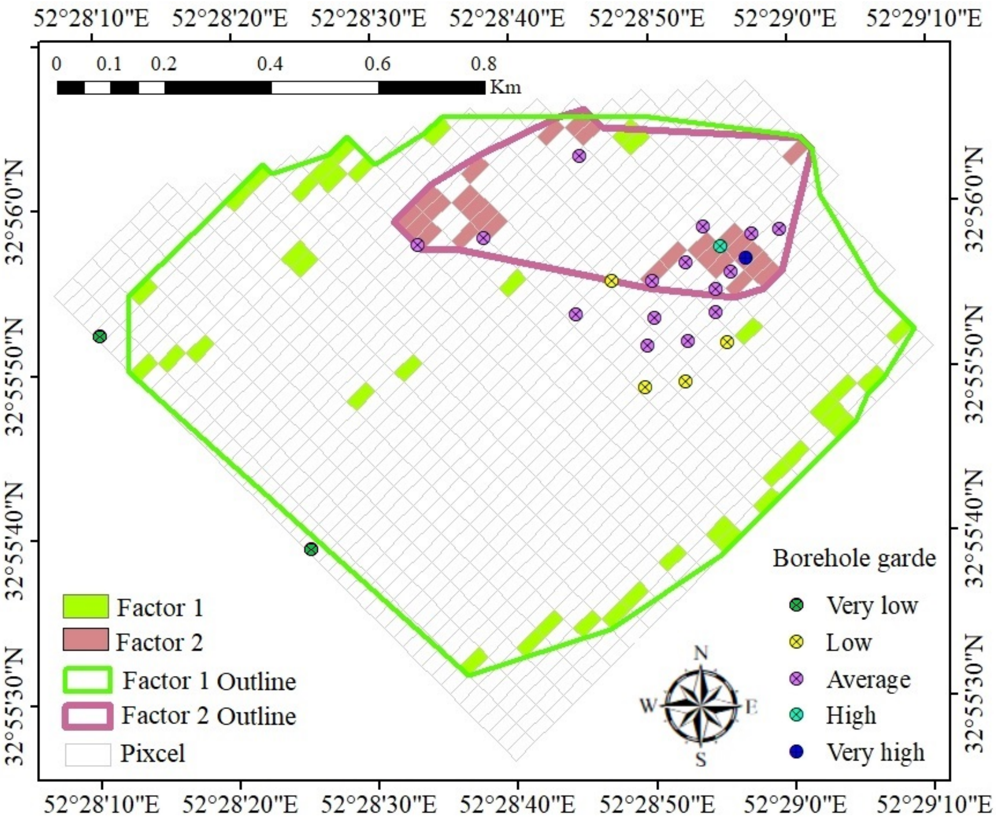


**Figure 5. Spatial distributions of two main factors derived from the staged factor analysis with drilled boreholes of the studied area (the average is defined for the cut-off grade of 0.2% copper).**

## 4. Discussion

The presence of different types of evidence would be more indicative for of the presence of a mineral deposit [35]. Thus, dispersion patterns of different indicator elements could be analysed for vectoring into mineralized zones [9]. Due to the scale dependency of geochemical patterns, it seems that the effects of this dependency should be considered and translated into mappable criteria at all scales of the targeting process.

This is because signatures of syn-mineralization processes are within and close to trap sites, i.e., in rock and in situ soils, but evidence relevant to post-mineralization processes appear in transported materials like stream sediments. That means anomalous contents of different indicator elements of a certain mineral deposit are simply mixed at regional to district scale exploration where the mineralized materials are released from the sources and move to downstream of the deposit sites. However, at deposit scale exploration program, the elemental dispersion patterns in rocks and in situ soils are the same as that they formed. Thus, it is better that different signatures, which show different dispersion patterns around trap sites, are not combined at local scale exploration.

## 5. Conclusions

In any attempt at geochemistry for mineral exploration, the exploration scale and the corresponding sub-systems of ore-forming processes must be contributed. For this, the categorisation of ore-forming processes into pre-, syn-, and post-mineralisation sub-systems facilitates a better understanding of how they operate in different scales. This study demonstrated that the exploration scale plays an important role on the reliability and usefulness of geochemical anomaly models. The results revealed that because the geochemical dispersion patterns of indicator elements in pre-, and post-mineralisation sub-systems is not the same; therefore, more accurate and reliable results will be obtained if we choose appropriate data processing procedure and approaches with regard to the exploration scale. Therefore, although integration may gain reliable results at the regional scale, due to the differences in the distribution of elements, there is no guarantee at the local.

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# آیا لزوما باید معرف‌های ژئوشیمیایی تلفیق شوند تا اثر قوی‌تری از ذخایر معدنی تولید گردد؟ ارائه بحث از منظر مقیاس مطالعات اکتشافی

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**چکیده:**

بررسی تاثیر گذاری مقیاس عملیات اکتشاف در اعتبار و صحت آنومالی های ژئوشیمیایی بدست آمده، موضوع اصلی مطالعه حاضر است. الگوهای پراکندگی ژئوشیمیایی عناصر متناسب با مقیاس مطالعات و نوع نمونه های برداشت شده، از مرحله اکتشافات ناحیه‌ای تا محلی متفاوت است. از این رو انتخاب روش‌های مدل‌سازی و مطالعه الگوهای توزیع و پراکنش عناصر با هدف شناسایی ناهنجاری‌های ژئوشیمیایی، بایستی با در نظر گرفتن مقیاس عملیات اکتشافی صورت پذیرد. در جهت نیل به این هدف در این تحقیق به دو سوال مهم پاسخ داده می‌شود: (1) آیا تلفیق شاخص‌های ژئوشیمیایی مختلف معرف کانی‌سازی در مقیاس‌های مطالعاتی و اکتشافی مختلف حتماً ضروری بوده و با نتایج مطلوب همراه خواهد بود؟ (2) مقیاس مطالعات اکتشافی چگونه می‌تواند بر روی الگوهای توزیع عناصر ژئوشیمیایی شاخص تاثیر گذار باشد؟ نتایج به دست آمده در این تحقیق نشان می دهد که مقیاس عملیات اکتشافی نقش بسیار مهمی در اعتبار و صحت آنومالی‌های شناسایی شده دارد، بدین صورت که اگر چه استفاده از شاخص‌های تلفیقی در مطالعات ناحیه‌ای با نتایج دقیق همراه است اما به دلیل ماهیت متفاوت توزیع عناصر در این مقیاس نسبت به توزیع محلی، ترکیب شاخص‌ها مختلف ژئوشیمیایی در مقیاس محلی منجر به شناسایی آنومالی‌های ژئوشیمیایی ناصحیح و کم اعتبار (به خصوص در مورد ذخایری که منطقه بندی عناصر در آنها وجود دارد) می‌گردد. درستی این نتیجه‌گیری با مقایسه نتایج به دست آمده از به کارگیری یک شاخص ژئوشیمیایی مرکب با یک شاخص ساده اثبات شد. در استفاده از شاخص ژئوشیمیایی تلفیقی، تقریباً کل محدوده مطالعاتی به عنوان آنومالی ژئوشیمیایی و امیدبخش شناسایی گردید در حالی که شاخص ساده تنها 10 درصد از وسعت محدوده را به عنوان منطقه ناهنجار معرفی نمود که با مقایسه با اطلاعات بدست آمده از حفاری‌های انجام شده در منطقه، انطباق بالایی نیز با مناطق کانی‌زایی مس دارد.

**کلمات کلیدی:** مقیاس عملیات اکتشاف، ناهنجاری ژئوشیمیایی، الگوی منطقه‌بندی، تلفیق، معرف قوی‌تر ژئوشیمیایی.

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