JME

Journal of Mining & Environment,
Vol.9, No.1, 2018, 277-292.
DOI: 10.22044/jme.2017.919

Application of concentration gradient coefficients in mining geochemistry: A comparison of copper mineralization in Iran and Canada

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Received 12 February 2017; received in revised form 11 May 2017; accepted 11 May 2017
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Abstract

In this work, the concentration gradient (CG) analysis of local-scale exploration for Porphyry-Cu deposits is applied in two zones using the G(*Vz)* index (CG(Zn*Pb)/CG(Cu*Mo)). The first zone is covered by a 1:2000 map of the Sungun and Astamal areas in NW Iran and the second one in the Inza area in British Columbia, Canada. The rock samples are taken from Sungun and Astamal and the soil samples are taken from Inza. The Inza samples are analyzed for Cu, Pb, Zn, and Mo elements by the atomic absorption method, while the rock samples of Astamal and Sungun are analyzed for Cu, Pb, Zn, Mo, Ag, As, and Sb elements. The indices of gradient geochemical zonality (G(*Vz)*) of multi-elements around the mineral deposits and their spatial associations with particular geological, geochemical, and structural factors are the critical aspects that must be considered in mineral exploration. The values for the G(*Vz)* indices allow a distinction between the sub-ore and supra-ore anomalies, which are associated with Zone Dispersed Mineralization (ZDM) and Blind Mineralization (BM), respectively. For a comparative identification of BM and ZDM, a supra-ore (Pb*Zn) anomaly, a sub-ore (Cu*Mo) anomaly, and Vz maps are used in place of the mining geochemistry representing the supra-ore gradient anomaly, sub-ore gradient anomaly and G(*Vz)* map. The G(Vz) model outperforms the Vz model. The introduced technique allows for a computational distinction between the BM and ZDM ore mineralizations without exploration drilling. Prior to writing this paper, the blind porphyry-Cu mineralization was intersected at depth through borehole exploration in a highly prospective zone delineated by the G(Vz) model. The results obtained confirm the usefulness of the G(Vz) modeling for local-scale targeting of blind mineral deposits.

Keywords: *Sub-Ore Gradient Anomaly, Supra-Ore Gradient Anomaly, Sungun and Astamal (Iran), Inza (Canada).*

1. Introduction

In the former Soviet Union (FSU), the concentration gradient (CG) methods were recommended for identification of the geochemical anomalies associated with mineral deposits [1]. Many of those methods led to successful exploration results in the FSU, China, and other countries. Geochemical gradient refers to the rate of element content change in unit distance. This value is equal to the difference of content between each two adjacent samples [2-6].

In particular, the mining geochemistry method efficiently differentiates between the mineralized and non-mineralized zones [7-10]. This method, although widely used in the FSU, China, and Iran, has not been utilized in other countries. Most mining geochemistry models apply remotely-sensed data, and have been developed for litho-geochemical surveys. These are generally useful for the identification of geochemical anomalies, and can be relevant factors for establishing (1) geochemical landscape; (2)

geochemical zonality; and (3) the type of mineralogical and geochemical anomalies (MGT) [9].

The mathematical methods for recognizing significant geochemical anomalies can be used as a key tool to develop an optimized area by reducing uncertainty in the numbers and locations of exploration boreholes. Several mathematical methods currently exist for mining geochemistry. The most widely used methods are the statistics and neuro-fuzzy methods [7]. Ziaii et al. (2009, 2012) have shown that the neuro-fuzzy and conventional zonality modeling provides the necessary information to separate BM (Blind Mineralization) from ZDM (Zone Dispersed Mineralization) [7, 9]. Although the alteration is useful for understanding the geology and mineralogy of the studied areas, the hydrothermal alteration model does not play a significant role in separating BM from ZDM at a local scale [7, 9]. There are several previous case studies for separation of geochemical anomalies from threshold and background levels using classic spatial statistic methods and geo-statistical methods or a combination of both including probability graphs, assessing uncertainty, and uni-variate and multi-variate analyses [11-13], the fractal concentration–area method [14-16], the multi-fractal inverse distance weighted method [16-19], the elemental concentration–distance method [20], the spectrum–area fractal model [15, 21], and finally, the spatial statistical methods such as kriging, moving average procedures, and spatial factor and multi-variate analyses [22, 23].

In this paper, detection of BM from ZDM has been discussed by CG of zonality index G(Vz) without the need to separate the threshold and background levels. CG is a significant geological characteristic parameter. Where there is a big change in the curves or surfaces, the gradient is greatest [4, 6]. Previous research works have used CG to determine the geochemistry of anomaly concentration zonation. Ke et al. (2007) have used the fractal content gradient for geochemical exploration in Hengxingcuo Yulong porphyry Cu-Mo deposits in Tibet. Their results show that the content-grad method is feasible and effective for enclosing the geochemical concentration focus [2]. Zhou et al. (2012) have used the fractal gradient method to delineate the geochemistry anomaly concentration zoning in the mine at Tibet Shigats. They provided the concentration zoning map of Au by the fractal gradient results [3]. Bin et al. (2013) have applied the fractal content-grad method to geochemistry anomaly delineation in the southern slope Caidamu in the dacaidan town area of Qinghai province. According to their results, the geochemical concentration focus enclosed using the fractal content-grads method shows a better coincidence with the delineation of ore body. Their results have shown that the content-grads method is feasible and effective for enclosing the geochemical concentration focus [4]. Chen et al. (2016) have applied the fractal gradient method for delineating the geochemical anomalies associated with copper occurrences in the Yangla ore field, China. Their study demonstrates that the fractal content-gradient method is convenient, simple, rapid, and direct for delineating geochemical anomalies and for outlining potential exploration targets [6].

Previous research works have applied the gradient method for delineation of surface anomalies. In this paper, we applied this method for detecting blind anomalies. The main objective of this paper is to demonstrate the advantages of the G(Vz) modeling over its conventional geochemical counterparts. Here, by applying a CG, we aim to demonstrate an improved method for the separation of BM from ZDM. Applications of the G(Vz) modeling are presented for three case studies using the data from NW Iran and the Inza area of British Colombia, Canada.

2. Materials and method

2.1. Concept of CG method

Sochevanov (1961) has proposed a multi-dimensional geochemical field analysis based on the notion that the geological space is composed of geochemical fields representing CGs of associations of chemical elements [1]. This analysis takes into account the dispersion of chemical elements to separate multi-element anomalies according to values of CG. It is useful to indicate that this method is for primary geochemical haloes and environments based on rock samples.

Recognition of CG for geochemical halos associated with blind mineralization can be achieved via four cases of complementary analyses [7, 8, 24, 25]: (1) analysis of element associations representing the supra-ore gradient and sub-ore gradient halos of mineral deposits; (2) analysis of a single component gradient, implying false anomaly; (3) analysis of mean values of indicator elements gradient outside significant geochemical anomalies to eliminate background noise in data analysis; and (4) mapping multiplicative geochemical gradient anomalies (i.e. CG indices).

Sochevanov (1961) has suggested the use of uneven distribution of the element content in the gradient as a criterion; this is determined by the difference in element content between each two adjacent samples (Equation 1) [1].

$$Gr = \frac{\Delta c}{\Delta x} \tag{1}$$

In this equation, Δc is the difference between element concentrations in two adjacent samples (ppm), Δx is the distance (in m) in a given direction (x) between two adjacent samples, and Gr is CG (in ppm/m).
In two dimensions, the gradient is given by the following formula [26]:

$$\nabla f = grad(f) = \begin{bmatrix} g_x \\ g_y \end{bmatrix} = \begin{bmatrix} \frac{g_f}{g_x} \\ \frac{g_f}{g_y} \end{bmatrix} \tag{2}$$

This vector has the important geometrical property that it points in the direction of the greatest rate of change at location (x, y). In this formula, $\partial f / \partial x$ is the gradient in the x direction and $\partial f / \partial y$ is the gradient in the y direction.
The magnitude of vector ∇f is denoted by M(x, y), where:

$$M(x, y) = mag(\nabla f) = \sqrt{g_x^2 + g_y^2} \tag{3}$$

The concentration gradient method can distinguish the sub-ore elements from the supra-ore ones in geochemical haloes. It decreases the effect of the background content when calculating the geochemical anomalies. A special approach is introduced to enhance the weak geochemical halos and to extend their size [27, 28].

2.2. Test area

Three case studies were investigated including mineralizations of the Sungun and Astamal areas in Iran and the Inza area in British Colombia. This study aimed to present a new method for the differentiation of porphyry blind mineralization from the dispersed zone of mineralization. Each case study represented different BM/ZDM situations in dissimilar landscapes under different geological conditions.

2.2.1. Geological and metallogenic settings of Sungun and Astamal (NW Iran)

The Sungun and Astamal areas are situated 75 km NW of Ahar in the NW of Iran (Sungun and Astamal village). The Sungun deposit is an important mine associated with calc-alkaline intrusive rocks within the Caenozoic Sahand-Bazman volcanic belt. The Sungun porphyry copper deposit is hosted by a composite intrusive comprised of early diorite/granodiorite and later monzonite/quartz– monzonite that was emplaced at a paleo depth of 2000 m and the temperature range of 670–780 ˚C (Figure 1a) [7]. Formation of the Astamal porphyry is due to the intrusion of the Astamal pluton of Oligocene age into Cretaceous limestone. The average composition of this pluton is granodiorite (Figure 1b, Table 1). Field investigation indicates that wide various porphyry alteration types including potassic, propylitic, argillic, and sericitic can be recognized in the wider area of Astamal [7, 29]. Although a wide alteration exists in Astamal, no significant economic mineralization has been found in this area. However, out of the alteration site at Sungun2, holds an economic porphyry copper deposit [7].

2.2.2. Geological and metallogenic settings of Inza (central British Columbia)

The Inza property is a copper-gold porphyry prospect located within the prolific Quesnel Trough. It is situated approximately 54 km NW of Fort St. James, located at 54° 52' 0" north latitude and 124° 36' 41" west longitude (Figure 2).
The Inza mining area lies within the early Mesozoic Quesnel Trough, which includes rocks of the upper Triassic to lower Jurassic Takla, Nicola, and Stuhini groups. To the west, the deformed uplifted Permian Cache Creek Complex rocks are separated from the Quesnel Troughby the Pinchi fault zone. To the east, the Manson fault zone separates this belt from the uplifted Proterozoic/Early Paleozoic Wolverine metamorphic complex and the Mississippian-Permian Slide Mountain Group (Figure 2) [31].
Alteration is only apparent in volcanic rocks and represented by pervasive chlorite formed as a result of regional green schist metamorphism. Patchy biotite, albite and actinolite alteration are present over small areas, and are thought to be related to the monzonitic intrusions. Mineralization is largely restricted to the volcanic rocks and consists of 1-5% finely disseminated pyrite and pyrrhotite with trace chalcopyrite locally (Table 1) [32-34].

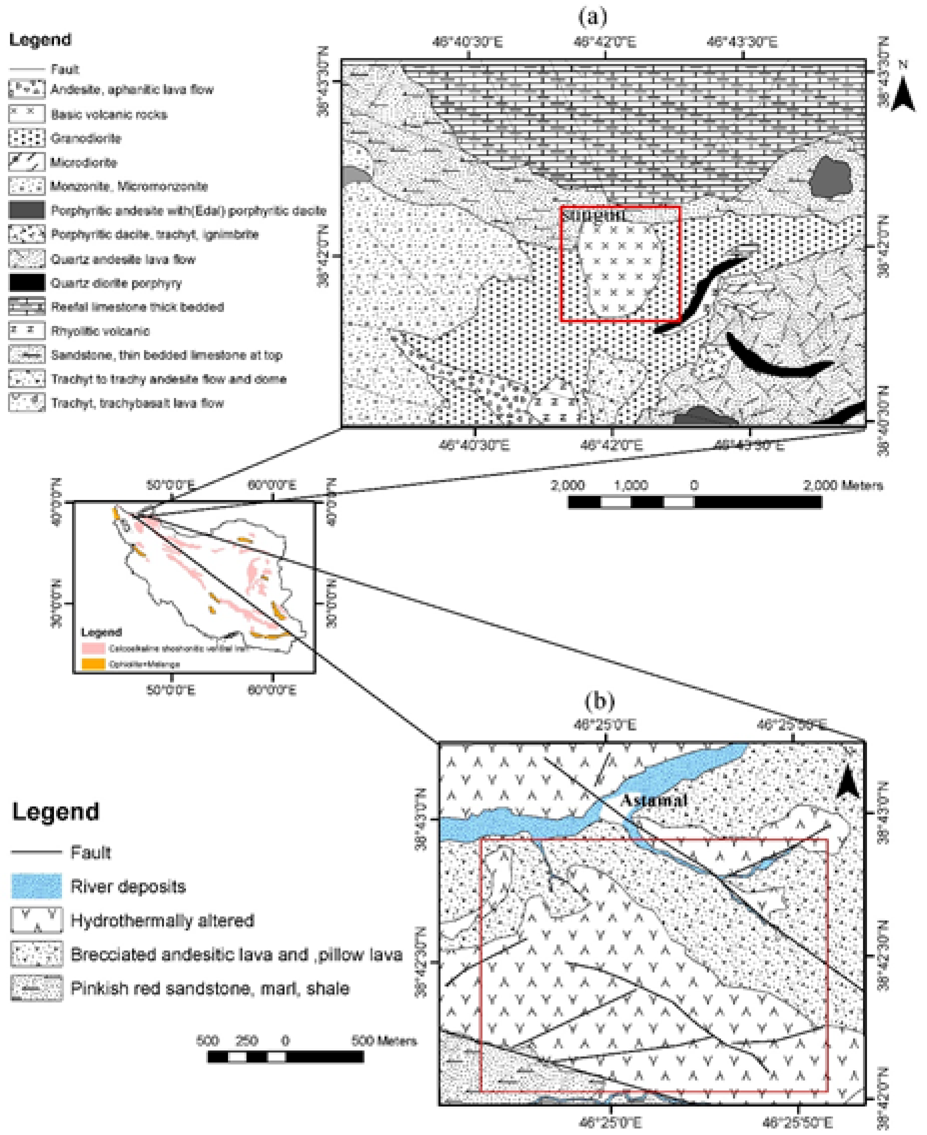

Figure 1. Simplified geological map of Sungun (a) and Astamal (b) [30].

Table 1. Characteristics of case studies in Sungun, Astamal, and Inza [7, 32-34].

Prospect /Deposit	Location	Host rock	Landscape	Alteration	Mineralogical and geochemical type
Sungun	Ahar- Iran	Diorite/granodiorite monzonite/quartz–monzonite	Mountainous humid zone in Northern sub-area, cold weather and snowy winters	Potassic, Phyllic, propylitic, and argillic alteration	Porphyry copper mineralization
Astamal	Ahar-Iran	Diorite/granodiorite sandstone, shale, marl, andesite	The mountainous humid–semiarid zone in Southern area, cold weather and snowy winters	various porphyry alteration types including potassic, propylitic, argillic, and sericitic	Porphyry copper mineralization
Inza	British Columbia- Canada	Basaltic volcanic rocks-monzonitic intrusions	Snowy winters (average temperature approximately -12.5 ^{0}C) with short warm summers (average temperature ~15.6 ^{0}C)	Potassic alteration suite consisting of K-feldspar, biotite, magnetite, anhydrite, gypsum, pyrite, and chalcopyrite	Porphyry copper-gold mineralization

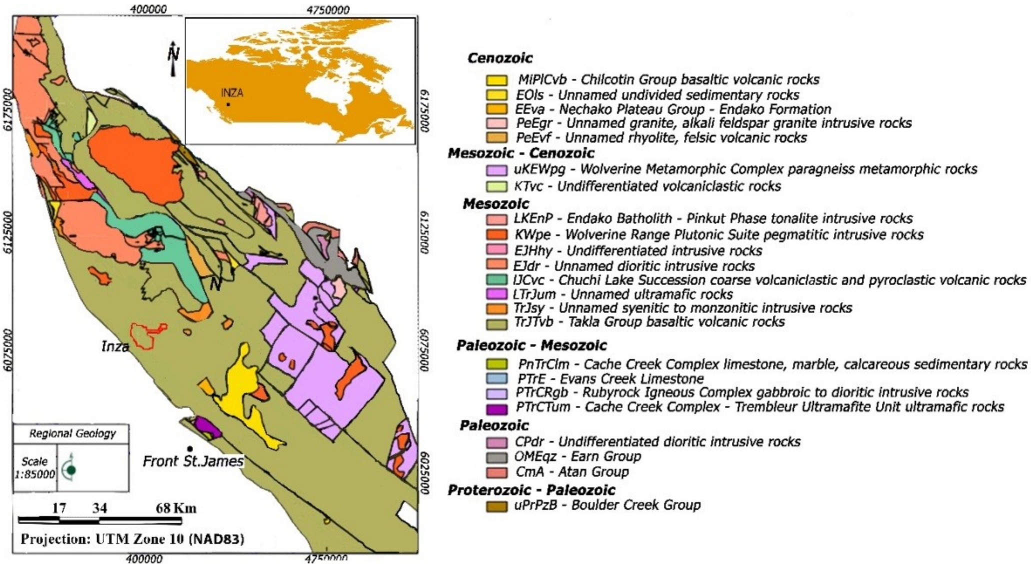

Figure 2. Regional Geology of Quesnel Terrane, Inza area is indicated with red polyline [32].

2.3. Spatial datasets

From various spatial databases of the Geological Survey of Iran (GSI), we used the following datasets for local-scale predictive mapping of prospectivity for porphyry-Cu deposits in the Sungun and Astamal areas in Iran. The rock sample data analysis in Inza was obtained from Strongbow Exploration Inc [32].

- Lithologic units from the 1:2000 scale map of Sungun and Astamal areas, NW Iran, and Inza area in British Columbia, Canada.
- A subset of soil geochemical data (436 soil samples analyzed for Cu, Pb, Zn and Mo by atomic absorption method) pertaining to the Inza area. Samples were taken along ten traverse lines with 50 m spacing between samples and 200 m spacing between lines.
- A subset of rock geochemical data (840 samples analyzed for Cu, Mo, Pb, Zn, Ag, As, and Sb elements by atomic absorption method data provided by NICICO (National Iranian Copper Industries Company)) pertaining to the Sungun area. The samples were taken from 19 profiles with 20 m spacing between samples and 100 m spacing between profiles.
- A subset of rock geochemical data (880 samples analyzed for Cu, Mo, Pb, Zn, Ag, As, and Sb elements by atomic absorption method data provided by NICICO (National Iranian Copper Industries Company)) pertaining to the Astamal area. Samples were taken along 19 profiles with 40 m spacing between samples and 100 m spacing between lines.
- A subset of rock geochemical data (sample analyses for Cu, Mo, Pb, and Zn by emission spectrometry method provided by IMGRE-RAS (Institute of Mineralogy, Geochemistry and Crystallochemistry of Rare Elements)). The samples were taken from 3 core drillings in the Sungun and Astamal areas.
- A subset of rock geochemical data (sample analyses for Cu, Mo, Pb, Ag and Zn by atomic absorption method). The samples were taken from 2 core drillings in the Inza area.

2.4. Anomalous geochemical field of porphyry-Cu mineralization

Here the individual uni-element data was interpolated in the case studies, and the values within the interpolated elements maps were individually rescaled to the range of 0, 1. [8, 35].

The multiplicative geochemical data for Cu*Mo and Pb*Zn was separately created for each of the three case studies. CG calculation was carried out in both the x and y directions using Equations 2 and 3 in the MATLAB software package. The spatial distribution pattern for the sub-ore gradient and supra-ore gradient was created as geochemical maps. Local anomalies of the sub-ore path-finder element gradient and supra-ore gradient were identified in such geochemical maps.

Average CG was calculated in each local anomaly for the sub-ore gradient and supra-ore gradient maps. Indices of gradient geochemical zonality (G (*Vz*)) were calculated from ratios of supra-ore to sub-ore path-finder element gradients around mineral deposits. The flowchart of this method is presented in Figure 3.

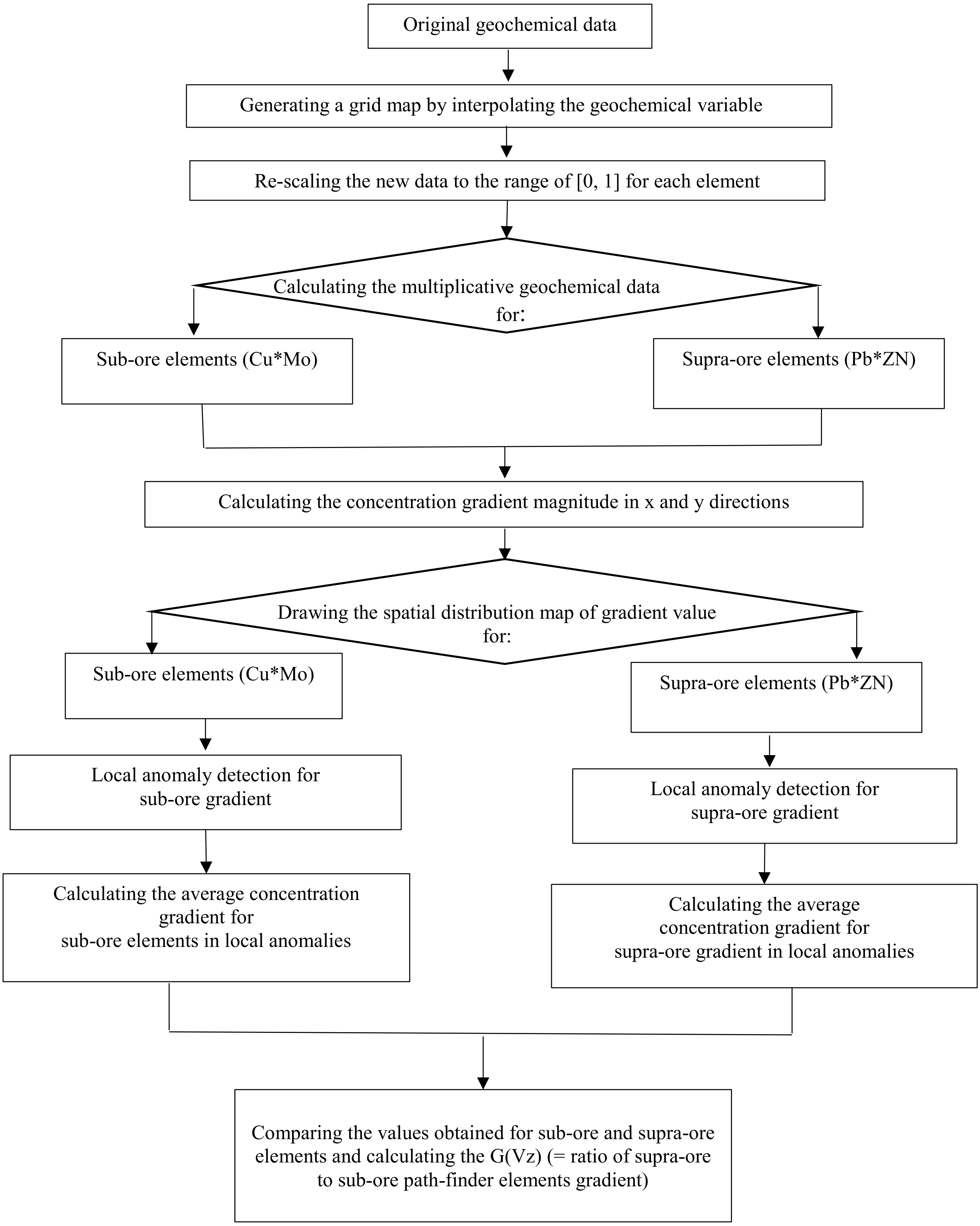

Figure 3. Flowchart of CG method.

3. Results and discussion

3.1. Anomalous geochemical field in typical standard porphyry copper mineralization in Iran

The multiplied haloes of Cu*Mo are related to the sub-ore mineral deposit, and the multiplied haloes of Pb*Zn are related to the supra-ore mineral deposit in Sungun and Astamal [7]. High anomaly of Pb*Zn exists in the western and central Sungun. These areas have high favorability for exploration of blind porphyry–Cu deposits. Cu*Mo is high in the east and west sides of this area. The anomaly maps of Cu*Mo and Pb*Zn in the Sungun area are presented in [7].

CGs of Pb*Zn and Cu*Mo were calculated for their distribution functions. We used a multiple elements map instead of the Cu map in the gradient analysis. High values of CG for the supra-ore elements (Pb*Zn) (Figure 4c) and sub-ore elements (Cu*Mo) (Figure 4d) exist in the eastern and western zones, respectively. Maps of the sample location and gradient of vertical zonality index (Pb*Zn/Cu*Mo) are presented in Figure 4.

The local anomaly Pb*Zn gradients and Cu*Mo gradients were detected in the gradient map (Figure 5). According to the local anomalies, the two areas of Sungun1 and Sungun2 were detected in this area. The average CG was calculated for the two separate sub-areas (Table 2).

The average CGs in these regions were calculated (Table 2). CGs of the supra-ore elements (Pb*Zn) and the sub-ore elements (Cu*Mo) were 0.0032 and 0.0014, respectively, in the Sungun1 deposit. The value for the supra-ore elements was 2.29 times higher than that for the sub-ore elements in this area.

The concentration gradients (CGs) show changes in the concentration values. High values of CG indicate an extreme change of concentration in the region. Significant differences between element concentrations in geochemical distribution maps relates to surfacing anomalies. Little differences between the element concentrations are related to the deeper geochemical anomalies. High values for the gradient of supra-ore elements indicate an anomaly related to surfacing. However, its low value for Cu*Mo suggests that it is related to the deeper anomaly in the Sungun area. These conflicting conclusions suggest that in fact there is a blind mineralization under the surface of Sungun1 deposit. This conclusion has also been confirmed in the previous studies [7]. There is no other information for the Sungun2 area; it was allocated as a waste deposit site in 1992. However, studies based on the traditional zonality method recognized Sungun2 as blind mineralization in 1994 [7].

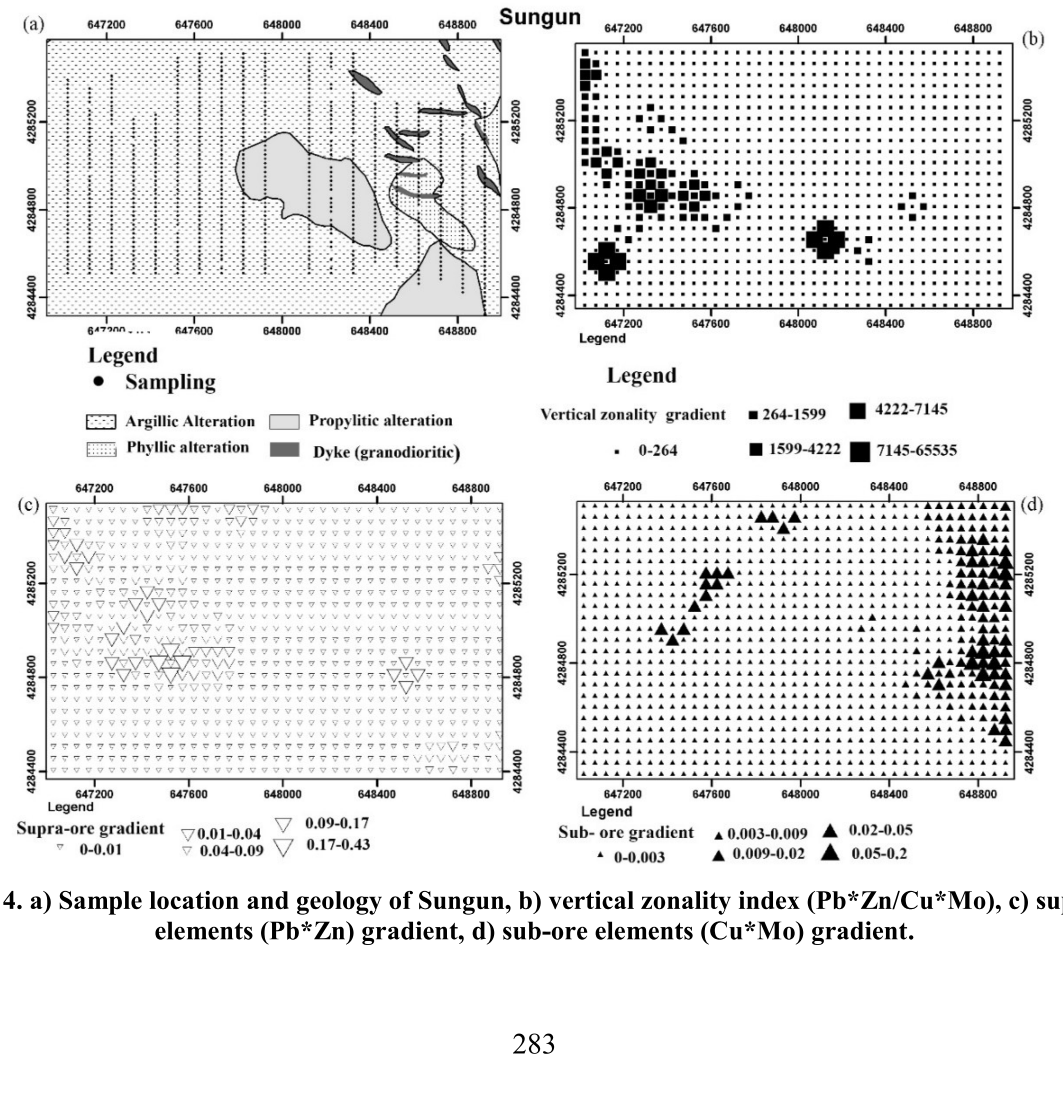

Figure 4. a) Sample location and geology of Sungun, b) vertical zonality index (Pb*Zn/Cu*Mo), c) supra-ore elements (Pb*Zn) gradient, d) sub-ore elements (Cu*Mo) gradient.

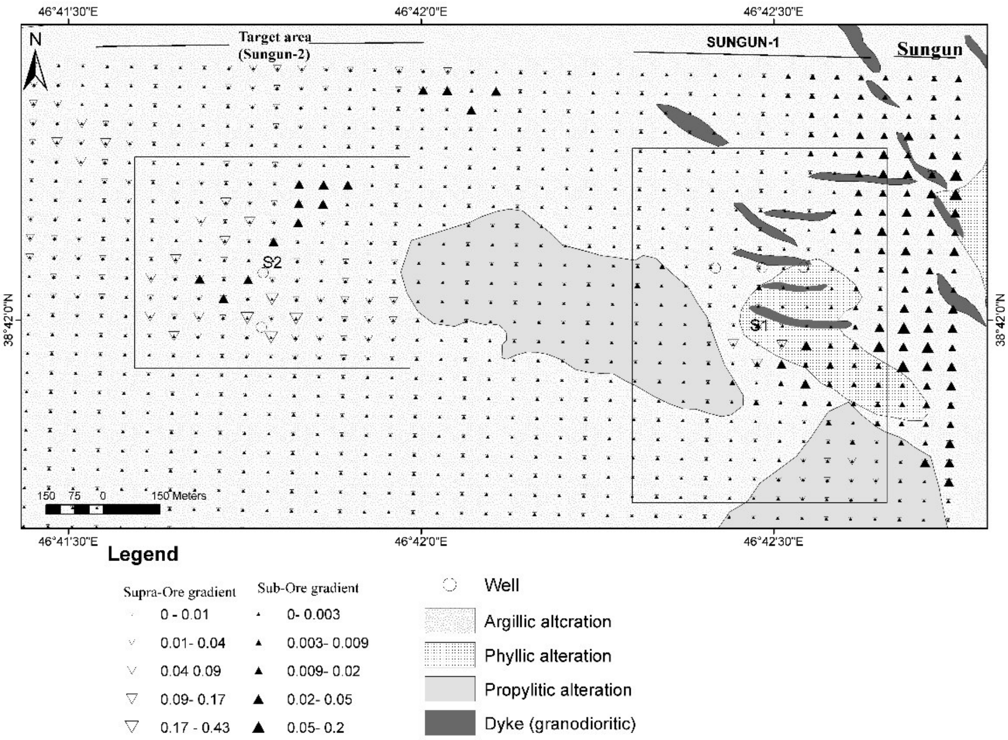

Figure 5. Coexistence of two local maxima for supra-ore and sup-ore elements in Sungun.

Table 2. Identification of Geochemical Anomaly (IGA) in Anomaly Geochemical Fields (AGFs) in case studies.

AGF	Local Anomaly	G(sub-ore elements)	G(supra-ore elements)	G(Vz)	IGA
Sungun	Sungun1	0.0014	0.0032	2.29	BM
	Sungun2	$6.8*10^{-5}$	0.0106	156	BM
Astamal	Astamal (A)	0.0057	$7.9*10^{-4}$	0.138	ZDM
	Astamal (B)	0.006	$2.7*10^{-4}$	0.045	ZDM
	Astamal (C)	0.0025	0.0023	0.9	ZDM
Inza	Inza I	0.008	0.01	1.25	BM
	Inza II	0.015	0.029	1.93	BM
	Inza III	0.008	0.024	3	BM
	Inza IV	0.0073	0.0092	1.26	BM

According to the CG method, Sungun2 was recognized as a blind mineralization because the gradient concentration of the supra-ore elements was 156 times higher than that of the sub-ore elements gradient. CGs of the supra-ore and sub-ore elements were 0.0106 and $6.8*10^{-5}$, respectively, in this area (Table 2).

According to the geological particulars of Sungun, diorite/granodiorite is porphyritic, and ranges from fine-grained in the northern part to coarse-grained in the west and NW, where it intrudes monzonite to quartz monzonite (Figure 1). The contact with the monzonite/quartz monzonite is not well-exposed and is commonly brecciated. A feature of the porphyritic diorite/granodiorite is that it contains numerous mineralized dykes. The contact between granodiorite rocks and Cretaceous limestone is well-exposed in the northern and eastern parts of the studied area. In the east, the latter has been altered to skarn, which locally hosts abundant copper mineralization [36].

The borehole number 66 in Sungun2 supports the results obtained using the CG method. The vertical zonality index (Pb*Zn/Cu*Mo) in this borehole decreases with depth (Figure 6b). Therefore, it suggests a blind mineralization at 600 m. The gradient of Pb*Zn/Cu*Mo deceases in depth along with the zonality index. The traditional method of zonality coefficients required information from the same deposits for comparison. The gradient of zonality index, however, presents the same results as the zonality index without the need for comparison with the similar type of deposit.

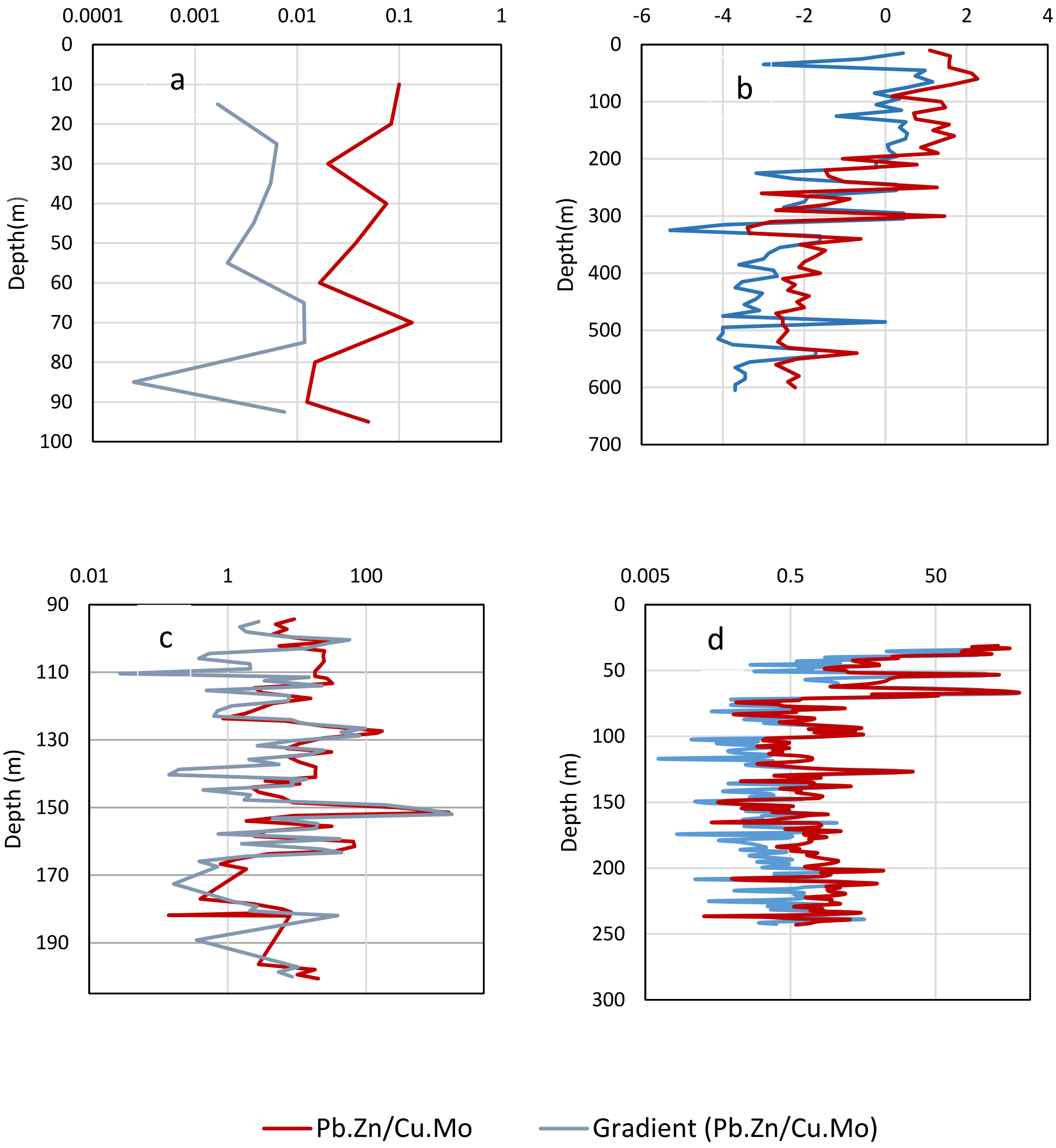

Figure 6. Variations in vertical zonality index (Pb*Zn/Cu*Mo) and its gradient in depth for boreholes of: a) Astamal-BH1 b) Sungun-BH66 c) INZA-11-07 d) INZA-11-08.

The anomaly maps of Cu*Mo and Pb*Zn in the Astamal area is presented in [7]. The zonality method in the south and north Astamal areas revealed geochemical anomalies with low grades of Cu and Mo. There was a low anomaly of Pb*Zn in the SE Astamal [7]. CG was calculated for Cu*Mo, Pb*Zn, and Pb*Zn/Cu*Mo in this area. The gradient maps are shown in Figure 7. High values for the supra-ore element gradients exist in the SE and NW of Astamal (Figure 7b). Gradient values for the sub-ore elements in the north and SE are high (Figure 7c). Local anomalies of the vertical zonality coefficient (Pb*Zn/Cu*Mo) gradients exist in the south and NW of the area (Figure 7d).

The coexistence of both the supra-ore and sub-ore local maxima implies blind mineralization [7]. Local anomaly of the supra-ore and sub-ore elements were distinguished in the Astamal area. Three anomalies of sub-ore elements (A, B, and C) were recognized in the Astamal area (Figure 8). Local anomalies of the supra-ore elements exist in zones A and C; no local anomaly for Pb*Zn exists in zone B. CGs of Pb*Zn and Cu*Mo for the A, B, and C zones were calculated seperately (Table 2). CG for the sub-ore and supra-ore elements were 0.0057 and $7.9*10^{-4}$, respectively, in zone A. The ratio of CG for the supra-ore elements to CG for the sub-ore elements in Astamal was lower than 1.0 in this zone. These ratios were 0.138, 0.045, and 0.9 in zones A, B, and C, respectively. The ratio of the supra-ore element gradients to the sub-ore elements in the three zones of Astamal was lower than 1.

Therefore, the anomaly is zone-dispersed mineralization, and blind mineralization does not exist in the Astamal area.
The submarine upper Cretaceous andesite rocks are the most prevalent units in the Astamal area. Submarine volcanic activities with mafic to intermediate composition (andesite, basaltic andesite, and pyroxene andesite) are alternatively inter-layered with sedimentary units. The sedimentary member of the Upper Cretaceous unit has a high development, and consists of flysch-type assemblage including alteration of thin to medium bedded sandstone, shale, marl, and conglomerate, which is covered by thick bedded to massive limestone [37].
ZDM anomalies in Astamal were confirmed by drilling drill-holes. Variation in the zonality index (Pb*Zn/Cu*Mo) and its gradient are shown in Figure 6a. The two values are almost constant from the surface to a depth of 100 m below the surface. Therefore, economic mineralization does not exist at depth; the Astamal area is a ZDM and a non-economic mineralization.
Blind mineralization and ZDM anomalies recognized with the zonality method are more coincident than those with alteration methods. This finding demonstrates that the traditional zonality and gradient concentration methods are more powerful than the alteration methods [7]. In this research work, although extensive alteration is observed in the Astamal area, it does not have any economic mineralization.

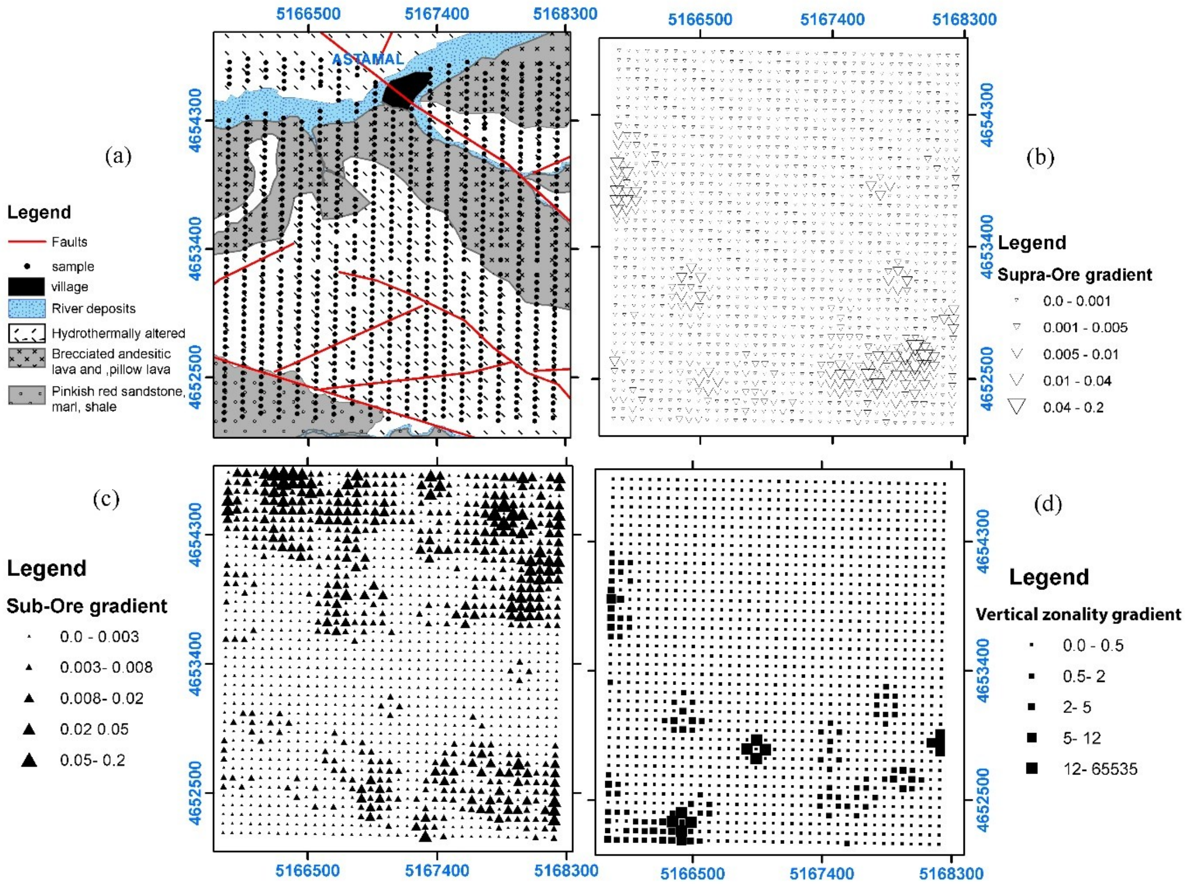

Figure 7. a) Geology of Astamal, b) supra-ore elements (Pb*Zn) grdient, c) sub-ore elements (Cu*Mo) gradient, and d) vertical zonality (Pb*Zn/Cu*Mo) gradient.

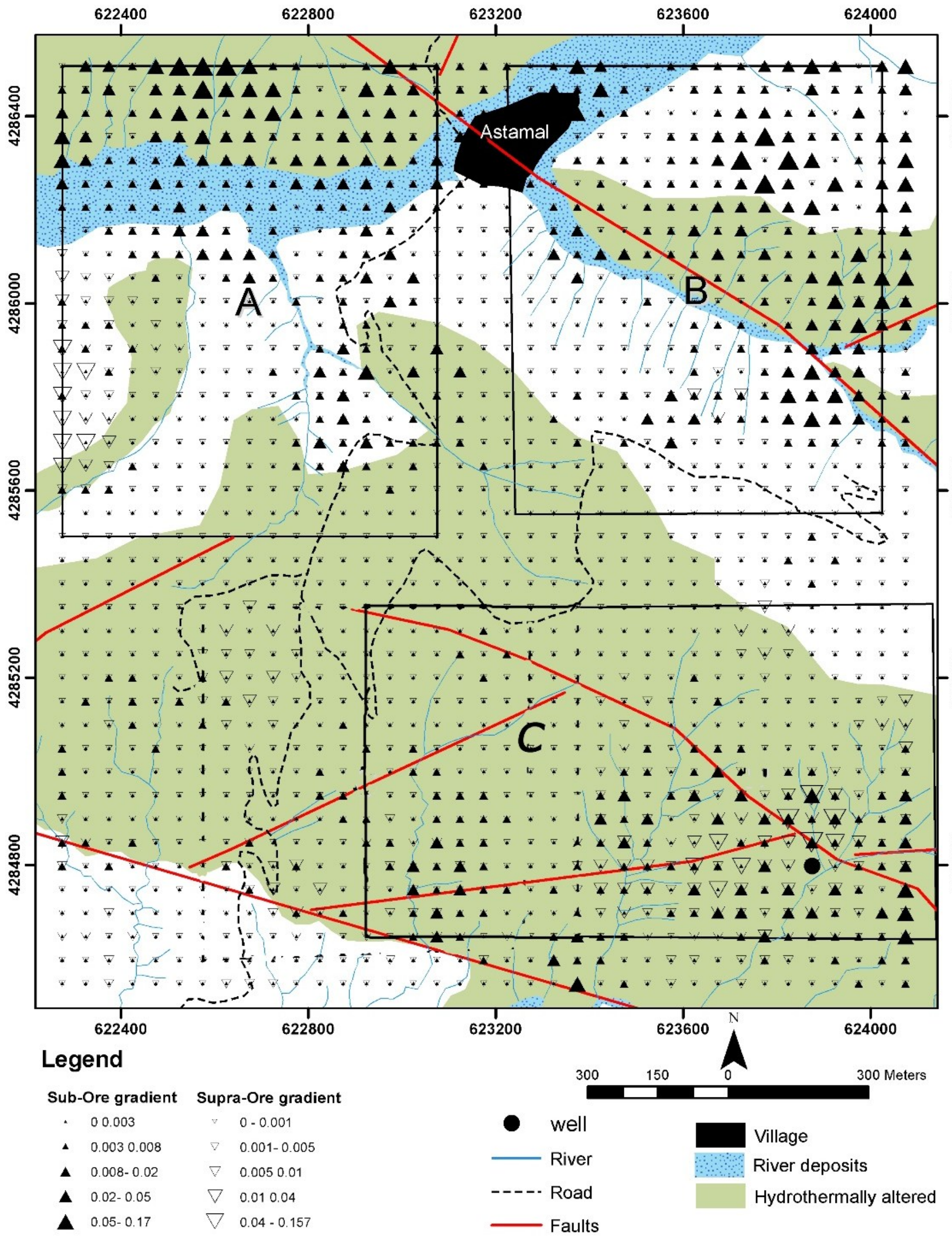

Figure 8. Co-existence of two local maxima for supra-ore and supra-ore elements in Astamal.

3.2. Anomalous geochemical field case study: a porphyry copper mineralization in Canada

The anomaly maps of Cu*Mo and Pb*Zn in the Inza area is presented in Figure 9. High anomalies of the supra-ore and sub-ore elements are in the north and south of the area, respectively. Volcanic sediments (argillitic, shales, and occasional wackes) exist in this area. Lithology and alteration indicate that this area is the main body of mineralized porphyry. Roughly centered in this area, both the alteration and mineralization are zoned. The innermost is the potassic alteration suite consisting of K-feldspar, biotite, magnetite, anhydrite, gypsum, pyrite, chalcopyrite, molybdenite, and gold [31].

CG of these two disperses were calculated. The distribution gradient maps are presented in Figure 10.

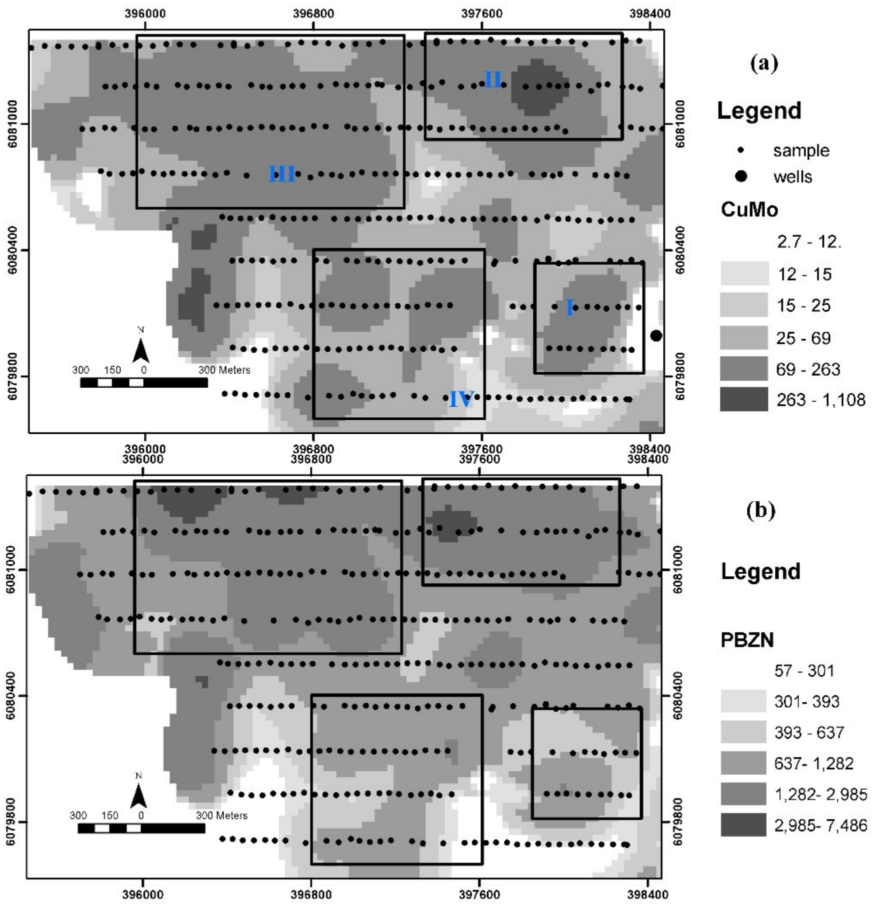

Figure 9. Geochemical map of: a) Pb*Zn and b) Cu*Mo in Inza.

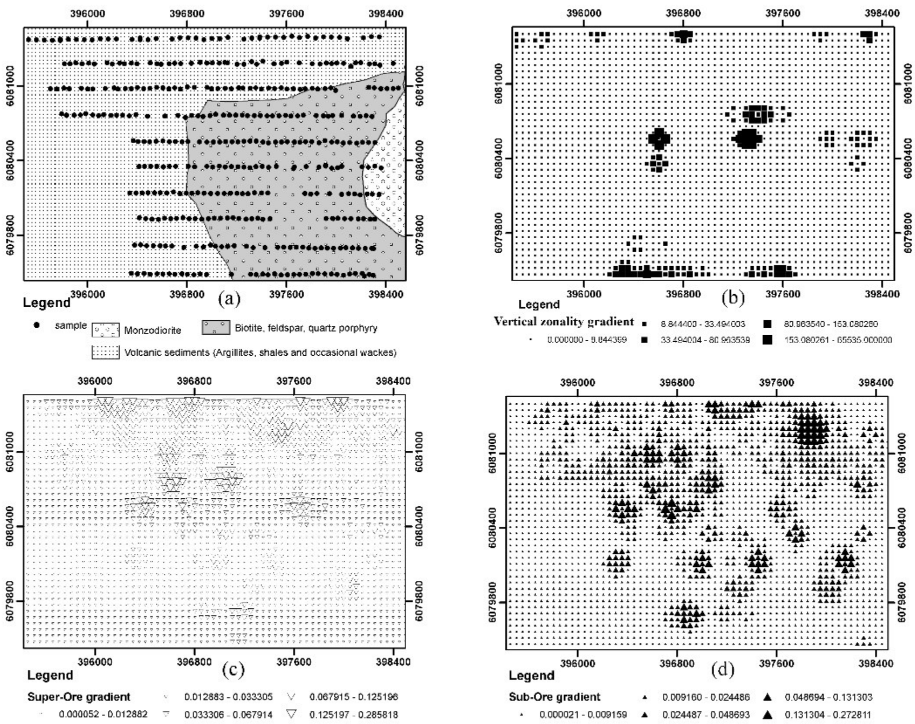

Figure 10. a) Geology and sample location of Inza, b) vertical zonality (Pb*Zn/Cu*Mo) gradient of Inza, c) supra-ore elements (Pb*Zn) gradient, d) sub-ore elements (Cu*Mo) gradient.

Co-existence of both the supra-ore and sub-ore local maxima was detected in this region (Figure 11). High values of the supra-ore and sub-ore gradient concentrations indicate the presence of four local anomalies in the CG map of Pb*Zn and Cu*Mo in the northern and southern zones of Inza.

The average CGs were calculated for these four local anomalies (Table 2). The concentration gradients for the sub-ore and supra-ore elements were 0.008 and 0.01, respectively, in zone I; their ratio was 1.25. The Pb*Zn changes were higher than the Cu*Mo changes in zone II; their ratio was 1.93. The ratios for zones III and IV were 3 and 1.26, respectively. The CG model suggests the presence of a blind mineral deposit in the Inza area; more investigation is required to determine the drilling point.

The property geology is represented by andesite, tuffs, and minor flows of the Upper Triassic Takla Group. Tuffaceous units range from thinly bedded fine muddy tuffs through massive fine-grained lithic tuffs to cherty lapilli tuffs.

Minor augite porphyritic flows are present on the eastern portion of the property, apparently capping the tuffaceous package. The volcanic rocks are grey, medium-grained and intruded by numerous lobate plutons of pale hypidiomorphic, granular monzonite. This may reflect potassic alteration [33]. Sparse quartz veins cutting the monzonite contain traces of molybdenite. Magnetite is finely disseminated throughout the monzonite, and is locally present in the volcanic rocks.

Drilled boreholes of INZA-11-08 and INZA-11-07 confirm the results of the CG analysis. The distribution of zonality index (Pb*Zn/Cu*Mo) in these boreholes is illustrated in Figures 6d and 6c. For boreholes of INZA-11-08, the vertical zonality index and its gradient value G(*Vz*) decreased from the surface to the depth. The value of this index is high at the surface, and decreases significantly at a depth of 67 m (Figure 6d). This variation shows an erosional surface in the center of haloes with outcropping weak mineralization in this location. However, the graph for INZA-11-07 is somewhat constant from surface to a depth of almost 200 m (Figure 6c). This graph shows zone dispersed mineralization in this location. Boreholes have been drilled outside the anomalies geochemical field. This investigation suggests, in order of importance, the Inza zones III, II, IV, and I, respectively, for borehole exploration.

According to Table 2, the contrast G(*Vz*) between the minimum value for Astamal (ZDM) and the maximum value for the Sungun (BM) standard porphyry copper mineralization is 3000.

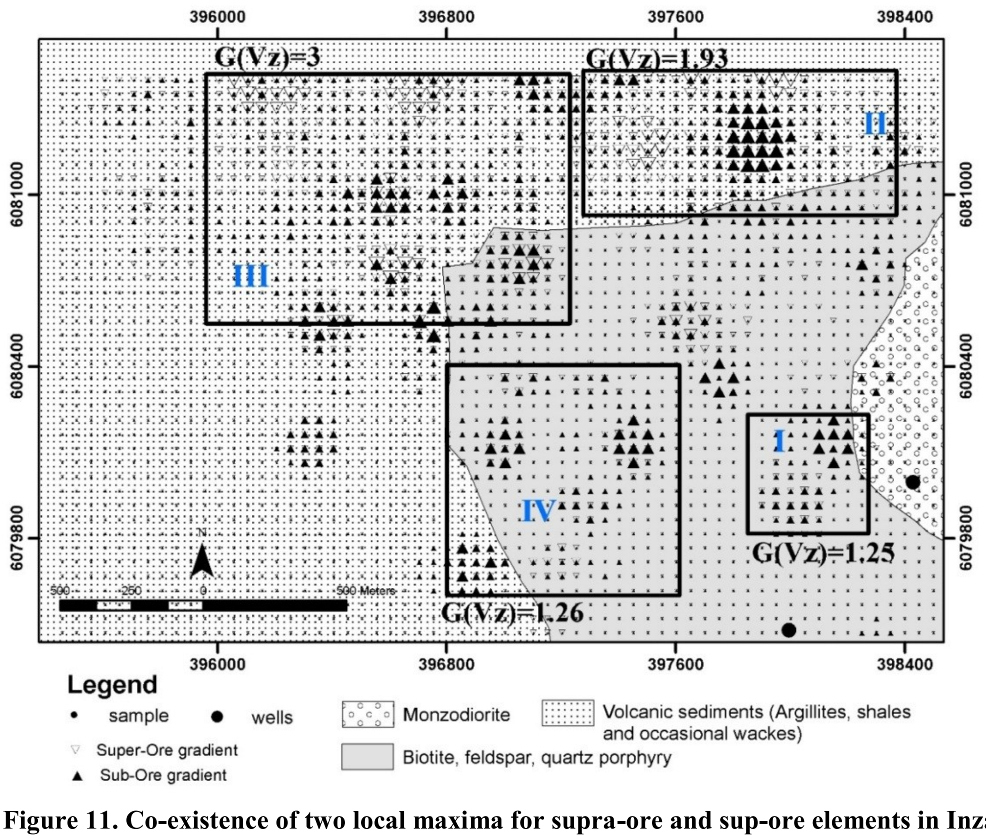

Figure 11. Co-existence of two local maxima for supra-ore and sup-ore elements in Inza.

4. Conclusions

Gradient is one of the most important characteristic parameters in the geochemical field. High values of this variable are related to the surface anomaly. The concentration gradients (CGs) of the sub-ore and supra-ore elements can help to detect blind mineralization from zone dispersed mineralization. Here, we applied this method for the Inza mining area in Canada. A geophysical operation has previously taken place in the Inza area, indicating the presence of a complex anomaly but this operation was an expensive and time-consuming procedure. However, the gradient method detected ZDM from BM anomalies in this area. According to this method, if the CG average for the sub-ore elements was higher than the value for the supra-ore elements, the anomaly would be ZDM. Also if the CG ratio for the supra-ore elements to the sub-ore element gradients is higher than 1.0, the anomaly will be considered a BM. In this research work, we used the CG results instead of anomalies of pathfinder elements in mapping mineral prospects. The findings showed that the pattern recognition technique can properly predict the deep and blind mineral deposits without drilling. Furthermore, the CG method suggested that Sungun1, Sungun2, and Inza are BM but the Astamal anomaly was identified as a zone dispersed mineralization. In this paper, two case studies of porphyry copper anomaly located in two countries with different landscape-geochemical conditions were studied. The CG method was utilized to identify the geochemical anomalies in these areas. This method can be applied in different landscapes; however, it must be investigated further in other prospects with different conditions, as well. The geochemical halos of mineral deposits at different depths are characterized by specific values of the G(Vz) index. Practical application of the G(Vz) index highlights the existence of erosion surfaces. Thus the G(Vz) index elucidates the vertical levels of geochemical anomalies. With respect to the present level of erosion, high values of a G(Vz) index implied the presence of blind deposits, whereas low values of the index showed outcropping or already eroded deposits. The high difference between G(Vz) values in the BM and ZDM anomalies of the results obtained here establish this factor as the best general indicator of blind porphyry-Cu deposits. According to the results of this study, G(Vz) is the most appropriate model for detection of the geochemical anomaly between BM and ZDM.

Acknowledgments

This research work was funded by the School of Mining, Petroleum, and Geophysics in Shahrood University of Technology. The authors would like to thank Levi Farrand and Mahdi Ziaei for their comments on the preliminary version of the manuscript. Helpful comments by the esteemed reviewer (Dr. Daneshfar) led to substantial improvements of the manuscript.

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کاربرد گرادیان غلظت در ژئوشیمی معادن: مقایسه کانی سازی مس در ایران و کانادا

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ارسال ۲۰۱۷/۲/۱۲، پذیرش ۲۰۱۷/۵/۱۱

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چکیده:

در این پژوهش شاخص گرادیان غلظت در اکتشافات ذخایر مس پورفیری در دو منطقه با به کارگیری شاخص G(Vz)= (CG(Zn*Pb)/CG(Cu*Mo)) به کار برده شده است. اولین زون در مقیاس ۱:۲۰۰۰ شامل منطقه سونگون و آستامال است و زون دوم منطقه اینزا در بریتیش کلمبیا، کانادا است. از منطقه سونگون و آستامال نمونه‌های سنگ و از منطقه اینزا نمونه‌های خاک برداشت شد. در نمونه‌های خاک برداشت شده از منطقه اینزا عناصر مس، سرب، روی و مولیبدن با روش جذب اتمی اندازه‌گیری شد و در منطقه سونگون و آستامال نمونه‌های برداشت شده برای عناصر مس، سرب، روی، مولیبدن، نقره، روی، آرسنیک و آنتیموان آنالیز شدند. شاخص زونالیته گرادیان غلظت ژئوشیمیایی چند عنصری در اطراف ذخایر معدنی و توزیع فضایی با ژئوشیمی، زمین‌شناسی و ساختار ویژگی‌های مهمی هستند که باید در اکتشافات معدنی در نظر گرفته شود. شاخص G(Vz) به تشخیص بین آنومالی‌های فوق کانساری و تحت کانساری کمک می‌کند که به ترتیب با کانی سازی پنهان و پراکنده در ارتباط هستند. برای تشخیص کانی‌سازی پنهان از پراکنده، آنومالی فوق کانساری (Pb*Zn) و تحت کانساری (Cu*Mo) و نقشه‌های شاخص زونالیته استفاده شد و نقشه گرادیان عناصر فوق کانساری، گرادیان عناصر تحت کانساری و شاخص G(Vz) رسم شد. روش ارائه شده به تفکیک ذخایر پنهان از پراکنده بدون نیاز به حفاری کمک می‌کند. در پژوهش‌های پیشین وجود ذخایر پنهان در عمق به وسیله گمانه‌های اکتشافی در مناطق مطلوب معرفی شده در این پژوهش اثبات شده بود. نتایج این پژوهش سودمندی روش گرادیان غلظت را در مقیاس محلی برای اکتشاف ذخایر پنهان نشان می‌دهد.

کلمات کلیدی: آنومالی گرادیان عناصر تحت کانساری، آنومالی گرادیان عناصر فوق کانساری، سونگون و آستامال (ایران)، اینزا (کانادا).
