

# Fuzzy logic mineral potential mapping for copper exploration using multi-disciplinary geo-datasets, a case study in seridune deposit, Iran

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**Abstract** This paper describes the application of the knowledge-based fuzzy logic method to integrate various exploratory geo-dataset in order to prepare a mineral prospectivity map (MPM) for copper exploration. Different geophysical layers which are derived from the magnetic and the electrical surveys, along with the ones extracted from the background geology (i.e., lithology, fault and alteration) and geochemical data are incorporated in such process. Seridune copper deposit located in the Kerman province of Iran is the case study to delineate its high potential zones of Cu-bearing mineralization for drilling additional boreholes. Four layers from the magnetic data involving upward continuation, analytic signal, reduced to pole and pseudo gravity are assigned in the multi-disciplinary geo-dataset to locate the intrusive complexes responsible for Cu mineralization. The apparent resistivity, chargeability and sulfide factor layers acquired from geo-electrical data are also included in the final preparation of MPM. Then the normalized weights of seven geophysical, three geological and one geochemical evidential layers as main criteria are determined based upon the knowledge of expert decision makers. Fuzzy operators (i.e., Sum and Gamma) are applied to integrate these

exploratory features. To evaluate the performance and applicability of the approach, the productivity of the drilled boreholes (Cu concentration multiplied by ore thickness) are used to validate the produced MPMs. It is shown that an optimum correlation coefficient of 0.86 exists between the MPM values and Cu productivity criterion along drilled boreholes.

**Keywords** Electrical layers · Magnetic layers · Geological layers · Geochemical layers · MPM · Porphyry copper

## Introduction

The main purpose in mineral prospecting is to explore new ore-bearing mineralization in a region of interest. Distinguishing high potential zones within the prospected area is one of the main objectives in mineral exploration. Various exploratory geo-dataset (comprising of geological, geophysical and geochemical evidential layers) are collected, analyzed and integrated for mineral prospectivity mapping (MPM) to delineate new prospective areas. Therefore, MPM is a multiple criteria decision-making (MCDM) operation that produces a predictive model to outline prospective areas (Najafi et al. 2014; Yousefi and Carranza 2015a, b). Various MPM approaches have been developed in the last two decades which can be categorized generally into data- and knowledge-driven ones (Pan and Harris 2000; Carranza 2008). In data-driven techniques, the information acquired from the known mineral deposits are used as ‘training points’ to establish spatial relationships between the known deposits and particular geological, geochemical and geophysical features based upon numerous statistical/mathematical algorithms (Carranza 2008). The relationships are quantified to assign the importance and weight of each evidence layer (Carranza and Hale 2002a) and are finally integrated into a single MPM

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(Nykänen and Salmirinne 2007). Examples of such MPM methods include weights of evidence (e.g., Agterberg et al. 1990; Carranza and Hale 2002b), logistic regression (e.g., Agterberg and Bonham-Carter 1999; Carranza and Hale 2001; Mejía-Herrera et al. 2014), neural networks (e.g., Harris et al. 2003; Nykänen 2008; Abedi and Norouzi 2012), evidential belief functions (e.g., Carranza and Hale 2002c; Carranza and Hale 2003; Carranza et al. 2005, 2008a), Bayesian classifiers (e.g., Porwal et al. 2006; Abedi and Norouzi 2012), support vector machines (e.g., Zuo and Carranza 2011; Abedi et al. 2012a), clustering methods (Abedi et al. 2013a) and random forest method (e.g., Rodriguez-Galiano et al. 2014; Carranza and Laborte 2015). The other techniques, in which a geoscientist's opinions are incorporated, are called the knowledge-driven approaches and include the methods such as the use of Boolean logic (Bonham-Carter et al. 1989), index overlay (e.g., Carranza et al. 1999; Mirzaei et al. 2014; Sadeghi et al. 2014; Sadeghi and Khalajmasoumi 2015), the Dempster–Shafer belief theory (e.g., Moon 1990; Carranza et al. 2008b), fuzzy logic (e.g., Abedi et al. 2013b; Moradi et al. 2015; Sadeghi and Khalajmasoumi 2015), wildcat mapping (Carranza and Hale 2002d), and various outranking methods (e.g., Abedi et al. 2012b, c; 2013c, 2015; Hossaini and Abedi 2015; Pazand and Hezarkhani 2015).

Recently two new variants of MPM techniques have been developed compared to the conventional ones that are (1) Hybrid algorithm by simultaneous consideration of both location of known mineral occurrences and expert judgments (Pazand and Hezarkhani 2015), and (2) Weighting to the continuous spatial evidence without using location of known mineral occurrences and without using expert judgments. Fuzzy logic MPM with continuous evidential data, data-driven index overlay, data-driven Boolean logic, expected value and geometric average are the developed methods to overcome the problem of exploration bias resulting from expert judgments in knowledge-driven MPM and from using characteristics of known mineral occurrences in data-driven MPM (Yousefi and Carranza 2014; Yousefi and Carranza 2015b).

Localizing of high potential zones to recommend exploratory drillings by incorporating diverse criteria and alternatives is developed in this study. In addition the results of application of a fuzzy logic method is investigated for a multi-disciplinary geo-dataset in porphyry copper exploration. Herein after a brief introduction of the background geological setting, the preparation procedure of eleven raster-based evidential layers derived from a multi-disciplinary geo-dataset are discussed for the real data pertaining to the Seridune porphyry Cu deposit located in Kerman, Central Iran. This region was studied in the work of Abedi et al. (2013b) by examination of a Fuzzy-AHP method to integrate only geophysical data. The main objective of this study is to suggest whether additional drilling is recommended or not. Finally, ore concentration multiplied by its thickness for an economical

cut-off value of Cu grad along seven boreholes were used as a productivity criterion to evaluate the generated MPMs.

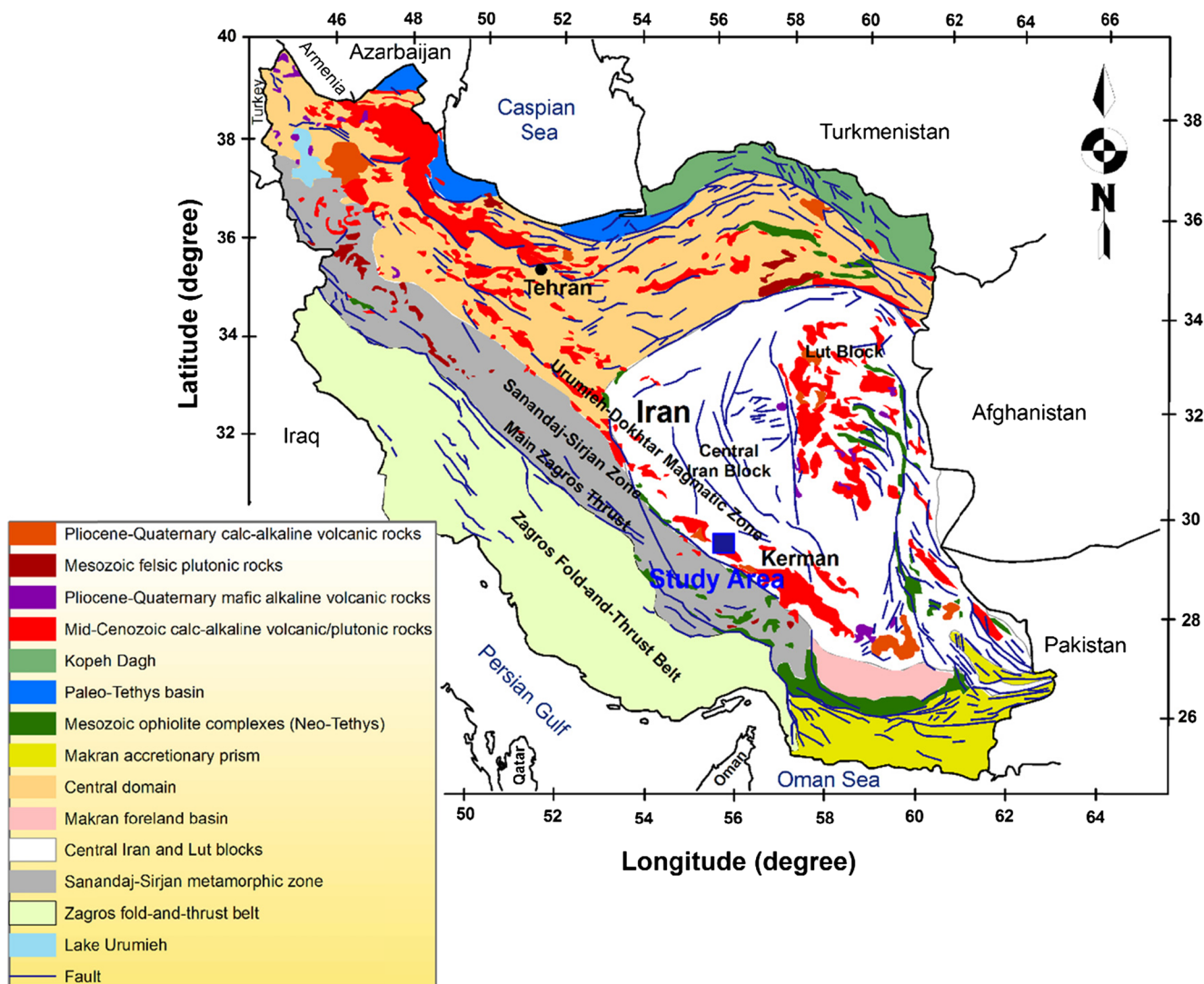
## Geological and alteration setting of seridune deposit

The prospect region is part of the Urumieh-Dokhtar magmatic arc assemblage (UDMA), where extensive Tertiary to Plio-Quaternary extrusive and intrusive units are exposed along a NW-SE trend. This belt shown in Fig. 1 was classified as an Andean type magmatic arc and resulted from the closure of the Neo-Tethyan ocean between Arabian and Eurasia plates (Alavi 1980; Berberian et al. 1982; Regard et al. 2004; John et al. 2010). The UDMA zone generally contains numerous porphyry-Cu deposits associated with granitoids, plutonic bodies and volcanic rocks. One of these porphyry sources is the Seridune prospect, located 3 km northeast of Sarcheshmeh (a world class porphyry copper mine in Iran). Seridune porphyry copper deposit occurs in a granodiorite-quartz monzonite pluton. The detailed lithological map of the Seridune prospect is shown in Fig. 2a. This deposit consists of Eocene andesite and trachyandesite intruded by upper Miocene granodiorite, which is cut by quartz monzonite and granodiorite porphyry dikes (Barzegar 2007; John et al. 2010).

Alteration mapping of the prospect area was carried out using a set of operations comprising of the Portable Infrared Mineral Analyzer of 145 samples, ASTER satellite images, XRD analysis of 22 samples, field observations and petrographic studies (Kazemi Mehrnia et al. 2011). The lithocap is characterized by an advanced argillic alteration assemblage. The alteration occurs at high topographic levels and on the flanks of the topographic heights. Post mineralization Pliocene dacite and Quaternary gravels cover parts of the andesite and intrusive rocks. The granodiorites, monzonites, and andesites adjacent to the intrusive rocks contain complexly intermixed argillic and sericitic (phyllic) alteration zones and an area of propylitically-altered rocks in the SE part of the prospect. North-trending silica lithocaps cut argillic, sericitic, and propylitic alteration zones. A zone of advanced argillic-altered rocks borders the lithocaps, and quartz stockwork veins are in the central part of the prospect (Barzegar 2007; John et al. 2010). Figure 2b presents a simple alteration map of the prospect area. Phyllic/sericitic alteration occurs in the central part of the sampled area. This spectrally distinct alteration assemblage occurs at all elevations, and is partially overprinted by advanced argillic alteration. Intermediate argillic alteration occurs on the flanks of advanced argillic and phyllic alterations (Kazemi Mehrnia et al. 2011).

## Data setting

The following subsections describe in detail the preparation of eleven evidential layers derived from geological, geochemical



**Fig. 1** Location of the study area in the general geological map of Iran (reproduced from National Geoscience Database of Iran, <http://www.ngdir.ir>)

and geophysical data in the studied area. Then the multi-disciplinary exploratory geo-dataset is constructed to employ the fuzzy operators in order to integrate all evidential layers. Finally, some MPMs generated from various values of gamma in Fuzzy procedure are portrayed to be discussed in the later section.

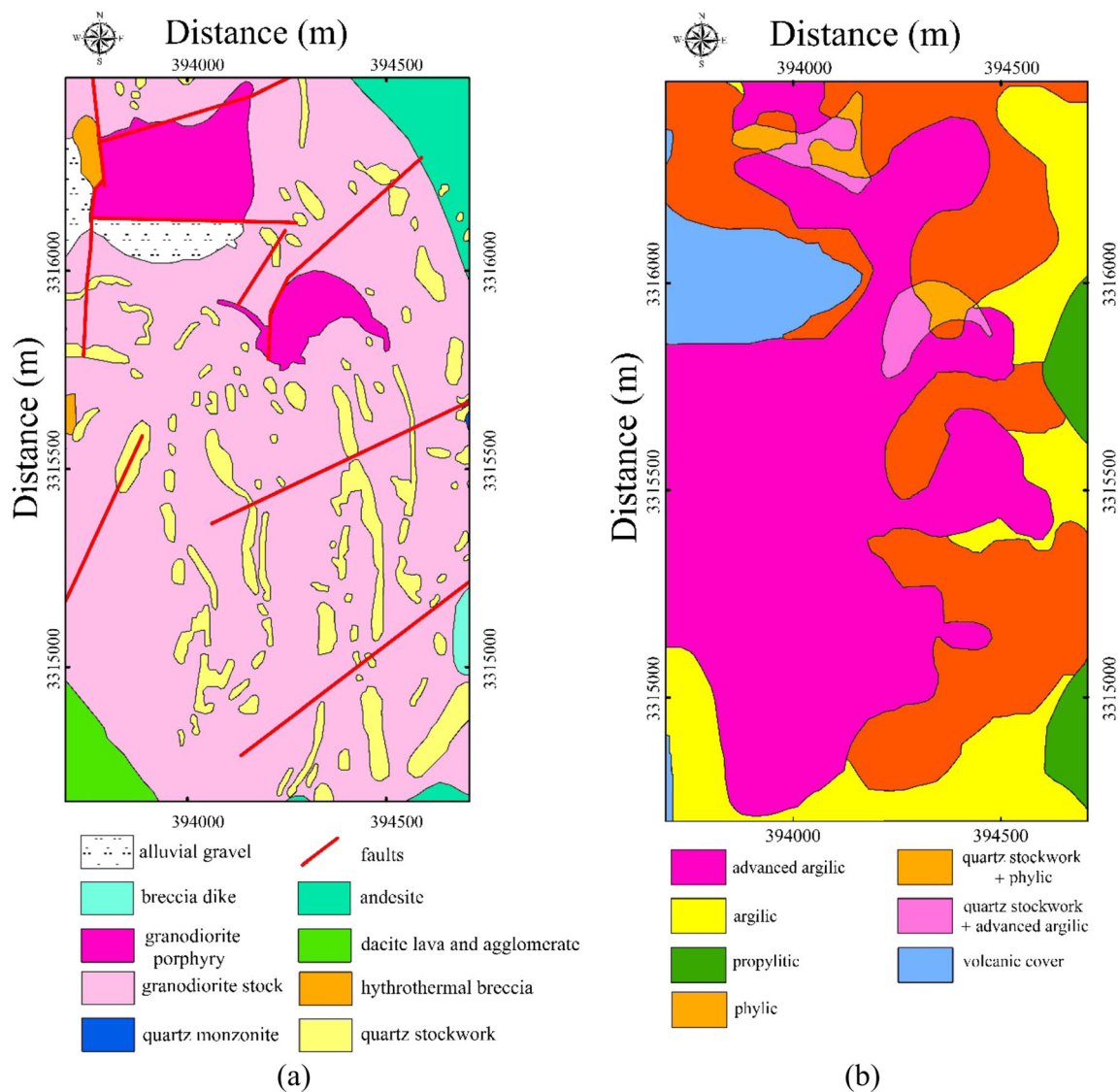
**Geological Layer**

The porphyry granodiorite rocks were considered the main lithology of Cu-bearing mineralization while the alluvial gravel has the lowest effect on ore occurrences. The importance of other rocks lay at this interval (Fig.3a). The buffered fault traces were taken into account as the second geological evidential layer (Fig.3b), in which the adjacent rasters have higher values. Minimum weight was assigned to the background of fault layer since has low favourability for probable

ore occurrences. Here five buffers with different intervals (i.e., <20 m, 20–35 m, 35–45 m, 45–50 m, and >50 m) around the main traces are considered to represent the presence of mineralization in the adjacent regions. The weighted layer of alteration was also considered as an evidential map for final MPM. Figure 3c presents this map in which the quartz stockwork-phyllitic alteration was chosen as main alteration zone for Cu mineralization while the unaltered volcanic rocks toke the minimum value of importance.

**Geochemical layer**

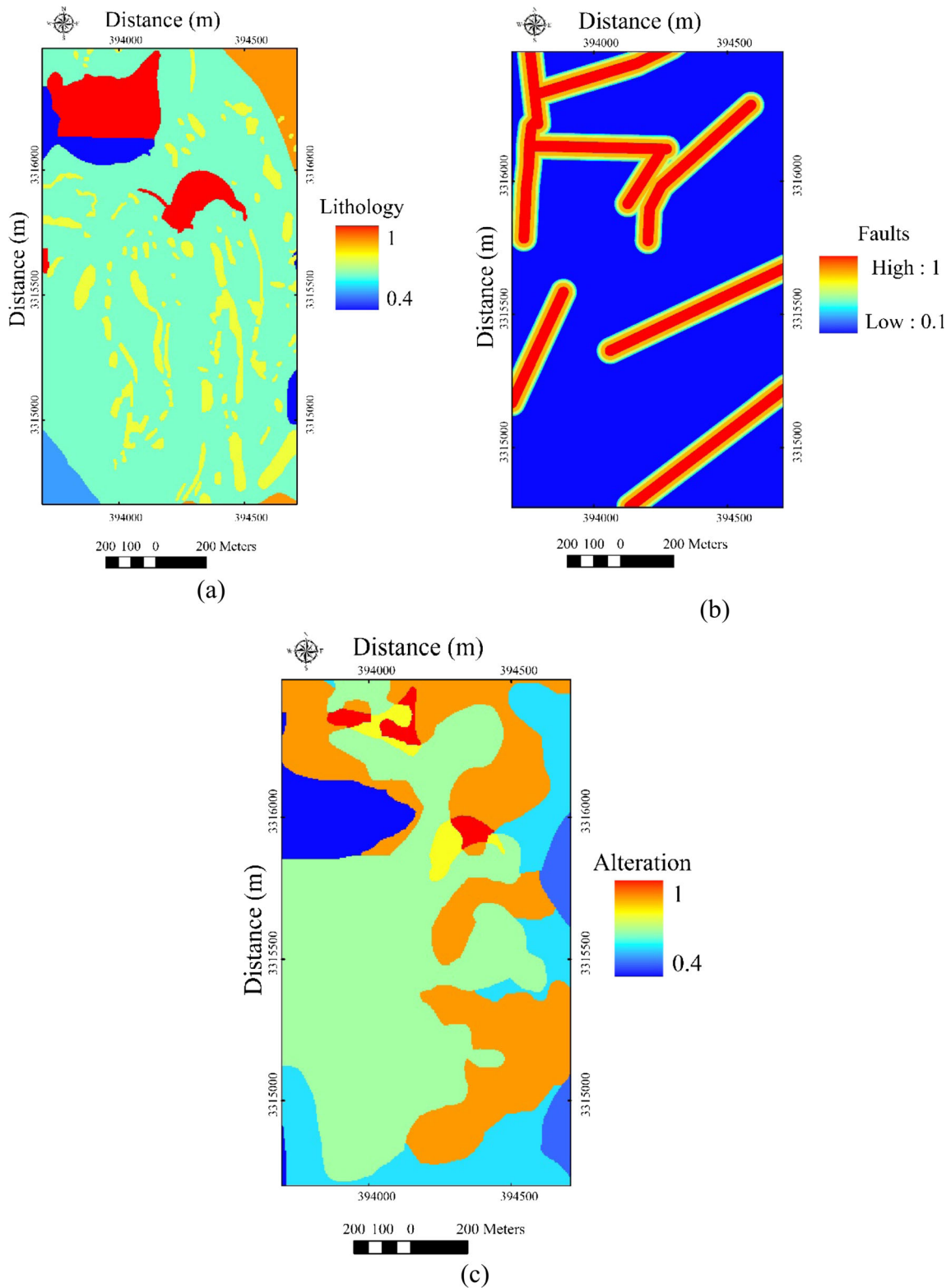
The geochemical layer shown in Fig. 4a indicates the distribution of metals, such as Cu, Mo and Pb. These elements have higher correlation with Cu concentration in the Seridune prospect. Since geochemical sampling was not conducted all over the region and subsequently access to the whole geochemical



**Fig. 2** The simplified geological map of the Seridune deposit, **(a)** the simple geological map, **(b)** the alteration map (reproduced from Barzegar 2007; Kazemi Mehria et al. 2011)

data was not possible. This layer was prepared based upon the on screen digitizing of previous published work by Barzegar 2007 (i.e., Chapter 6, Fig. 6.14). The distribution of metals is compiled from total of 100 rock samples collected throughout the Seridune prospect. The statistical parameters (e.g., range, mean, and median) are summarized for Cu, Mo and Pb elements in Table 1. The pattern of geochemical anomalies resulted from the concentrations of such metals is presented in Fig. 4a. The Cu and Mo show a concentric zoning over the two main quartz stockwork zones, meanwhile the strongest anomaly of Cu (>1000 ppm) occurs within the quartz stockwork zones associating with the quartz-sericite alteration. The copper anomaly extends toward the pyrite shell where the Cu content in the host rocks is more than 400 ppm. The high copper concentrations in rock correspond

to the abundance of malachite, azurite, chrysocolla ores and traces of chalcopyrite and bornite in veins. The Mo shows an anomaly of >30 ppm within the quartz stockwork zone although some of the samples are below detection limit for Mo. The Pb anomalies (> 400 ppm) overlay the argillic and locally the chlorite-epidote alteration zones around the iron-oxidized-pyrite shell. Metals (e.g., Cu and Mo) deposited by the early-transitional and the late hydrothermal process, were remobilized by leaching, transported towards the shallow groundwater table, and formed an enriched zone. The pattern of metal zoning in the Seridune prospect is inferred to be controlled by hydrothermal and supergene alteration processes (Barzegar 2007). The weighted layer of geochemical data shown in Fig. 4b was prepared based upon the favorability of mineral occurrence in the region.

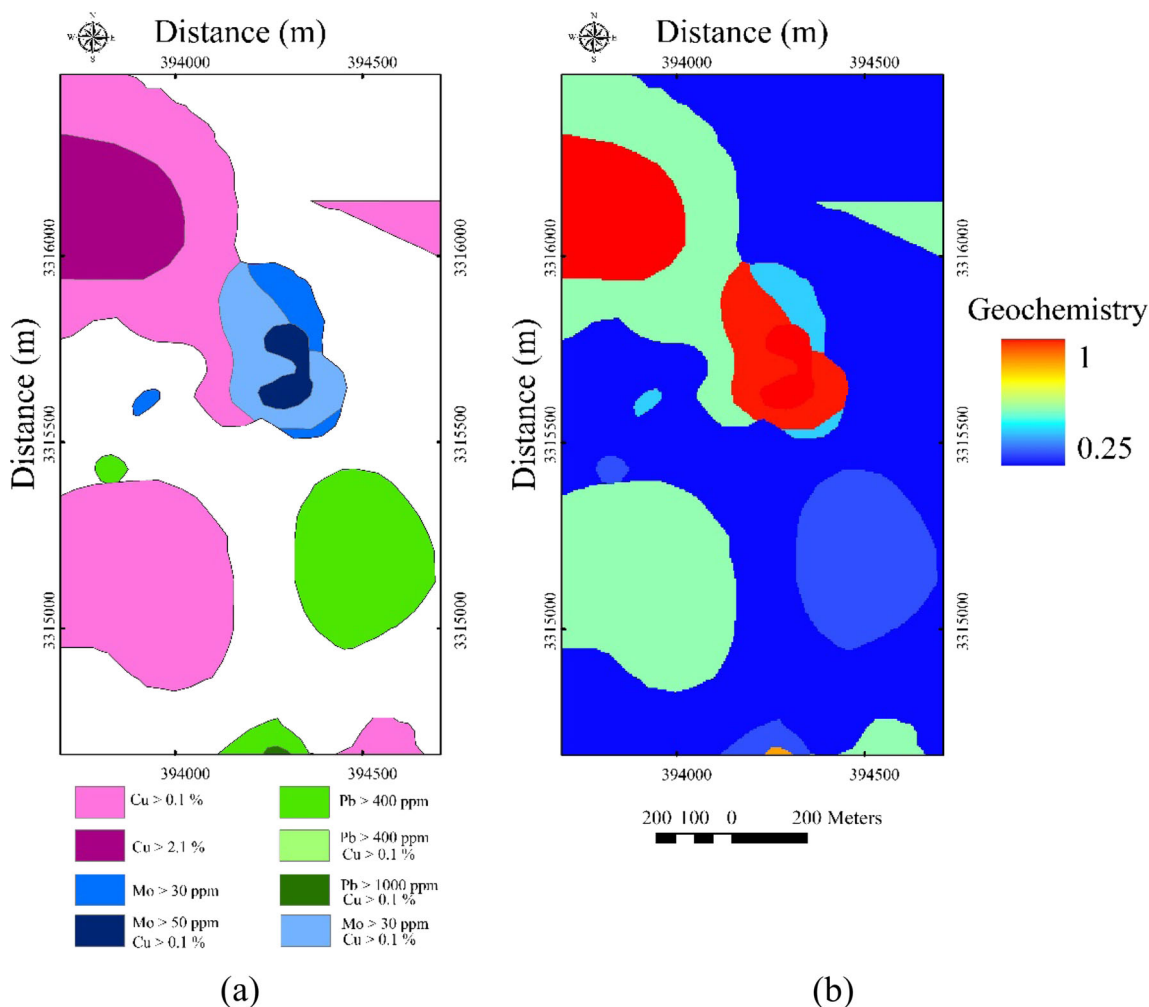


**Fig. 3** Evidential geological layers for MPM preparation, (a) rock types (lithology), (b) buffered faults, c altered zones

**Geophysical layer**

Two prevalent geophysical tools to prospect porphyry copper deposit are magnetic and electrical surveys. Magnetic methods

are used in the exploration and characterization of porphyry type deposits worldwide (Oldenburg et al. 1997; Hernández Pardo et al. 2012; Abedi et al. 2013d; Clark 2014). The primary control on bulk magnetic properties of host rock and magnetic



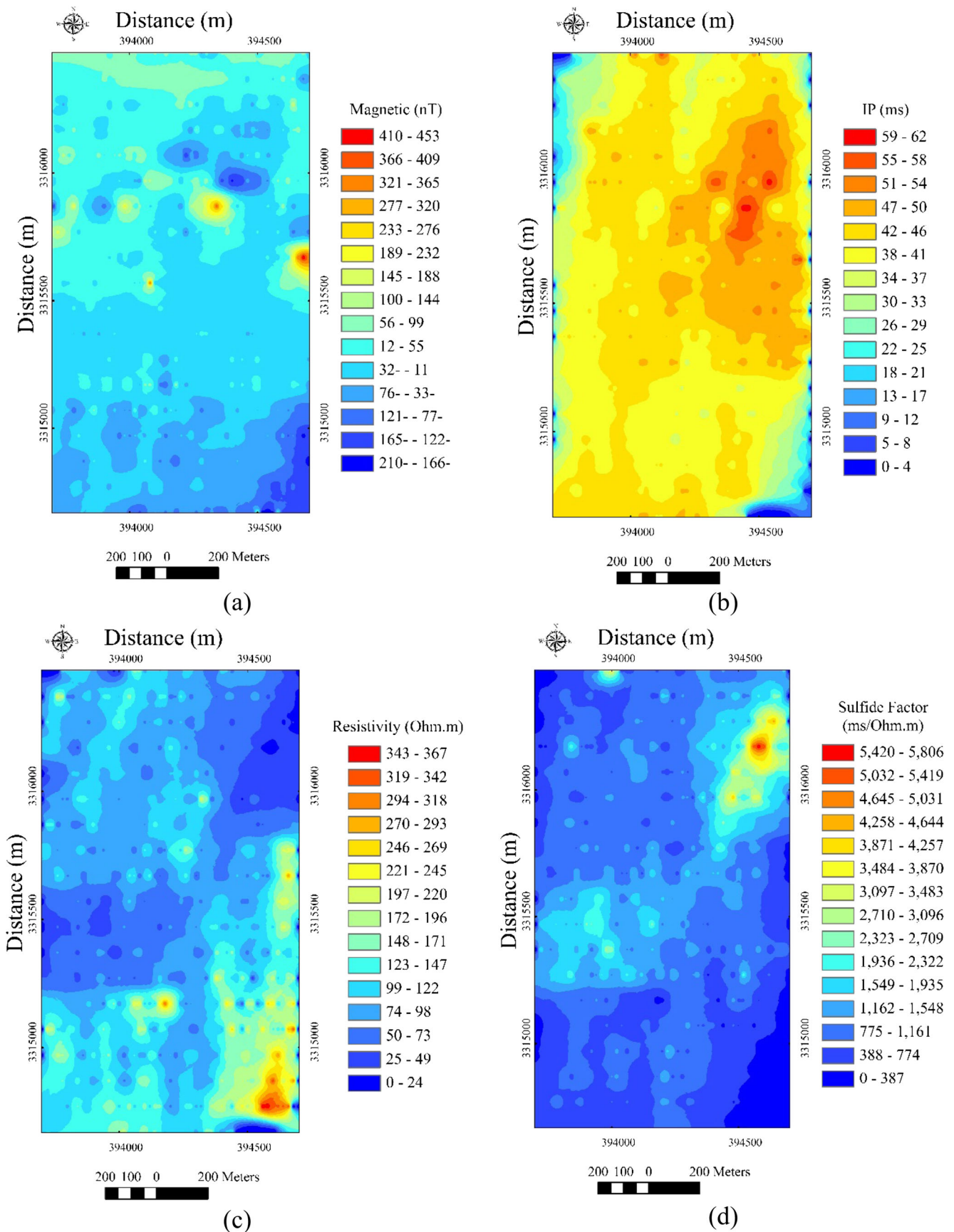
**Fig. 4** Geochemical layer, **(a)** metal concentration map, **(b)** weighted evidential map of geochemistry

intrusions is the partitioning of iron between oxides and silicates (Clark 1999), although sulfide minerals associated with hydrothermal alteration also provide fundamental, localized geophysical anomalies (John et al. 2010). Simple models for porphyry type deposits, especially copper, involve contrasting zones of alteration centered about the deposit. Magnetic anomalies reflect the location of these zones: (1) weak local magnetic highs over the potassic zone, (2) low magnetic intensity over sericitic zones, and (3) gradually increasing intensities over the propylitic zone (Thoman et al. 2000). In addition, minerals and rocks associated with hydrothermal alteration often have

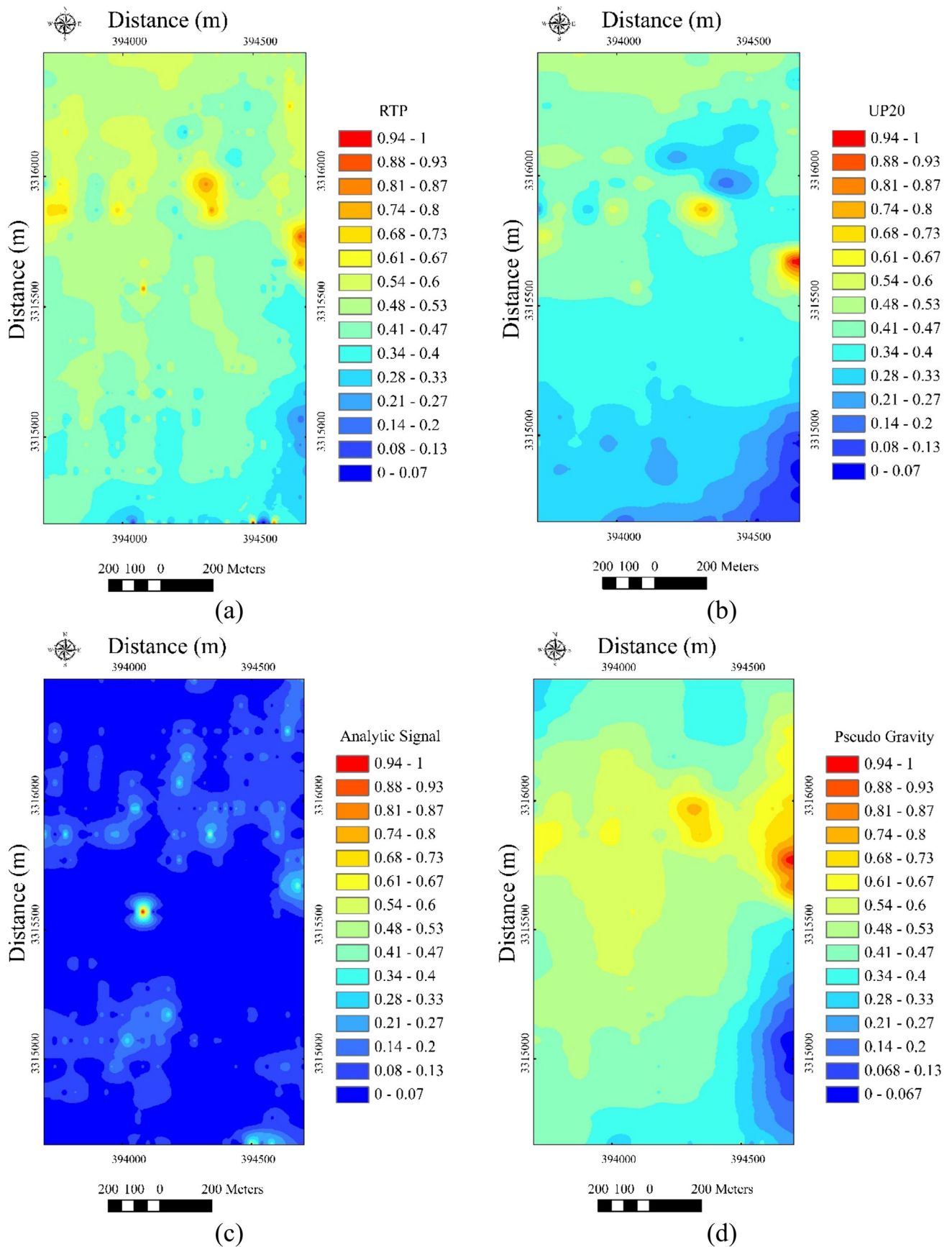
**Table 1** The statistical characteristic of the geochemical evidential layers (Barzegar 2007)

Element	Cu (ppm)	Mo (ppm)	Pb (ppm)
Range	1000–81,000	2–98	11–2024
Mean	1681	26.8	160
Median	66.5	20.85	66.50

anomalous electrical properties. Subsequently geophysical methods that detect and model such properties play important role in the exploration and characterization of porphyry copper deposits. Like the distribution of magnetic minerals, geoelectrical properties reflect the type and degree of hydrothermal alteration (Oldenburg et al. 1997; John et al. 2010). Hydrothermal minerals relevant to geophysical exploration are pyrite, chalcopyrite, chalcocite, biotite, and sericite. Similar to the magnetic anomalies, we would expect to see the intensity and type of alteration reflected in resistivity anomalies, with lowest resistivity centered on sericitic alteration that is developed in zones of most fracturing and fluid flow (Thoman et al. 2000; John et al. 2010). The dispersed nature of sulfide minerals in porphyry systems is particularly suitable for induced polarization (IP) methods as well (Sinclair 2007). In porphyry copper deposits, the strongest IP responses correlate with quartz-sericite-pyrite alteration (Thoman et al. 2000; John et al. 2010). The zone of potassic alteration in the core of the deposit is often low in total sulfide minerals while the surrounding zone of sericitic alteration has



**Fig. 5** Geophysical data, (a) residual magnetic anomaly, (b) IP “chargeability” map, (c) apparent resistivity map, (d) sulfide factor map



**Fig. 6** Geophysical evidential layers, (a) RTP, (b) UP20, (c) AS, (d) PG, (e) IP, (f) RS, (g) SF



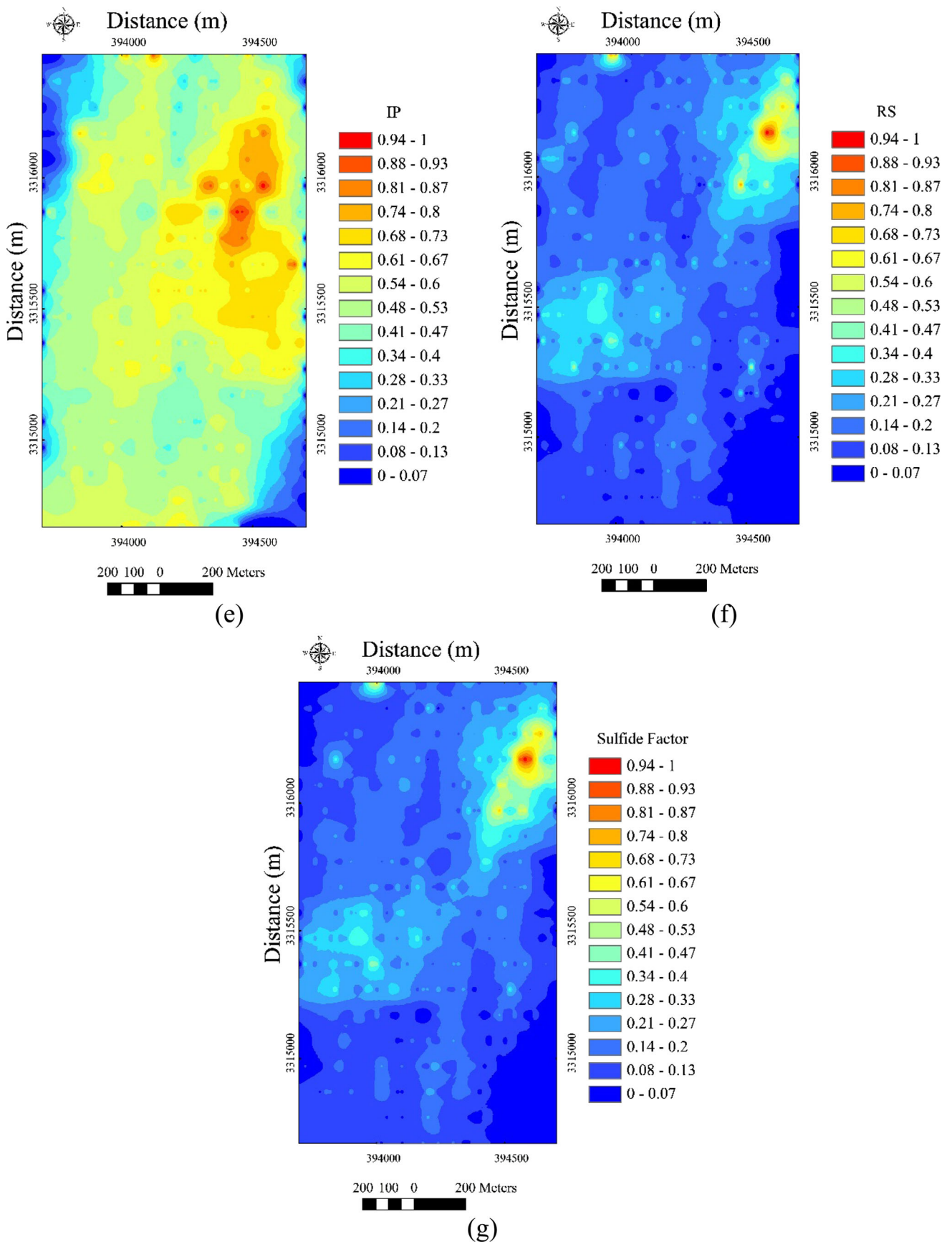


Fig. 6 (continued)

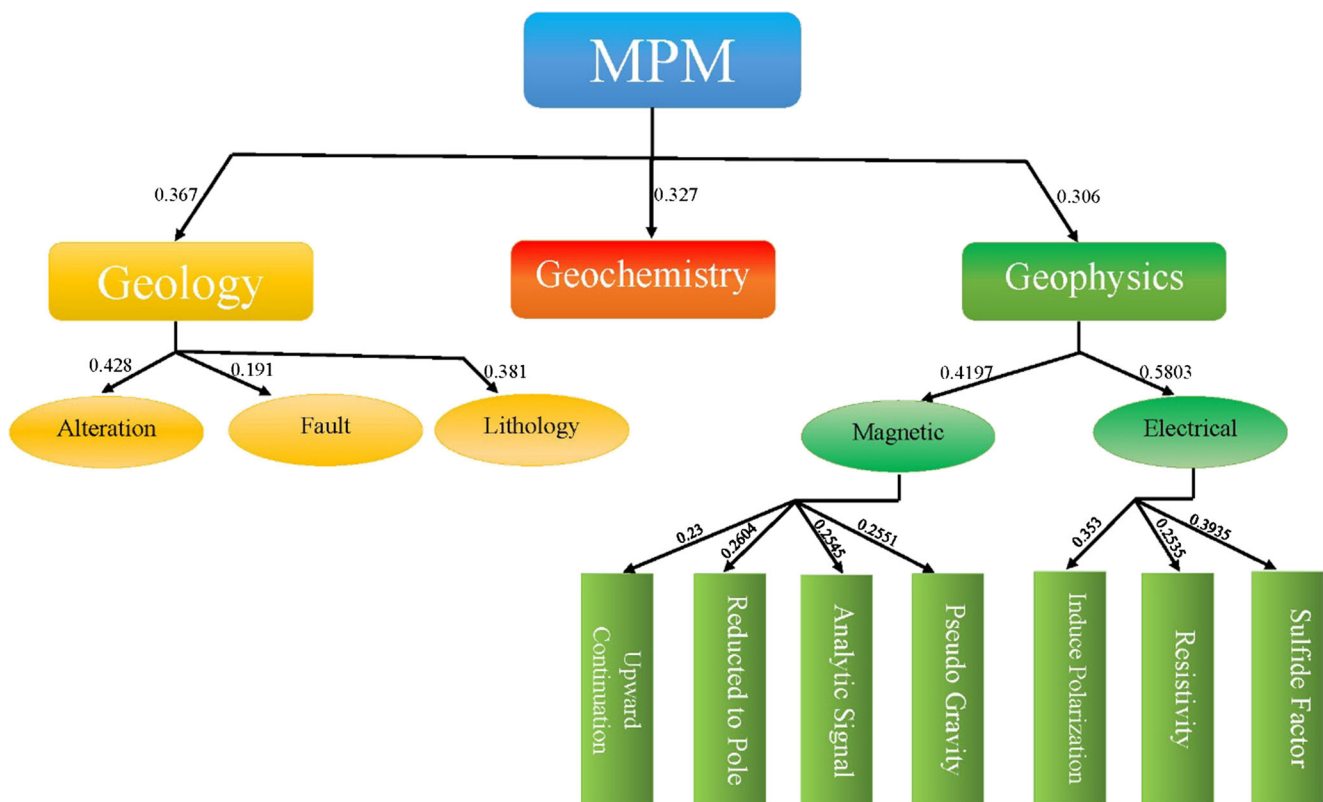
high sulfide content, including pyrite, and the distal zone of propylitic alteration has low pyrite. Thus, the sericitic zone of alteration is an important IP target (John et al. 2010). Therefore, various evidential layers can be derived from the magnetic and geo-electrical surveys to produce final MPM (Abedi et al. 2012a, 2012b; Abedi et al. 2013b).

In this study, seven geophysical layers are extracted to prepare prospectivity map. Ground-based magnetic data acquisition was the first conducted geophysical survey in the area, whereby distances between profiles and stations were 100 and 20 m, respectively, to cover the whole area with a dense pattern of survey. Magnetic prospect along with the rectangle gradient array are two common preliminary geophysical surveys in exploration of porphyry type deposits. Based upon the acquired results, it is decided to conduct 2D electrical profile over high potential zones detected by processing of such surveys. Here the regional geomagnetic field was 45,770 nT (inclination = 46.4°, declination = 2.3°). The residual magnetic data after removing the regional trend of the Earth's magnetic field have been plotted in Fig. 5a. A general filter operation applied to the residual magnetic data is the reduced to the pole (RTP) shown in Fig. 6a, which converts magnetic anomaly to symmetrical pattern by transmitting the magnetization vector to the pole. RTP technique eliminates the dipolar nature of magnetic anomalies and puts the peak of anomaly over the causative magnetic source (Ansari and Alamdar 2009).

Analytical upward continuation filter was used because it is suspected that copper deposit exists at depth. This method calculates the magnetic field further to the causative source and consequently results in a better map of deep deposit, reduces the effect of shallow structures with high frequency and remove noise effect on the observation (Abedi et al. 2013b). Indeed, it could better present the main body of causative sources in depth. Map of residual RTP magnetic data that were upward continued to 20 m (UP20) is shown in Fig. 6b.

Many filters are available to enhance magnetic field data, such as downward continuation, horizontal and vertical derivatives, and other forms of high-pass filters. One of these techniques is the analytic signal method that is effective to detect and enhance the borders of causative sources (Fig. 6c). The basic concept of the analytic signal method for magnetic data was extensively discussed by Nabighian (1972, 1974, 1984). This filter could better present the locations of ore-bearing intrusive complexes in the prospecting region.

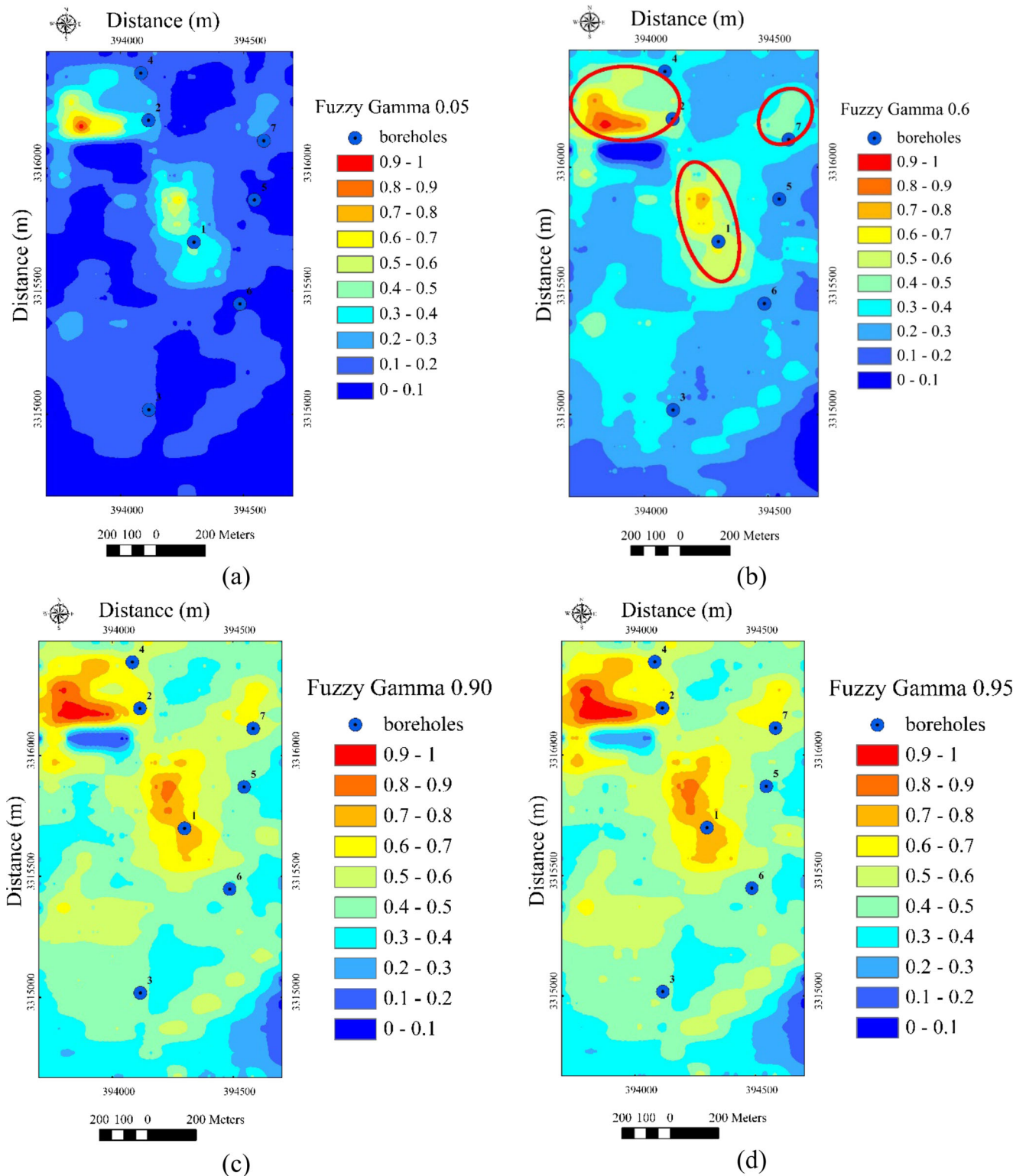
Pseudo gravity (PG) transformation of magnetic data is based upon Poisson relation that transforms magnetic anomaly to gravity one. The assumption is that both the magnetic and gravity signals are caused by the same anomalous body (with the same geometry) and that magnetic anomalies are entirely induced by the present geomagnetic field (no remanent magnetization). This filter can show the boundary of anomalies better than magnetic data (shown in Fig. 6d), and



**Fig. 7** The inference network for preparation of the final MPM. The normalized weight of each evidential layer has been superimposed on it

can be a simple tool to interpret by geologist (Abedi et al. 2013b). Interested readers are referred to Blakely (1995) for additional details of this transformation.

The most common geophysical methods for exploration of sulfide mineralization are geo-electrical techniques (Oldenburg et al. 1997; John et al. 2010). In this study, resistivity (RS),



**Fig. 8** The final MPM for different values of Fuzzy Gamma operator, (a) 0.05, (b) 0.60, (c) 0.90, (d) 0.95. The locations of drilled boreholes have been superimposed on the maps with circle symbol. Three ellipsoids present the location of high potential zone of Cu-bearing mineralization

induce polarization (IP) “chargeability map”, and sulfide factor (SF) map (as a ratio of chargeability to resistivity) are used (shown in Fig. 5b, c and d). Rectangular array with 1200 m space as current electrode was used in the study area such that distances between profiles and stations were 100 and 20 m, respectively. The values of these map were linearly transformed to the interval of 0–1 to present high potential zones for Cu-bearing mineralization (Fig. 6e, f and g). The lower values of RS layer in Fig. 5c correspond to higher potential zones in Fig. 6f, whereas high values of IP and SF maps correspond to high potential zones of probable mineral occurrences in the region.

### Mineral potential mapping

The inference network for preparation of the final MPM is shown in Fig. 7. The normalized weight of each evidential layer which has been derived from the results of previous studies (Abedi et al. 2013b) and the knowledge of experts in porphyry Cu exploration has been superimposed on the network. The fuzzy operator Sum and Gamma were used to integrate eleven evidential layers extracted from a multi-disciplinary geo-dataset of geology, geophysics and geochemistry. The fuzzy Sum operator were applied to seven weighted geophysical layers in order to generate a sum map of geophysics criteria, and also the sum operator employed to three geological layers for preparation of a sum map of geology. Subsequently the fuzzy Gamma operator was used to integrate three layers consisting of the one geochemical layer and two fuzzy Sum maps of geophysics and geology. Different values of Gamma ( $\gamma$ ) were considered to prepare final MPM shown

in Fig. 8. High values of the generated MPMs correspond to high potential zone in Seridune copper deposit for ore-bearing mineralization. The locations of seven drilled boreholes have been superimposed on the final MPMs. The Cu concentration along each borehole at depth is shown in Fig. 9 for all drilled ones. The MPM maps for four different values of  $\gamma$  (i.e. 0.05, 0.60, 0.90 and 0.95) are indicated in Fig. 8 in which high values of MPM or higher favorability for Cu occurrences correspond to the regions with red color. The rest of the area with blue color has lower potential for ore mineralization and consequently is excluded from further investigation.

### Discussion

To evaluate the results of produced MPMs, the information acquired from seven drilled boreholes is considered. To rank the importance of each borehole, a productivity criterion consisting of the amount of Cu grade above an economical cut-off value multiplied by its thickness above assumed threshold is used. Higher values of this criterion correspond to boreholes with higher productivity in crossing the main source of ore mineralization. Table 2 indicates the productivity values for seven boreholes assuming three cut-off grades value of Cu (i.e. 0.10, 0.15 and 0.20 %). The cut-off value of 0.2 % Cu is also the economical threshold for ore extraction and mine designing.

Based upon the productivity values presented in Table 2, the boreholes 2, 1 and 7 have respectively the highest value that could properly crosses the main source of Cu mineralization.

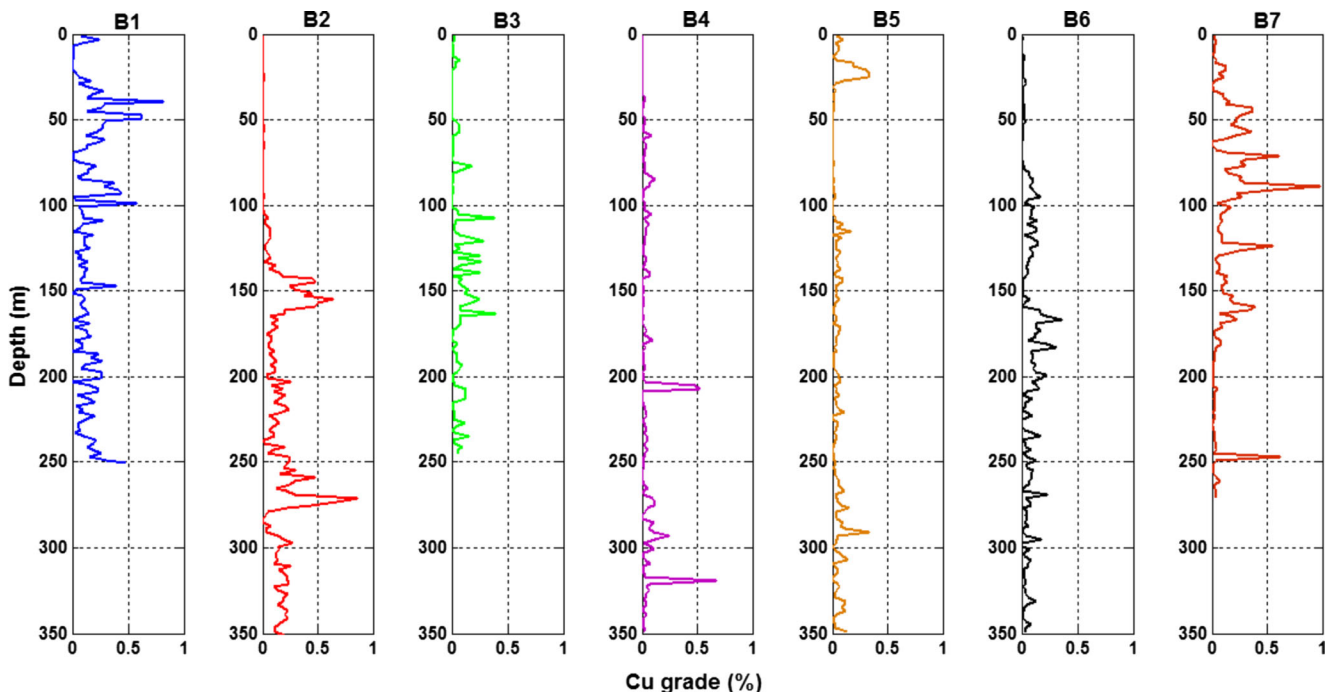


Fig. 9 Seven drilled boreholes in the studied area in which Cu concentration versus depth are plotted

**Table 2** The productivity values of seven drilled boreholes for three cut-off value of Cu grade

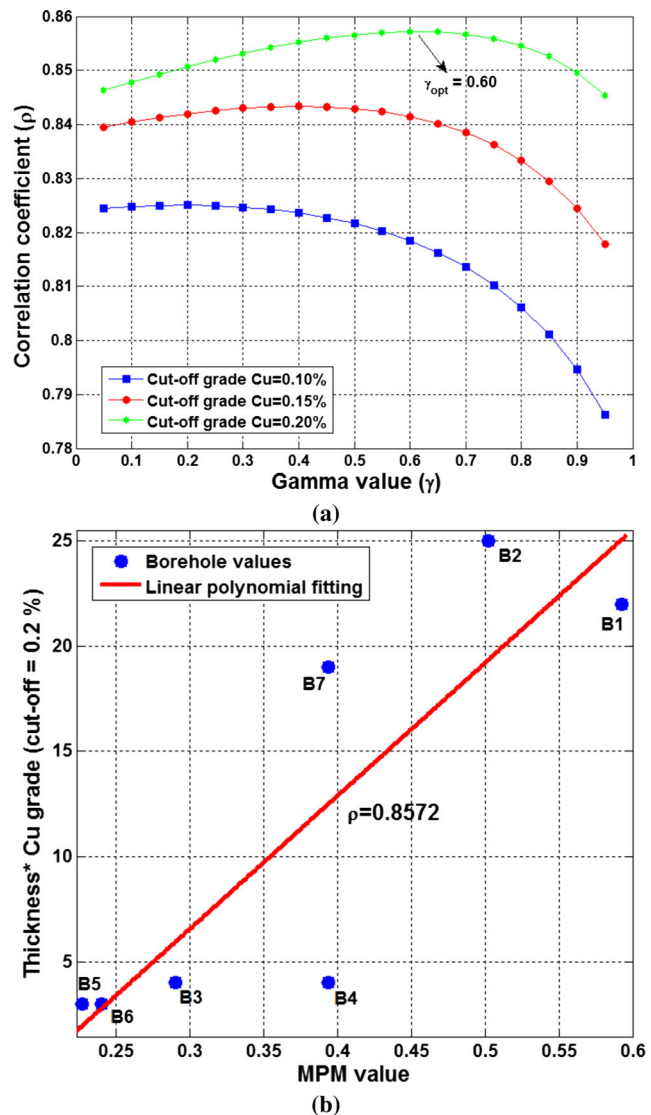
Borehole ID	X coordinate (m)	Y coordinate (m)	Length (m)	Cut-off value of Cu grade (%)			Rank
				0.10	0.15	0.20	
1	394,299	3,315,699	251	32	27.00	22	2
2	394,114	3,316,195	360	37	31.00	25	1
3	394,116	3,315,018	247.7	7	6.00	4	5
4	394,083	3,316,386	353	5	4.00	4	7
5	394,546	3,315,870	350.3	6	4.00	3	6
6	394,486	3,315,448	350	11	6.00	3	4
7	394,584	3,316,112	272.5	25	22.00	19	3

To evaluate the results acquired from the integration of the multi-disciplinary geo-dataset, the correlation coefficient ( $\rho$ ) between the productivity values and MPM values for different amounts of  $\gamma$  was calculated. Figure 10a shows the curves acquired from three cut-off grade of Cu in which the curve of  $\rho$  versus the amount of  $\gamma$  have been plotted. The higher amount of  $\rho$  indicates that the produced MPM for that amount of  $\gamma$  could better present the location of Cu mineralization. Indeed, the MPM map would be better in agreement with the drilled boreholes. The  $\rho$  values for an economical cut-off grade value of 0.2 % Cu reaches to a maximum at  $\gamma_{opt}=0.60$ . The  $\rho$  value is equal to 0.86 for  $\gamma_{opt}$ . Figure 10b shows the scatter plot map of the productivity values acquired from seven boreholes versus the MPM values for  $\gamma_{opt}=0.60$ . The fitted linear curve has a  $\rho=0.86$ . It shows the high applicability of the fuzzy operators in generating MPM based upon diverse evidential layers of exploratory data.

For an economical cut-off grade value of 0.2 % Cu and different amounts of  $\gamma$  operator, the  $\rho$  values changes at interval of approximately 0.84–0.86. Therefore, the final produced MPM is not substantially sensitive to unknown value of  $\gamma$ . The optimum MPM map shown in Fig. 8b presents three separated high potential zones (with red color) in which the MPM values attain to maximum amounts. These three zones are recommended for additional exploratory drilling in the Seridune Cu deposit in order to acquire more accurate information about ore occurrence and grade of Cu in the high potential zones of such mineralization. Compared to the rest of drilled boreholes with approximately similar low values of productivity criterion, three productive ones (i.e. boreholes 2, 1 and 7) have the highest values and locate at three suggested high potential zones for further investigation (Fig. 8b).

**Conclusion**

The mineral prospectivity/potential map was prepared by fusion of diverse evidential layers derived from a multi-disciplinary



**Fig. 10** Validation of MPM with seven drilled boreholes, (a) correlation coefficient values versus different Fuzzy Gamma values for different cut-off grade of Cu concentration, (b) the curve of the productivity value of drilled boreholes versus MPM value assuming a cut-off grade of 0.2 % and an optimum value of  $\gamma=0.6$

exploratory geo-dataset. Eleven layers extracted from the geological, geophysical and geochemical data were successfully integrated by the usage of the fuzzy operators of sum and gamma. The produced MPM could appropriately delineate high potential areas of Cu-bearing mineralization at three separated zones of Seridune prospect. The productivity of seven drilled boreholes in the region were in good agreement with the results of the MPM maps. These productivities were calculated by multiplying Cu concentration and ore thickness along each borehole for a threshold value of Cu grade. Three high ranked boreholes which showed the highest productivity values were located at three recommended high potential zones of Cu occurrences in prepared MPM, showing the strong applicability of the produced MPM to recommend additional exploratory boreholes for further investigation of the Seridune porphyry copper deposit. The highest correlation coefficient between the productivity criterion and MPM map was about 0.86 as well.

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