

# Fuzzy logic modeling for hydrothermal gold mineralization mapping using geochemical, geological, ASTER imageries and other geo-data, a case study in Central Alborz, Iran

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**Abstract** The study area is located ~50 km in the north of Tehran capital city, Iran, and is a part of central Alborz Mountain. The intrusive bodies aged post Eocene have intruded in the Eocene volcanic units causing hydrothermal alterations in these units. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images were used to map hydrothermal alteration zones. The propylitic, phyllic and argillic alteration and iron oxide minerals identified using Spectral Angle Mapper (SAM) method. Structural lineaments were extracted from ASTER images by applying automatic lineament extraction processes and visual interpretations. An exploration model was considered based on previous studies, and appropriate evidence maps were generated, weighted and reclassified. Ore Forming Potential (OFP) map was generated by applying Fuzzy SUM operator on alteration and Pb, Cu, Ag, and Au geochemical anomaly maps. Finally, Host rock, geological structures and OFP were combined using Fuzzy Gamma operator ( $\gamma$ ) to produce mineral prospectivity map. Eventually, the conceptual model discussed here, fairly demonstrated the known hydrothermal gold deposits in the study area and could be a source for future detailed explorations.

**Keywords** GIS · Remote sensing · Gold mineralization · Fuzzy · Alborz

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## Introduction

One of the most important steps of mineral exploration involves the collection, analysis, and integration of data from different surveys (e.g., geological, geophysical, geochemical) for mineral prospectivity mapping (MPM) to delineate prospective areas for further investigations.

The geo-processing methods for MPM are divided into two main categories: empirical (data driven) and conceptual (knowledge driven) methods (Bonham-Carter 1994). In the empirical approach, the known mineral deposits are used as ‘training points’ for examining spatial relationships between the known deposits and particular geological, geochemical and geophysical features. The identified relationships between the input data and the training points are quantified and used to establish the importance of each evidence map and finally integrated into a single mineral prospectivity map. Examples of the empirical methods used are weights of evidence, logistic regression and neural networks. The other major branch is the conceptual (knowledge driven) approach, where we use re-formulation of knowledge about deposit formation into map-able criteria (i.e. threshold values in geochemistry and geophysics etc., certain structures or formations in the geological maps). The areas that fulfill the majority of these criteria are highlighted as being the most prospective. These methods are dependent on the geologist’s input and exploration models being thus fairly subjective in nature. By selecting a conceptual method one can benefit from the expertise of the geologists during the modeling process exceeding the capabilities of pure statistics. The methods belonging to this branch include Boolean logic, index overlay (binary or multi-class maps), the Dempster-Shafer belief theory, and fuzzy logic overlay). The selection of the preferable method is thus often made based on the available datasets and the goals of the modeling (Nykänen and Salmirinne 2007). The fuzzy logic method has been recently widely implemented for the data

integration and MPM purposes (Bonham-Carter 1994; Carranza and Hale 2001; Quadros et al. 2006; Nykänen and Salmirinne 2007; Nykänen et al. 2011; Abedi et al. 2012, 2013a, b). The fuzzy method enables evidence maps to be combined into a series of steps regarded as an inference net (flowchart), instead of combining them in a single operation. The inference net is a simulation of the logical process defined by a specialist (Quadros et al. 2006).

In this study the fuzzy logic technique selected due to its flexible capability to demonstrate its potential for exploration of the hydrothermal gold mineralization in the study area located in the north of Tehran, Iran. Several studies have shown the feasibility of multispectral remote sensing for mapping the hydrothermally altered rock (e.g. Rowan et al. 1977, 2006; Buckingham and Sommer 1983; Almeida-Filho and Vitorello 1997; Kruse et al. 1993; Sabins 1999; Ferrier et al. 2002; Agar 2005; Tommaso and Rubinstein 2007; Azizi et al. 2010; Gabr et al. 2010). Spectral discrimination of potential areas of gold mineralization (e.g., hydrothermal alteration zones and iron gossans) is a common application of remote sensing (Gabr et al. 2010). Here, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data processes and analyzed for gold mineralization mapping in the study area.

Spectral angle mapper (SAM) method is one of the most powerful remotely sensed data processing for geological prospects (Kruse et al. 1993). It was developed for hyperspectral images earlier, and then used widely for lower resolution imageries (Rowan and Mars 2003). This technique has been recently used to map alteration zones related to Cu and Au mineralization (Tommaso and Rubinstein 2007; Azizi et al. 2010; Gabr et al. 2010).

The distribution pattern of hydrothermal alteration zones used as a key to allocate the main outflows of the hydrothermal system, which may lead to the recognition of mineralized zones within the study area. Then, a GIS-based spatial analysis was applied to evaluate the gold potential in the study area via mineral favorability maps in order to define areas for detailed investigations.

## Geological setting

The study area is located in the northern Iran, and is a part of central Alborz Mountains (Fig. 1). The Alborz Mountain Range is a part of Alpine-Himalaya orogeny that is located at the south of the Caspian depression in the north of Iran. Alborz belt was affected by several successive tectonic events, from the Eo-Cimmerian orogeny to Late Tertiary-Quaternary intercontinental transpression (Allen et al. 2003), and is still strongly seismically active (Ritz et al. 2006). Important compressional events also occurred at the end of the Cretaceous (Guest et al. 2006), related to retro-arc compression induced

by the subduction of the Neotethys below the Sanandaj-Sirjan zone and by the subduction of the Nain-Baft ocean directly below Central Iran (Ghasemi and Talbot 2006). These compressional events have played a major role in evolution of the Alborz Tertiary magmatism. Following the late Cretaceous orogenic movements in Iran, immense volumes of lavas with tuffaceous and other clastic sediments were deposited during Eocene times. A part of these volcanic rocks are exposed in the Central Alborz Mountains. The composition of volcanic rocks ranges from basalt to rhyolite. Tertiary sub-volcanic igneous rocks are also found as sills, dykes and stocks in the Central Alborz Mountains, in the north of Tehran. The igneous rocks have intruded sedimentary, volcano-sedimentary and volcanic rocks of Eocene age and causing hydrothermal alteration in these units.

There are signs of Au, Cu and Pb mineralization in the area. In the northern part of Darband, silicic, kaolinitic and sericitic tuffs exposed beside the thick andesitic lava flows. Hydrothermal phases related to abundant small intrusive bodies and dykes affected tuffs through faults and fractures and caused alteration and formation of pyrite in these rocks (Axen et al. 2001).

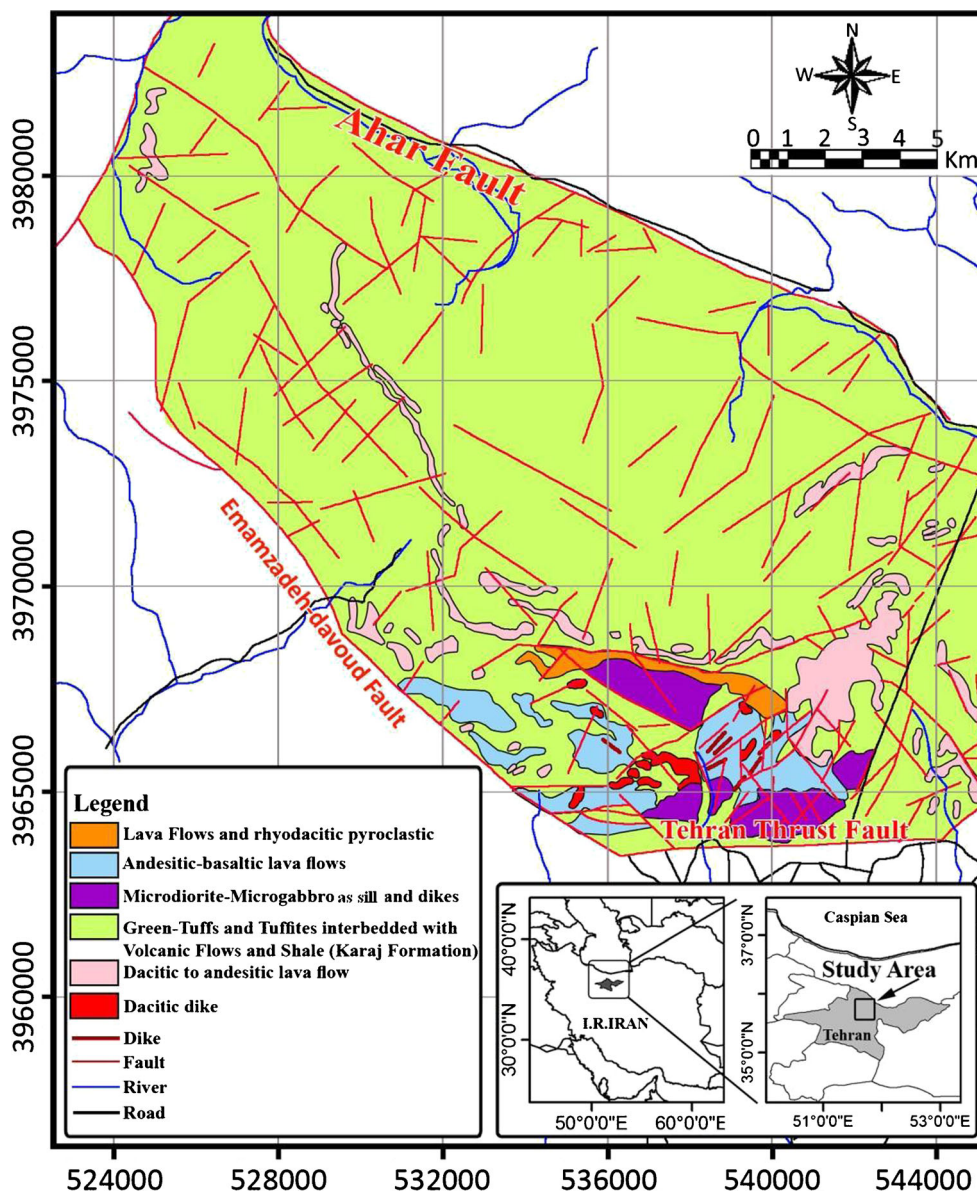
## Material and methods

### Field data

Two Fieldwork surveys were conducted in May and August 2010. These works included collecting structural data, sampling hydrothermally altered and unaltered rocks, recording the locations of mineralized zones. The coordinates of all sampling location recorded by a handheld GPS. Forty-five thin sections and 18 polished sections of hard and unaltered rocks, and hydrothermally altered rocks prepared for microscopic studies. Volcanic rocks are the most frequent outcropping rocks, although sedimentary rocks are also common in the central part of the study area (Fig. 1). The hydrothermal alteration is classified as phyllic, propylitic and argillic alteration. The study area is characterized by igneous rocks that frequently show the effects of hydrothermal alteration. Known Au indexes are located in these hydrothermally altered rocks.

A geochemical exploration project was conducted in 2004 in the north of Tehran province, Iran by Geological Survey of Iran (Asvadi 2004). In this project, more than 250 hard rocks and stream sediment samples were collected and analyzed for 44 elements. In the current study, 52 stream sediment samples pertaining to the study area selected to determine Au, Ag, Cu and Pb geochemical anomalies. Graphite furnace AAS used to determine Au and ICP-MS used to analyze other elements. The detection limits of the instruments are 1 ppb for Au and 0.01, 0.2 and 0.2 ppm for Ag, Cu and Pb.

**Fig. 1** Location and geological map of the study area (Amini and Emami 1993). Map is projected in UTM zone 39, northern hemisphere



For modeling of uni-element geochemical anomalies thresholds estimated as the mean plus twice the standard deviation of a data set. Based on classical statistics and hypothesis testing, data should approach a symmetrical distribution and show presence of one population before any threshold estimation methods are applied (Carranza and Hale 2009). Histograms applied to characterized empirical density distribution of raw uni-element data sets (Au, Ag, Cu and Pb). The empirical density distributions of the data sets are all moderately right-skewed.  $\text{Log}_e$  transformation (Carranza and Hale 2009) applied to reduce asymmetry of empirical density distribution of data sets.

Each uni-element data set then interpolated to a raster using Kriging tool in ArcGIS® 9.3 and reclassified to a continuous scale from zero to one (from unfavorable to favorable) based on the defined thresholds.

This expedition revealed groups of stream sediment geochemical anomalies typical of epithermal gold±silver and base metal mineralization and used to identify anomalous zones of critical elements for gold exploration (Fig. 2).

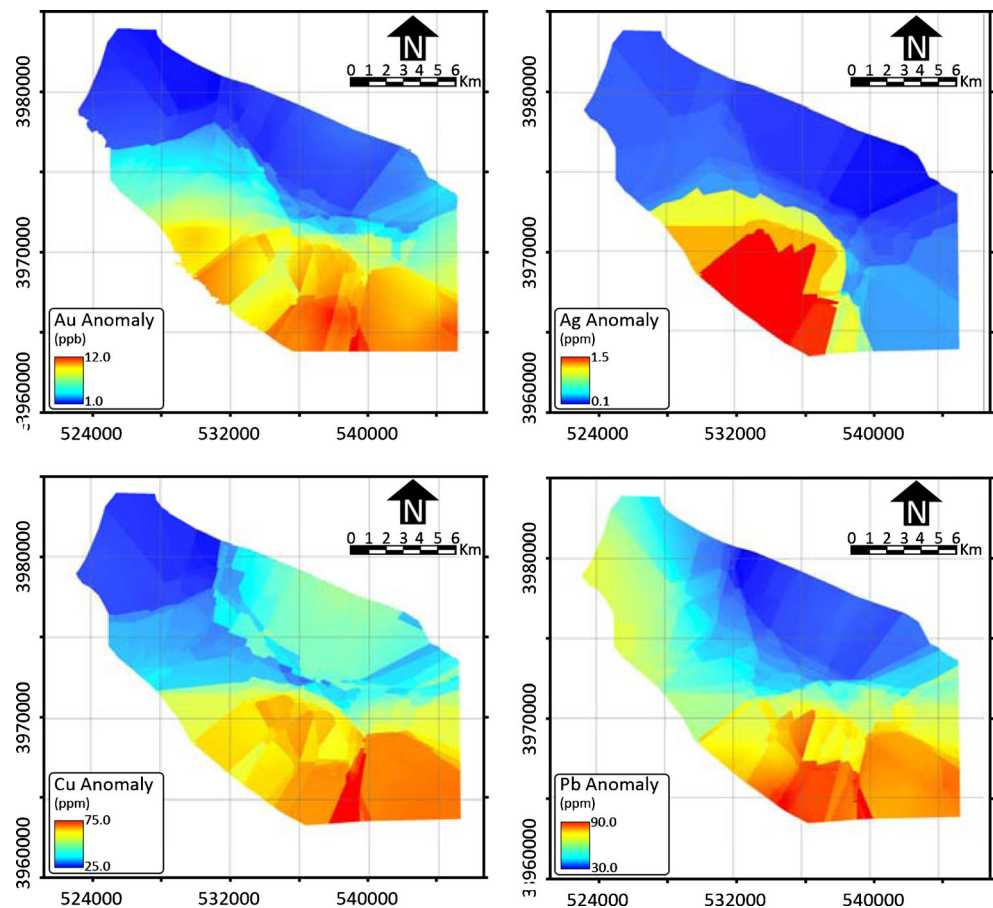
Satellite data

In the current study, ASTER data was used where the scene was collected on 10 August 2003. To preserve the spectral characteristics of the SWIR bands, the VNIR bands were spatially resized (nearest neighbor algorithm) to match the spatial resolution of the SWIR bands.

To minimize scattering and atmospheric absorption effects, ASTER data was converted into surface reflectance using FLAASH (Fast Line-of-sight Atmospheric Analysis of Hypercubes) module in ENVI®. Some major affecting



**Fig. 2** Geochemical anomaly maps of Au, Ag, Cu and Pb in the study area. Geochemical data obtained from, Asvadi 2004



parameters such as location of the area, average terrain elevation and satellite altitude, date and time of image acquisition, spectral response functions of the ASTER bands, and water vapor and atmosphere visibility values were specified in the atmospheric correction model. Details on the method can be found in Takashima et al. (2001).

On the ASTER false color composite image RGB: 631 (Fig. 3a), vegetation covers are in green color and hydrothermal gossans display in red color (Kalinowski and Oliver 2004). The red patches on the image were cross checked by field work. The collected tuffaceous rock samples were rich in iron-oxide minerals that represent gossan.

The principal component analysis (PCA) technique widely used in the image processing industry today to enhance and separate certain types of spectral signatures from the background (Gabr et al. 2010).

PCA applied to subsets of ASTER bands that selected according to the position of characteristic spectral features of key alteration minerals in the VNIR and SWIR portions of the spectrum. After applying PCA, the eigenvector matrix used to calculate PCA for each subset, used to identify which PC contains the target (mineral) information. The PC that shows the highest eigenvector contains the target spectral information (Crosta et al. 2003). In the current study, three subsets of ASTER bands (Table 1) selected according to the spectral

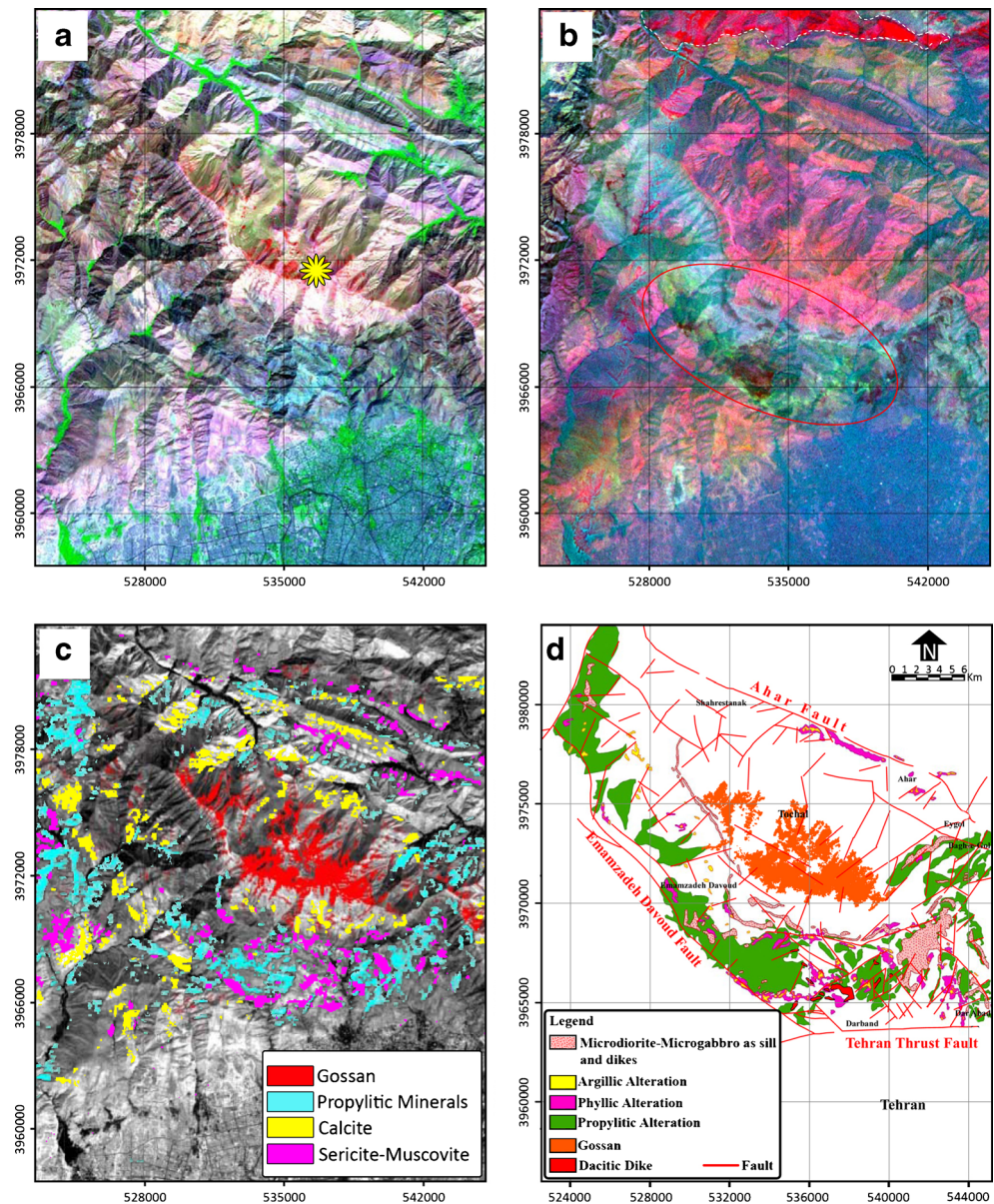
signatures of the key alteration minerals to detect hydrothermally altered zones in the study area.

After applying the PCA technique to each subset of ASTER bands, three mineral abundance images produced that each one showing areas most likely to contain the alteration minerals listed in Table 1. A color composite of abundance images in RGB mode (RGB: (PC3: 8,5,2), (PC3: 4,6,7), (PC3: 4,5,7)), used to discriminate the alteration zones in the study area. The greenish blue patches (in the red ellipse) show the hydrothermally altered rocks in the study area (Fig. 3b).

A partial spectral unmixing method based on the “Spectral Hourglass” scheme (Kruse et al. 2003) available in ENVI 4.7<sup>®</sup>, applied to separate different alteration zones in the study area (Fig. 3c). This method starts with reducing abundant information and data dimensionality using the Minimum Noise Fraction (MNF) transform then subsequently applies Pixel Purity Index-Mapping (PPI) for the determination of the purest pixels in the image and the extraction of end members utilizing the n-Dimensional-Visualizer tool (n-D-Vis). The extracted end members are then compared to known spectra from USGS spectral libraries to further identify and prepare for Spectral Angle Mapper (SAM) classification (Gabr et al. 2010). Finally, different alteration zones detected in the study area were mapped and are shown in Fig. 3d.



**Fig. 3** ASTER false color composite RGB: 631. Vegetation and gossans display green and red, respectively. The *asterisk* shows the location of rich iron-oxide tuff sample. **b** ASTER PCA false color composite RGB: (PC1: 8,5,2), (PC2: 4,6,7), (PC3: 4,5,7). The green-blue patches are hydrothermally altered rocks and light green patches are magmatic units (in the red ellipse). **c** Classification of major hydrothermally altered zone minerals using Spectral Angle Mapper (SAM) techniques. **d** Classified hydrothermal alteration map of the study area using ASTER satellite image analysis



Automatic lineament extraction process for ASTER data carried out with LINE module of PCI Geomatica® software. Then, the extracted linear features were compared with false composite color images RGB: 631 and RGB: 321 to detect structural lineaments visually. N-S and NE-SW trends of

faults expected to be significant sites for deposition of gold in the study area (Asvadi 2004).

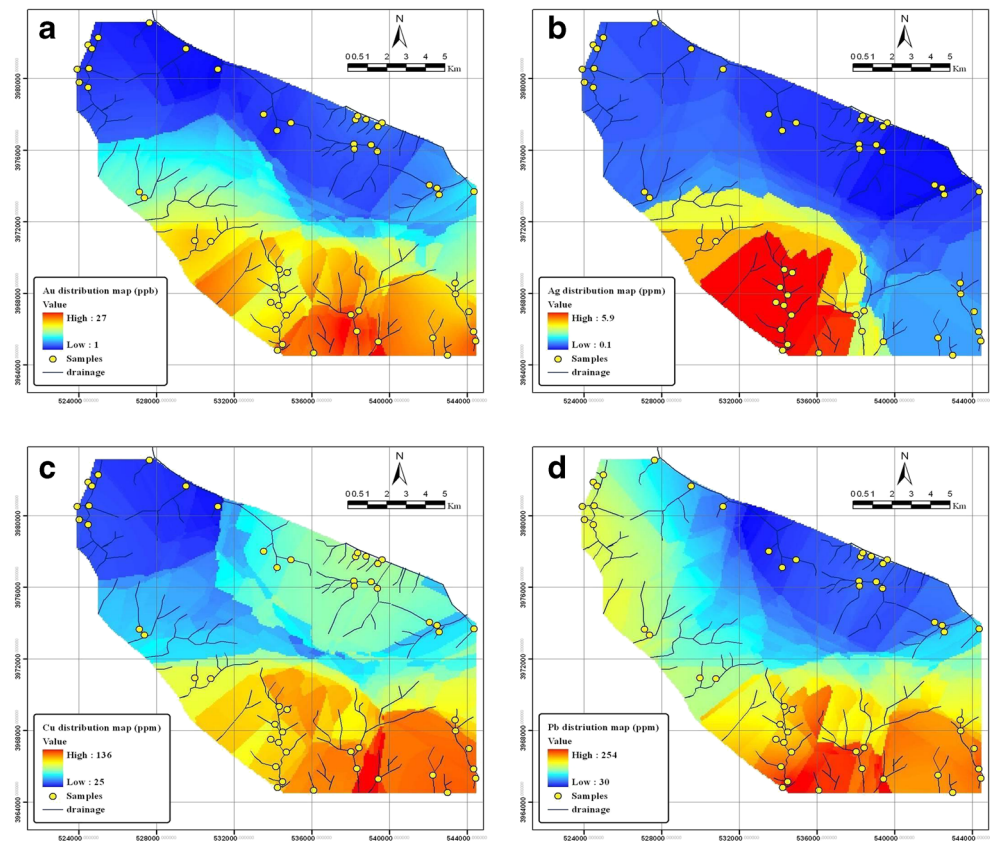
**Table 1** Subsets of ASTER bands used to generate mineral abundance maps in the study area through PCA

	Alteration minerals		
	Kaolinite+Sericit	Alunite	Calcite+Chlorite+Epidote
ASTER bands	4	4	2
	6	5	5
	7	7	8

### Data analysis

A summary of data analysis methods for mineral potential mapping used in the current study is represented in Fig. 4. Exploration model defines the characteristics of deposit type, and thus gives guidelines for selecting the relevant data, especially those data best reflecting the measurable or mapable features related to deposit type (Nykänen et al. 2011). Exploration model also helps us to decide how to weight the relative importance of evidence maps for estimating the mineral potential. Proximity of deposits to some feature, such as

**Fig. 4** Concise data analysis methodology for mineral potential mapping



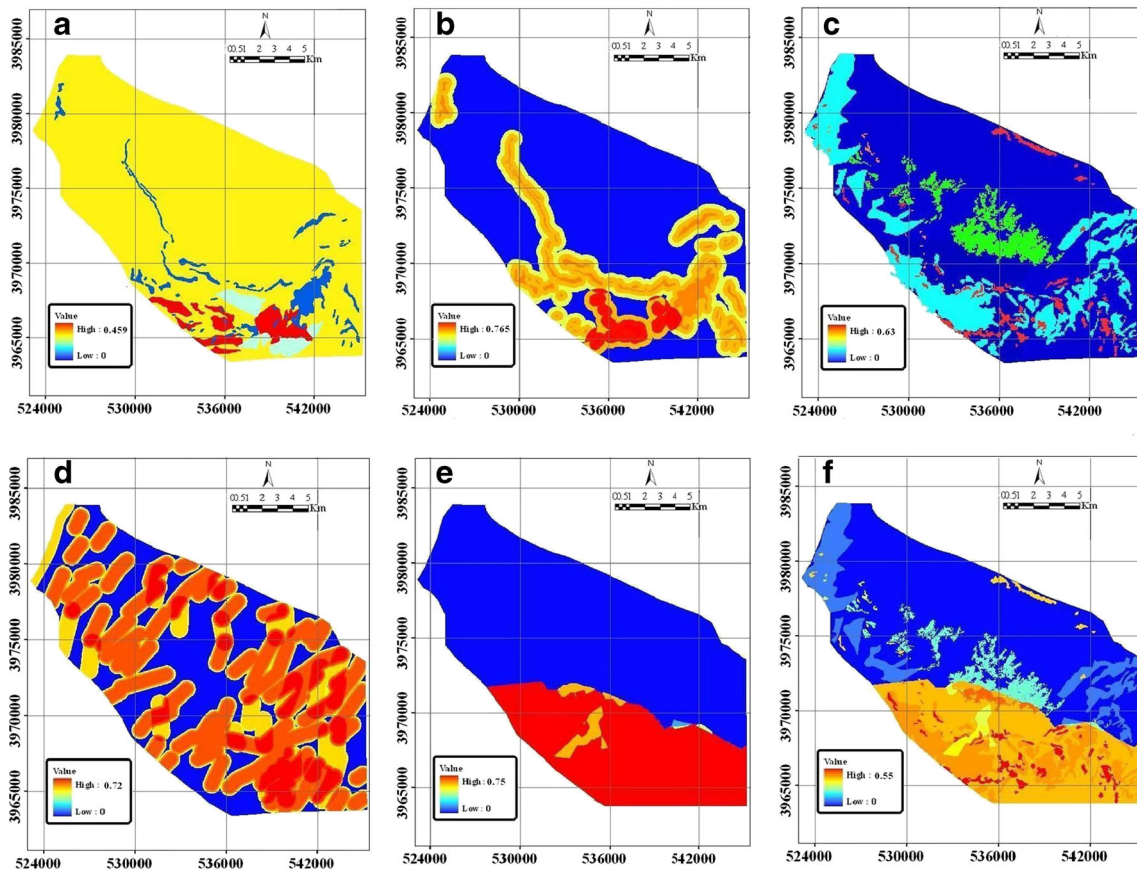
intrusive bodies, faults or certain types of hydrothermal alteration, is one of the most widely used association in mineral assessment (Raines 1999).

The study area has numerous features such as volcanic activity of Neogene, alteration related to widespread fracturing, existence of pyrite, chlorite, epidote and calcite associated with hydrothermal alteration, the main host rocks including intrusive porphyry and extrusive flow rocks and known gold occurrences that related to epithermal gold mineralization.

According to the exploration model, the following evidence maps were created:

- Volcanic units:** intermediate to felsic volcanic rocks such as dacitic dykes and microdioritic sills, dykes and stocks intruded volcanic flows and Karaj formation tuffs (Fig. 1). The volcanic flows where intruded by felsic rocks considered as possible host rocks. Field works revealed that andesitic-basaltic lava flows had more possibilities of mineralization than tuffs and andesitic flows. Thus, volcanic units were weighted based on geological and petrographic studies (Fig. 5a). Geological contacts of dikes and sills also considered as more possible location of mineralization. Dikes and sills were buffered up to 700 m and weighted based on geochemical studies by Geological Survey of Iran (Alavi et al. 2005) (Fig. 5b).
- Hydrothermal alterations:** field and petrographic studies revealed that phyllic alteration zone had more indexes of gold mineralization. However, some gold index was reported from the argillic and gossan zones (Asvadi 2004). The hydrothermally altered units were weighted for each alteration zone (Fig. 5c).
- Linear Structures:** Epithermal deposits develop along faults and fractures that formed in response to the region's major structural adjustments during volcanic events and considered as potential localizers for ore deposition (Boleneus et al. 2001). Structural and paleo-stress studies showed that the NE-SW and N-S conjugate sets are mostly strike slip faults with the north westerly characterized by dextral sense of movement, and primary ore mineralization is confined these structures (Eliasi and Ahmadian 2008). Thus, the NE-SW and N-S faults extracted from ASTER data and geological map of the study area were buffered with 100 m wide bands extending in all directions from each fault to 600 m and weighted based on the previous works e.g. Asvadi 2004 and Eliasi and Ahmadian 2008 (Fig. 5d).
- Geochemical anomalies:** Ag, Cu and Pb are paragenetic with gold mineralization. Combination of these members with fuzzy max-operator (Or) creates the maximum positive evidence for favorability outputs.





**Fig. 5** The reclassified evidence maps. **a** Host rock potential for mineralization, **b** Dikes and sills contact buffers, **c** Mineralization potential map in the hydrothermally alteration zones, **d** NW-SE and N-S faults buffers, **e**

Geochemistry evidence map developed from geochemical anomaly maps, **e** Ore forming potential map created from fuzzy SUM-Operator on geochemistry and reclassified weighted hydrothermal alteration maps

The Au anomaly combined with the other geochemical members output by fuzzy min-operator to control the smallest membership values and maximum paragenetic occurrences at each location. The geochemistry map created as an evidence of geochemical anomalies (Fig. 5e).

The evidence maps then fuzzified or rescaled from zero to one (from unfavorable to favorable for gold mineralization). Then, each rescaled evidence map was assigned a fuzzy membership values ( $\mu$ ) on the basis of the mineral deposit model. The weighting assigned to each evidence layer is also dependent on the relative importance of one dataset against another.

The rescaled evidential maps were integrated in complex combinations using variable fuzzy operators (Bonham-Carter 1994).

## Results and discussions

Petrographic studies revealed that the intrusive and volcanic rocks are rich in light colored minerals (68 % to 88 %) and poor in colored rock forming mafic minerals (4 % to 18 %). Thus, during the hydrothermal alteration process, the

hydroxyl group of minerals could have occurred much easily from alkali feldspar and plagioclases. The hydrothermally altered rocks display as green-blue while the magmatic units display green tones on ASTER enhanced images (Fig. 3b). However, satellite data analysis made it possible to identify chlorite–epidote, calcite–dolomite, sericite, alunite and gossan zones. As previously noted (Asvadi 2004), phyllic and propylitic alteration types are seen in the study area, while less amount of argillic alteration were detected (Fig. 3d). Silicic, kaolinitic and sericitic tuffs crop out besides the thick andesitic lava flows which are the hydrothermal phases related to small intrusive bodies and dikes. Hydrothermal alteration minerals such as pyrite, calcite, quartz, epidote and chlorite are present in faults and fractures.

Hydrothermal deposits develop along faults and fractures. Increased permeability along faults probably controlled the pathways followed by fluids that deposited metals and gangue minerals (Boloneus et al. 2001). Therefore faults and major fractures are considered as potential localizers for ore deposition. The major faults extracted from enhanced ASTER satellite image and geological map of the study area, and then NE-SW and N-S buffered with 100 m wide bands extending up to 600 m.



The fuzzy logic technique was used to construct a prospectivity mapping model for hydrothermal gold deposits and highlighted potential exploration targets in the study area. Some evidence maps were used for evaluating the importance of each data set in data analysis algorithm. Geochemical anomaly maps were derived from geochemical data sampling which are able to identify the local mineral anomalies.

Combination of evidence maps using fuzzy logic union operand (OR) made it possible to create an output, whose membership values are controlled by the maximum values of any of the input evidence. By using this operator, any positive evidence may be sufficient to suggest favorability. Fuzzy SUM operator used to show the equal contribution of alteration and geochemistry membership values, known as Ore Forming potential (OFP) map (Fig. 5f). Finally, the combination of suitable Host rock, geological structures and OFP using Fuzzy Gamma operator ( $\gamma=0.9$ ) is defined in terms of combination of the fuzzy algebraic product and the fuzzy algebraic sum, to develop mineral potential map (Fig. 6).

The prospectivity map highlighted three potential exploration targets for gold mineralization within the study area. These demonstrated targets compared with the results of the previous geochemical exploration project conducted in the study area. The predicted favorable zones coincide spatially with anomalous zones for stream sediment Au, Ag, Zn and Pb contents (Fig. 2) and suggested for future detailed exploration.

### Conclusion

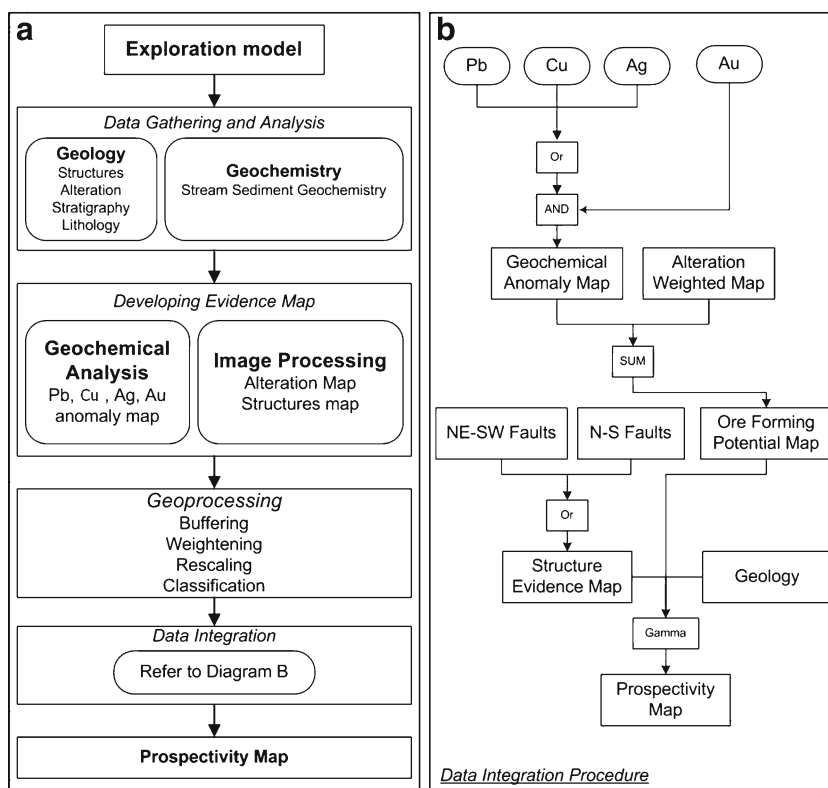
This paper is a case study of fuzzy logic modeling using ASTER imageries, geochemical and geological data to produce a prospectivity map of hydrothermal gold mineralization in central Alborz, Iran.

ASTER imagery used to map hydrothermal alteration zones and extract the structural lineaments. Based on the exploration model considered for the study area, appropriate evidence maps include hydrothermal alteration, geochemistry anomalies, host rock and structure maps were developed, weighted and reclassified. Finally, fuzzy operators are applied to produce mineral prospectivity map.

Mineral prospectivity map comparison with field studies and previous geochemical exploration project conducted in the study area revealed that the fuzzy logic model describes fairly well the favorability of the hydrothermal gold deposits in the study area. All produced maps in this study should be perceived as the preliminary evaluation of the study area in a reliable manner. The maps are a valuable data source for the detailed studies to be conducted in the future.

As a consequence, the use of satellite images for hydrothermal alteration mapping and spatial data modeling during the early stages of mineral exploration has been found to be very successful in delineating the hydrothermally altered rocks. Conceptual fuzzy-logic method also gives a flexible tool to test exploration models in an easily understood manner

**Fig. 6** Prospectivity models for hydrothermal gold deposits using fuzzy logic for integrating data from various sources as described in Fig. 4. Asterisks represent the known Au indexes



for geologists. The uncertainties of the fuzzy-logic modeling could not be estimated easily, but an expert validation process would in many cases be appropriate and lead to reliable results.

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