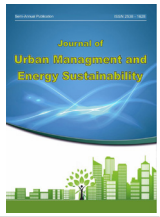
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CASE STUDY RESEARCH PAPER

Remote Sensing Studies and Satellite Image Processing for Mineral Potential Mapping nd Identification of Areas Prone to Mineralization in the 1:100,000 Borujerd Sheet

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ABSTRACT

Remote sensing is a rapid, low-cost tool for the early stages of mineral exploration, particularly in structurally complex terrains such as the Sanandaj–Sirjan zone of Iran. The 1:100,000 Borujerd sheet exposes a Triassic volcano-sedimentary sequence metamorphosed to greenschist facies and intruded by the Jurassic Borujerd granitoids, and it hosts high aeromagnetic anomalies and gold and copper occurrences; however, its alteration zones and structural controls have not been mapped systematically. This study aims to process and interpret Landsat ETM+ data to identify hydrothermal alteration, lineaments and lithological units and to delineate areas with high mineralization potential. After radiometric and geometric correction, band ratio 5/7, band subtraction, false-colour composites, the Crosta principal component technique and the software defoliant method were applied to map hydroxyl-bearing minerals and iron oxides, and directional and edge-enhancement filters were used to extract lineaments; the results were checked against the geological map and field observations. Iron-oxide, iron-hydroxide and argillic alteration zones were discriminated and show a close spatial relationship with faults. One group of alteration zones follows the older NW–SE faults in carbonate and metavolcanic units, whereas a second group lies along younger N–S faults and at fault intersections within the intrusive bodies. Integration of the alteration, lithological and structural layers delineated six promising areas, including the Nalkhast intrusive bodies, the northern and eastern margins of Kuh-e Nal, and the Mohsen Ebn-e Ali–Khayan metavolcanic belt. These targets warrant follow-up geochemical sampling and field verification.

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INTRODUCTION

Today, the use of diverse remote sensing data in the exploration of economic mineral deposits has become common practice in modern prospecting, and this gives these data particular value in mineral exploration. Because of the large areas they cover and their multispectral and multitemporal coverage, remote sensing data can be used to identify metallogenic provinces, belts and mineralization sites. Remote sensing and GIS are modern methods that are now used as valuable tools for detecting mineral deposits or for separating areas prone to mineralization from other areas (Asadi, 2000; Asadi & Hale, 1999). Systematic, targeted and staged exploration, together with the integration of its results, plays an important role in reducing the cost of mineral exploration and in the quality of the results obtained. Accordingly, in the reconnaissance, prospecting and preliminary exploration stages, satellite image processing is one of the tools that can contribute significantly to reducing exploration costs. Remote sensing data have a high potential for identifying alteration zones associated with ore deposits and, consequently, for exploring mineral deposits. Geological mapping and the identification of faults and fractures that control mineral deposits at regional and local scales play a major role in identifying prospective areas and in focusing exploration on the identified sites (Sabins, 1999). Applications of remote sensing data in exploration and geology generally include regional lineament mapping, local fracture mapping, mapping of geological units and identification of different mineral groups (Dalati, 1995). The 1:100,000 Borujerd sheet lies between longitudes 48°30′–49°00′ E and latitudes 33°30′–34°00′ N in the Sanandaj–Sirjan structural zone and covers an area of about 2580 km². The aeromagnetic map shows high and extensive magnetic anomalies (Fig. 1). Based on the results of the regional geochemical survey of the 1:100,000 Borujerd sheet (Mosadegh, 2002), the study area has been recognized as important in terms of mineralization potential, and further exploration has been recommended. Given the favourable geology of the Sanandaj–Sirjan zone, including its particular tectonic setting and the presence of metamorphic rocks and intrusive bodies, this area has a high potential for mineral exploration (Ghorbani, 2002). In this research, the exploration investigations of the study area are based on the processing of ETM satellite images, and the results are then integrated to delineate areas with high mineralization potential (promising areas).

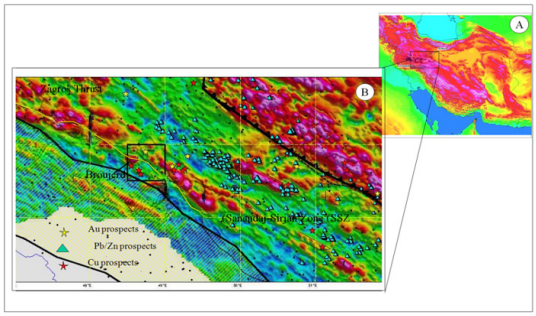


Figure 1: (A) Aeromagnetic map of Iran (areas shown in purple and red have the highest magnetic anomalies). (B) Aeromagnetic map of part of the Sanandaj–Sirjan belt: a high and extensive magnetic anomaly is observed in the Borujerd area.

MATERIALS AND METHODS

Geology

The study area is located in the Sanandaj–Sirjan tectonic zone, one of the large and important structural zones of Iran (Mohajjel et al., 2003). Tectonically and magmatically, this zone was affected by events related to the opening and closure of the Neotethys from the Late Palaeozoic to the Tertiary. According to the 1:100,000 Borujerd geological sheet (Hajmalali, 1991), the oldest known sediments in the area are Triassic pelitic and calcareous sediments, which are unconformably overlain by Jurassic sediments. The Upper Triassic–Jurassic rocks comprise phyllite, mica schist, quartzite, cherty limestone, and metamorphosed acidic and basic tuffs. After undergoing regional metamorphism, this assemblage was intruded by granitic, granodioritic and quartz-dioritic bodies. The intrusive bodies of the

area have two different compositions and morphologies, namely granitic bodies with low-lying topography and granodioritic bodies with rugged topography, and they have produced a contact metamorphic aureole in the Upper Triassic–Jurassic rocks. The most important geological event in the area is the emplacement of the Borujerd granitoid in the Middle Jurassic (Ghaderi et al., 2004), which intruded the phyllites. According to the 1:250,000 Lorestan geological map, the rock units of the region form two belts: the metamorphic and magmatic belt of the Sanandaj–Sirjan zone, which extends from the north–northeast to the south–southeast of the area, and the Zagros fold-and-thrust belt in the northwest to southwest of the area; their ages range mostly from Jurassic to Recent. The Borujerd igneous bodies (mainly granite and granodiorite) have intruded the metamorphic rocks. The presence of metamorphic rocks (mainly schist, slate, hornfels and marble) and the intrusion of acidic to intermediate plutonic rocks into them may favour contact-metamorphic mineralization in the northeastern parts of the area (western parts of Borujerd County). In the east of the Borujerd sheet (Khayan village area, 20 km southeast of Borujerd city), volcanic–metamorphic (metavolcanic) units underlie a metamorphic unit (marble). Talc mineralization occurs at the contact between these metavolcanic units and the adjacent sedimentary rocks and marbles. The Chaghalvandi unit (Kasian area), in the southwestern parts of the Borujerd sheet, mainly comprises Upper Jurassic volcano-sedimentary rocks that have been thrust over the sediments (Fig. 2).

The volcanic units at Kasian comprise volcanic and subvolcanic bodies that are locally accompanied by iron-oxide and argillic alteration. The Chaghalvandi unit also includes a tectonized coloured mélange (about 100 m × 45 km) composed of dolomitic limestones, calcite veins and radiolarian limestones. A very small outcrop of volcanic rocks occurs in the northwest of the sheet. A radiolarian limestone band and a small gabbro outcrop southwest of Vanaei village are comparable with the Kermanshah ophiolitic complexes. Talc mineralization occurs in the metavolcanic assemblages of the eastern parts of the Borujerd sheet, around Goushe Mohsen Ebn-e Ali village (east of Khayan village). According to the 1:5000 map, the stratigraphic sequence of the area is of Middle–Late Triassic age, trends NW–SE, and comprises an assemblage of metamorphosed submarine volcano-sedimentary rocks, including marble, quartzite, and an intermediate and basic volcanic suite with structures ranging from lava flows to tuffs. Petrographic studies show that the rocks of the study area include granite, granodiorite and quartz diorite; these bodies trend NW–SE and cover half of the study area. The granites and granodiorites of the Borujerd area have a granular texture, and an assemblage of metamorphic rocks, metamorphosed in the greenschist facies and exposed along a SW–NE direction, includes metavolcanics, hornfels, spotted schist, slate and marble. The alteration types

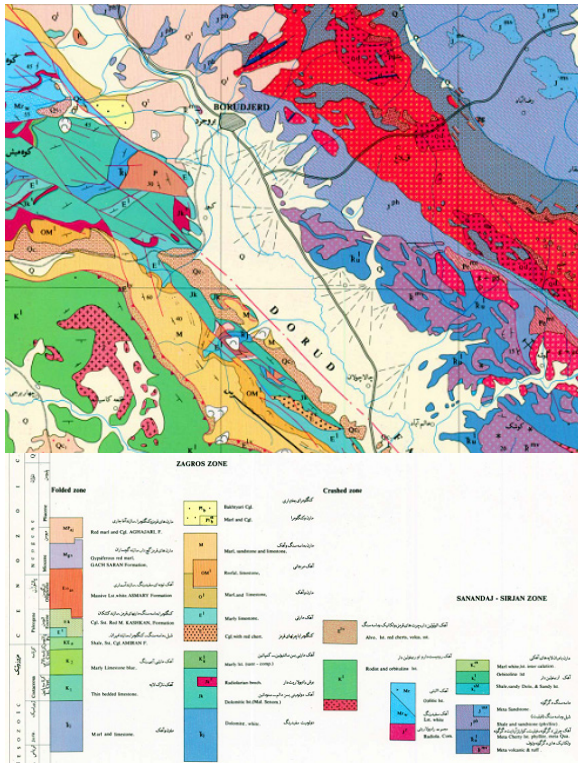


Figure 2: Part of the geological map in which the study area is located.

in the study area include propylitic alteration, observed in the Goushe Mohsen Ebn-e Ali area, and argillic alteration, which occurs sporadically in the granitic and granodioritic rocks. Chloritic and silicic alterations are also present. Because of its proximity to the collision zone between two tectonic provinces, this area has undergone particular deformation, such that all rock units have been thrust over one another from the northeast towards the southwest. The fault systems in the area are low-angle and compressional, and the thrusting is directed from north to south. The main faults trend NW–SE, following the main Zagros trend, and NE–SW-trending faults have displaced the first-generation faults (Akbari & Rasa, 2007).

FINDINGS AND DISCUSSION

Remote Sensing Studies

Landsat 7 ETM+ data (path/row 166/37) were used for this study. The sensor records six reflective bands at 30 m spatial resolution, a thermal infrared band (band 6) at 60 m and a panchromatic band (band 8) at 15 m (Chander et al., 2009; Flynn et al., 2001). In this project, bands 5, 1 and 7 were used because of their effectiveness in interpreting geological features. The 15-m panchromatic band 8 was mainly used to produce the outputs and to increase the spatial resolution of the images (fusion). The satellite data were obtained in GeoTIFF format without georeferencing; radiometric and geometric corrections were applied in ENVI software, and the data were then processed. After correction and subsetting of the study area, the histogram of pixel values in each band was examined separately, and interactive stretching was applied to enhance ground features in each band. The most important part of remote sensing work in an area is the interpretation of satellite data and their use in geology, which includes regional lineament mapping, local fracture mapping, mapping of geological units, identification of different mineral groups and assessment of the mineral potential of the area. At this stage, the processed data are presented as final outputs. Information extraction and identification of surface geological features from the images were carried out using two approaches: spatial and spectral pattern recognition. The resulting images were processed and interpreted as described below to detect and discriminate the controls on mineralization in the area:

Detection of probable alteration zones

Recognizing alteration zones is one of the criteria for identifying mineralized areas. If the type of alteration is also determined, it can help to define an appropriate model for mineralization in the area. Altered zones are identified using various processing methods, mathematical functions and statistical techniques. Probable alteration zones (clay minerals with OH groups, iron oxides, and propylitic alteration containing chlorite and epidote) were detected using the Crosta method (Crosta & Moore, 1989) and the software defoliant method (Fraser & Green, 1987). Training sites observed during preliminary fieldwork (alteration zones) were also used.

The study area consists of regionally metamorphosed rocks as the background, within which a contact metamorphic aureole formed as a result of the emplacement of the intrusive body. ETM data can extract and discriminate a number of minerals based on their spectral patterns. Spectral processing of the satellite data included input of reflectance/radiance data by scene, spatial subsetting, noise reduction and whitening of the bands, and the use of false-colour composite (FCC) analysis, band ratios and principal-component images (Berger, 2000; Tangestani & Moore, 2000) to identify anomalies for a preliminary investigation of spectral variability, followed by interpretation and validation of the results, which included integration with other information layers produced in a GIS environment to obtain the best results, ground control and the introduction of promising areas (Venkataraman, 2000). These methods were used to map the alteration zones of hydroxyl-bearing and iron-oxide minerals from ETM images of the

study area. The three main minerals in argillic alteration are illite, kaolinite and montmorillonite, to which alunite should be added in vein-type deposits. The diagnostic spectral features of these minerals lie in the shortwave infrared (SWIR) region. Considering the spectral response of these minerals, resampled to the ETM sensor in ENVI version 4, minimum reflectance is observed in band 7 and maximum reflectance in band 5. Therefore, ETM5/ETM7 ratio images can be used as an index for detecting altered areas. To identify hydroxyl-bearing minerals, the band ratio 5/7, PC4(5,7) and PC4(1,4,5,7), and band subtraction (5−7) were used. Hydroxyl-bearing pixels were detected by all these methods. For iron-oxide minerals, the diagnostic spectral features of all these minerals lie in the visible and near-infrared (VNIR) region. The Crosta method, with substantial modifications, was also used to detect iron oxides in the area. To identify iron-bearing minerals, PC3(1,3,4,5) was used (Tangestani & Moore, 2000; Zhang et al., 2007).

Accordingly, four bands (5, 4, 3 and 1) were selected (band 7 was excluded to avoid hydroxyl-bearing minerals, and band 2 was excluded because of its similarity to band 1) and entered into a principal component analysis. Given the spectral characteristics of iron-oxide minerals and field observations, pixels containing these minerals appear dark in PC4 of the principal component analysis. To display the zones or pixels containing iron oxides as bright, a negation was applied. A false-colour composite (RGB) of PC4, PC3 and PC2, with negation applied to PC4, shows the pixels containing iron-oxide minerals. In the eastern parts of the Borujerd sheet, about 25 km southeast of Borujerd city, an extensive area of OH-bearing minerals was interpreted using the above method; these zones are mostly associated with the metavolcanic rocks of the area. Because the Mohsen Ebn-e Ali talc occurrence lies in this area, these zones may correspond to hydrous magnesium silicates (talc). In the southwest of the Borujerd sheet (north of Kasian village), the volcanics of the Chaghalvandi unit are slightly affected by argillic alteration. In addition, because the reflectance spectra (infrared absorption features) of limestones are similar to those of hydrous clay minerals (argillic alteration), limestones under particular conditions may in some places have been mapped together with argillic alteration.

One type of alteration, including iron oxides in carbonates and metavolcanics, follows the NW–SE fault trend, whereas a second series of alteration, comprising iron-oxide and argillic alteration, has been identified mainly within the intrusive bodies, along N–S faults and at fault intersections. This overlap reveals the relationship between alteration zones and tectonic zones. The role of structural features, including folding, joint and fracture systems and faults, in the emplacement of intrusive bodies and the development of hydrothermal alteration is very important. Fracture density (lineament density) in the area is high. These fractures can store and transmit large volumes of groundwater and hydrothermal fluids, which is an important factor in identifying areas with mineralization potential (Figs. 3–5).

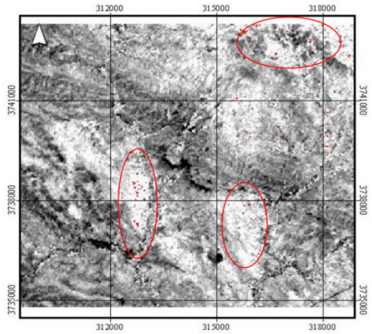


Figure 3: Bright pixels show intrusive bodies, and red pixels show probable alteration zones based on their spectral pattern.

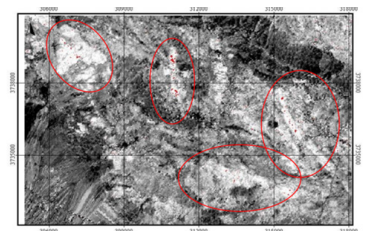


Figure 4: Bright pixels correspond to metavolcanic units, and red pixels show iron-bearing minerals.

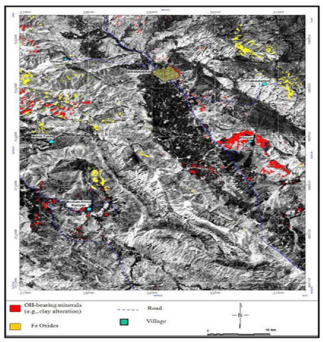


Figure 5: Enhancement of hydrous minerals and iron oxides in the 1:100,000 Borujerd sheet.

Detection of geological structures such as lineaments and faults

Satellite images enable geologists to identify the relationship between ore deposits and regional linear structures. In a metallogenic province, the abundance of fractures and lineaments can guide ore exploration, because fractures act as conduits for ore-forming fluids. Local fractures can also be detected in satellite images using various image processing methods, such as filters that enhance linear features. However, although structural features play an important role in the formation of mineralized zones, not all of these structures are necessarily related to mineralization. Therefore, examining their relationship with hydrothermal alteration in the area is the next step in exploration. To detect structures, false-colour composites (RGB), principal component analysis and directional filters (3 × 3 and 5 × 5 kernels to detect faults with different azimuths) were used. Linear structures resulting from tectonic activity, especially faults, are an important factor in the formation of mineral deposits and play a significant role in the formation of an orebody. To better discriminate and enhance structural features, low-pass filters, such as a 3 × 3 median filter, and high-pass filters, such as edge detectors, were applied to the satellite images in different bands (Nezampour, 2006). The identification of lineaments, together with field observations, made it possible to evaluate indicative patterns for identifying promising areas.

The ETM data of the Borujerd sheet were examined to detect structural features. Based on the images and the results of ground control, the activity of the main faults in two directions, NW–SE and NE–SW, can be recognized (Fig. 6). Because of its proximity to the collision zone between two tectonic provinces, this area has undergone particular deformation, such that all rock units have been thrust over one another from the northeast towards the southwest. The location of the Borujerd sheet in the Sanandaj–Sirjan zone and parts of the folded Zagros has produced distinctive structural features in the area. The main group of faults, which trend NW–SE following the main Zagros trend, lie at the contacts between different rock units and are the oldest faults in the area. The second group of faults trends NE–SW; these faults mostly cut the intrusive bodies and their surroundings and have displaced the first-generation faults. They are younger, and the main drainage channels also follow this trend (Akbari & Rasa, 2007).

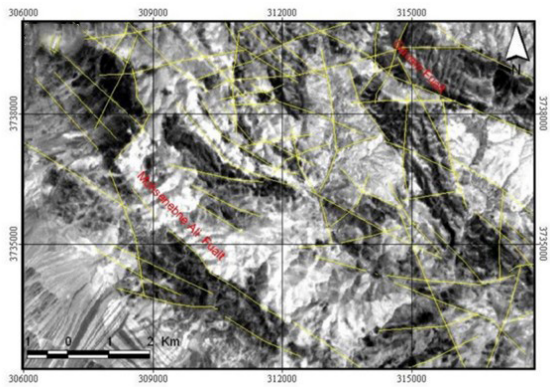


Figure 6: Map of linear features interpreted from ETM images of the study area.

Discrimination and identification of rock units

In identifying rock units that are in some way related to mineralization, a particular rock unit may be the source of the element of interest, depending on the type of commodity sought. Identifying the rock units of the study area therefore has a considerable effect on recognizing promising areas.To identify these rocks, false-colour composites, supervised classification, the geological map and the reflectance spectra of the target

rocks were used. Metavolcanic, metamorphic and granitoid rocks are located in the northwestern parts of the Borujerd sheet, southeast and east of Borujerd city. These rocks can be clearly distinguished from one another. Granites appear in light tones, granodiorites and quartz diorites in light yellow, and metavolcanic rocks in green (the Khayan village area in the east of the Borujerd sheet, outlined by closed red lines, which has high talc potential). Metamorphic rocks appear dark brown (hornfels black), and vegetation appears blue.

RESULTS AND CONCLUSIONS

Integration of the maps of rock units, alteration zones and tectonic structures with field checks showed that the tectonic structures have two main trends with high fracture density, and that the relationship between alteration zones, fractures and areas prone to mineralization can be recognized in the study area. Therefore, based on these studies, the intrusion of the Jurassic intrusive bodies of the Borujerd area (Ghaderi et al., 2004) into the metamorphosed Triassic sedimentary–volcanic sequences can be considered a target for finding high mineralization potential. Most of the mineralization in the area is directly or indirectly related to the intrusive bodies.

Based on satellite image processing, promising areas and areas with potential for different types of metallic and non-metallic mineralization were identified in the area:

-North of Mohsen Ebn-e Ali village: this area consists of a metamorphosed sedimentary–volcanic sequence in which iron-bearing minerals aligned with the NW–SE (older) faults were identified.

-Promising areas in the eastern and western Nalkhast intrusive bodies and their surroundings: given the results of satellite image interpretation, including iron-oxide and argillic alteration, the influence of faulting and the proximity of the intrusive body to carbonate units, this area can be considered promising.

-North and east of Kuh-e Nal: according to the remote sensing results, the intrusion of the granodioritic body into metavolcanic units and carbonate rocks, the intersection of several faults, and alteration aligned with the N–S (younger) faults are significant.

-The southwestern part of the area around Kasian village, in the altered volcanic and subvolcanic units and some limestones of the Chaghalvandi unit.

-The Khayan village area, in volcanic, subvolcanic and metavolcanic units.

-The northwestern part of the area (east and southeast of Vanaei village).

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